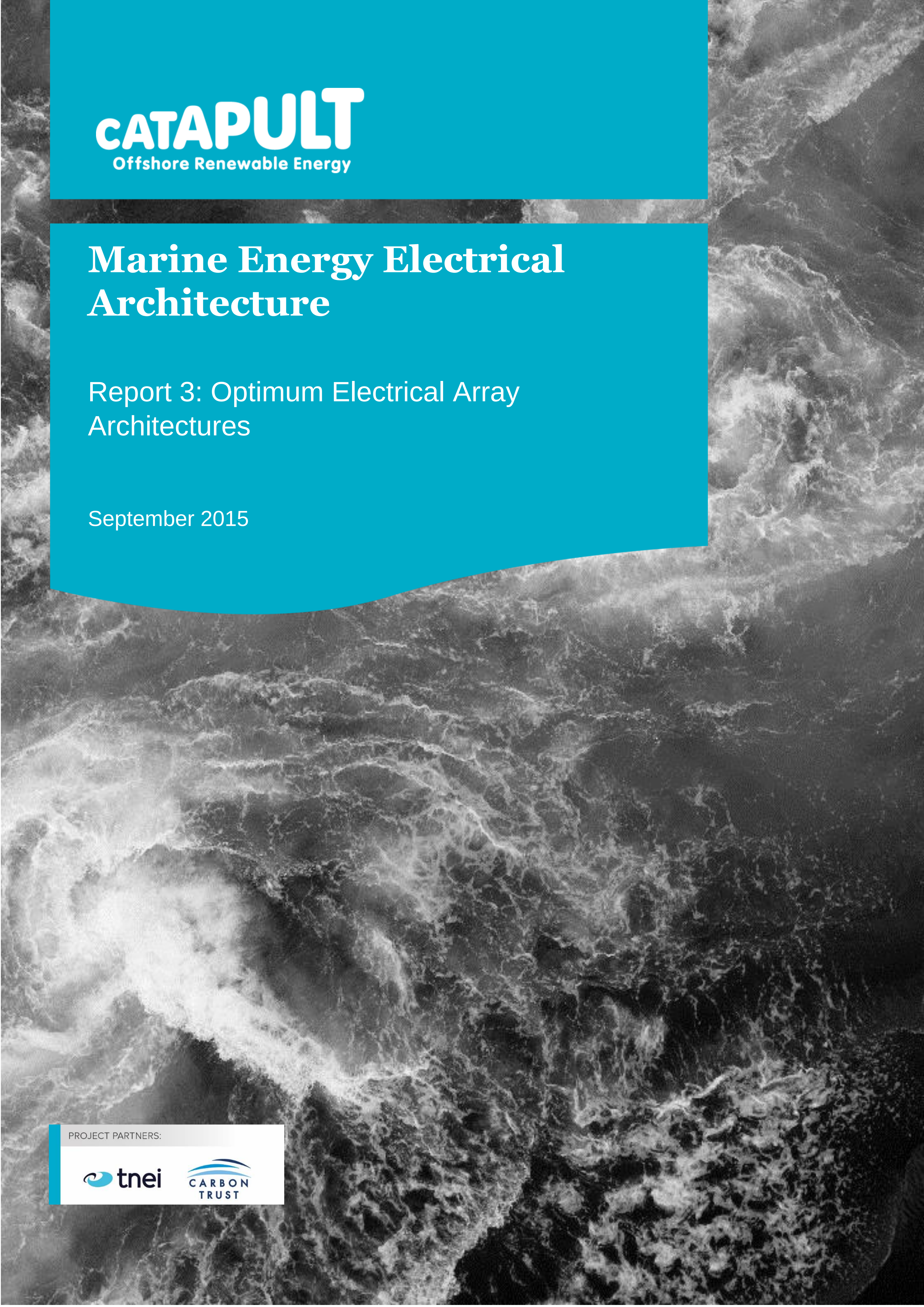

CATAPULT
Offshore Renewable Energy

Marine Energy Electrical Architecture

Report 3: Optimum Electrical Array Architectures

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1 Executive summary

The wave and tidal sector is moving from single device demonstration sites to multi-device arrays. One of the challenges the industry faces is the design of a cost effective and efficient electrical network to collect and transmit power from these devices to the shore. For some projects, such as MeyGen in the Pentland Firth, the solution is to connect each turbine to the shore individually. However, for projects further from shore or with complex landfall conditions, a marine electrical array will need to be designed and built. This report was commissioned by the Offshore Renewable Energy (ORE) Catapult under the umbrella of the Marine Farm Accelerator to investigate an optimum architecture for such arrays. Based on previous work on the subject, the report looks at a number of options for marine array electrical architectures. Taking into account feedback from manufacturers and developers, four options for multiple device connection were identified. These were:

- Direct Connection;
- Surface Piercing Hub;
- Floating Hub; and
- Subsea Radial Network.

Each of these connection options was analysed and an estimation was made of the relative Capex and Opex costs. In addition, the technology required to realise each option was also investigated and specific areas of development identified. Direct connection of individual devices using horizontal direct drilling is a method that is already in use but costs of using this method build up rapidly as the marine farm moves further from the shore. For marine farms at any distance from the shore, surface piercing hubs represent the least risk in terms of available technology but may be expensive to build and may have consenting issues. Savings can be made in the use of floating hubs but these will require the adaptation of existing technologies. The least expensive option would appear to be subsea radial arrays. However, these will require the development of new subsea plant using existing components and will present challenges in terms of deployment and cable management. It is clear that technology development opportunities exist that will allow the future cost of constructing a marine electrical infrastructure to be reduced.

In the future, the marine farm developer will have a crucial role in deciding on an optimum design of marine farm architecture. They will have to make the difficult decisions on issues such as device type and connection options. They will have to take into account not only the capital cost but also the inherent difficulties with servicing marine energy devices. These decisions and the experience gained from early projects will ultimately shape the development of the most efficient marine energy electrical architecture. This report attempts to provide some information on the unique set of challenges that marine energy devices place on any electrical system.

Although a tidal device resembles a conventional offshore wind turbine, the electrical system of a marine device means that the array designs used for wind turbines will not always work or are not the most efficient method for connecting marine energy devices. This study started by looking at the common electrical architectures of marine energy devices. It was clear that the electrical architectures varied from device to device. The voltage generated by marine devices is less than those of offshore wind turbines with the result that the output current is much higher. In addition, many of the devices opted to output power at variable frequency with the result that a location for a power converter needed to be found in the architecture remote from the device. In this instance, it is likely that the converter will be located above the waterline. Taking these and other constraints into account, it was necessary to look at alternatives to the standard radial array for architectures that could meet the requirements of all wave and tidal devices. A ‘star cluster’ hub-based layout where the devices individually connect to a central hub was identified as the arrangement that met all the requirements. In this arrangement, each device individually connects to a central hub. If the devices connecting are variable frequency, the hub can contain the required number of converters. In addition, the hub will also house a transformer to step up the voltage and reduce the electrical losses incurred transmitting the electricity to the onshore connection point. Once this architecture had been identified, a number of options regarding the modular arrangement of 4, 6, 8 and 16 device hubs were investigated. A single hub servicing 16 devices was shown to be the most cost effective, as the cost of the hub structure was split between the 16 devices. It is currently possible to construct a classic wind farm radial array but this is only feasible with devices that produce fixed frequencies. The devices are also limited to a small number and need to be sited close to shore. A possible design utilises subsea transformers to increase the capacity of a radial array. However, as noted above, it will be up to the developer to decide on the risk and cost of using subsea transformers and whether this is the best option for the particular project.

2 Introduction

This is the third and final report for the Marine Farm Accelerator electrical architecture project. The project was commissioned by the ORE Catapult under the umbrella of the Marine Farm Accelerator and carried out by TNEI Services. Over the next few years, marine energy converters (MEC) in the form of wave and tidal devices will develop from single device demonstration projects to multi-device commercial arrays. As they do, they will require a cost effective and reliable way of transmitting power from multiple machines to an onshore grid connection point. The Marine Farm Accelerator has acknowledged a need to identify a preferred marine electrical architecture that can be adopted by as many wave and tidal devices as possible. This report builds upon two previous reports completed as part of this project, which are:

1. Report 1 : Landscape Map and Literature Review (WP1) and;
2. Report 2 : Review of SSE Contractor Reports (WP2)

Report 2 examined the previous concept studies carried out by GE[1], ABB[2], and Siemens[3] on tidal arrays (the stakeholders summary report was also reviewed[4]). At the start of the project, there were no preconceived ideas of what form an optimum array architecture should take. The intention was to develop an array architecture to meet the needs of the device manufacturers and the project developers. By taking this approach, it was possible to use the stakeholder response to filter out designs that were not currently technically or commercially viable. Architectures that relied on large amounts of electrical plant on the seabed were ignored. Discussions with developers indicated that the preference was to keep as much technology as possible above water due to issues surrounding access for repair and maintenance. As a result of this filtering, four candidate architectures presented themselves; one that involved horizontal direct drilling; two that were based on the star cluster hub formation and one based on a radial formation. The star cluster hub formation can be developed using either surface piercing or floating hubs and will work with fixed frequency or variable frequency devices, while the radial network will only work for fixed frequency devices.

This report starts with a review of the findings of WP1 and WP2. This shows how the information gained through stakeholder engagement activities and a literature review has informed the development of an optimum electrical array. It provides an overview of which devices could connect to such an array and how their operation affects the design of the array. The following section discusses the requirements placed on a marine energy electrical array other than the main electrical connection and how this will affect the array design. The concepts of collection, aggregation and transmission are introduced which allow each section of

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[1] http://www.scottish-enterprise.com/~/media/SE/Resources/Documents/STUV/Tidal-Electrical-Architecture-Report-GE
[2] http://www.scottish-enterprise.com/~/media/SE/Resources/Documents/STUV/Tidal-Electrical-Architecture-Report-ABB
[3] http://www.scottish-enterprise.com/~/media/SE/Resources/Documents/STUV/Tidal-Electrical-Architecture-Report-Siemens
[4] http://www.scottish-enterprise.com/~/media/SE/Resources/Documents/STUV/Tidal-Concept-Studies-Sector-Stakeholders-Summary-Report

an array to be defined by its function. The components that are required for the development of an array are discussed and are rated in terms of technology readiness level (TRL). One of the main considerations in developing the array architectures is to try and use components that are commercially available and have proven to be reliable. In some instances, such as the floating hub and radial network, existing technologies will require further development in order for the successful integration of the component to be fully realised. Where this is the case, it has been made clear that these options will not be viable until the specific component required has been developed.

With this background in place, the array options available to marine devices are examined. The constraints in place on the array design by the device electrical architecture and the project location are assessed. The choice of how device type (fixed frequency or variable frequency output), the size of project, and the distance to the connection point, will dictate the optimum array architecture for the site is reviewed. The array concepts are then developed into possible options for commercial arrays. A modular approach is taken and star cluster hub arrays are built up using 4, 6, 8 and 16 device hubs of 2 MW machines to build up a basic 32 MW array. Both surface piercing and floating hubs are considered and comparative Capex and Opex calculations are presented for both systems. A similar analysis is carried out for radial arrays and considers the architectures from the perspective of the voltage output of the device from 6.6 kV to 33 kV. The result of the research showed that the most mature option, the fixed hub, was the most expensive. Both floating hubs and radial networks were less costly in terms of relative Capex and Opex and will represent areas where cost reduction will be possible. However, both these options are riskier and will require further development and demonstration before they will be ready for commercial deployment.

3 Work Package 1 Overview

3.1 Introduction

Work Package 1 consisted of a literature review and the development of a landscape map of wave and tidal device types. As the design of offshore arrays is in its infancy, the research undertaken was important in providing the information required to guide the design of an optimum array architecture. The landscape map aspect of the study was central to providing an overview of the diversity of devices available to construct a wave or tidal farm. Previous theoretical work on marine electrical arrays tended to look at the design of the array and then look for a wave or tidal device to work with that particular architecture. The starting point for this project was to look at the devices available to a developer and come up with a set of optimum electrical array architectures. At the time of writing there are a number of devices on the market that are ready for installation into a commercial array. All of these have settled on an internal electrical architecture and they are unlikely, in the near future, to redesign electrical systems of the machine to suit particular type of electrical array architecture.

The literature review concentrated on three major publications and various conference papers. The main publications reviewed were:

- Electrical Design for Ocean Wave and Tidal Energy Systems, Raymond Alcorn and Dara O’Sullivan (400pp), IET Publications 2013;
- Integrating Wave and Tidal Current Power, numerous authors: operating agent: Gourd Bhutan, Powertech Labs, Canada (178pp), International Energy Agency Implementing Agreement on Ocean Energy Systems 2011; and
- State of the Art Assessment and Specification of Data Requirements for Electrical System Architecture, numerous authors (94pp), DT Ocean Deliverable 3.1, European Commission’s 7th Framework Programme 2014.

All of these were informative on a wide number of subjects relating to wave and tidal devices and all covered electrical array architecture. The array architecture analysis tended to be based on offshore wind farm array architecture. This resulted in architectures that assumed that the turbines were fitted with power converters (which many are not) and that it would be easy to loop a cable in and out of a turbine to produce a radial array. As the study carried out for WP1 revealed, subsea cable connectors for turbines (either wet or dry mate) are an expensive component of the electrical system and it is neither economical nor practical to expect a device manufacturer to install an additional set of connectors. While there is some crossover with the offshore wind industry, the array architecture for marine energy devices presented a unique set of constraints which informed the direction of this study.

3.2 Device Types and Definitions

3.2.1 Introduction

Stakeholder engagement involving 16 device manufacturers was carried out and this yielded 10 responses. Additional information was gathered from manufacturer websites and sources such as conference presentations. From this, it was possible to start to classify devices in various categories. This helped in categorising turbines into different classes with the same common requirements for an electrical array.

3.2.2 Wave or Tidal, Fixed or Floating?

Figure 1 shows sixteen devices categorised as either generating energy from the tidal stream or wave motion and considers whether it is floating or fixed to the seabed. From this study, a number of broad statements can be made:

- Most tidal devices are fixed to the seabed and most wave devices are floating. The exceptions being Scotrenewables and Nautricity that have floating tidal devices and Aquamarine Power who have a seabed fixed wave device. The Tocardo T series and Schottel STG generators are platform-agnostic and can be installed on a floating or fixed device.
- Most tidal devices have a horizontal axis 2- or 3-blade design (similar to a wind turbine) with the exception of OpenHydro and Nautricity devices.
- Aside from the Wello Oy devices, wave devices tend to produce energy by hydraulic systems. This is either converted to electricity on the device or is used to transmit pressurised water to shore. Once onshore the pressurised water is converted to electricity using a pelton turbine. Both Carnegie and Aquamarine have signalled their intention to start to generate electricity on board the machine in future designs.

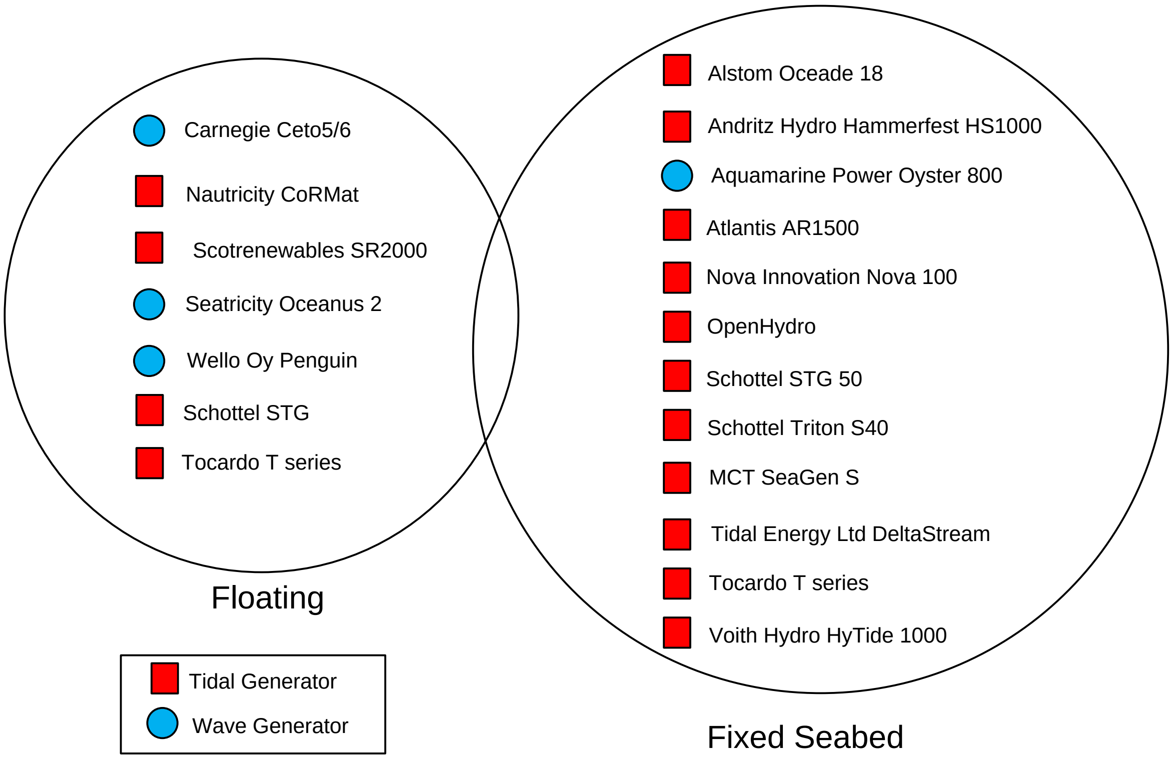

Figure 1 Overview of Marine Energy Converters

3.2.3 Converter Location

As the majority of tidal devices resemble wind turbines it is commonly assumed that they contain the same electrical systems as a wind turbine. A closer look at the electrical systems of the individual devices shows that this is definitely not the case. The main difference is that while all wind turbines contain some sort of power conversion as part of the electrical system many tidal stream devices elect to do their power conversion remote from the device (a full description of the role of the power converter is given in Appendix 1). In the design of an electrical architecture for a marine farm whether the machine has on board conversion or not will the first decision point that the developer will need to make. Choosing a generator only device will mean that a there is less technology situated subsea which, in theory, means that the system will be more reliable. However going down the generator only route places a number of constraints on the designer and these will be discussed fully as part of this report. Choosing a device with an on-board converter will allow more options with regards to the design of the electrical array but with the possible additional burden on operation and maintenance of having power conversion situated subsea. A list of commercially available devices is listed in Table 1. This shows that the market is fairly evenly split between generator only devices and devices with on-board conversion. The MeyGen project first phase will use three Atlantis machines and an Andritz / Hammerfest Machine. For this project each machine will be individually connected to a converter situated in an onshore enclosure. In this instance the developer has decided to situate the power conversion onshore to make it easier to carry out repair and maintenance. However, as will become clear, this arrangement is only possible as the turbines are situated relatively close to the shore / grid connection point. Reliability and availability data will improve as the industry develops and this will allow developers and designers to make informed decisions as to the best location for the converter.

3.2.4 Fixed and Variable Frequency

Whether or not the device has on board power conversion will form the basis for much of the discussions regarding the various array architectures. In order to distinguish between devices that have on board converters from those that don't, the terms fixed frequency and variable frequency are used. Fixed frequency refers to those devices with converters and variable frequency refers to those that don't. This definition has been chosen as, in most cases, the output of a generator used in marine devices is at variable frequency while the output of a converter is fixed at grid frequency which in the UK will be 50Hz.

Device	**Voltage**	**Notes**
Devices with Converters or Rectifiers (Fixed Frequency)		
Alstom Oceade 18	6.6 kV	1.4 MW machine
Tocardo T Series	400 V	500kW PMSG with converter
Carnegie Ceto 6	11 kV	Hydraulic to electrical conversion in device
Scotrenewables SR2000	6.6 kV	
Wello Oy Penguin	11 kV	1 MW floating device with all equipment on board
Tidal Stream Triton	13.8 kV	Uses 40 Schottel STG turbines in groups of 10 gathered onto a DC bus.
Nautricity CoRMat	3.6 kV DC	Device uses Permanent Magnet Axel Flux Generator passively rectified to DC
Albatern	1 kV DC	PMSG with passive rectifier
Generator-Only Devices (Variable Frequency)		
Andritz Hydro Hammerfest HR1000	<6.6 kV	Permanent Magnet Synchronous Generator
Atlantis Resources AR1500	<6.6 kV	Induction Generator
Nova Innovation Nova 100	-	Voltage not available
OpenHydro	-	Voltage not available. Device uses Permanent Magnet Synchronous Generator
Schottel STG	440 V	4 Pole Asynchronous Generator
Tidal Energy Limited DeltaStream	6.6 kV	Induction Generator
Voith Hydro	-	Voltage not available. Device uses Permanent Magnet Synchronous Generator
Hydraulic Devices		
Carnegie Ceto 5	NA	
Seatricity Oceanus 2	NA	Onshore conversion of hydraulic to electric energy using a pelton turbine
Aquamarine Power Oyster	NA	Next generation will be fitted with a WavePod power conversion device

Table 1 List of Device Types

3.2.5 Voltage Levels

Along with the converter location, the voltage level at which an array operates at is one of the other major factors in the design of an electrical array architecture. Historically, the offshore wind industry has adopted 33 kV 50Hz AC as a preferred collection voltage. Taking a device-led approach, it is clear from Table 1 that the manufacturers have settled around a voltage between 6.6 kV and 11 kV. Operating at 33 kV has the advantage of reducing transmission losses and array cable sizes. However higher voltages place a larger burden on the design of the device as extra insulation and separation of components has to be considered. Space is at a premium in marine energy devices and this may be the reason why devices that generate at 33 kV are not being produced. This will particularly be the case for generator-only devices where generator size increases with the voltage due to insulation requirements. In the short and medium-term, any marine device architecture for a collection network is expected to operate at between 6.6 kV and 11 kV.

