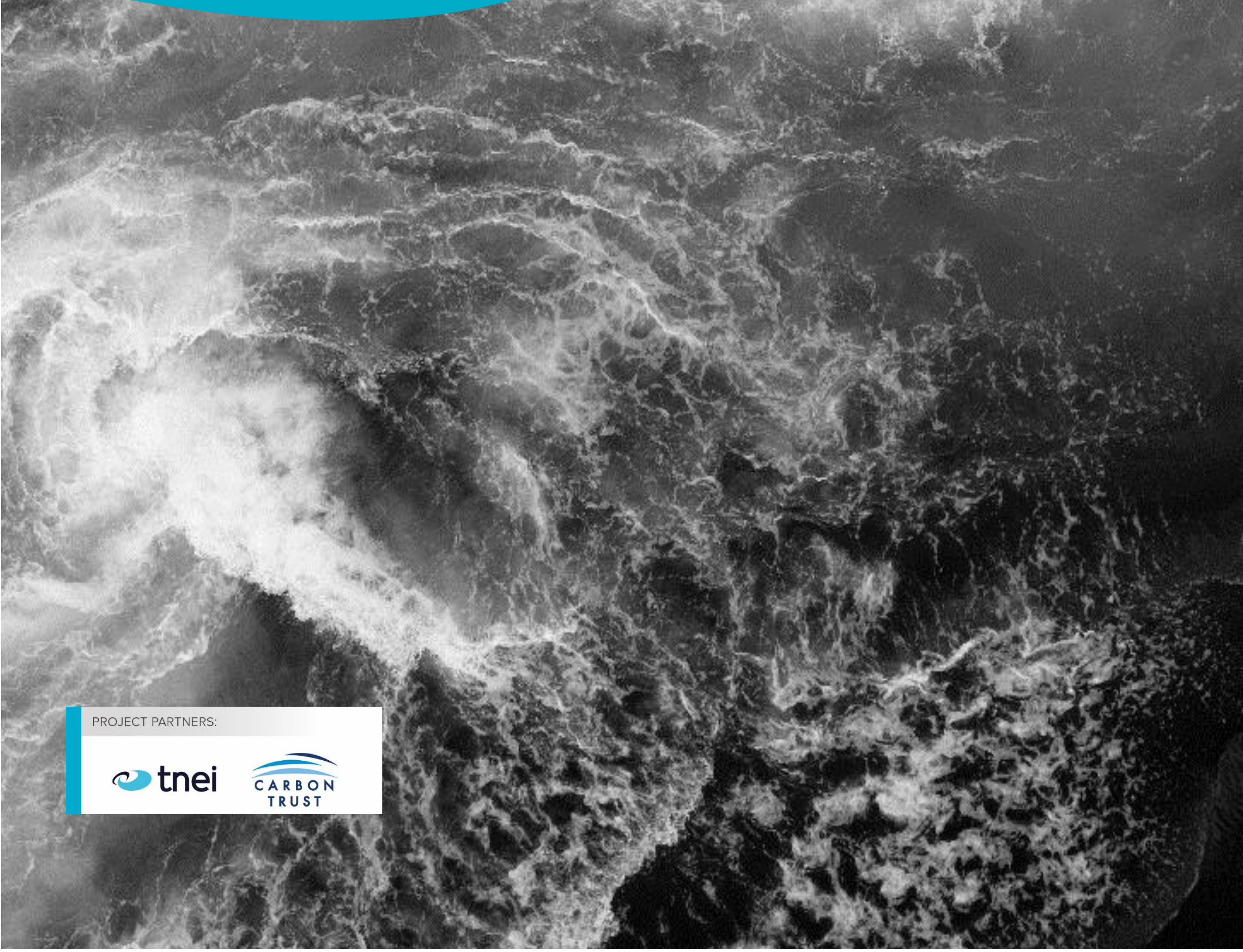
CATAPULT
Offshore Renewable Energy

Marine Energy Electrical Architecture

Report 1: Landscape Map and Literature Review

September 2015



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Contents

List of Tables

List of Figures

1 Executive summary

This document is the first of three reports that consider the future options for an industry preferred marine energy electrical architecture. The work was commissioned by the Offshore Renewable Energy (ORE) Catapult under the umbrella of the Marine Farm Accelerator and carried out by TNEI Services.

Over the next few years, marine energy converters 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 ORE Catapult has acknowledged a need to identify a preferred marine electrical architecture that can be adopted by as many wave and tidal devices as possible. By developing a common architecture, a universal set of operating constraints and components can be identified. Having a defined set of components will allow industry to further identify areas of product improvement and development to drive down cost, increase reliability and to lower the levelised cost of electricity from the electrical infrastructure.

This report presents a landscape map and the results of a literature review. The second report will provide an overview of the previous concept studies carried out by ABB, General Electric and Siemens. The third report will use the knowledge gained from the first two pieces of work to develop a set of preferred marine array architectures.

The development of the landscape map serves two functions. The first is to provide information on commonalities amongst devices to feed into the architecture study and the second is to provide an overview of the marine energy devices installed or under development in the UK. A technical questionnaire was sent out to all members of the Marine Farm Accelerator Device Advisory Group (DAG) and other manufacturers. The responses to this questionnaire were augmented by information in the public domain, including manufacturer and test centre websites. This information was used to build up a map of the devices that could be connected in an electrical array architecture.

The initial brief for the project was to look at array architectures for 30MW, 100MW and 200MW arrays for an example 1 MW device. The results of the survey showed that of the 17 devices reviewed, 10 were 1MW level or less and 7 were over the 1MW level. The trend is for manufacturers to increase outputs up to the 1.5 to 2MW level. As a result, this report considers a device rating of 2MW.

From the perspective of power generation, all of the machines considered in this report generate electrical power by producing AC rather than DC current. As the literature review shows, MECs that generate DC current are popular topics for research as this allows for the use of DC collector networks, which provide for the efficient aggregation of power generated from multiple devices. In reality, there are a few manufacturers actively developing machines that generate DC current, however these have not yet reached commercial production. The design of a preferred architecture will therefore focus on medium voltage (MV) AC.

Manufacturers were asked to provide information on power conversion and voltage transformation. In this context, power conversion describes any type of power electronics situated between the generator and electrical output of the machine. From the perspective of an electrical array design, MECs that can carry out power conversion on-board present the fewest challenges. As these are straight forward to aggregate together into arrays using a cable network. If a MEC is fitted with a generator and no power converter, the design of the array is more complex as power conversion needs to take place at some point in the array remote from the machine.

The output voltage level of the MECs surveyed ranged from 400V to 13.8kV, with 6.6kV to 11kV being the most common MV output. The voltage output of the MEC will need to be high enough to reduce currents and therefore keep cables to a manageable size. It will also need to be low enough to allow for the use of commercially available subsea connectors. An important consideration when deciding voltage levels for an offshore array is the distance from the shore at which it can operate effectively. This will be examined in the final report.

Since the design of tidal electrical arrays is in its infancy, there is no body of literature based on operational experience to inform this study. In addition to the concept studies that are being reviewed in work package two (WP2), there are three significant pieces of work on wave and tidal generation:

- Electrical Design for Ocean Wave and Tidal Energy Systems by Raymond Alcorn and Dare O’Sullivan. Published by the IET.
- Integrating Wave and Tidal Current Power report published by the International Energy Agency (IEA).
- State of the Art Assessment and Specification of Data Requirements for Electrical System Architecture report published by DT Ocean.

These pieces of work were broad ranging and all looked at the subject of electrical array architecture. All considered the options available, which included radial networks with various degrees of redundancy and star cluster networks.

While the literature discusses electrical arrays, none presents a preferred architecture. Many options in terms of types of MECs and redundancy architectures are considered. Radial networks are based on the offshore wind model and no consideration is given as to how a cable will loop in and out of each MEC. This leads to suggested architectures that are not physically or commercially viable. A lot of analysis is undertaken around DC collection and aggregation architectures, however there are few MECs in development that produce DC.