3.2.6 Subsea Connectors

The research carried out in WP1 showed that subsea connectors are the third limiting factor in the design of a subsea network besides output voltage and current. Most of the devices reviewed had removable electrical connections. These were either dry mate, where the connection is made on the surface but is watertight, or wet mate where the connection can be made underwater. The advantage of a wet mate connector is that it reduces the time that it takes to disconnect a device for service and repair. In addition the device can also be installed prior to connection and large cable loops on the seabed floor can be avoided. The disadvantage is that they are currently a costly component of the electrical infrastructure. They also impose a limit on the take-off voltage of the devices they are fitted to. From the manufacturers that responded, this would seem to be up to 6.6 kV. As the voltage level increases, the size of the wet mate connector will increase and it may become difficult to integrate it into the overall device design. At present, any electrical array architecture that can be used with wet mate connectors is limited to voltage in the region of 6.6 kV. Wet mate connectors which can handle larger voltages are under development. Once and when these are tested and proven, it will then be possible for the manufacturers to look at designing machines that output at higher voltages. An increase in voltage levels is likely to incur an increase in costs for each device. However the increased voltage level will remove the constraints in terms of distance and number of devices connected that are currently in place.

3.2.7 Commercial and Demonstration Sites

As part of the research carried out in WP1, developers and test site operators were asked how they approached the challenge of developing an electrical array. The responses were interesting as they showed the diversity of approaches that can be taken. The MeyGen project will use two different tidal energy converters; three fitted with a PMS generator and one fitted with an induction generator. All of these machines will have an individual connection to shore where it will connect to its own power conversion equipment situated in a building onshore.

There is a similar set up at the European Marine Energy Centre (EMEC) in Orkney where each test bay consists of an individual connection. The WaveHub test centre in Cornwall has four testing bays for wave devices but due to the distance from the shore and the grid connection point (25 km in total) the direct connection of each device is not practical. This site uses a passive hub which sits on the seabed. This contains four bays and it able to connect two pairs of devices at either 11 kV or 33 kV.

4 Work Package 2 Overview

In 2013, SSE Renewables and a number of other industry stakeholders commissioned three concept engineering studies investigating the electrical infrastructure required to connect commercial-scale tidal arrays. General Electric, Siemens and ABB were commissioned to produce reports looking at the development of arrays with an installed capacity of 30 MW - 200 MW. The resulting reports provided a number of further development recommendations but did not provide a consistent view as to the development of an optimum array architecture. WP2 of this project involved a detailed review of these three reports to see if they contained any concepts that could be used to inform the direction of this piece of work. Taken as a whole, the 3 reports present seven system concepts:

- One looking at connection to an onshore converter;
- Two looking at radial connections; and
- Four looking at a hub arrangement.

The common approach of all the contractors was to develop the array concept first and then assume a device design that would work with it. This led to the development a number of architectures using DC transmission as well as architectures where a large amount of the electrical plant was situated subsea. Discussions with developers revealed a strong preference for locating electrical infrastructure plant onshore or, if that was not practical, on the sea surface. Taking these findings into account, many of the proposed concepts in these reports are unlikely to be developed as they would be unattractive to developers. However, once the marine energy sector matures, these reports will provide some useful pointers into the development of alternative generating technologies.

The GE report covers the issue of zero sequence currents and the effect of these currents will need to be considered for the proposed hub configuration where the generator and converter are at different locations. There will be circulating current caused by the differences in the generator winding capacitance to ground and the converter capacitance to ground. If no protective measures are taken to prevent the circulating current, the electrochemical erosion of any sacrificial anode or metallic part in direct contact with sea water will occur. The GE report offers a number of measures to mitigate this effect.

5 Introduction to Subsea Electrical Arrays

5.1 Introduction

In much of the early work carried out on the subject of subsea electrical arrays, the techniques developed in the offshore wind industry were used as the basis for the conceptual design of those available for marine energy devices. The assumptions made were that tidal devices could be considered as subsea wind turbines and would behave in the same way. The electrical system would be similar with a generator, converter, transformer and switchgear. The unit would generate at 33 kV AC and be able to handle multiple cable connections. In reality the marine energy converters that have been developed do not meet these requirements. Some do not have converters and all of them generate at voltages of 11 kV or less. The majority of the devices only consist of a single cable connection so are not able the handle the multiple cable connections required for a radial (or branched) array. In designing an optimum array architecture it is necessary to take into account the constraints placed on the system by the design and operating behaviour of the various devices.

An electrical array for a marine energy system has a number of functions other than the primary purpose of high voltage power transfer. It also has to be able to accommodate an auxiliary power connection to each device as well as providing a communication network between the devices. These requirements will differ depending on whether the device generates at a fixed frequency (has a converter in the unit) or is variable frequency (generator-only). This section will look at how the differing requirements of each class of device will need the development of different architectures. This section will initially look at the array requirements for seabed fixed devices and move on to discuss the additional requirements for floating devices.

5.2 Marine Array Electrical Network

The IEA report reviewed in WP1 provided a useful method of categorising the function of each part of a marine array electrical network. The network is split into 3 elements: collection, aggregation, and transmission that cover the network from the connection to the device to the grid entry point. The definition of the three elements is as follows.

Collection: This describes the cable system from a single device to the location where it connects to the aggregation section of the electrical network. This could be a converter collection bus bar or multi way hub/ connector depending on device type and layout. It will include the connection to the device via wet mate or dry mate connectors. For floating devices the collection system will become more complex as it will involve dynamic umbilical cables.

Aggregation: This describes the section of the network were a number of machines are connected together electrically. This can only be done post-converter where the power output of each machine has been converted to fixed frequency. For devices with on-board converters, the aggregation can happen using the cable network. For devices without on-board converters, this will happen elsewhere in the network depending on where the converters are located.

Transmission: The transmission section of the network is where the output of all or part of the aggregation network is stepped up in voltage. This is done for a number of reasons;

- To match the marine farm output voltage to the grid connection point voltage;
- To reduce the current; and
- Reduce the losses and increase the transmission distance.

To illustrate this Collection, Aggregation and Transmission concept it is worth looking at a few examples. Figure 2 shows a simplified example of the arrangement used for the first four tidal energy converters (TECs) installed at the MeyGen site. The TECs do not have on-board converters so the collector network (blue) will consist of the cable connection from the device to the machine-side converter. The aggregation (red) will take place on the bus bar that connects the grid-side connectors together. Transmission (green) happens in the same building and the output of the tidal farm is connected to the local network. This type of configuration is only possible when the site is close to shore and it is possible to run a cable directly to each device. At larger distances the transmission losses will reach a level where it becomes more practical to place the electrical infrastructure offshore.

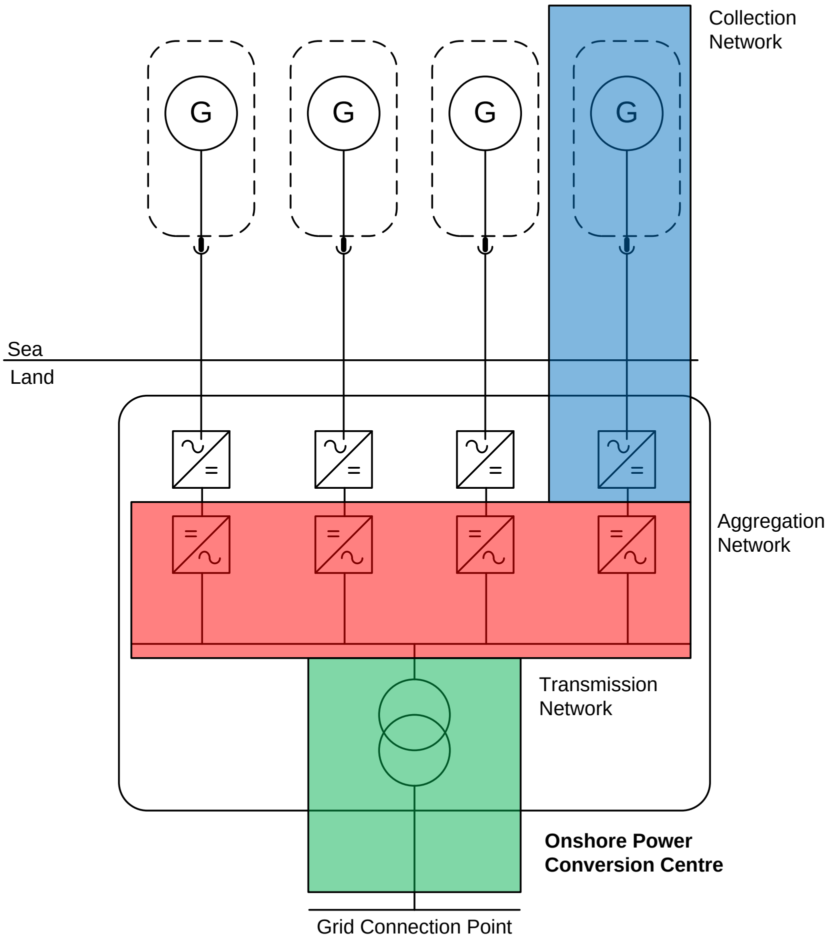

Figure 2 Generator Network

Figure 3 shows an alternative configuration that can be used when the devices are fitted with a converter and can generate at a fixed voltage and frequency. In this instance the individual cable connections from each device to the hub are the collector network, the aggregation happens at the bus bar connected to the input of the step-up transformer. Transmission in this case happens on the offshore hub but if the tidal farm was close enough to shore this transformation could happen onshore with the aggregation happening on an offshore surface piercing or submerged hub (this is the arrangement of the WaveHub facility). This arrangement is sometimes called a ‘star cluster’ as the individual machines radiate from a central core. It will be one of the topologies considered later on in this report.

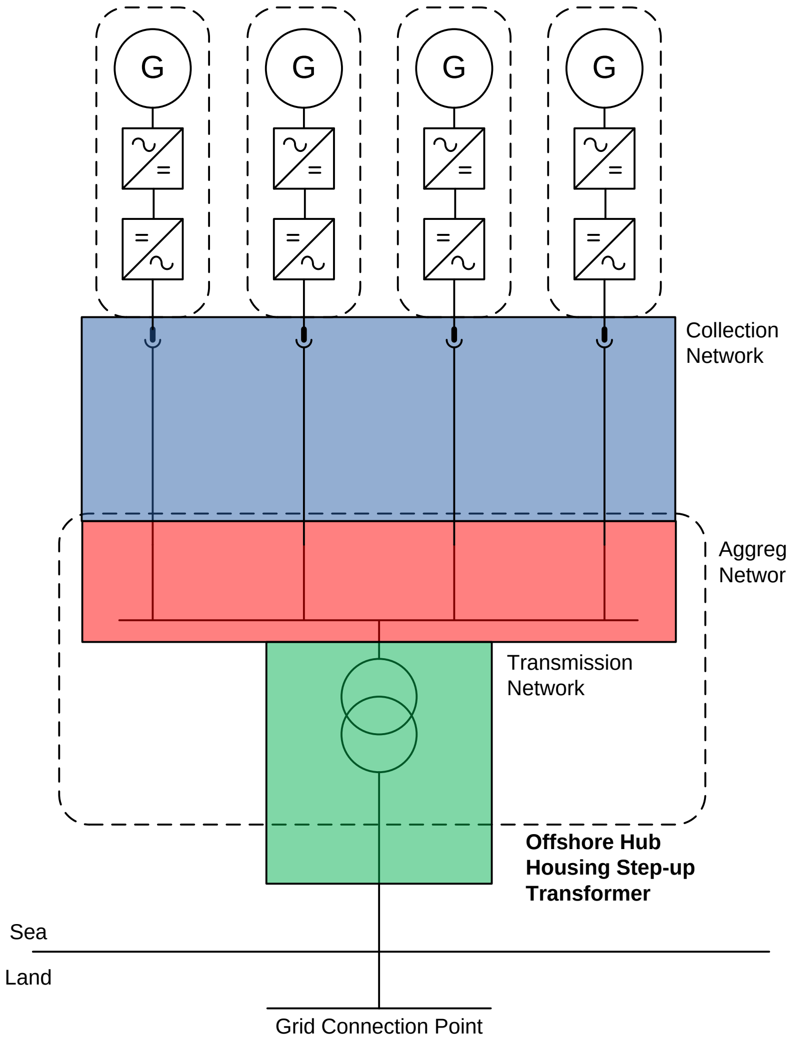

Figure 3 Star Cluster Configuration

Another alternative array architecture for converter enabled machines is shown in Figure 4. This is known as a radial network and is similar to the layout used for offshore wind farms. In this case the collector network will consist of an umbilical cable connected to the main cable using a specialised subsea connection system (discussed in the next section). The main cable will then become the aggregation network. Transformation will happen either onshore or offshore depending on how far the marine farm is from the grid connection point. There will be a limiting factor to how many devices that can be connected together this way and this will depend on the power output of the device, the output voltage and the maximum rating of the cable and connector system that can be used for the main collection cable.

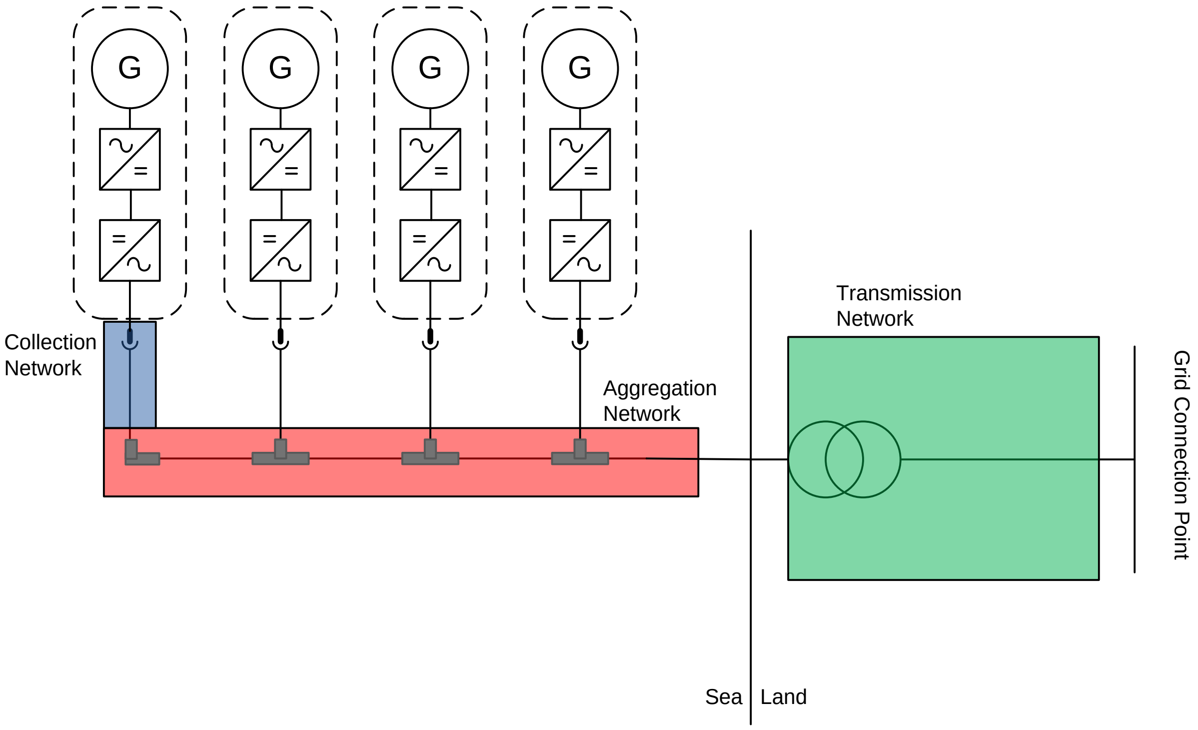

Figure 4 Radial Configuration

5.3 DC Aggregation

All of the examples above show configuration for AC networks. It is possible to design an offshore system with a DC collection and aggregation network by rectifying or converting the output of the machine to DC.

Figure 24 in Appendix 1 shows a typical arrangement where individual DC generating machines connect to a common collector/aggregation network and are converted back to AC using a single inverter. There are two manufacturers that have taken up the DC current generation option as a fundamental part of their design strategy and have done so as a way of simplifying the electrical connection to shore. These are Albatern and Nautricity, their approaches are outlined below:

Albatern: The Albatern WaveNet Series 6 is a 7.3kW wave device that will generate at 1kV DC. The hydraulic action of the device operates a fixed displacement motor which in turn runs a permanent magnet synchronous generator. The output of the generator is passively rectified to DC. The DC output of the device can then be transmitted to shore and connected to a dedicated single inverter on the shore. The device is modular and a number of devices can be connected together in a lattice formation. A common hydraulic bus promotes synchronisation of generator speeds allowing efficient parallel operation and load sharing between generators. Nodal switching on both hydraulic and electrical sides provides a high degree of in-built redundancy. The system is undergoing trials with six S6 units constructed and awaiting deployment for full characterisation. The underlying approach is scalable and the design for a larger 75kW unit (capable of forming arrays in excess of 10 MW) is at an advanced stage.

Nautricity: The Nautricity CoRMat is a 500kW tidal device that is tethered to the seabed and floats in the marine column. It produces variable AC voltage and frequency from a permanent magnet axial flux generator. To keep the electrical system simple Nautricity have decided on a passive rectification system using a 3 phase rectifier and a capacitor to output 3.6kV DC. The capacitor, and the additional capacitance provided by the cable act to buffer the output of the device and will allow multiple devices to be connected together. A single device has been tested at EMEC with a remote rectifier but the plan is to house the rectifier and capacitor on the device. By keeping to passive components for rectification this allows the device to be aggregated using a radial array and will help to keep costs down.

5.4 Auxiliary Power

The majority of devices, whether fixed or variable frequency, will have a requirement for low voltage AC and DC power for the device subsystems. These subsystems could include blade pitching system, yaw system and cooling system as well as control and communications. Where the device is fitted with a converter, it is usual that the device can obtain its low voltage supply from the device’s 6.6 kV or 11 kV supply via an internal step-down transformer. This option is not normally available for variable frequency devices where the auxiliary power needs to be sourced externally. Auxiliary power will normally be 400VAC 3-phase. There are issues in transmitting low voltages over long distances as the voltage will drop the further it travels from the source. Providing auxiliary power is one of the main functions of any array architecture and while it may be possible to situate a device some distance from the shore, the limiting factor may be the ability to provide auxiliary power over this distance. In order to overcome this problem, the auxiliary power will need to be transmitted offshore at medium voltage and then stepped down to 400VAC locally and distributed via a separate LV cable network to each device.

5.5 Communications

Another function of the electrical array is to provide a communications link between the device and the shore. For fixed frequency devices the communication link will provide access to the device’s controller and allow for control of the device and feedback of the status. For variable frequency devices the communications will link the pitch system and generator in the device with the remote converter. In order to optimise the power output of variable frequency devices the converter and the blade pitch system work in tandem and so require a high speed communication link (this also happens on fixed frequency machines but as the converter is installed in the device it all happens on board). The communication links will use fibre optic cable that is integrated into the high voltage cable system. Equipment manufacturers take this requirement into account and connectors and hubs normally contain a facility for splicing and connecting fibre optic cables. Fibre optic cable can transmit data over long distances so this does not place any restrictions on the design. However fibre optic cable is fragile and it is common for systems to have multiple redundant cores.

5.6 Distance from Shore

The voltage level that the marine energy device generates at and the distance from the shore will have a fundamental effect on the design of a marine farm electrical array. When discussing the distance from shore it is also crucial to consider the distance from the shore line to the grid connection point. In some cases it will be possible to build the control buildings to hold the necessary electrical plant close to the shore (as in the case of MeyGen where the transformers and converters are housed close to the landfall). However, it is possible that some projects will have the control buildings and grid connections several kilometres from landfall and this distance needs to be considered as part of the network.

Section 3.2 illustrates how the manufacturers have settled on voltage levels between 6.6 kV and 11 kV for the connection voltage for marine devices. In order to build up a picture of what distances these voltages will support, a number of load flow studies were performed on single machine and for radial arrays of three devices for 6.6 kV and five devices for 11 kV. A full explanation of the study methodology is explained in Appendix 5. The results of the study are shown in Table 2 and Figure 5. If an acceptable value for cable losses of 2% is taken then the maximum distance each network can support can be identified. This is shown in Table 2 where the distances for 95mm^2 cable are also given. These figures are instructive as they start to point towards the requirement for the use of offshore transformers for arrays relatively close to shore.