In order to develop a preferred electrical architecture, it has been necessary to reduce the number of options considered. The manufacturer's survey provided useful information in terms of power output (≥ 2 MW) and voltage levels (AC at circa 6.6kV), providing key inputs into the preferred architecture. The development of both array and star cluster topologies will depend on the use of hubs, subsea connectors and cable splitters. Many of these components are in their infancy and further development will be required in order to put these into mass production and start to drive down costs.

2 Introduction

The marine energy industry has reached the stage where a number of devices have completed pre-commercial full scale demonstrations. Over the next few years, array-level projects will start to be constructed. One of the challenges facing the marine energy industry is the need to reduce the Levelised Cost of Energy (LCoE) of these projects. The lack of a standard marine electrical architecture means that it is difficult to identify areas where cost savings can be made.

To address this issue ORE Catapult, under the umbrella of the MFA, has instigated a project to identify a preferred array electrical architecture. The aim of the project is three fold:

- Review previous and current work on the subject;
- Engage with industry to develop an optimum array electrical architecture; and
- In identifying an optimum array architecture reduce the LCoE.

The initial brief for the project was to look at architecture solutions for single 1MW rated wave or tidal devices connected in marine energy parks of 30MW, 100MW and 200MW. A survey of the marine energy converters during this project has shown device sizes can be up to 2MW and beyond. The project will now look at connecting single 2MW devices.

The project was split up into three work packages with the output of each work package consisting of a report. This first work package is a knowledge gathering exercise involving stakeholder engagement and a literature review. MEC manufacturers were approached and asked to provide technical details of their machines. Other industry players such as marine energy test centre operators and developers were also approached to provide feedback. The literature review included books, reports and conference proceedings. The intention was that the findings of this report would be used to suggest a set of preferred architectures.

This is the report for the first work package (WP1) which will provides a landscape map and a literature review. The intention is that this report can be used as a resource for those new to the electrical aspects of wave and tidal power generation. Unlike the wind industry, where wind turbines conform to a common set of design principles, wave and tidal devices have been developed with a variety of ways of generating power from the movement of the ocean. The manner in which they extract kinetic energy from the marine resource, as well as the conversion of the mechanical energy to electricity, can differ from machine to machine.

The purpose of this project is to investigate the challenges of developing viable marine array architectures that would be manufacturer agnostic and to focus on the development of an architecture that can be deployed for the widest number of devices. The first task of this report was to carry out a survey into as many MECs as possible so that they could be classified. This classification was then be used to inform the constraints of a preferred array architecture. In addition, the findings were also used to build up a landscape map of wave and tidal devices. An overview of each device surveyed is presented in the report.

In the literature review, publications from the last three years were studied. At present, marine energy array architectures are in their infancy. No literature was found that covered the experience of operating more than one device in an array formation. All the literature reviewed dealt with the conceptual side of developing array architectures or focused on an analysis of the available generating technologies. From the perspective of array architecture, all the previous work took a similar approach. It considered the relative merits of radial arrays, redundant radial arrays and star clusters. An analysis of the relative normalised costs of each option was carried out, which suggested some lower cost topographies.

3 MEC Overview

3.1 Introduction

This section covers the knowledge gathering activities carried out to build up a landscape map of the variety of MECs available. A full list of device manufacturers approached for this study and details of their devices are provided in Appendix 1 and Appendix 2. In addition, test centre operators were approached to provide details of their facilities and projects.

3.2 Approach to Stakeholder Engagement

Consultation was undertaken by questionnaire. Of the 17 candidates approached, ten provided some form of response. The questionnaire contained 18 questions, presented in Appendix 3.

3.3 Classification of MECs

The first step in the process of identifying common electrical array architecture was to classify the devices into a number of categories to identify commonalities. The MECs were classified according to the following criteria:

- Type of device
    - Floating or fixed
    - Wave or tidal
- Generator size (rated MW)
- Voltage output range
- Generator type
- Converter type
- Use of wet or dry mate subsea connectors

3.4 Hydraulic Power Take-Off Devices

The above list does not fully capture other emerging technologies available for power take-off from wave devices. A wave device has to generate power from a wave every couple of seconds. In order to turn this into usable electrical energy, designers have turned to hydraulic storage and generating systems. These use a set of accumulator tanks to store the kinetic energy of each wave. This stored energy is then released in a controlled manner to drive a hydraulic turbine which in turn drives a generator. As the release of the energy stored in the accumulators can be controlled, the speed of the turbine and hence the generator can also be controlled. This allows for the generator to run at a fixed frequency.

3.5 MEC Deployment

3.5.1 MeyGen

MeyGen is the first commercial-scale tidal array that is financed and under construction in the UK. It is situated in the Pentland Firth and will be built in two phases, this first is for 86 MW with the second phase taking this up to 398MW. The first four tidal turbines to be installed will come from Atlantis (one turbine) and Andritz Hydro Hammerfest (three turbines). There is no electrical array for these devices. Rather, each turbines electrical connection will be brought to shore via horizontal direct drilling and will be fed into individual power converters and transformers in the onshore power conversion centre. The site has a 15MW connection to the Scottish Hydro Electric Power distribution network. The larger site will connect into the 132kV transmission network. The site is close to shore with the furthest turbine being no more than 2.5km offshore. Being a commercial venture, MeyGen's decision on device selection and array architecture has been made with regards to economy and efficiency. The company has identified the power conversion electronics as being vulnerable and has made the decision to house these onshore. The Atlantis turbines are fitted with a permanent magnet synchronous generator (PMSG) and the Andritz Hydro Hammerfest turbines are fitted with induction generator, both generating at MV (<6.6kV). As there is no straightforward way to parallel PMSG and induction machines together, this decision has resulted in each machine being connecting to shore individually. One of the stated advantages of this method, is that there are no shared components between the devices, which provides an element of redundancy. As all the turbines are less than 2.5km from the shore, there will be no issues of voltage drop or significant power loss. These could be drivers that could make power conversion and voltage step up an option. As the project develops, there will be pressure to reduce the number of cables coming on shore. A multi-core cable containing a number of individual MV circuits has been suggested.

3.5.2 Wave Hub

Wave Hub is a wave energy device demonstration facility based in Cornwall. The site is 8km^2 and is situated 16km from the mainland at a depth of between 48 to 58 meters. The site is designed to allow four sets of devices from different manufactures to be tested simultaneously. WaveHub affords an insight as to how an offshore array could be developed. Central to the site's electrical architecture is a subsea collection hub produced by JDR Engineering. This hub lies on the seabed and allows for the collection of four cables. These then connect to a common bus bar for transmission onshore using a single cable. At 11kV, the hub has a capacity of 16MW. It can also be operated at 33kV with a capacity of 50MW. For this application the transmission cable to shore consisted of six 300mm^2 conductors and 48 optical fibres. The two sets of conductors allowed for the hub to be configured as two separate circuits. The four connections for the MECs are made using four separate 300m tails, which are permanently connected to the hub. The hub has a gravity base that is protected by rock dumping. The hub has been designed to be maintenance free for the 25 year design life of the project. There is no switchgear or other electrical components in the hub. At the time of writing the WaveHub has been installed and is waiting to connect to candidate devices[1].

3.5.3 European Marine Energy Centre (EMEC)

EMEC was established in 2003 and provides open sea testing for both wave and tidal devices.

The centre is spread over a number of facilities in the Orkney Islands. The wave energy test site is in Stromness and the tidal energy site is off the island of Eday, there are also two smaller scale test sites. Each test facility has an 11kV substation and each device can connect to the grid via an individual subsea connection. At present, all MECs connect individually and the owners are responsible for ensuring the power produced is at 11kv and 50Hz and meets acceptable power quality requirements.