The value of 2% was chosen as this is historically the highest acceptable level of cable network losses for an onshore wind farm. In reality, the acceptable level of losses would be calculated on a project by project basis. This would be dependent on variables such as:

- Number of devices;
- Output power of devices;
- Output voltage of devices;
- Cable size options;
- Cable cost options;
- Distance to connection point; and
- Connection arrangement (HDD, hubs or radial arrays).

Array		Distance
1 x 6.6 kV	**400 mm^2**	7 km
3 x 6.6 kV	**400 mm^2**	2 km
1 x 11 kV	**400 mm^2**	20 km
5 x 11 kV	**400 mm^2**	5 km
1 x 6.6 kV	**95 mm^2**	2 km
1 x 11 kV	**95 mm^2**	5 km

Table 2 Maximum distances for 2% cable losses

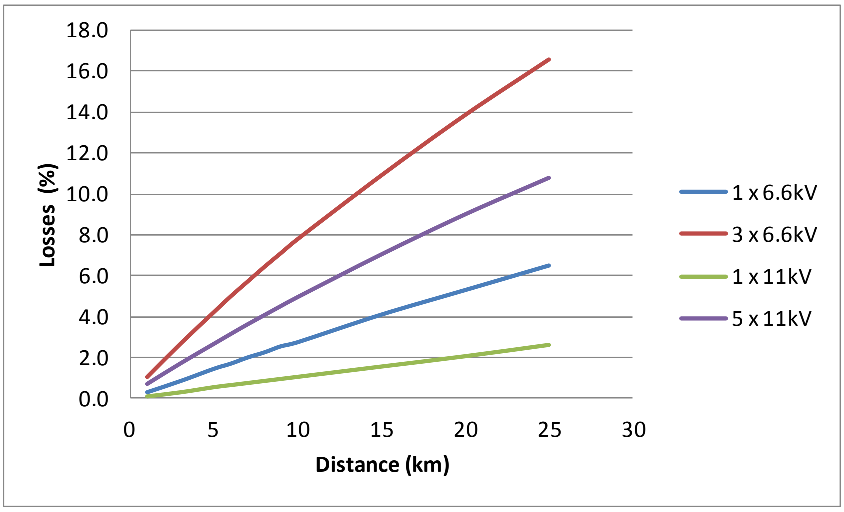

Figure 5 Losses for 400mm^2 Cable over Distance for 2MW Marine Devices

5.7 Distances between Devices

The layout of the devices in a marine farm will have an impact on the design and cost of the inter array cabling. In a number of the early studies, the spacing of the machines is taken to be on an 800 m by 400 m grid. This may be the case for wave devices which can take up a lot of area, but is not the case for tidal devices. In discussion with developers it is clear the spacing of seabed mounted tidal devices is much smaller, consisting of 8 to 12 blade diameters i.e. 160 m to 240 m based on a 20 m blade diameter. The depth of the ocean also needs to be considered when looking at cable lengths. If the array architecture uses subsea hubs with dry mate connectors there will need to be sufficient cable for these to be lifted out of the water for maintenance or repair.

6 Components of a Subsea Electrical Array

6.1 Introduction

This section introduces the various components that will go into the construction of a subsea electrical system. In the development of an optimum subsea electrical array architecture, it is important to understand how each component fits into the system. There needs to be consideration of the cost, both capital and operational, and any constraints it places on the array design. Thought also needs to be given to the TRL of the component. One of the aims of this piece of work is to identify areas that would benefit from the involvement of ORE Catapult and using the technology readiness scale is a useful tool to achieve this.

6.2 Technology Readiness Level

Technology Readiness Levels for wave and tidal devices were published in the IEA/OES Report into testing and evaluating Ocean Energy Systems[5]. The table from the report is reproduced below in Table 3. It covers wave and tidal devices separately to take account of the different technologies and development timescales (tidal current devices being more advanced). While it is intended for marine energy devices it is useful to use this as a benchmark for the development of subsea electrical array components.

Wave Energy Development		**Tidal Current Development**	
Stage 1 TRL 1-3	Concept validation. Prove the basic concept from wave flume tests in small scale	Tidal current energy conversion concept formulated	Stage 1 TRL 1-3
Stage 2 TRL 4	Design validation, Subsystem testing at intermediate level, Flume tests scale 1:10, Survivability computational fluid dynamics; Finite element analysis dynamic analysis; Engineering design feasibility and costing	Intermediate scale subsystem testing, Computational fluid dynamics, Finite element analysis, Dynamic analysis	Stage 2 TRL 4
Stage3 TRL 5-6	Testing operational scaled models at sea and subsystem testing at large scale	Subsystem testing at large scale	Stage 3 TRL 5-6
Stage 4 TRL 7-8	Full scale prototype tested at sea	Full scale prototype tested at sea	Stage 4 TRL 7-8

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[5] A summary report prepared by Ramboll to the OES-IA
Annex II – Development of Recommended Practices for Testing and Evaluating Ocean Energy Systems
August 2010
OES-IA Document nº T02-0.0

Stage 5 TRL 9	Economic validation; Several units of pre-commercial machines tested at sea for an extended period of time.	Commercial demonstrator tested at sea for extended period	Stage 5 TRL 9

Table 3 Technology Readiness Levels for Wave and Tidal Devices

6.3 Cable Systems

6.3.1 Subsea Cables and Installation

Cable systems cover the cables themselves as well as other accessories that will be required in order to connect wave and tidal devices. The cables themselves are well advanced as they have benefited in recent years from the development of the offshore wind industry. However, the conditions for laying cables on the seabed for marine devices pose some unique challenges. For offshore wind farms it is possible to bury the cable under the silt on the seabed. This is often not possible for marine farms. These will have to be situated in areas of high tide and these tides will act to wash away the seabed leaving the underlying rocky surface exposed. In addition, the tides also act on the cable and cause it to move. In all, this presents a very aggressive environment for cables. The rocky surface means that it is not easy to pin the cable to the seabed at regular intervals. Methods that can be used to secure the cable involve concrete mattresses. In these the cable is fed through a pipe which has a flexible matrix of concrete pads laid over it to secure it to the seabed. Rock dumping can also be used; this involves the large mesh bags full of rocks that can be lowered onto the cables. This method has been used at the WaveHub site where not only the cable but the hub itself is secured using this method. If the site is close to shore, direct horizontal drilling can also be used and this is the preferred method of the MeyGen site. The following methods have been used:

- EMEC: Armour casing and concrete mattress
- WaveHub: Rock dumping
- Strangford Lough (MCT): Horizontal direct drilling
- MeyGen: Horizontal direct drilling

Discussion with cable laying specialists has also suggested that close attention to the bathymetry is crucial, as it is often possible to use the seabed contours advantageously. There is likely to be a good deal of learning over the next few years as the optimal methods for cable installation are discussed.

6.3.2 Dynamic Umbilical Cables

While tidal devices will be secured to the seabed using static cables, floating wave and tidal devices will require flexible umbilical cables. These types of cables are well advanced as they have been used extensively by the offshore oil and gas industry at depths well in excess of those expected for marine farms. However as these cables are designed for production platforms they may not be economical for use on 2MW wave and tidal generators. In addition wave and tidal devices will put different forces on these cables.

6.3.3 Bend Restrictors and Bend Stiffeners

These are devices that protect umbilical cables from being stressed beyond their design limits and these are illustrated in Figure 6. Bend stiffeners protect the cable going into where the cable connects to the device or the junction box. Bend restrictors are placed along the cable in areas where it is possible that the cable will bend beyond it maximum bending radius. The restrictors will allow the cable to move freely up to a point but will then lock into position to prevent any more movement. Bend restrictors can also be made buoyant to keep the cable at a certain depth and so help reduce the weight of the cable pulling on the device.

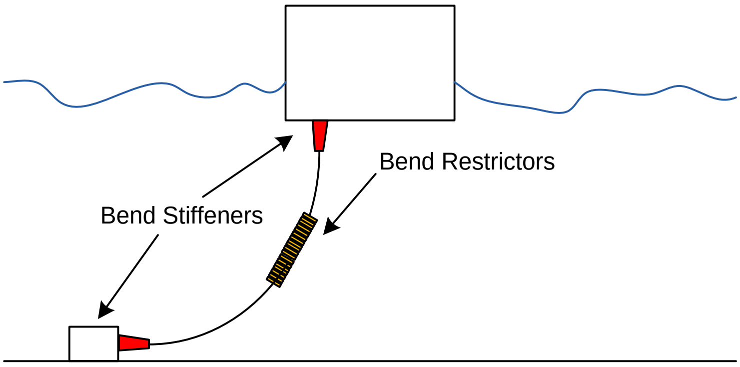


Figure 6 Bend Restrictors and Resistors

6.3.4 Cable TRL

Most of the cables and components are fully mature technologies and are at TRL 9 (where 9 is the maximum). The only area which is not fully developed is the securing of the cable to the seabed. A number of methods have been tried on various sites however it is likely that it will still be some time before there is clarity on the most cost effective and reliable method. As such this currently has a TRL of between 6 and 8.

6.4 Subsea Connection Systems

6.4.1 Introduction

Connection systems cover the connection of the power output of the device to the electrical system as well as the connection of low voltage auxiliary power and fibre optic communication. This process is complicated by the fact that these connectors are situated under water and are subjected to the corrosive effect of sea water and excessive pressure. Subsea connection systems fall into two classes; wet mate (which can be connected under water) and dry mate (where the connection needs to be made onshore or on a vessel).

6.4.2 Dry Mate Connectors

Dry mate connectors are the more mature of the two classes of connector. They can handle higher currents and voltages. The do require to be lifted out of the water in order to be connected and disconnected and in order to do this a spare length of cable is required on each side of the connector that is double or triple the sea depth. This cable will need to be managed on the seabed so it is not damaged by the force of the tides.

6.4.3 Wet Mate Connectors

Theoretically, wet mate connectors can be used at any point in the electrical infrastructure. However, due to their expense they tend to only be used on the device itself. A wet mate connector can connect to a device in two ways, either directly or via a stab plate arrangement. A direct connection will involve a Remotely Operated Vehicle (ROV) or possibly a diver unplugging the unit. A stab plate can include an arrangement of three-phase high voltage power, three-phase low voltage auxiliary power and fibre optic communication installed as part of the device foundation structure. This is permanently connected to the marine farm electrical array. When the nacelle is lowered on to the foundation structure, the connectors automatically mate and make contact. This system is used on the Alstom and Atlantis devices. A TRL review of wet mate connectors will show that units that operate at around the 6.6 kV mark are relatively mature and, although only available from a limited number of manufacturers, are in operation on a number of sites. At 11 kV the MacArtney device has been tested and is at a TRL of 7. At higher voltages, a number of manufacturers are developing systems that will operate at 36 kV but these are in their infancy so will have a TRL of 4. As the previous section demonstrated, there are distinct advantages to being able to transmit at higher voltages so even getting connectors to operate up to 11 kV could provide benefits in terms of small radial arrays.

6.5 Converters

All marine energy devices will contain a converter at some point in the electrical system. Where this converter is located will be one of the main factors in deciding how the array architecture will be developed (Appendix 1 contains a full description of the relationship between generators and the converter). Marine energy converters (MEC) that contain an on-board converter can have their output aggregated further upstream in the electrical system than machines that do not contain a converter (see Figure 2 to Figure 4 for illustration).

The reliability of the converters themselves would seem to be an area of concern with developers. In the analysis of the three SSE reports, two of the manufacturers gave mean time between failures (MTBF) of 15 years (ABB) and 16 years (Siemens). These depended on the converter being serviced every two to three years. However, both manufacturers have suggested that this service interval can be increased to five years for device based converters. This is due to the undersea device being relatively dust free so will not require the filters to be changed as regularly. These MTBF figures and maintenance intervals will play an important part in a developer’s decision on which turbines to use and the subsequent array layout. A converter on land or on a surface piercing / floating hub will be easier to maintain and repair than one situated subsea. The developers of the MeyGen project have made the decision to use variable frequency tidal turbines and place the converters onshore, which is an option open to them as the site is close to shore. The cable loss study in Section 5.6 shows that at distances over 2-3 km, the power losses become a consideration, so for sites further from the shore the converters will need to be either on-board the device or situated on a hub.

6.6 Surface Piercing Hubs

As this project has progressed it has become clear that a hub arrangement is one that will form the backbone of a large electrical array and is compatible with devices with both on-board and remote converters. The environmental impact of these surface piercing hubs is considered in the next section. Consideration will also need to be given to the cable de-rating factors imposed by the J tube transition pieces. Depending on the type of MEC used, the surface piercing hubs will fall into three categories.

- **Aggregation Only:** This could be used for gathering fixed frequency turbines (fitted with on-board converters) together in a star cluster formation as shown in Figure 7.

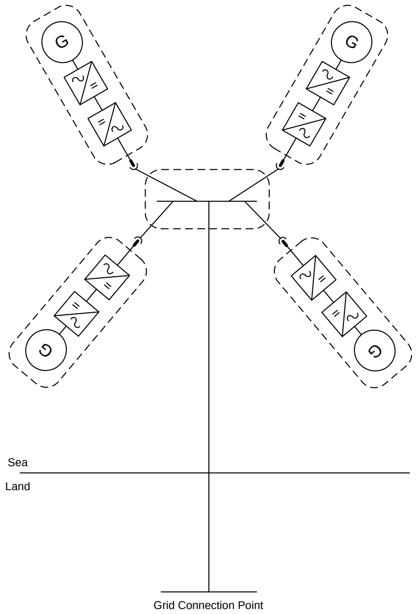


Figure 7 Aggregation Only Arrangement

- **Aggregation and Transformation:** This would also only be used for fixed frequency turbines but would also have a transformer on board. This would aggregate the output from a number of turbines and then step up the voltage to 33 kV or 132 kV in order to transmit it efficiently to the onshore grid connection point.

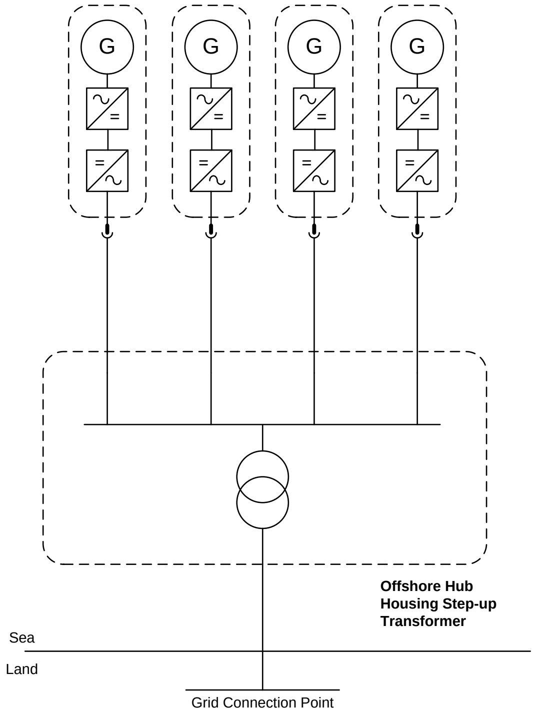


Figure 8 Aggregation and Transformation

- **Conversion, Aggregation and Transformation:** This will be the option when variable frequency turbines are used. In this instance, a machine-side converter will be required for each MEC. These can then be connected to single or multiple grid-side medium voltage converters to produce a fixed frequency output. The output is then transformed to 33 kV or 132 kV in order to transmit it efficiently to the onshore grid connection point. Figure 9 shows the two variations with multiple grid side converters on the left and a single grid side converter on the right.

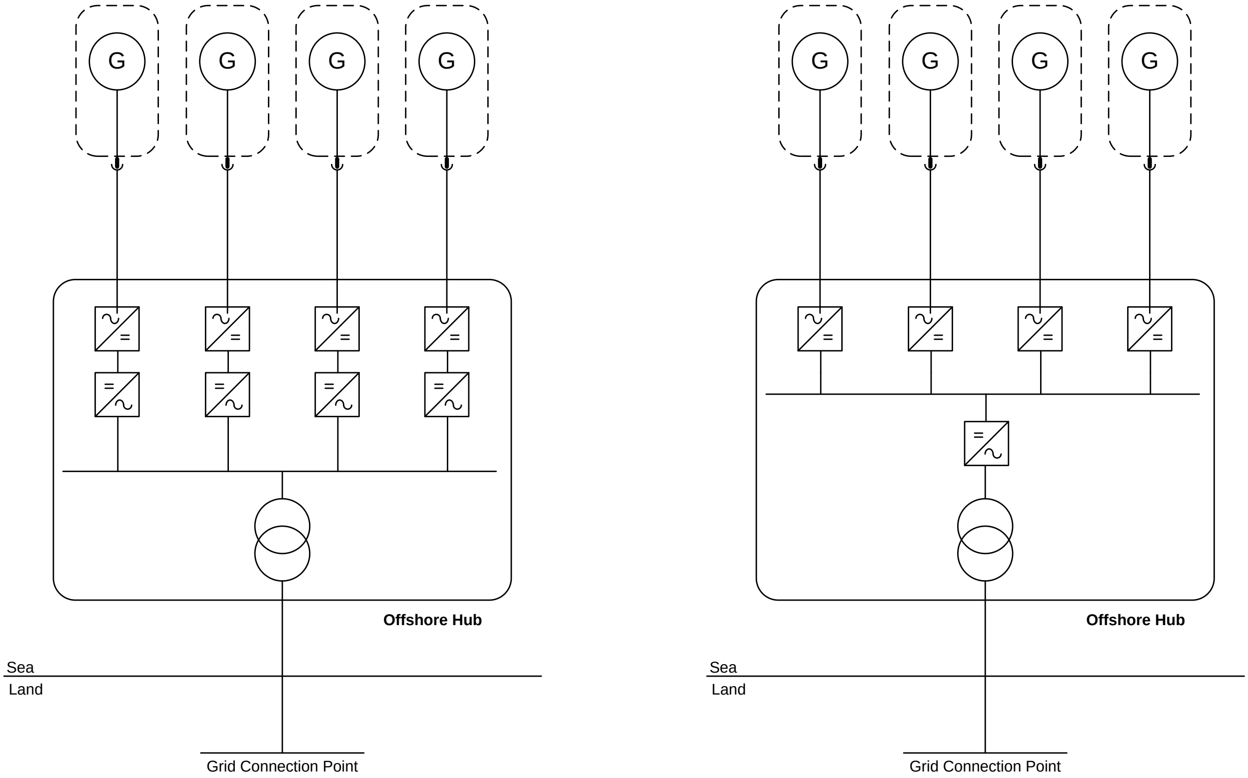


Figure 9 Multiple and Single Grid Side Converters

6.7 Floating Hubs

A floating hub may be a viable alternative to a surface piercing hub both in terms of cost and reduced visual impact. It would also be more economic to deploy and could be removed to shore for servicing. On a small scale, the company Bluewater produce a multi-use tidal energy conversion platform that could be adapted as a floating hub for a number of MECs. From a TRL perspective the platform has undergone some sea trials at EMEC so is at a 7. Its use as a multi-turbine connection hub is probably at a 5. On a larger scale, there may be some spin off to the work being done on floating wind turbines. These are currently at the sea trial stage and could provide a platform for multiple converters and transformers. However, implementation of such a large device is a long way off in practical terms and would have to have a TRL of 3. In both such systems the challenge is likely to be multiple power take off connectors that would need to be provided, and the forces placed on these by the dynamic motion of the platform. Using a number of small scale floating hubs may be a practical alternative to a single surface piercing platform should this prove difficult to get through planning.

6.8 Subsea Hubs

There are a number of subsea hubs available on the market from MacArtney, JDR, Hydro Group and Alstom. All of these would be classed as aggregation hubs (they contain no power electronics or transformers) and can be used to collect the output of a number of fixed frequency machines. An overview of each hub is presented below.

- MacArtney: A modular expandable hub, it is not known if it has been deployed.
- JDR: Developed a 4-way hub used for the Wave Hub facility, TRL 8.
- Hydro Group: Has a commercially available multiple connection cable system, TRL 9.

Alstom: A proposed project involving a floating nacelle that can be lowered onto a subsea structure with multiple wet mate connectors fitted to a stab plate. Literature says it will allow connection of between 3 and16 turbines. Currently at pre-test design stage so TRL 3. Comments at a recent conference suggest this will only be available if it is used with Alstom tidal current turbines.

6.9 Subsea 3-Way Connectors

One of the assumptions made by the early studies into marine arrays was that the MEC electrical system was similar to that of a wind turbine and contained a ring main unit. It would therefore be able to accept a dual cable connection with one input from the previous device and one output to the next device. In reality this is not the case and most TECs (with the exception of MCT) do not have sufficient space for a ring main unit, and the number of cable connections is limited to one. Subsea cable connection systems, be they wet mate or dry mate, are expensive and it does not make commercial sense to add this cost on to a machine if it is not required. In order to be able to build a radial array of marine energy devices, as shown in Figure 10, a 3-way subsea cable connector is required. Figure 11 shows an example of a 4-way subsea connector that contains high voltage power, low voltage power and fibre optic communication connections.