3.5.4 Fair Head, West Islay and Westray Tidal Energy Parks

The development of these three projects is being led by DP Energy. Fair Head is off the North Antrim coast in Northern Ireland and is a proposed 100MW development. West Islay is a 30MW development off Argyll and Bute in South West Scotland. Westray South is located in the Westray Firth in Orkney and is a proposed 200MW development. DP Energy takes a project first approach such that planning for the device type and electrical array architecture at the scoping and consultation stage is technology neutral.

DP Energy does not consider direct cabling to each device as a viable economic option for these commercial-scale developments and expects to collect the power from the turbines in offshore hubs. The West Islay site is some 6km from the nearest land and the cliffs at Fair Head limit the option of cable routes to the grid connection point. The technology neutral planning approach will allow the developer to make a decision on the most appropriate arrangement of generator, converter and array architecture later on in the project cycle, post consent award but prior to financial close. This decision will be based on a techno-economical evaluation. Consideration will be given to both subsea and surface piercing (or floating) hubs housing switchgear, power converters and transformers. Furthermore, consideration is also being given to using any surface structures/hubs, used for electrical collection/conversion equipment, to assist in navigation marking of the site, for example if possible situating them at the edges of the site boundary.

[1] C. Spradbery 'Design and Engineering of the Wave Hub Project ' 3rd International Conference on Ocean Energy, Bilbao, Spain, 2010.

4 Analysis of MEC Data

4.1 MEC Types

Generally, tidal powered devices are fixed to the seabed and wave powered devices float, Figure 1 shows this with a few exceptions. The Aquamarine Oyster is the only fixed seabed wave device but both Nautricity and Scotrenewables have floating tidal devices. The Schottel STG and Tocardo T series units are both multi-use small generators that can be used in both fixed and floating platforms. The figure also shows that the majority of MECs are for tidal applications. An array architecture for floating devices will have to consider the use of dynamic umbilical power cables. This will be needed to transmit power from the surface to the electrical infrastructure on the seabed.

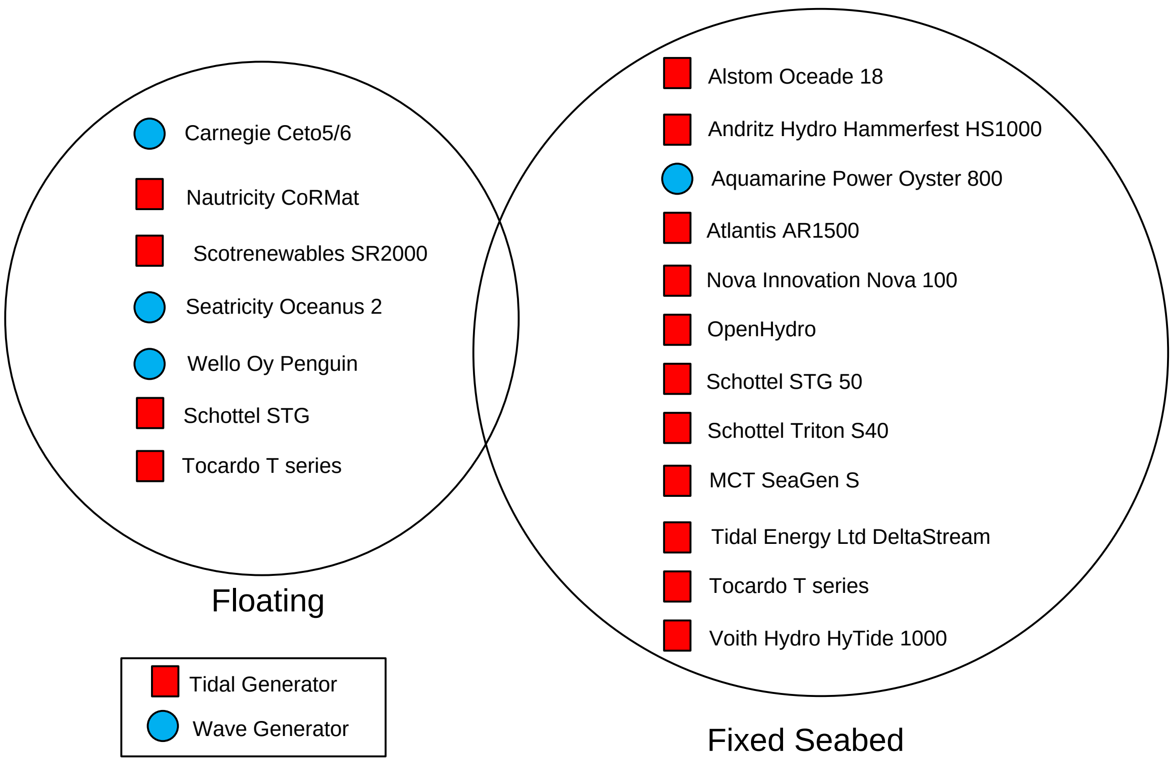

Figure 1 Marine Energy Converters by Device Type

4.2 MEC Power Output Levels

4.2.1 Introduction

The brief for this project was to look at electrical array architectures for 1MW machines. Figure 2 shows the MECs in ascending order of power output. Historically, 1MW has been considered as the standard rating for horizontal axis tidal energy converters (TECs). However, as trials have progressed, both Alstom and Atlantis have increased the size of their machines by 40-

50%. Scotrenewables and OpenHydro machines will generate at 2MW. The Schottel Triton S40 is made up of up to 40 smaller units and therefore can generate up to 2.5MW. It is clear that there is a move to larger sizes with 2MW seeming to be the upper limit for single device machines at present. As a result, the project will focus on 2MW devices in arrays of 30MW, 100MW and 200MW.

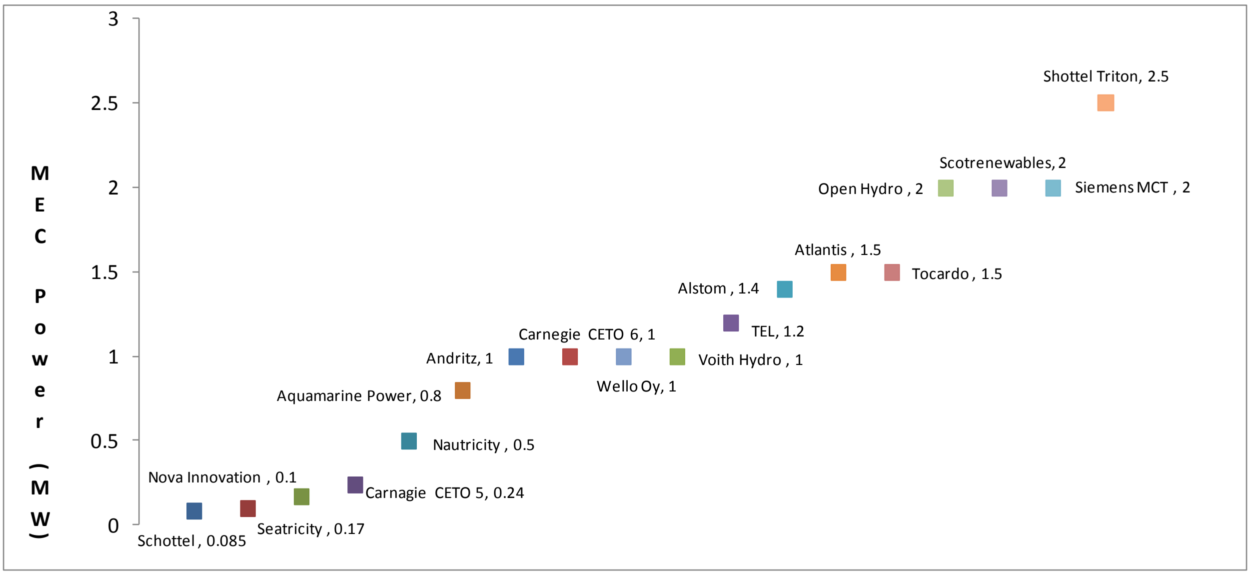

Figure 2 Power Rating of Candidate Machines

4.2.2 Output Voltage

Figure 3 shows the range of output voltages from the MECs in ascending order. These were identified either from the response to the questionnaire or from information in the public domain.