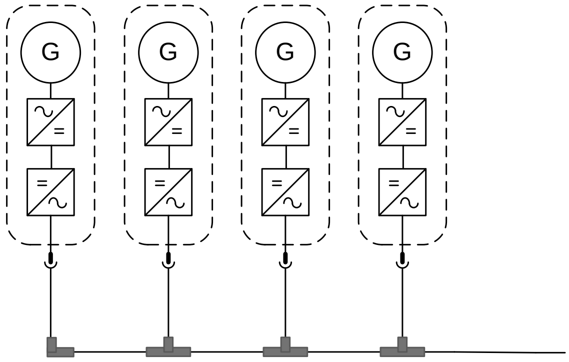


Figure 10 Single Connection Radial Array

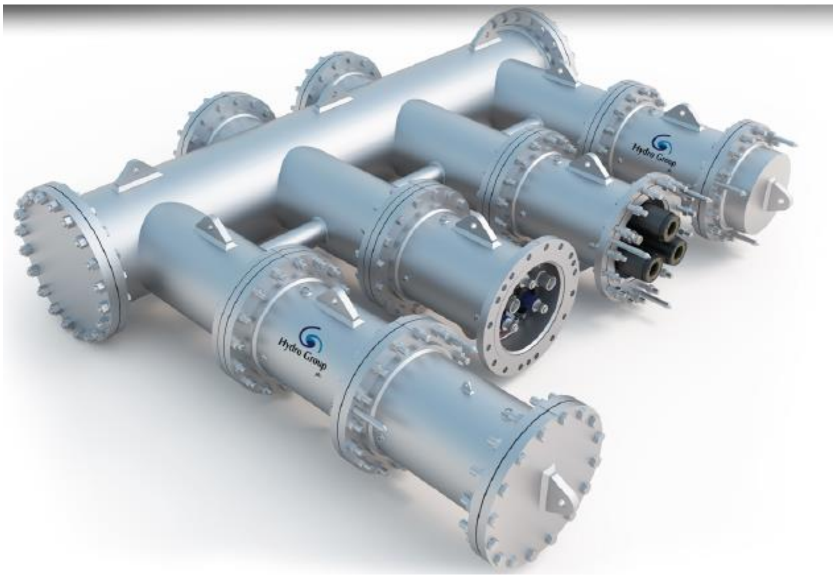


Figure 11 Hydro Group Power Distribution Hub (picture used with permission of Hydro Group)

A hub such as the Hydro Group example shown above will operate at up to 20 kV and up to 630A. This would be sufficient to support five 2 MW fixed frequency turbines operating at 11 kV in a radial string at a distance of 5 km from the connection point. This device makes it economical to create small scale radial networks. This technology is at TRL 9.

6.10 Transformers

Depending on the size of the marine farm and the distance from shore, the voltage will need to be stepped up to either 33 kV or 132 kV. This will be discussed further but it is worth noting that at 132 kV an offshore electrical system is considered as a transmission asset and will have to be owned and operated by an offshore transmission operator (OFTO). While it is possible for the transmission system to be constructed by a third party, it is normal for the developer to build the transmission system and then transfer the assets to the OFTO once they are commissioned and energised. The OFTO has strict availability targets to meet so will tend to look for a conservative design of the transmission asset.

7 Options for Basic Array Architecture

7.1 Constraints in Designing an Electrical Array

7.1.1 Introduction

The optimum design of larger electrical arrays will be driven by the constraints placed on the electrical system by the choice of device and the size and location of the project. The following section will look at how these constraints influence the design of the network.

7.1.2 Distance from Shore / Grid Connection

As the majority of machines generate at 6.6 kV or 11 kV, the transmission losses will need to be taken into account when considering the network topology. The distance that needs to be considered is not only the distance of the marine farm from shore but also the distance from the substation / control room where the metering circuit breaker measuring the marine farm output will be located. While the subsidy for wave and tidal in the form of ROCs and CfD remains high, the revenue lost due to transmission cable losses can be substantial. The further the marine farm gets from the shore, the more economically important it will become to transmit at higher voltages, to reduce the current and thereby reduce the transmission losses.

7.1.3 Size of Project

This project looks at marine farms of 32 MW, 100 MW and 200 MW arrays of 2 MW machines. As the analysis in the following sections show, when considering a surface piercing hub, a single hub of 32 MW (or 16 machines) has been chosen as the optimum maximum size for the purposes of aggregation. For larger arrays, there are two options for transmitting the power to shore which will depend on the distance to the connection point. For near shore marine farms, each 32 MW hub would be able to directly transmit to shore at 33 kV with an onshore step-up transformer to 132 kV or 275 kV. For larger farms further from shore it may be practical to place the step-up transformer offshore on a dedicated platform and transmit the power to shore at 132 kV. For this scenario the 132 kV platform would be owned and operated by an offshore transmission operator (OFTO) so it makes sense for it to be situated on a separate platform from the other plant.

7.1.4 Location of Converter in the System

The electrical system of each marine energy device will have to have a fully rated converter in order to synchronise the power output to the grid frequency. This converter can be located on the device, on a surface piercing or floating hub or onshore. From an operation and maintenance point of view it is preferable to have the converter in a location that is easily accessible. The optimum location for a converter is on land. The next favoured location will be on a surface piercing or floating hub. Least favoured from a maintenance standpoint is having the converter located in the device nacelle. However, from an electrical network point of view the situation is reversed. Having an on-board converter will allow the devices to be easily aggregated either as part of the cable network (Figure 4) or via a common busbar on a surface piercing or floating hub (Figure 3). It will be the developer that will ultimately make the decision as to whether to have the power conversion on the device or at a remote location. Both types of device are available and at a stage where they can be installed as part of a commercial array.

7.1.5 Auxiliary Power

Auxiliary power is the individual low voltage power that each device requires to operate. This will power any blade pitch or nacelle yaw motors, heating systems and control/comms systems. For devices with an on-board converter that produce a fixed frequency output this can be derived its own high voltage 3-phase connection, and stepped down via an on-board transformer. This is not an option for variable frequency devices where the auxiliary power has to come from an external source. It is difficult to transmit power at low voltages over long distances due to the resistance within the cable and the resulting volt drop effect. This limits the distance that low voltage power can be transmitted to hundreds of meters rather than kilometres. This would result in the variable frequency devices requiring an auxiliary supply from a local hub or a secondary high voltage auxiliary supply and a step-down transformer within the device.

Environmental and Navigational

One of the challenges posed by the proposed use of any surface piercing equipment is gaining planning consent from the Marine Management organisation in England and Wales or Marine Scotland. This will require a creative approach as many of these hubs will be visible from shore. The MCT Sea Gen tidal turbine has a surface piercing element. Considerable work went into designing the surface piercing element of this device to minimise the visual impact. The traditional design of a surface piercing platform tends to involve modular components housed in units similar to shipping containers which is not visually attractive. It has been suggested that hubs can usefully be used to mark the boundaries of a site. Using four surface piercing hubs (one at each corner of the site), will provide a better visual marker than buoys. It is clear that there will be work required to understand the concerns of the planning bodies with regards to visual impact, and the creative methods that will be required to address these issues.

7.2 Array Types

7.2.1 Introduction

This section will introduce the various methods that can be used to build up an electrical array and how they are impacted by the constraints detailed above.

7.2.2 Direct Connection to each Device

Direct connection describes the method where each device has an individual cable connection to shore. This is the method used for the MeyGen project where all the devices are variable frequency and the converters are located onshore. However this method could equally be used for fixed frequency devices, although the system is only effective when the device is a short distance from the shore or connection point. The long cable runs will be subjected to high losses and direct drilling of each cable is expensive. This method does have the advantage of having a high level of fault tolerance as any cable failure will affect the output of only one device.

7.2.3 Radial Networks

It has been common to look at radial networks when considering marine farm array architecture as the system is ubiquitous in the design of offshore wind farm networks. However a closer look at the design of marine energy devices shows that they are not suited for radial arrays. They have a single power connection and no internal ring main unit which means that it is not possible to loop the array cable in and out of the device. This can be overcome by using the three way connector introduced in Section 6.9. The further limiting factor on the development of a radial network is the voltage limit of the unit. The current output of devices operating at 6.6 kV and 11 kV limit the number of devices on a string to three or five respectively (examples of the current output are given in Table 4). In order to develop a radial architecture of up to ten devices it will be necessary to operate the array at 20 kV or 33 kV. If it is not possible to develop the devices to a stage where they can output at these voltage levels it is worth considering using individual subsea step-up transformers local to the device. A possible concept is shown in Figure 12 below.

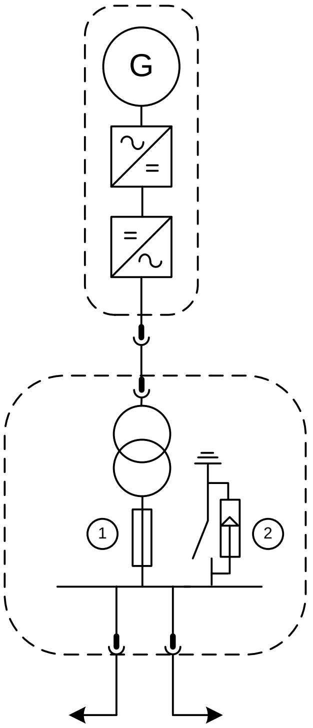


Figure 12 Possible Arrangement for a Subsea Transformer System

Subsea transformers are commercially available and have been in use by the oil and gas industry since the late nineties. By coupling this with the 3-way connector discussed in Section

6.9 and including a set of fuses (1) and an earth switch and surge arrestor (2) it will be possible to have each device generating at 20 kV or 33 kV. The intention would be that the transformer would be connected to the marine energy device and to the array using dry mate connectors. It is expected that the unit would be require minimal maintenance, but should it need to be serviced or repaired the whole unit could be lifted out of the water. The unit could then be replaced with an identical standby unit. If no replacement unit is available, the array cable could be joined together with a compatible splicing unit. While both subsea transformers and 3-way connectors are available, integrating them together in this way would be a novel approach and would require some development and engineering to ensure a cost effective and reliable design. It does demonstrate that, while it is possible, there will be challenges in developing radial networks for marine energy devices.

7.2.4 Star Cluster Networks

Given the difficulties in developing a radial network, as discussed in the previous section, the optimum array network using currently available technology will be a star cluster topology. Examples of a star cluster network are illustrated in Figure 2 and Figure 3 in the earlier sections of this report. Star networks have the advantage that they can be used for either variable frequency or fixed frequency turbines. For variable frequency devices they will provide a platform for the converter that is relatively close to the turbine and will allow for aggregation to take place on the platform before the voltage is stepped up for efficient transmission to the shore. It will also provide a platform for distribution of auxiliary power to each device. For fixed frequency devices the plant on the platform is simpler as there is no requirement for converters. The technology and techniques for building surface piercing platforms are well developed from the experience of the offshore wind industry. In this report options for the connection of 4, 6, 8 and 16 marine devices to a single surface piercing hub are considered, and an optimum configuration suggested.

One of the main objectives of this report is to look at how to reduce the cost of connecting multiple marine energy devices. As such the report looks at the possibility of using floating hubs as an alternative to surface piercing hubs. While there are no commercially developed floating hubs there are floating tidal stream platforms produced by Scotrenewables and Bluewater. The Bluewater BlueTEC 2 MW platform is a multi-use floating platform that is intended to be used for turbines, but could possibly be adapted to house converters and transformers. The challenge with this approach will be to ensure that cost effective connectors and umbilical cables are designed to withstand the dynamic forces that they will be subjected to. As mentioned previously such cables are already in use by the oil and gas industry but may need to be adapted to meet the physical requirements and cost constraints of a marine energy installation. However, this challenge is common to all floating devices and will be subject to development as the industry matures. In this report options for the connection of 4, 6, 8 and 16 marine devices to a single floating hub are considered and an optimum configuration suggested.

7.2.5 Redundant Networks

This report has not looked at the topic of redundant network topologies (other methods of redundancy may be considered and are mentioned later). These are only applicable for radial networks and are difficult to construct with the current technology available to marine devices. To be effective, a redundant network topology requires that each generating unit be fitted with a ring main unit so that the faulted section of cable can be isolated and the return ring be switched into circuit. As discussed in Section 7.2.3, marine energy devices are not fitted with such ring main units. The development of a redundant network would require the removal and reconfiguration of a number of subsea 3-way connection units. The effort involved in this activity would mean that it would probably be more cost effective to replace the faulted cable as this would take a similar amount of time.

7.3 Decision Trees

7.3.1 Introduction

In order to illustrate how the constraints covered in section 7.1 will guide the developer or designer to a certain array configuration a set of decision trees are provided below. These assume as device output voltage of 6.6kV, 11kV, and 20kV. A commentary is provided on how the various constraints affect each decision point.

7.3.2 6.6kV Network

Figure 13 shows the decision tree for a device generating at 6.6kV. The consequences of each decision point are outlined below.

Converter. Whether the device is fixed frequency (on-board converter), or variable frequency (remote converter), will dictate whether it is possible to use a radial network as shown in options 2 and 4. A radial network is only possible with fixed frequency devices.

Distance from the Connection Point. In this example we have used the distance figures from section 5.6, where a single device can be situated up to 7 km from the connection point, while maintaining cable losses of less than 2%. At distances less than 7 km, it is possible to make a direct connection to each device regardless of it being fixed or variable frequency (options 1 and 6). A radial connection for three fixed frequency devices is also possible (option 2), although at 7 km the cable losses will increase to 6%.

Consent for Surface Hub. As covered in the previous section, surface hubs (either fixed or floating) can be used for housing step up transformers and converters. It will be necessary to obtain consent to situate these offshore, as they will have a visual and environmental impact. In this example, at less than 7 km offshore, a platform would only be used for option 5 if direct connection of each unit was not possible due to difficult landfall conditions or cost. At greater than 7 km offshore, surface piercing or floating hubs would be used to aggregate the output of the marine farm devices and step up the voltage for transmission to shore. This would be used for options 3 and 7. If no consent is for a surface piercing or floating hub available a set of fixed frequency devices can be connected as a radial array using the subsea transformer system described in section 7.2.3. (Option 4) For variable frequency devices a direct connection is still possible, but with increased losses and also the challenge of providing auxiliary power (Option 8).

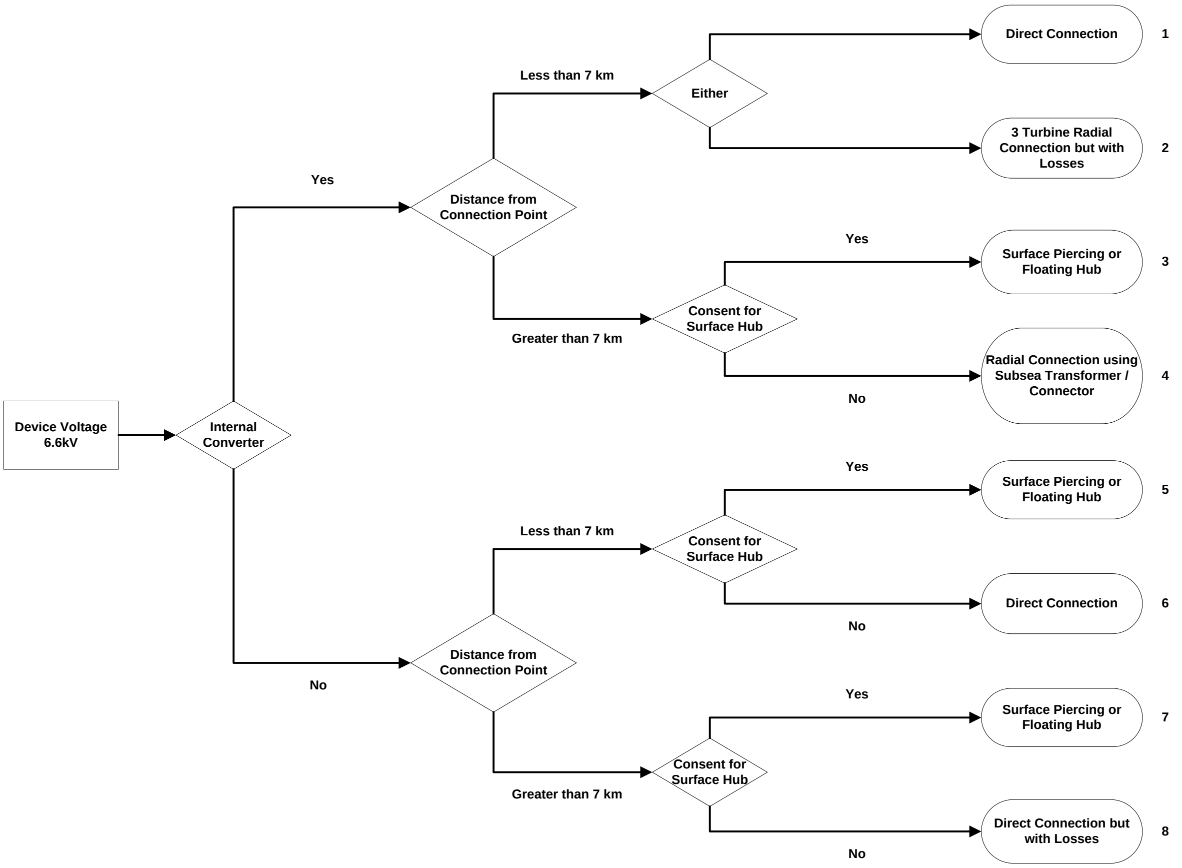


Figure 13 6.6 kV Decision Tree

7.3.3 11 kV Network

By increasing the voltage of the device, the output current will reduce. This will have will have a beneficial impact on the electrical network, in terms of the distance and number of devices that can use a radial array.

Converter. The increase in voltage from 6.6 kV to 11 kV will not have an impact on the decision of whether the device is fixed or variable frequency.

Distance from Connection Point. The reduction in current will mean that the cable losses for the electrical network will be reduced. It will be possible to make a direct connection to each device up to 20 km from the connection point, while keeping the losses to below 2% (Option 1 and 6). However, at this distance the cable cost of connecting to each device individually will become prohibitive, so this may not be practical. At these distances a radial connection of up to five devices is possible using fixed frequency machines (option 2). This would mean that five devices can be fed from a single cable.

Consent for Surface Piercing Hubs. For distances over 20 km and as an alternative to direct connection at distances less than 20 km, a surface piercing or floating hub could be used to aggregate the outputs of the devices and step up the voltage (option 3, 5 and 7). The output of the marine farm can then be transmitted to shore using fewer cables. If there is no consent for a surface piercing or floating hub, a radial array using subsea transformer systems is an option (option 4). It is likely that direct connection to each device over 20 km (option 8) will be prohibitively expensive, so variable frequency devices at this distance are unlikely to be an option.

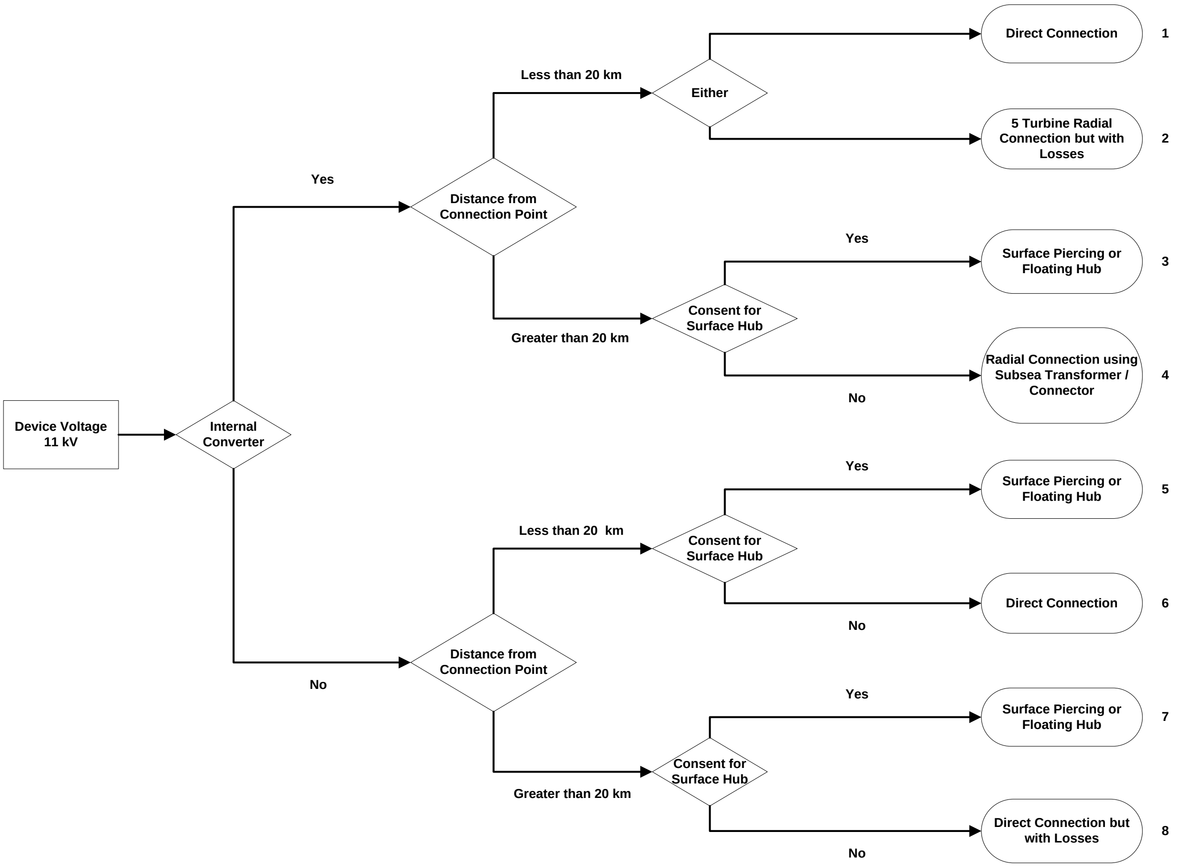


Figure 14 11 kV Decision Tree

7.3.4 20 kV Network

At present there are no commercially available machines that generate at 20 kV. However at the higher voltages the options for connecting devices economically increase so there is a driver in terms of cost reduction in increasing the output voltage and reducing the output current of the devices.

Converter. As the following descriptions will demonstrate, the higher voltage will mostly benefit fixed frequency devices as the options for multi device arrays are increased.

Distance to Connection Point. For single device direct connection the increase in voltage largely removes any practical upper limit to the distance in terms of losses. However as with the 11 kV device options the direct single connection of devices over long distances will be prohibitively expensive. The increase in voltage will mean that fixed frequency devices can be connected together in radial arrays as shown in option 2, where eight devices can be connected together with at a distance of up to 6 km with cable losses kept below 2%.

Consent for Surface Piercing Hubs. One variation possible at higher voltages is to use a surface piercing or floating hub purely for aggregation. This is demonstrated in option 1. In this design all the eight devices could connect to a common bus bar on the hub, and a single cable used to connect the hub to the onshore connection point. As the hub would contain only switchgear, it could be a cost effective alternative to option 2 using subsea connectors. For distances over 6 km there will be a trade off in losses and at some point it will be necessary to install hubs with step up transformers (option 3) or use subsea transformers (option 4). For the variable frequency devices, running at 20 kV will allow for single device connections much further from shore, but the cost of running a single cable to each device will mean that a surface piercing or floating hub fitted with a transformer (if consented), will become the more attractive (option 7).

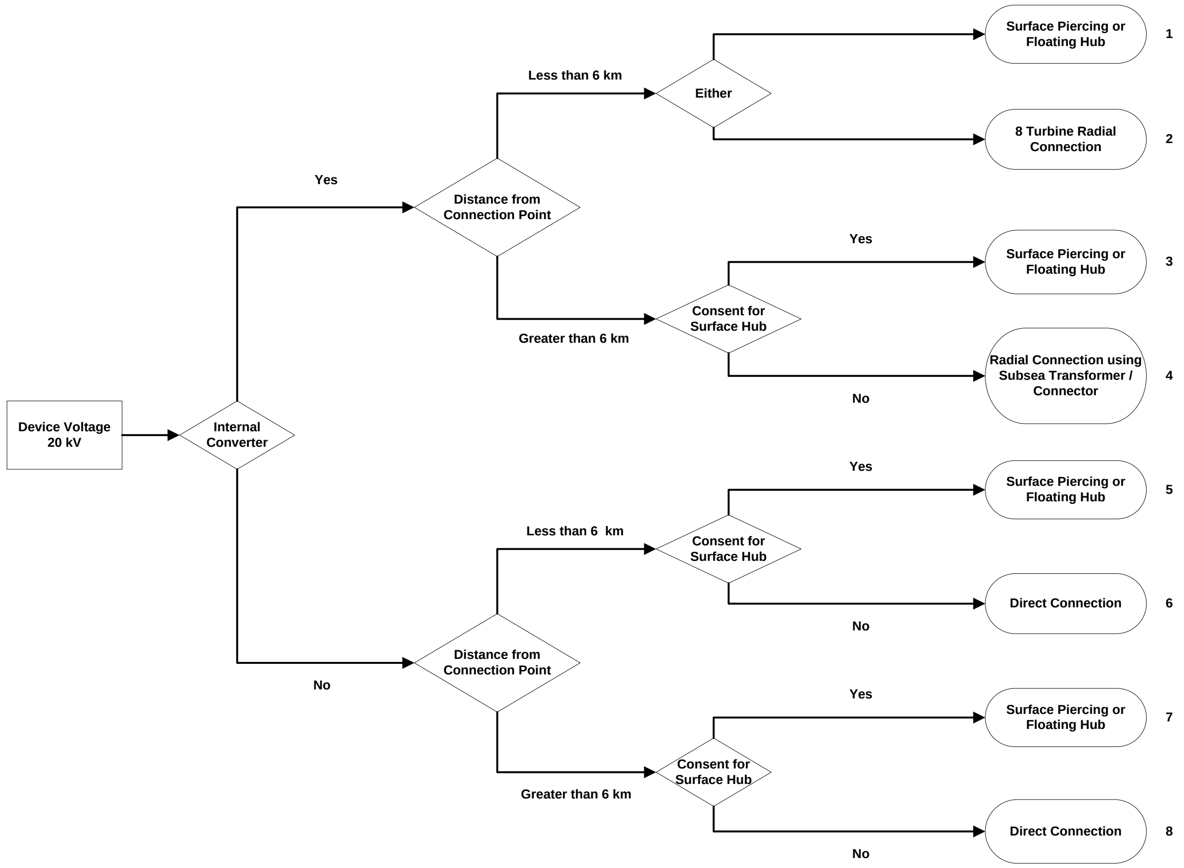


Figure 15 20 kV Decision Tree

8 Commercial Array Architectures

8.1 Modelled Array Architectures

The original scope for this report was to look at electrical architectures for a marine farm of 30 MW, 100 MW and 200 MW consisting of 1 MW machines. The initial studies carried out as part of the landscape review for the first report, showed that the typical output for a marine device was increasing from 1 MW, and that 2 MW machines would be common in the future. As such the network design looked at the same MW output levels but using 2 MW machines.

8.2 Device Spacing

The spacing of the devices was also considered. From discussions with developers the spacing of tidal stream devices is 8 to 12 blade diameters downstream with a cross spacing of 3 to 5 blade diameters with alternative rows staggered. Given a blade diameter of 20m this equates to a spacing of 160 m to 240 m and 60 m to 100 m. For these studies we have considered a turbine spacing of 200 m x 100 m.

8.3 Cable Types and Ratings

These studies are based on the figures given in the ABB XPLE Submarine Cable System Guide. Copper conductors have been used for the extended current carrying capacity and 3 core cables have been used. The devices are assumed to be operating at unity power factor. Each 2 MW device operating at full power will produce the following current.

Voltage (kV)	Current (A)
6.6	175
11	105
20	57.7
33	35

Table 4 Current Rating for a 2 MW Marine Device

The current rating for transmission cables are as follows:

- 400mm^2 3 core copper cable is 590A
- 500mm^2 3 core copper cable is 655A
- 630mm^2 3 core copper cable is 715A

A de-rating factor of 20% was applied to all hub cables, in order to take account of the passage through the J tube from the seabed to the platform. These figures were used to calculate the number of devices that could be serviced from a single hub.

8.4 Surface Piercing and Floating Star Arrays

Taking the 30 MW array as a starting point, the report takes a modular approach to developing the various array architectures for surface piercing and floating hubs. Initial building blocks of 4, 6, 8 and 16 turbine hubs are considered. These can be configured into a 32 MW architecture with a single cable connecting the array to the onshore connection point. In order to keep the size consistent the 6-way clusters are built up of one 6-way and two 5-way clusters. These 32 MW blocks can then be multiplied to provide a 96 MW array, and a 192 MW array. These are all shown graphically in Figure 16. The output of each hub would consist of a single 33 kV connection and a fibre optic data connection. For larger arrays, each 16-device hub could cable directly to shore. Alternatively, for larger arrays at a distance from the shore/ connection point it will be possible to connect these to a separate hub containing a 33 kV/132 kV transformer. Using the ratings from the previous section a 630mm^2 3 core cable would be required to connect the array to the shore.

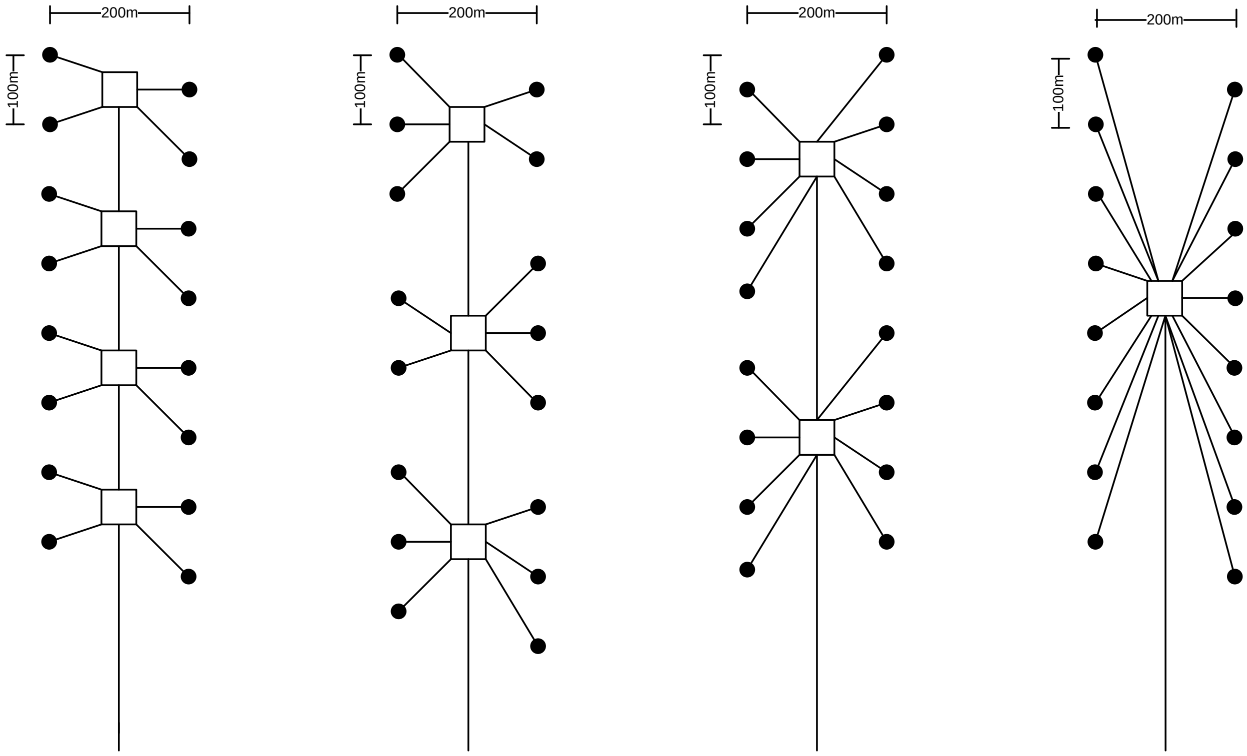
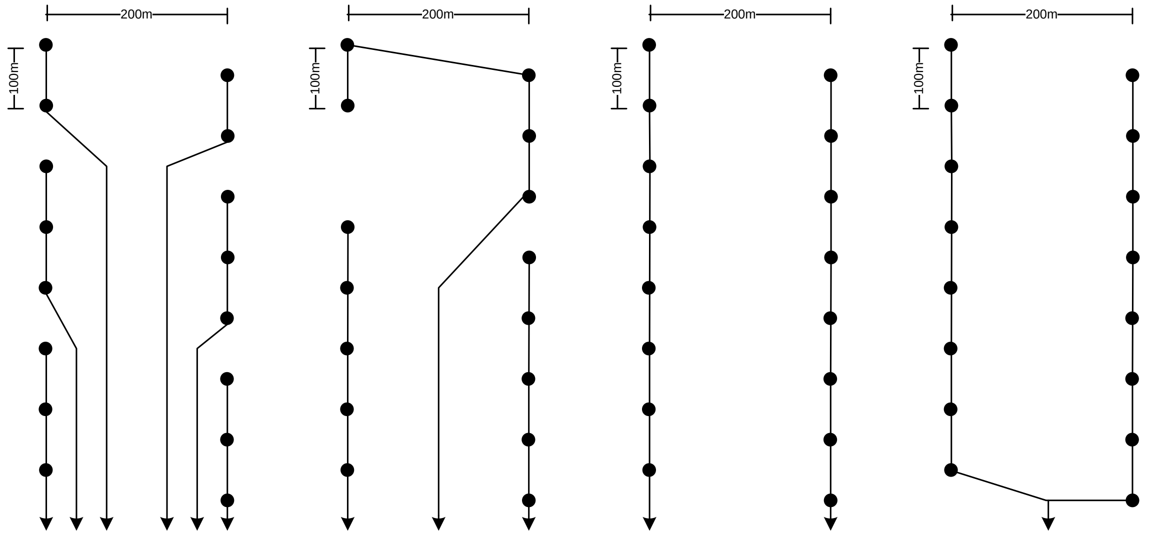


Figure 16 4, 6, 8, and 16 Device Architectures

8.5 Radial Arrays

For radial arrays the voltage of the device and the current carrying capacity of the three-way connector is the limiting factor for the number of devices that can be connected together. As an example, the Hydro Group three-way connector has a current carrying capacity of 630 A and a maximum voltage rating of 20 kV. This could support the first three array architectures illustrated in Figure 17 (the 11 kV array is reduced to 15 MECs due to the current capacity of the three way connector). It is unlikely that the 6.6 kV or 11 kV arrays would prove to be viable due to cost and the relatively short distances that they could transmit power over, before the losses became unacceptable. A 20 kV array would be possible using the current technology but a 33 kV array would require the development of cost effective 33 kV three way connection systems.



6.6 kV 11 kV 20 kV 33 kV

Figure 17 Possible Radial Arrays

8.6 Cable Systems for Wave Devices

This study has tended to focus on the array requirements for subsea tidal stream devices rather than the requirements of wave or floating tidal devices. There are several reasons for taking this approach. The majority of the devices that have been tested and are ready for commercial deployment are tidal stream devices, and it is clear from discussions with developers that the first large scale commercial arrays will be tidal. The design of a subsea array architecture is simpler and will provide the backbone for an architecture that can be used for floating devices. Floating devices will require the addition of umbilical connectors and associated accessories as discussed in 6.3 but the hub or radial array layout will remain the same. One thing that will change is the spacing which will be larger for wave devices and more like the 400 m to 800 m spacing that has been used in the previous studies.

9 Analysis of Array Options

9.1 Introduction

The previous section outlined the four array architecture options that will be available for the connection of large scale marine energy devices. To recap, these are:

- Direct Connection: This covers the single connection of each device to a dedicated control building onshore. There is likely to be an element of horizontal direct drilling (HDD) to take the cable some or all of the distance to the device.
- Star Cluster with Surface Piercing Platforms: These will house transformers ancillary equipment and converters (if variable frequency devices are used). These will be permanently attached to the seabed.
- Star Cluster with Floating Platforms: The current design of floating tidal stream platforms such as Scotrenewables and Bluewater could be adapted to house converters, transformers and ancillary equipment.
- Radial Arrays on Seabed: The components for developing radial arrays are available but would require some additional engineering to integrate them. They may prove to be an attractive option when planning permission for surface piercing or floating platforms is not forthcoming.

9.2 Cost Analysis for Marine Array Architectures

Providing accurate CAPEX and OPEX figures for future marine strategies is challenging. Of the four architectures presented in this report, only two, (direct connection using HDD and the surface piercing hub), could be designed and built using current technology. The other two architectures will require development and testing and as such there are no figures available for how much it would cost to realise these. In addition, as there have been no such arrays built to date there will be an additional first of a kind premium applied to the cost of the initial deployment of any of these architectures. Taking this into account it was decided to take a comparative approach to the capital cost analysis for the four architectures. The comparative approach involved applying a range of costs (low, mid and high) to the various components of each array architecture. This way the cost of each architecture could be built up and each of the array options within each array architecture (i.e. 4, 6, 8 and 16 hubs), can also be compared. Taking this approach, it is possible to identify the optimum array option within each array architecture and also compare the cost of the four architectures. While it is not possible provide accurate costs for the array architectures this approach will provide guideline figures of how much a developer should budget for the electrical array architecture infrastructure.

9.3 Cost Calculations

For the direct connection option, costs obtained from a previous marine project study carried out were used to provide cost estimates for horizontal direct drilling (HDD). For the fixed and floating hub architectures the cost of each hub was split between cable costs, fixed cost and variable cost which are covered in detail below. By taking this approach it was possible to identify the most cost effective array option within each array architecture. The radial array was calculated separately as there is little commonality apart from cable between the equipment used for this array and those used for hubs.

- Direct Drilling Cable Costs: Horizontal direct drilling involves the use of specialist drilling equipment and vessels. The costs for HDD range from £1.8k per metre, to £2.7k per metre. This consists of the cost of the cable. £1.35k to £2.35k per metre for drilling and lining. Each MEC will require an MPV for 3 days at £75k per day. There will be an additional £13.5k per cable run for miscellaneous costs such as winch hire, drilling team etc. In addition to these costs, there will be the cost of the onshore control building and substation which has been calculated as £1.8m. For HDD the distance between the device and the control building has been assumed as 1km for each of the sixteen devices in the example project.

- Cable Cost: For the hub and radial array projects the cable cost covers the cost of the cable supply and installation from each device to the hub(s) up to the perimeter of the marine farm. It does not consider the cable or installation costs to shore/connection point or the grid connection substation. There are three cable cost scenarios considered, low at £0.5k per metre, medium at £1k per metre and high at £2k per metre. The varying costs reflect both the commodity price variation and any specialised cable protection systems that will be required depending on the site seabed conditions.

- Hub Fixed Costs: The fixed cost of each fixed or floating hub will consist of the equipment that will be common to each hub and not vary with the electrical capacity of the hub. For fixed hubs this has been set at £5M per hub. For floating hubs where costs are less well defined but are likely to be less expensive there is a high cost of £2M per hub and a low cost of £1M per hub. Fixed costs will include:

    - Hub structure including the foundation for fixed hub or mooring arrangement for floating hub;
    - Personnel safety and survival facilities;
    - Cable riser system and hang off for 33 kV cables;
    - 33 kV switchboard and auxiliary equipment; and
    - Protective systems (e.g. fire suppression).

- Hub Variable Cost: The variable cost will cover the components whose size and cost will vary with the electrical capacity of the hub. For fixed hubs and high cost floating hubs the figure will be £500k per MW and for the low cost floating hub this will be £300k per MW.
- Radial Array Costs: A cost analysis was carried out on for the four radial array options for voltages from 6.6 kV to 33 kV as shown in Figure 17. As discussed previously there are drawbacks with radial systems operating at 6.6 kV and 11 kV using connectors only. At these distances the cable losses mean that this option will only work over relatively small distances. In order to construct a radial network that is able to transmit at distances over 5 km it is necessary to develop a hybrid connector / transformer system as discussed in Section 7.2.3. As this piece of equipment has not yet been developed it is difficult to put a cost to it, so a range of costs have been used in this analysis. A range of three figures have been chosen to cover a cost of a connector / transformer system from £300k up to £600k for an 11 kV unit to £500k to £800k for a 33 kV unit. For a 6.6 kV radial array, no transformer would be required. There are additional cable costs associated with radial connections. The connector and transformer will need to have sufficient extra cable to allow it to be lifted from the seabed. This arrangement is shown in Figure 18.

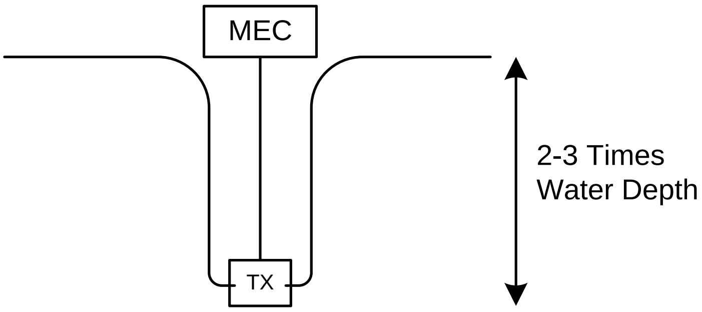


Figure 18 Tidal Array Cable Arrangement (Plan View)

9.4 Presentation of Results

The results of all the CAPEX analysis for all four connection options are presented below both graphically and in tabular form. For HDD the figures for all three cost options are given in Figure 19 and Table 5. For the fixed hub architecture Figure 20 shows the cost based on the medium value for subsea cable costs (£1k per metre). Figure 21 shows the cost for the floating hub architecture, which this is reflects the higher cost hub and the medium cable costs. Both sets of architectures are compared in Table 6. The radial array costs are classified by voltage level and are presented in Figure 22. This presents the costs for high cost connectors and medium cost cable. The full results are presented in tabular form in Table 7. Full results for all the CAPEX options can be found in Appendix 2.