Both the Schottel and Tocardo devices are low voltage. The Schottel device is designed to be integrated into larger arrays on a platform such as the Triton S40; the Tocardo is fitted with integral power electronics and is intended for near shore applications. 6.6kV to 11kV is the general voltage level for most of the machines, which represents the lowest UK distribution voltage. The Aquamarine Power Oyster voltage level is based on the Bosch Rexroth WavePOD demonstration unit output and could be altered using the onboard transformer. The Schottel Triton output is based on their Canadian project and could be reduced by changing the onboard transformer.

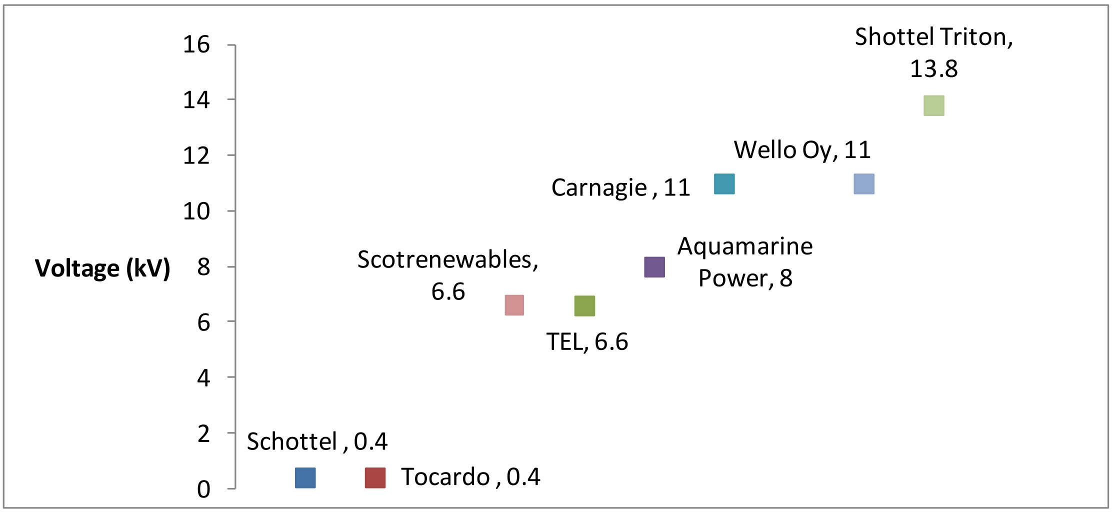

Figure 3 Output Voltage Levels

4.2.3 Generator Types

Manufacturers favour either induction machines or permanent magnet synchronous generators. This aligns with the finding of the literature review which do not favour generators that use slip rings as these require regular maintenance.

4.2.4 Power Conversion/Conditioning and Voltage Transformation

An important consideration in the design of an array network is whether it has any function in aggregating the power coming from the individual machines or is just used as a collector. If the generator is connected to the grid via some form of power electronics in the machine, it is assumed that the power electronics will condition the power from the MEC. It will ensure that the frequency is in sync with that of the connected grid and that the voltage is controlled within a manageable dead band. In this case, the array will act as a collector network. If the machines are not fitted with any power electronics, the design of the array becomes more complex as the power electronics need to be located somewhere on the network other than on the machine. A number of demonstrator projects have opted to locate the power conditioning equipment onshore. From the survey results, it is clear that the Tidal Energy Limited currently relies on an onshore based converter and transformer system as do the Andritz Hammerfest and Atlantis machines that will be used at MeyGen. The machines from Alstom, Tidal Stream (Triton S40), Scotrenewables and Tocardo all produce ‘grid ready’ electrical power. This means that the power is processed by an AC-DC-AC power converter within the MEC.