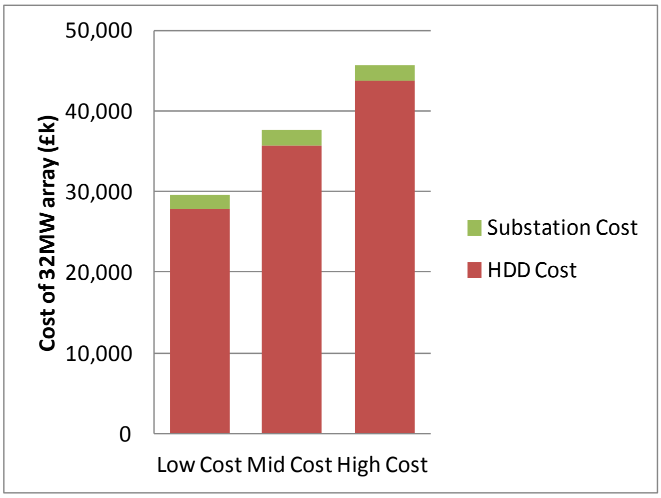


Figure 19 Horizontal Direct Drilling Costs

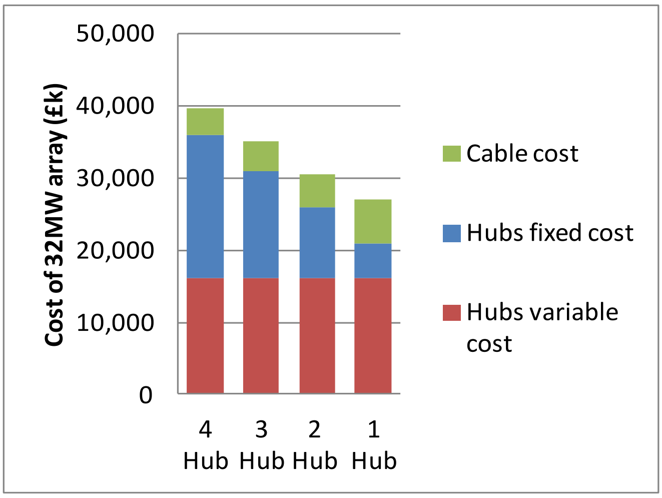


Figure 20 Fixed Hub Total Costs

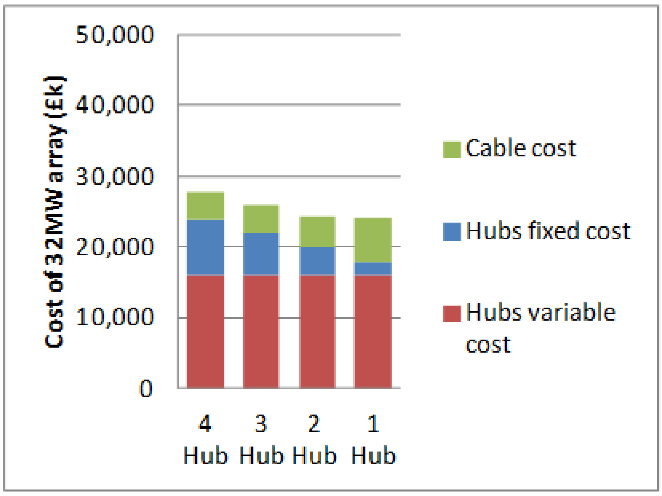


Figure 21 Floating Hub Total Costs

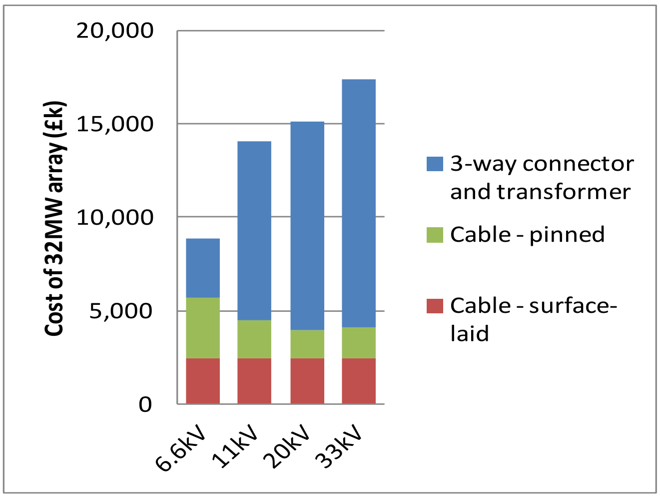


Figure 22 Radial Array Costs

Hub Configuration	Low Cost	Med Cost	High Cost
HDD (£K) based on 1 km per MEC	27,816	35,816	43,816
Sub Station (£K)	1,834	1,834	1,834
Total (£K)	29,650	37,650	45,650

Table 5 Horizontal Direct Drilling Costs

Hub Configuration	4 Hub	3 Hub	2 Hub	1 Hub
Low Cable Costs				
Fixed Hub (£K)	37,875	33,000	28,225	24,025
High Cost Floating Hub (£K)	25,875	24,000	22,225	21,025
Low Cost Floating Hub (£K)	15,475	14,600	13,825	13,625
Mid Cable Costs				
Fixed Hub (£K)	39,750	35,000	30,450	27,050
High Cost Floating Hub (£K)	27,750	26,000	24,450	24,050
Low Cost Floating Hub (£K)	17,350	16,600	16,050	16,650
High Cable Costs				
Fixed Hub (£K)	43,500	39,000	34,900	33,100
High Cost Floating Hub (£K)	31,500	30,000	28,900	30,100
Low Cost Floating Hub (£K)	21,100	20,600	20,500	22,700

Table 6 Fixed and Floating Hub Costs in Tabular Format

Connector Option	6.6 kV	11 kV	20 kV	33 kV
Low Cable Costs				
High Cost Connector (£k)	6,025	11,250	13,175	15,350
Mid Cost Connector (£k)	4,425	9,000	10,775	12,700
Low Cost Connector (£k)	4,025	6,750	8,375	10,200
Mid Cable Costs				
High Cost Connector (£k)	8,850	13,500	15,150	17,400
Mid Cost Connector (£k)	7,250	11,250	12,750	14,750
Low Cost Connector (£k)	6,850	9,000	10,350	12,250
High Cable Costs				
High Cost Connector (£k)	14,500	18,00	19,100	21,500
Mid Cost Connector (£k)	12,900	15,750	16,700	18,850
Low Cost Connector (£k)	12,500	13,500	14,300	16,350

Table 7 Array Costs in Tabular Form

9.5 Discussion of Results

9.5.1 Introduction

The above results allow each array architecture to be evaluated against each other as well as identifying which is the most significant cost driver of the options within each array architecture. Care should be taken when comparing the figures for the different architectures as the costs of some of the components needed to realise the individual architecture have been estimated. However given this restriction some broad assertions can be made.

9.5.2 Direct Connection

For the direct connection method the cable costs take up the overwhelming majority of the cost of the array and should be the focus on any cost reduction. The figures above are based on 1km of cable to each device. Cost reduction can be achieved by reducing the amount of length the cable to each device will need to be direct drilled. It may be possible to direct drill the first 250 m - 500 m to a point on the seabed and then have the cable secured to the seabed using a more economical solution such as concrete mattress or rock dumping.

9.5.3 Fixed hub

There are numerous fixed hubs in operation in both the oil and gas and offshore wind industries. The challenge for the tidal industry will be to develop an economical operational fixed hub design. The costs shown here will indicate the target cost for a surface piercing platform rather than an actual cost. Care will need to be taken to make the design as lean as possible while maintaining a safe operating environment. The figures show that of all the configurations of surface piercing hubs a single hub feeding sixteen devices is the most cost effective.

9.5.4 Floating Hub

With the floating hub, the array concepts start moving into areas where development will be required. Compared to the fixed hub, the floating hub appears to offer some cost reduction which is mainly due to the reduction in the fixed costs associated with the foundation and support structure. Also of interest, is the small difference between the costs of the four floating hub options. A single hub designed to service four units would seem to the easiest to develop and would remain economic when compared to larger floating hubs. In addition, in terms of umbilical cable connections the larger floating arrays may be more difficult to manage.

9.5.5 Radial Arrays using Transformer and Three Way Connectors

This array architecture is the most optimistic in terms of development requirements but will be the only method available for building a radial array architecture. The components required to build this transformer / connector device currently exist but would need work to integrate them into a single unit. The figures are based on a price range for each unit of £500k to £800k each. At this stage, these costs are purely speculative but do provide a target cost for developing such a unit. There are some caveats to consider when considering developing a radial architecture:

- This array architecture is only applicable for use with devices with on board converters that are able to produce power at fixed grid frequency.
- There would be a relatively short window between tides in which to connect up and lower the transformer / connector unit onto the seabed. This would require trained technicians and specialist handling equipment.
- Each unit will have three sets of cables of between 40 m to 150 m in length (see Figure 18). This will require a cable management system in order to avoid this cable lying loose on the seabed.
- This system has relatively low redundancy as all the devices are electrically connected together with no way to isolate a device if it is defective or is being removed for servicing. This will be reflected in the OPEX costs.

9.5.6 Cable Costs

The analysis of the arrays looked at a cable cost spread of between £500 per metre and £2k per metre. It is clear from the results that there could be significant saving made in a reduction of cable costs and efficiencies in the installation and protection techniques. This is a topic that is under consideration in the industry and the figures shown above tend to justify cost saving efforts in this area.

9.6 Accuracy of Costs

How accurately do these figures represent the actual cost of a marine electrical system? F. Sharkey[6] suggests that the electrical system should form 20-25% of the cost of the entire project and bases this on the offshore wind industry costs. He also suggests that the installed cost for an ocean energy system should be the same as that for offshore wind and quotes €4M/MW as an appropriate value. Looking at other published sources, the World Energy Council Cost of Energy Report[7] gives a figure between $6.73M/MW to $16.05M/MW (£4.03M to £10.27M) with a median cost of $9.28M/MW (£5.94M). Figures form a Black and Veatch audited study are quoted on a Triton website[8]. These give costs of between £3.5M/MW to £4M/MW. The only actual device cost quoted by a manufacturer can be found in the reNews Global Marine Report 2015[9] in this article Scotrenewables give a figure of £6.5M for a fully installed SR2000, their 2 MW machine. Adding 25% to this £6.5M to account for the electrical system will give a total figure of £8.125M for an installed device. This suggests that a £4/MW for the total cost of a marine device including electrical system is a reasonable starting assumption.

Based on this £4M/MW cost for a tidal project, the total cost of a 32 MW project would be £128M, 25% of this would be allocated to the electrical system which would equate to £32M. Cost will have to be allocated for an onshore substation and a cable connection from the hub(s) to the shore. The onshore substation will cost between £1-2M and the cable cost will be dependent on the number of hubs and the distance to shore (these costs do not apply to the direct connection option which includes the substation). A single 33kV cable to connect the array to shore will cost approximately £453,500 per km (see Appendix 4 for details). For a marine farm 5km from shore this would equate to £27.7M for the fixed / floating hub or radial array and £4.3M remaining for the substation and connection to shore. The £27.7M allocated for the array plant and cabling costs are in line with the figures given for the fixed and floating hub at mid cable cost and for the costliest radial array option shown in Table 6 and Table 7. While the figures given for the cost of these array options are subjective they are intended to provide a guide to the maximum costs of engineering and manufacturing the various parts of the marine array.

9.7 Allocating Converter Costs

The relative location of the converter has not been considered in the cost calculation for the design of the arrays. As part of the stakeholder engagement for this project a number of manufacturers provided information on their machines on the proviso that it was not used in any comparative analysis. With respect to the manufacturers this report has not looked at relative costs of having a converter situated on the device or on the hub. The expectation is that

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[6] Page 330 Electrical Design for Ocean Wave and Tidal Energy Devices" published by IET 2013.

[7] World Energy Council Cost of Energy Technologies 2013

[8] Triton Platform website http://www.tidalstream.co.uk/html/costs.html

[9] reNEWS Marine Special Report 2015 released 21 May 2015 page 6. www.renews.biz

variable frequency devices without converters will cost less and will therefore offset the cost of installing the required converters on a hub.

9.8 Electrical System Losses

Load flow calculations were carried out on all four layouts to calculate the losses incurred by the cables and transformers. The values are presented below and show that the losses decrease with the number of hubs. This is to be expected as the cable lengths for the device connections will be less. These only show the losses for the cable connections from the devices to the hub and not for the rest of the electrical network connection from the hub to the shore.

Option	Losses (kW)
4 hub (4x4)	131
3 hub (2x5, 1x6)	121
2 hub (2x8)	108
1 hub (16)	102

Table 8 Losses for Hub Based Array

There will also be losses due to the converter. Full conversion of the output of the devices will take place either on the device or remotely. The conversion losses will therefore be the same for fixed or variable frequency machines.

10 Opex Costs

10.1 Introduction

Existing operational data from the individual devices will be based on performance from prototype units from demonstration sites, and will be unduly pessimistic if it is available at all. In addition, the lack of any operational marine farm arrays also means that there are no reliable costs for the operation of these although some pointers may be taken from the offshore wind industry as well as the oil and gas industry.

10.2 Carbon Trust OPEX Calculation Tool

The Carbon Trust has produced a Marine Cost Methodology and Calculation Tool[10] which provides a useful breakdown of the operational costs of a marine energy project, which is split up into the following subsections:

- Planned Maintenance Costs
- Unplanned Maintenance Costs
- Monitoring and Control
- Rent
- Insurance

The operation costs were allocated to these subsections in the following manner (a full explanation of costs and assumptions is given in Appendix 3

Planned Maintenance:

This covered the routine maintenance which was considered the same for fixed and floating hubs. It was assumed that maintenance on a 16 device hub would take ten days. Six days was allocated for 6 and 8 device hubs and four days for a 4 device hub. This resulted in a greater maintenance time the more hubs in an array. Loss of energy is considered but will be the same for all hub options. For radial arrays it is assumed that there will be two major refurbishments in the lifetime of the project. This will involve the connector/ transformer unit being removed and taken onshore for servicing.

Unplanned Maintenance:

For fixed and floating hubs this will involve a two day trip per hub once a year. In addition each floating hub will be brought into port for a major refit once in the projects twenty year lifespan. For the radial system, five transformers will be replaced during the lifetime of the project.

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[10] http://www.carbontrust.com/resources/tools/marine-energy-cost-estimation

Monitoring & Control, and Rent:

Both of these are based on figures given by the Carbon Trust. The figures used are 25% of full value to reflect the proportion of overall operating costs allocated to the electrical system.

Insurance:

The Carbon Trust suggests that 5% of the operating cost will be insurance. This figure has been applied to the fixed hub option. The floating hub option has 7% applied as this is likely to be riskier and the radial option has 10% applied for the additional risk of having plant subsea.

Loss of Energy:

Options for strike prices between £305 and £100 per MWh have been calculated to demonstrate the impact the cost of energy has on the array option.

10.3 Array OPEX Results

The nine figures in Appendix 3 represent the results of the OPEX calculations. In each instance three plots are presented, which show the impact of the loss of energy on each OPEX option at a nominal strike price of £305, £200 and £100 per MW/h.

It should be noted that these maintenance costs are not for the whole marine farm but only for the electrical infrastructure. It does not take into account the maintenance requirements of the MEC in terms of routine maintenance or of the unplanned maintenance of the converter system regardless of whether it is located in the MEC or remotely on a platform.

10.4 Analysis of Results

A number of conclusions can be gained from the results that suggest the direction that array designs may take in the future. The most striking result is the impact that the loss of energy has on the fixed and floating hub calculations. At £305 per MW/h this dominates the overall costs of operating the array. In addition a high cost for loss of energy will favour the smaller hubs as these will have fewer devices out of service during periods of planned and unplanned maintenance. The results for the radial array are markedly different. For this option there are relatively few components but these are costly and situated subsea. The costs for operating the radial array are therefore concentrated on the repair and maintenance of the subsea connector and transformers systems. As these will be designed to have as little maintenance as possible the costs due to loss of energy make up smaller proportion of the overall operating costs than they do for the hub arrangements.

Based on the figures used and the assumptions made on maintenance regimes, the hub options both have similar operating costs with the fixed hub being slightly less costly. The radial array options presents the most cost effective option as this involves fewer components with a high reliability. Broadly speaking there is an inverse correlation between the readiness of the technology to construct an array and the relative operating cost of operating the array.

The relative feed in tariff for the project will have a big impact on the maintenance regime with the higher tariff requiring extra plant and crew in place to facilitate rapid change round of defective components. As such the cost of operating and maintaining the array will generally reduce as the loss of energy penalty lowers and techniques and processes are reduced.

11 Conclusions

11.1 Introduction

The purpose of this project was to identify a set of marine array architectures that could be utilised for the first generation of commercial marine energy arrays. By taking into account the needs of the manufacturers and developers it has been possible to propose a set of architectures that can be constructed with currently available plant and technology, as well as proposing array architectures that, if developed, will reduce the electrical infrastructure costs of future marine farms. The report details the four possible methods that can be used to connect marine devices electrically: direct connection, surface piercing hubs, floating hubs and subsea radial arrays.

11.2 Array Options

Direct Connection

Direct connection using the horizontal direct drilling methods is currently being used for the MeyGen project. Apart from the onshore substation and control building there is no array electrical plant on the surface so consenting issues are low to medium for this option depending on the foreshore impact. Horizontal direct drilling is, however, costly and is only practical for devices close to shore and with easy landfall conditions.

Surface Piercing Hubs

For marine farms that are at a distance from shore or cannot support multiple cable landings (as is required by HDD) a surface piercing hub is an option. The technology required to construct a surface piercing hub is available from the oil and gas and offshore wind industries. The challenge for surface piercing hubs will be constructing one within the budget of a ten to twenty device marine farm. This report has assumed that the initial target price for a wave device in the example sixteen device farm will be £4M per MW and that 25% of this cost (£32M) will be allocated to the electrical infrastructure including: offshore array, subsea connection from array to shore and grid connection/ substation. Depending on the cost of the substation and the distance from shore there budget cost for developing the array infrastructure could be in the region of £25M. In a report on offshore wind costs[11] the Crown Estate have identified a cost of £90M for a 500MW surface piercing substation platform. While this is much larger in terms of transformers and electrical systems the structure and ancillary equipment will be similar. Apart from the relatively high cost another issue with surface piercing hubs is the planning consent that they will require. Surface piercing hubs will be large structures and for a marine farm will be relatively close to shore. It will therefore have a significant visual impact and obtaining consents will be challenging.

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[11] A guide to an offshore wind farm by BVG Associates The Crown Estate

Floating Hubs

In order to reduce costs, minimise the visual impact and still keep the main electrical plant above the water line this report looked at the option of floating hubs. The idea of a using a floating platform to house transformers and converters came from the example of the Scotrenewables tidal device and the Bluewater multipurpose platforms. Both of these marine devices use a floating steel structure to house the electrical equipment. It should therefore be possible to adapt the current design to remove the generators and to house a transformer, ancillary equipment and, if required, converters. The advantage of this approach is that these support devices have already undergone sea testing so there is some confidence that they will be structurally sound. From a cost standpoint floating hubs represent a saving when compared to surface piercing hubs. From a consenting standpoint floating hubs will present a much lower profile than a surface piercing hub and would have a less significant visual impact. The Capex calculations show that there is relatively little cost difference between a four device floating hub and a sixteen device floating hub. In addition, the Opex costs show that, given a high feed in tariff, a four device hub is the most cost effective. It would seem that the next step should be the development of a four device floating hub which would focus on adapting the current platforms to house the relevant electrical plant and also focus in on the power connectors system.

Subsea Radial Arrays

The final option chosen for the report is a subsea radial array. As a method for connecting multiple generating units a radial array is very efficient. However for a number of reasons outlined in the report, radial arrays are difficult to achieve using the current generation of marine devices. Nonetheless by developing existing subsea connectors and transformers into a hybrid system it is possible to construct a radial array for fixed frequency marine devices. Subsea connectors and transformers already exist and the challenge would be to develop this hybrid system to operate maintenance free for long periods of time (this report considers two services in a twenty year lifespan). The Capex and Opex costs indicate that if it can be achieved these radial arrays will be cost effective when compared to the surface piercing or floating hubs. However it should be noted that besides the development cost for the device consideration also need to be given to how these units will be deployed and also how the cable will be managed on the seabed. It is likely that the costs of realising this type of array for the first time will be much higher than the figures quoted here.

11.3 CAPEX and OPEX Comparisons

An overview of some of the figures and analysis of all the array options is covered in Table 9 below. These provide a selection of figures from the Capex and Opex calculations as well as a comment on the consenting risk and technology barriers to developing an array option.

For the Capex figures that medium cable cost examples have been used for the hub array option and in addition for the array options the highest device cost has been chosen. The

Capex for direct drilling uses the medium cost for the HDD option for a 1km connection for each device. For the Opex calculations the loss of energy has been calculated at £200 per MW/h. Although the current strike price at the time of writing is £305 this is only for a limited number of devices and will drop after these have been installed. The figures for the HDD are for the complete project but for the other project the cost of the onshore substation (£1-2M) and the cost of the cable connection to shore (£453k/km) will need to be included.

11.4 Challenges of Developing the First Arrays

The above four options present the array possibilities for the connection of the first generation of marine farms. However the research into this report has shown that there is no one size fit all option that will suit every project. Each Project will present a number of variables that will need to be considered prior to making the decision as to which array architecture suits best. Some of these variables will be clear, such as the distance to shore, land fall conditions and the consenting requirements. However some of the variables, such as whether to use fixed or variable frequency devices will be subjective and will depend on the developers' attitude to the risk of having converter technology situated in the device.

Option	**Capex Annual £M**	**Opex Annual £k**	**Consenting Risk**	**Technology Barriers**
Direct Connection	43.2	Low	Medium (foreshore impact)	Low
4 Surface Piercing Hubs	39.75	634	High (Due to visual impact)	Low
3 Surface Piercing Hubs	35	749	High	Low
2 Surface Piercing Hubs	30.45	707	High	Low
1 Surface Piercing Hubs	27.05	880	High	Low
4 Floating Hubs	27.75	764	Medium (Less visual impact the surface piercing)	Medium (adaptation of existing technology required)
3 Floating Hubs	26	823	Medium	Medium
2 Floating Hubs	24.45	783	Medium	Medium

Option	**Capex Annual £M**	**Opex Annual £k**	**Consenting Risk**	**Technology Barriers**
1 Floating Hubs	24.50	941	Medium	Medium
6.6 kV Array	8.85	684	Low	High (New technology development required)
11 kV Array	14.1	699	Low	High
20 kV Array	15.15	784	Low	High
33 kV Array	17.4	801	Low	High

Table 9 Array Options in Tabular Form

12 Further Work

12.1 Introduction

During the preparation of this report the authors have identified a number of areas which may benefit from the involvement of ORE Catapult as a partner in a joint project.

12.2 MVDC Marine Network Demonstrator

As the study notes there are some advantages in the use of MVDC in the collection, aggregation, and transmission of power from a marine farm. MVDC technology is still relatively new and there are various proposals for a demonstrator facility to be built to advance this technology to commercial deployment. If a demonstrator can be built that can be used with marine devices this may stimulate the development of marine devices that generate at direct current.

12.3 Control System for Multiple Variable Frequency Machines.

Appendix 1 covers the reasons that why it is not desirable to connect two variable frequency machines in parallel. It may be useful to commission an academic body or industrial manufacturer with expertise in rotating machines to look at the challenges of connecting variable frequency machines in parallel. They may be able to identify some design changes and control techniques that would allow more than one device to run from a single converter.

12.4 Design of Surface Piercing Hubs

This report has identified surface piercing hubs as a possible connection option for the first generation of marine farms. As present these types of structures are not visually appealing, but as they are usually situated far from shore this has not been as issue in the past. Surface piercing platforms for marine farms can be visible from shore so some consideration as to the visual impact of the design will need to be considered.

12.5 Design for Floating Hubs

Scotrenewables and Bluewater have demonstrated that the concept a floating tidal stream platform is viable to the stage that Scotrenewables are developing a 2 MW commercial device. The report indicated that cost savings over fixed hubs can be achieved by using a floating hub to house transformers and converters. An initial step towards developing this concept could be to engage Scotrenewables, Bluewater or other manufacturers to look at a concept design of a four device floating hub with an integral transformer and converter based on their platform design.

12.6 Dynamic Umbilical Cable Design

These cables will be required for floating devices. These cables are in use by the oil and gas industry but tend to be designed for greater depths than those experienced by platforms used for marine energy. In addition the cables on a floating marine device will undergo different stresses than those of the experienced by a floating platform. In order to reduce the cost of these cables it would be useful to develop a functional specification that reflected the relatively shallow depths that these will operate in, and the forces that the marine device will apply.

Appendix 1 Generators and Converters

This Appendix is intended to give some background on the role of generator and converter in the MEC electrical system for those new to the subject. All marine energy systems will contain a generator and a converter somewhere in the electrical chain and it is this arrangement that will dictate the design of marine farm electrical array. All of the tidal machines considered in this study contain a generator. These are fitted with either a permanent magnet synchronous generator (PMSG) or an induction generator. The main difference between them is that the magnetic field in a PMSG is provided by a permanent magnet while the magnetic field in the induction machine rotor coils (rotating inner section) is induced by the magnet field in the stator coils (stationary outer section)[12]. Neither the induction generator nor the PMSG are suitable for direct connection to the grid but need to have their output modified to produce electrical current at a constant frequency and voltage. In marine energy converters this is done by a converter (sometimes called a back-to-back converter). A converter consists of three sections; a converter that converts AC current into DC current, a DC bus and an inverter that will generate an AC waveform from the DC bus. A very simplified diagram of the arrangement is provided in Figure 23. The advantage of this arrangement is that the behaviour of the generator is decoupled from the supply grid by the converter. This decoupling is useful as the generator-side converter and the grid-side converter can be controlled separately. The generator-side converter can used to adjust the electric field in the generator to maximise power output. The grid-side converter can be used to adjust the phase angle between the voltage and the current it is producing and so regulate the reactive power output.

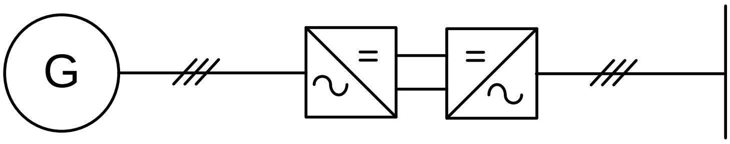

Figure 23 Simplified Diagram of a Back to Back Converter

As discussed in the body of the report it is not common to aggregate generators unless they have been through a converter. This is difficult to do for the following reasons:

- The frequencies must be equal. A mismatch in frequencies of the two machines will cause the generator with the lower frequency to be picked up as a load by the other machine, which can cause an overload in the generators or distribution system;

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[12] For an excellent overview of generators and tidal energy systems J. Bard and P. Kracht have a section (2.5) in the IET book "Electrical Design for Ocean Wave and Tidal Energy Devices" published by IET 2013.

- The terminal voltage must be equal. If the two voltages are not equal one of the generators could be picked up as a reactive load by the other and result in high currents exchanged between the 2 machines; and
- The voltages must be in phase. A mismatch in the phases will cause opposing voltages to be developed. The worst case would be 180° out of phase resulting in opposing voltages twice the size of the operating voltage. This will lead to high current flows that could cause damage to the generator or distribution systems.

The converter will ensure that the output of the device is at a constant voltage and frequency so that they can be easily aggregated.

One alternative arrangement of the converter, DC bus and inverter arrangement is to use multiple converters and a single inverter. This arrangement is show in Figure 24. The DC bus acts as a collector network as the voltage will be constant and there is no frequency component that would cause motoring. This brings advantages in cable sizing and costs. This arrangement is used in the Tidal Flow device where 10 Schottel STG generators are connected to a single inverter. Developments in Medium Voltage DC technology are being considered by Scottish Enterprise, GE and others. Once there is a reliable and cost effective medium voltage DC conversion and transmission system available it will be worth returning to the SSE reports to look at some of the DC options explored within them.

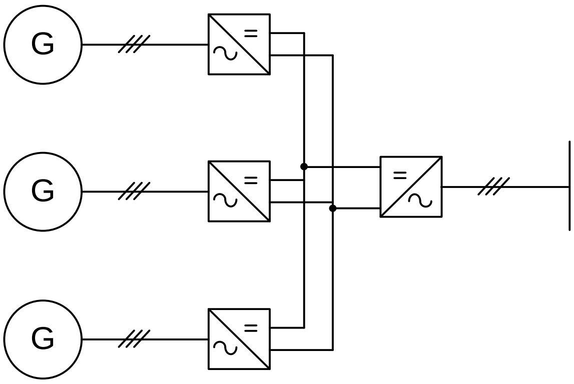

Figure 24 A DC Collector Network

Appendix 2 CAPEX Results

The following pages contain the plots for capital expenditure calculations for the surface piercing (fixed) hubs, floating hubs and radial arrays. They are all based on a 32 MW sixteen device array apart from the 11 kV array which is restricted electrically to 30 MW. The array options are split into a number of hubs. For example, 4 hub denotes four hubs servicing four devices each. The fixed hub options are presented with three cable costs form low (£500 per metre), to high (£2k per metre). There are two sets of floating hub options presented for high cost floating hubs and low cost floating hubs. These are also presented with three cable cost options each. For the radial arrays these a split by voltage level from 6.6 kV to 33 kV three sets of results are presented based on a cost option for the array equipment from low to high.

Fixed Hub Layouts

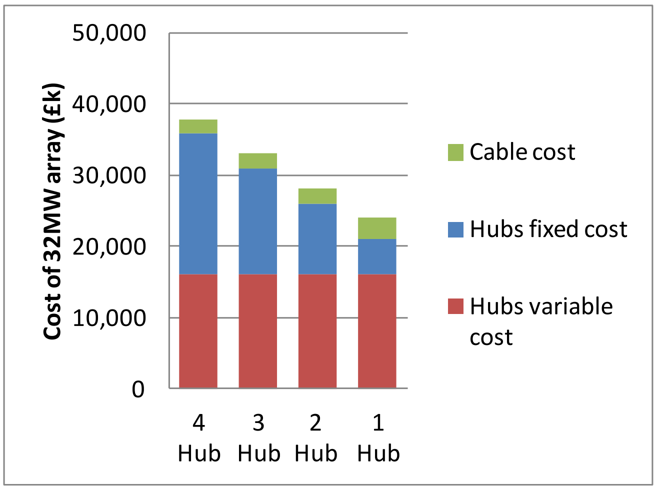

Figure 25 Fixed Hub Low Cable Cost

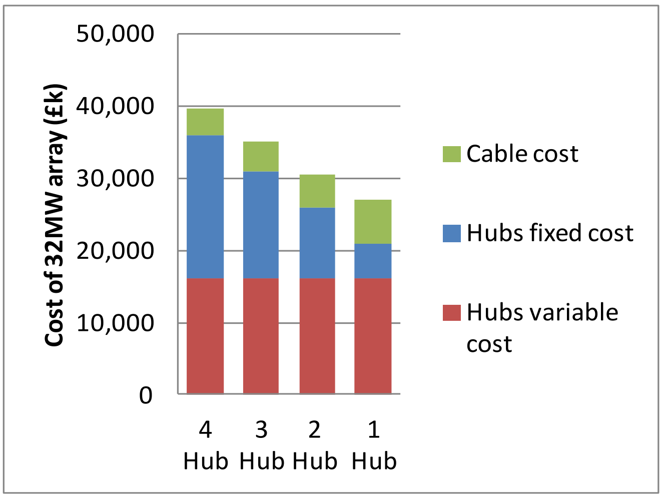

Figure 26 Fixed Hub Medium Cable Cost

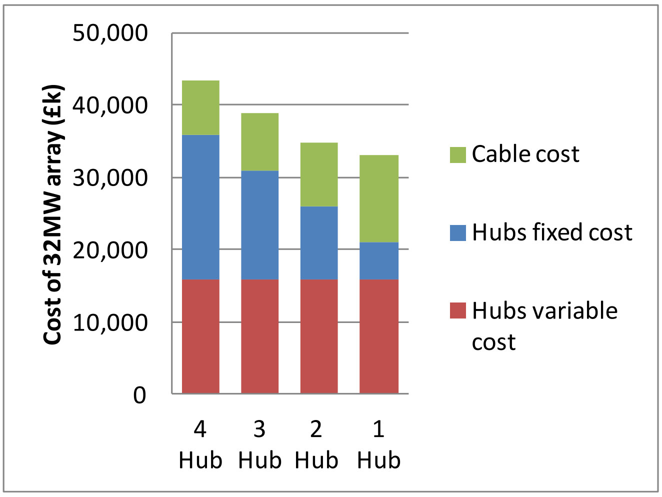

Figure 27 Fixed Hub High Cable Cost

High Cost Floating Hub Layouts

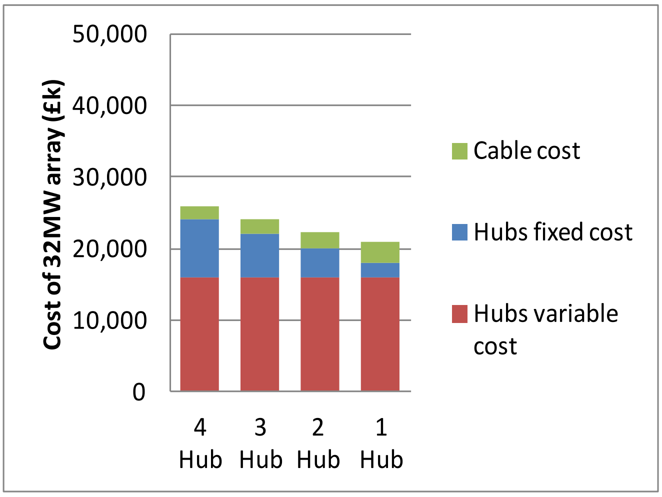

Figure 28 High Cost Floating Hub Low Cable Costs

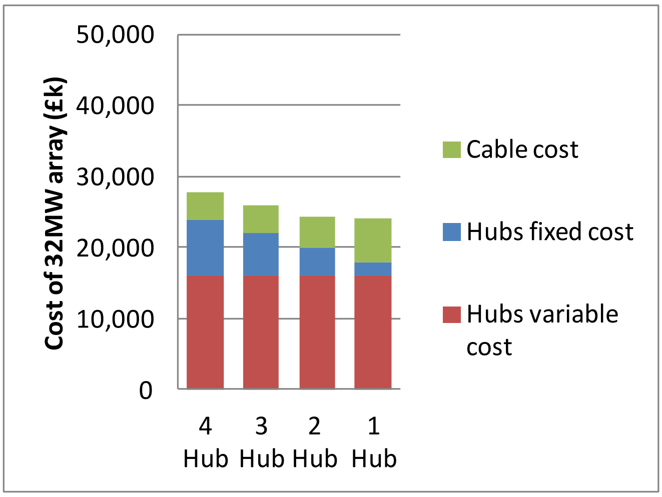

Figure 29 High Cost Floating Hub Medium Cable Costs

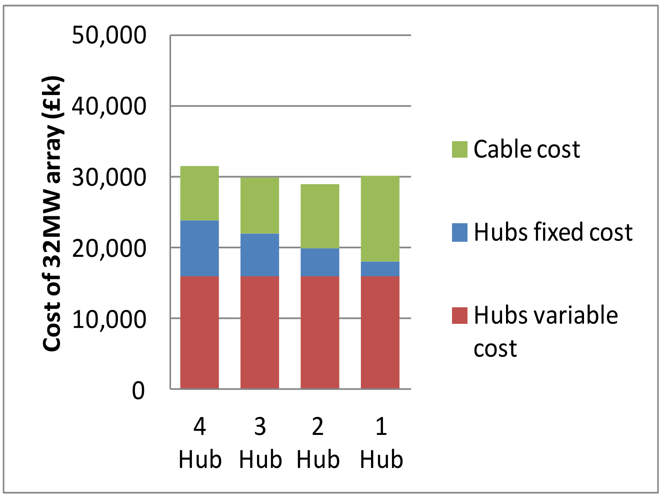

Figure 30 High Cost Floating Hub High Cable Costs

Low Cost Floating Hub Layouts

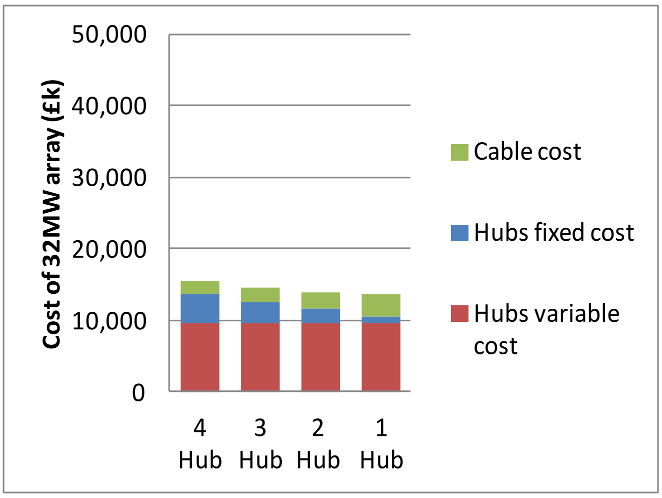

Figure 31 Low Cost Floating Hub Low Cable Costs

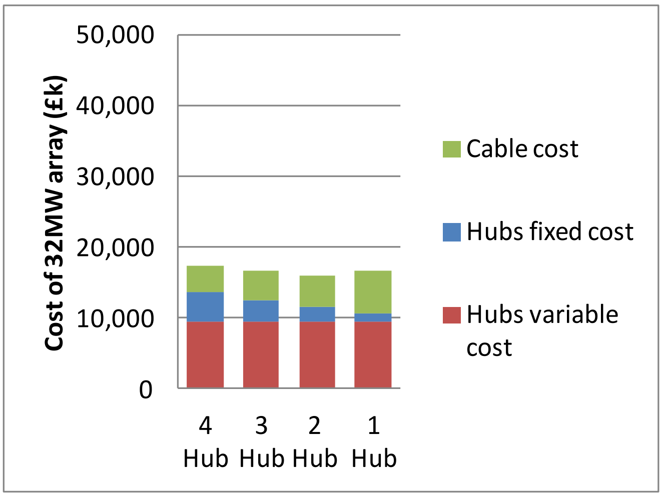

Figure 32 Low Cost Floating Hub Mid Cable Costs

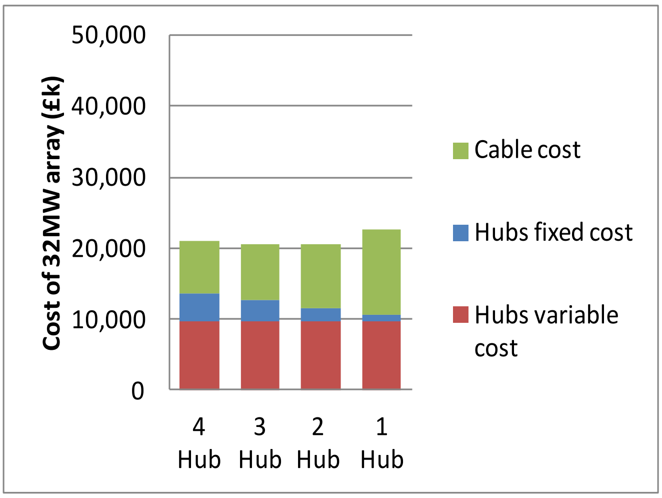

Figure 33 Low Cost Floating Hub High Cable Costs

High Cost Radial Arrays

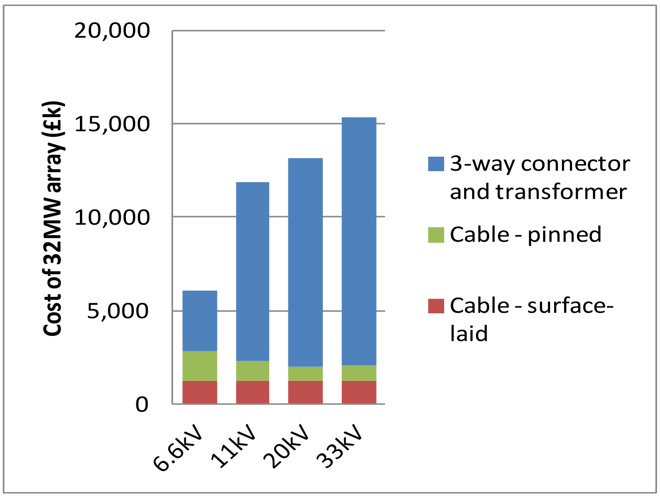

Figure 34 High Connector Cost Low Cable Cost

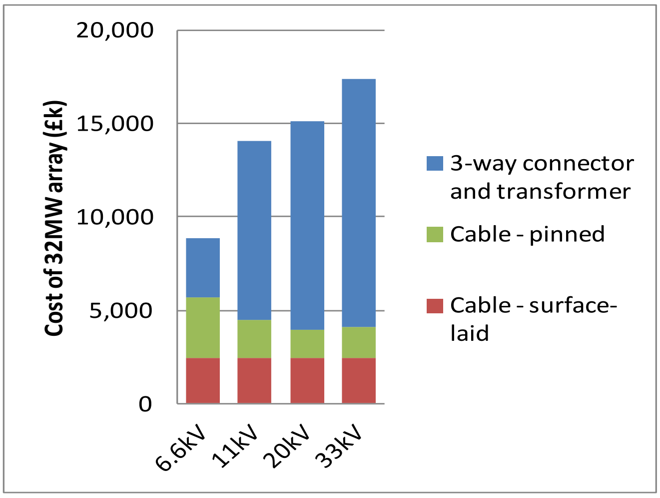

Figure 35 High Connector Cost Medium Cable Cost

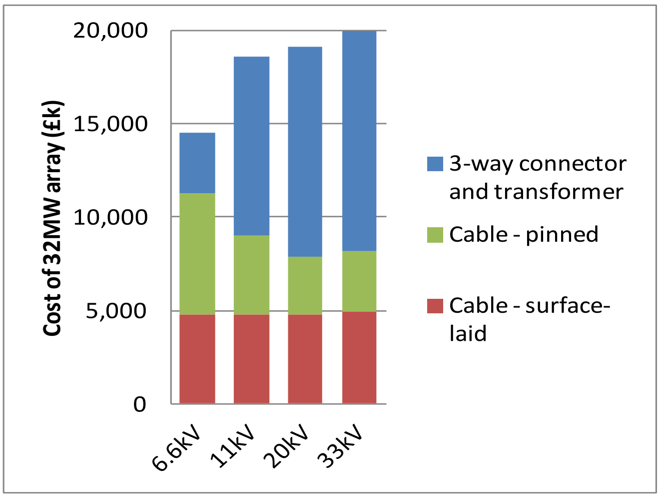

Figure 36 High Connector Cost High Cable Cost

Medium Cost Radial Arrays

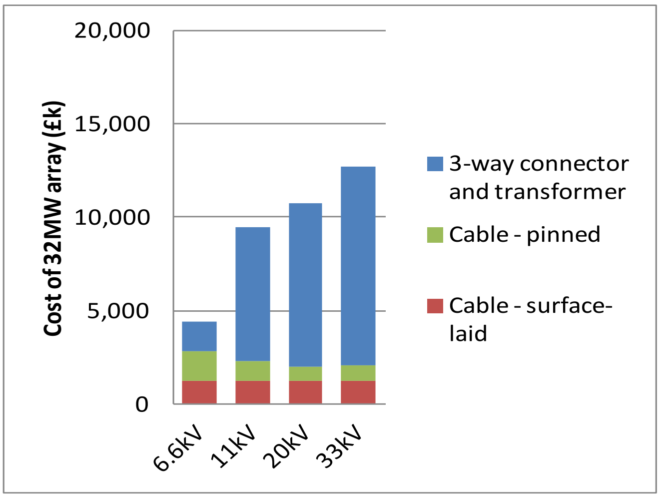

Figure 37 Low Connector Cost Low Cable Cost

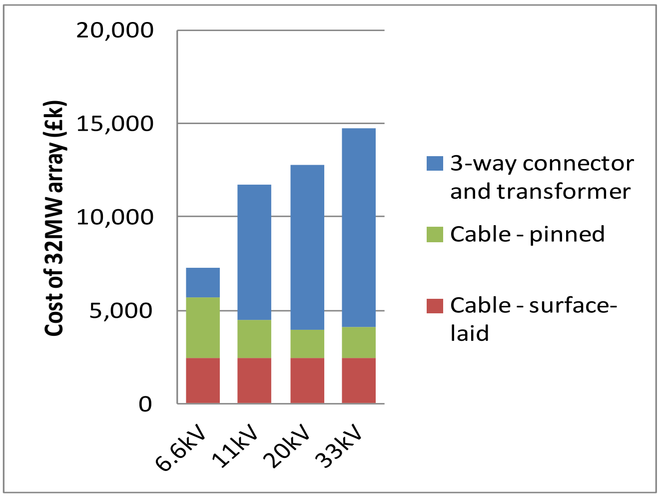

Figure 38 Low Connector Cost Medium Cable Cost

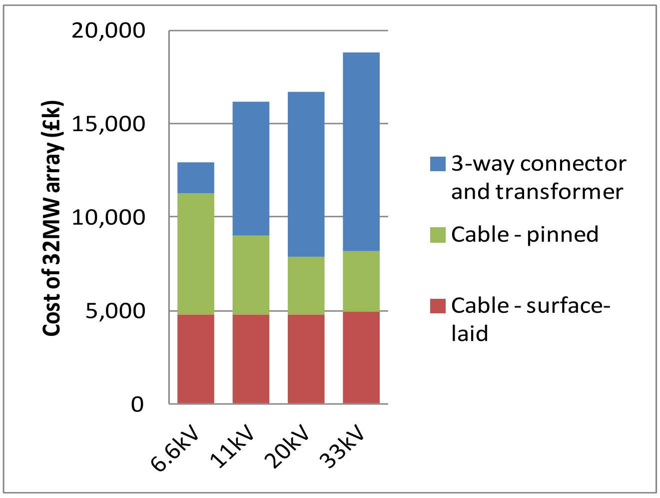

Figure 39 Low Connector Cost High Cable Costs

Low Cost Radial Arrays

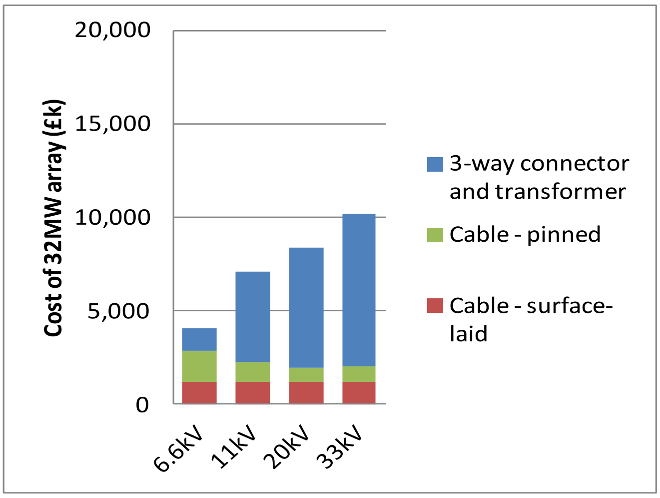

Figure 40 Low Connector Cost Low Cable Cost

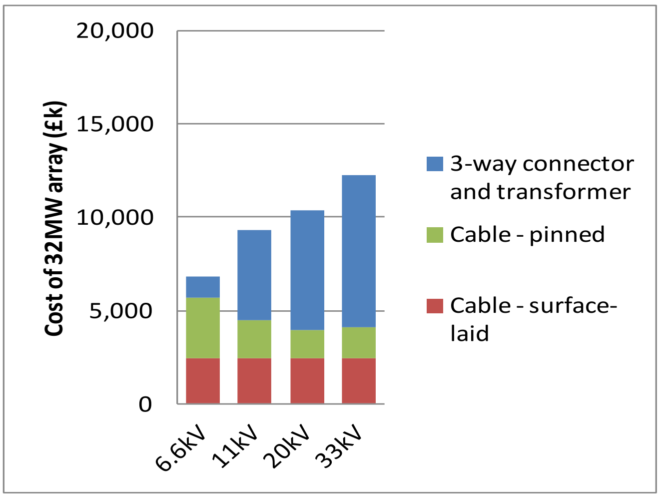

Figure 41 Low Connector Cost Medium Cable Cost

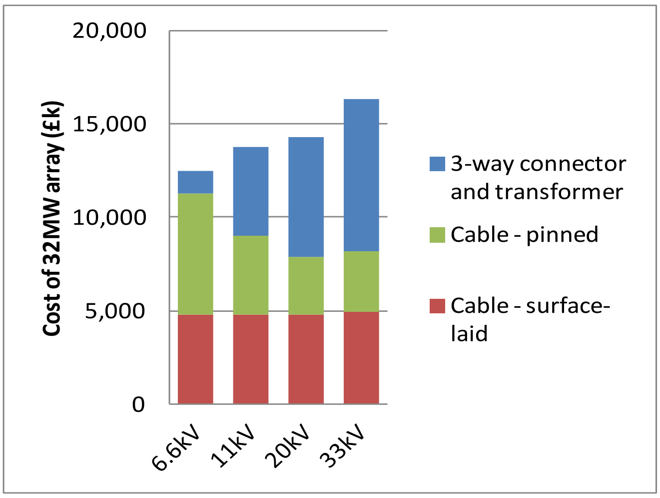

Figure 42 Low Connector Cost High Cable Costs

Appendix 3 OPEX Results

The following pages contain the results of the OPEX calculations. Each array option is presented with three variable rates used for the loss of energy from £305 per MW/h to £100 per MW/h.

Fixed Hub Annual OPEX Costs

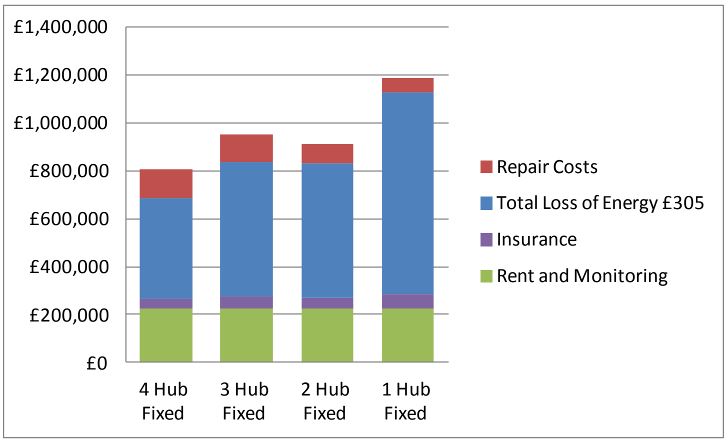

Figure 43 Fixed Arrays at £305 per MW/h Loss of Energy

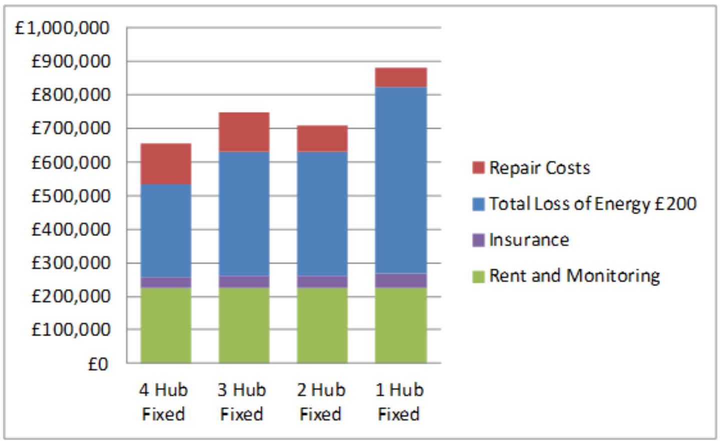

Figure 44 Fixed Hubs at £200 per MW/h Loss of Energy

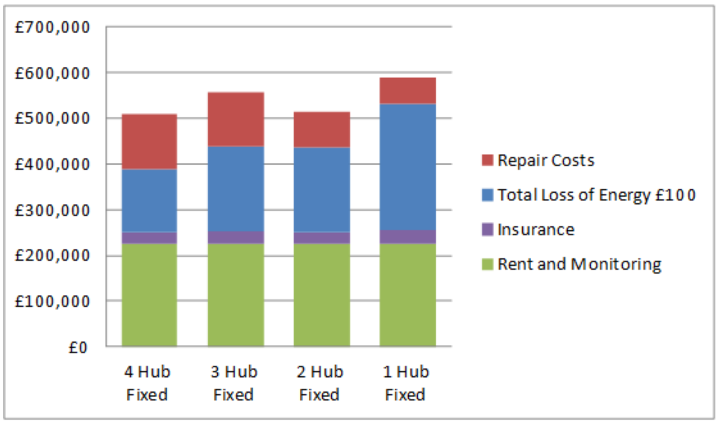

Figure 45 Fixed Hubs at £100 per MW/h Loss of Energy

Floating Hub Annual OPEX Costs

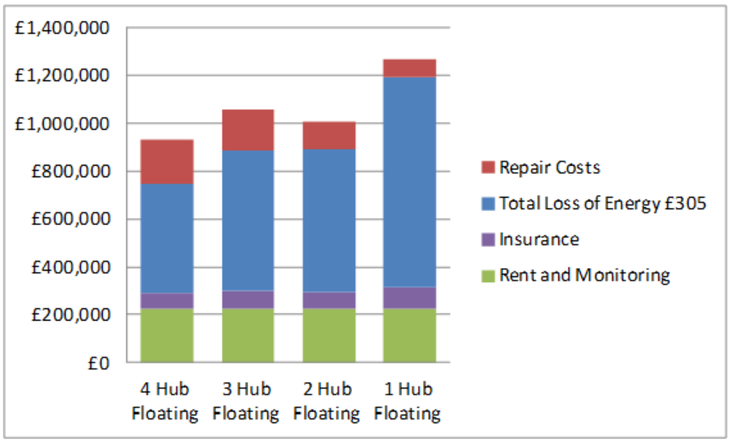

Figure 46 Floating Hubs at £305 per MW/h Loss of Energy

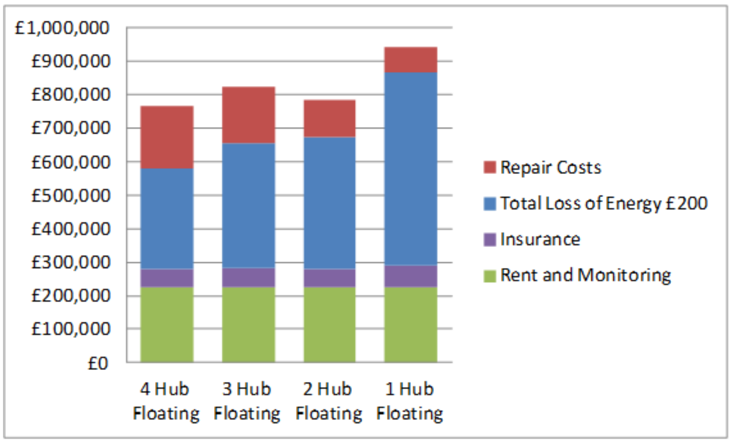

Figure 47 Floating Hubs at £200 per MW/h Loss of Energy

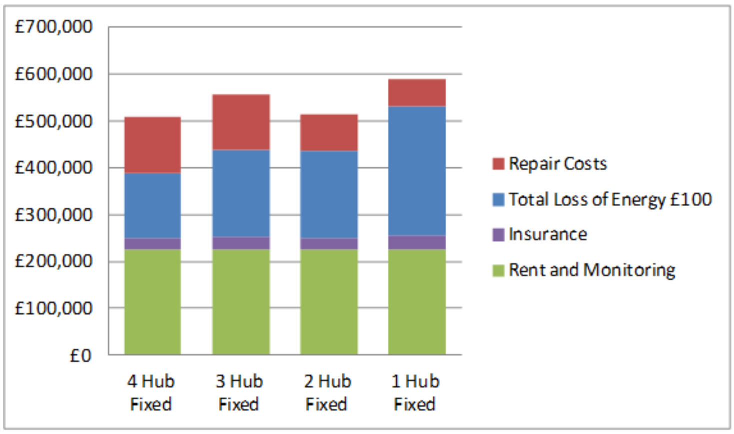

Figure 48 Floating Hubs at £100 per MW/h Loss of Energy

Fixed Array Annual OPEX Costs

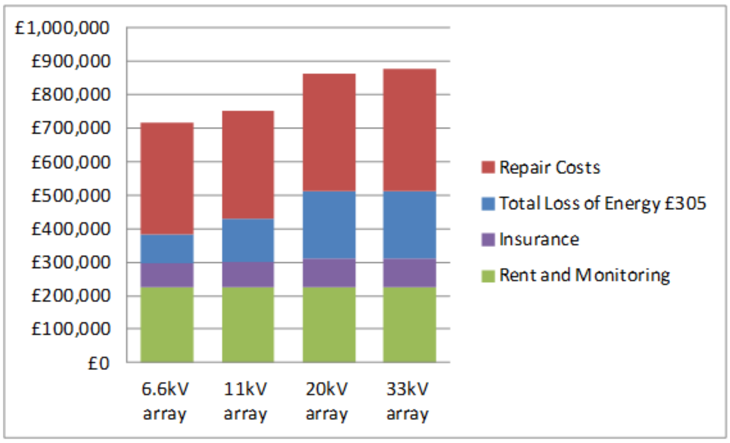

Figure 49 Radial Arrays at £305 per MW/h Loss of Energy

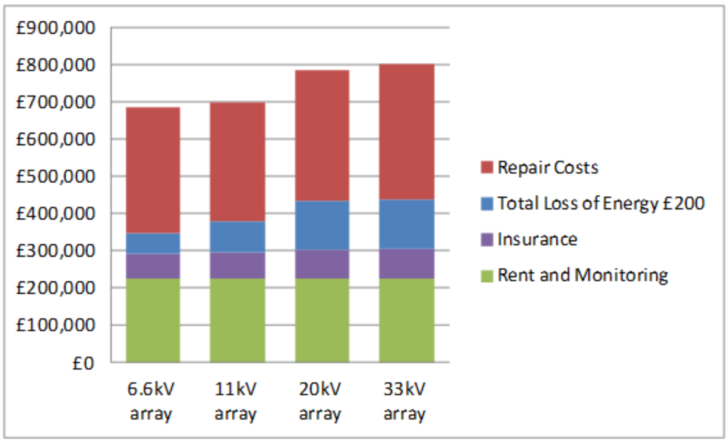

Figure 50 Radial Arrays at £200 per MW/h Loss of Energy

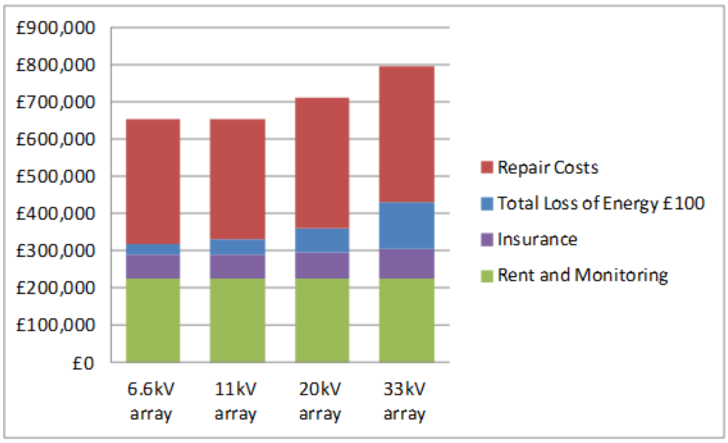

Figure 51 Radial Arrays at £100 per MW/h Loss of Energy

Appendix 4 CAPEX and OPEX Assumptions

Array to Shore Connection Cable:

The CAPEX costs for the arrays do not consider the cost of connecting the array to the onshore substation. As the distance to the shore and connection point will be different for each project this cost will be variable. The calculations below are for the costs of surface laying the cable and will be on the lower end of the scale. The cable may need to be attached to the seabed using methods such as pinning, rock dumping or the use of concrete mattresses.

Multipurpose vessel (MPV) 3 Days hire at £75,000 per day	=	£225,000
Cable costs 33kV 240mm^2 €280 or £215 per metre	=	£215,000
Miscellaneous costs £4,500 per day for 3 days	=	£13,500
Total per km	=	£453,500

Planned Maintenance Fixed and Floating Hubs:

For each fixed and floating hub there will be an annual maintenance inspection. These are costed based on the following assumptions:

- Maintenance times for hubs will vary with size.
    - 4 device hub 4 days each;
    - 6 and 8 device hubs 6 days each;
    - 16 device hub 10 days.
- Maintenance crew will consist of four technicians at £800 per day (wages and expenses).
- The vessel to take the crew out and back each day will be £1,500 per day.
- Each hub will have £5000 in consumables.
- It is assumed that the hub will not be operating during maintenance and will incur loss of energy depending on the prevailing feed in tariff.

Planned Maintenance Radial Arrays

For the radial arrays it is assumed that each transformer / connector unit will be removed from the water twice in its lifetime for a major refit. The costs are based on the following assumptions:

- To remove/ service and replace the transformer will take 2 days.
- Lifting vessel hire for each day will be £75,000.
- Four technicians at £800 per day will be used.
- An additional 4 day per array is allowed for weather delay.
- Refurbishment costs will be £25,000 per unit.
- Loss of energy will be per string for the duration of the service plus 2 days for the entire farm to be out of service to switch in and out the string.

Unplanned Maintenance Fixed and Floating Hubs

For fixed hubs this will involve one trip per year for 2 days involving.

- £1,500 for vessel hire.
- Two technicians at £800 each per day.

For floating hubs there will be the addition of 1 major repair one in the lifetime that will involve towing into dock:

- Large Vessel at £75,000 for 4 days per hub.
- Crew of four at £800 each per day for 14 days.

Unplanned Maintenance Radial Arrays

For the radial system it is assumed that there will be five major failures that will require the replacing of the transformer / connector unit with the following costs

- Large Vessel Hire at £75,000 per day.
- Unit held as spare costed at £200,000 for a 6.6 kV unit to £800,000 for a 33 kV unit.
- Four technicians for four days.
- Array to be out of service for 21 days to take account for arranging repair (vessel hire etc).

For other costs the figures from the Carbon Trust marine energy cost estimation tool were used as follows.

Monitoring and Control: Based on the Carbon Trust figures, this will be £675k per annum for the whole project so will be 25% of this for the electrical infrastructure.

Rent: Based on the Carbon Trust figures, this will be £225k per annum for the whole project so will be 25% of this for the electrical infrastructure.

Insurance: The Carbon Trust report gives insurance at 5% of the total operational cost. This will be applicable to the fixed hub scenario, but the floating hub and subsea radial array will be viewed as riskier so will have insurance rates of 7% and 10% applied respectively.

Loss of Energy per Day

A calculation of the revenue lost during maintenance and repair was made based on the strike price. The highest value strike price was £305 per MW/h which is the represents the highest price quoted in the current EMR round. Additional cost were calculated for a strike price £200 and £100. The daily loss of energy was found by multiplying the strike price by 24 hours, a capacity factor (30%) and the rating of the machine (2 MW).

Appendix 5 Distance Loss Model

In building the model for the distance calculations the following assumptions were made:

- The machines had an active power output of 2 MW which equated to 175 A for 6.6 kV and 105 A for 11 kV. Power factor was considered as 1.
- The cable was assumed to be 400 mm^2 3 core copper cable. This had a current carrying capacity of 590 A. The reason for choosing this size is that it is within the maximum operating current of the Hydro Group power distribution hub rating of 630 A.
- At 6.6 kV this equates to 3.37 devices, and at 11 kV 5.6 devices, hence 3 and 5 devices were chosen. This also provides headroom for the devices to operate at a power factor other than 1.
- Inter array cable lengths were chosen as 300 m to give a maximum spacing of approximately 200 m and sufficient cable at 50 m depth to allow a distribution hub to be lifted out of the water.
- Cable data from ABB XPLE Submarine Cable Systems was used with additional information from Land System Cables User Guide.

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