4.3 Wet Mate Connectors

Wet mate connectors offer a degree of flexibility for the removal of individual parts of marine energy array infrastructure for servicing but come at a cost. A single mating set of power, auxiliary and data connections can account for 15% of the cost of the electrical infrastructure of each MEC. Three companies use, or will use, wet mate connectors, these are:

- **Alstom** A wet mate connector is used on a patented stab plate system which connects the nacelle to the seabed fixed tripod. The tripod contains a fixed cable. Alstom notes that the current choice of wet mate connectors limits the output to 6.6kV.
- **Scotrenewables** The 250kW unit uses wet mate connectors and this may be the case for the newer 2MW device.
- **Tidal Energy Limited** The demonstrator system has nacelles that are permanently fixed and cabled. However, in response to the questionnaire it have indicated that in future the nacelles will be removable and will be fitted with wet mate connectors.

5 Literature Review

5.1 Introduction

An initial search was carried out for papers, proceedings and reports with the IEEE, the IET and CIGRE. In addition, the output of the DT Ocean project ‘optimal design tools for ocean energy arrays’ was reviewed. Few academic papers or conference proceedings, were available compared with the offshore wind sector. The following documents from the last three years were identified for detailed review:

- Electrical Design for Ocean Wave and Tidal Energy Systems, Raymond Alcorn and Dare 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
- 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
- Power Conversion Systems for Tidal Power Arrays, Sandeep Bala, Jiuping Pan (7pp), IEEE Conference Paper 2014

The following sections provide a review of these documents.

5.2 Electrical Design for Ocean Wave and Tidal Energy Systems - IET – 2013

5.2.1 Introduction

This book was produced by the IET as part of their renewable energy series. Only those sections of the book relating to tidal array architectures are considered in this review.

5.2.2 Electrical Generators in Ocean Energy Converters

This chapter looks at fixed speed and variable speed generators. While the fixed speed generator was simpler than the variable speed option there were several drawbacks associated with using this technology namely:

- Low energy capture;
- Mechanical stress;
- Power quality; and
- Reactive energy compensation requirement.

The advantages of using power converters was discussed and doubly fed induction generator (DFIG) and full converter topologies were presented. Various generator configurations were also presented:

- Brushed synchronous generator (SG);
- Squirrel cage induction generator (SCIG); and
- Permanent magnet synchronous generator (PMSG).

DFIG and the brushed synchronous generators required the presence of a brush system to excite the rotor. The implications of the use of brushes with regards to operation and maintenance were discussed. Figures were given for brush wear of between 3,500-8,750h[2]. The effective annual operation of a MEC is 5,000h. The conclusion is that this would involve a biannual change of brushes. A biannual maintenance schedule would be considered onerous so these types of generators should not be considered suitable for MECs.

PMSG and SCIG were then considered. The SCIG is of a simpler construction than the PMSG. The PMSG uses rare earth magnets (NdFeB) that are highly sensitive to corrosion. However, the PMSG has a higher power-to-weight ratio (3-3.8 kg/kW compared to 4-4.5kg/kW compared to the SCIG)[3] and will have an advantage in terms of shock loading for the rest of the MEC design.

5.2.3 Cabling and Umbilical Array Layout

Subsea Components

This chapter focuses on the lack of an adequate array architecture definition. The introduction to the chapter notes the difficulty in the definition of the array architecture depending as it does on a number of different technical aspects and considerations. The chapter looks at the components required to construct an offshore connection and the way that these can be deployed. It also goes into details on the construction of offshore cable and also includes a discussion on bend stiffeners. Connectors are mentioned but only briefly and there is only one mention of wet mate connectors.

The section starts off with an example of an electrical infrastructure that contains all the elements of an MEC array, namely:

- Unit power distribution: This is a dynamic umbilical cable that connects to the MEC.
- Farm power distribution: Static cable and joint box.

[2] M.V.R.S. Jensen 'Long –term high resolution wear studies of high current density electrical brushes, in Proceedings of the Fifty First IEEE Holm Conference on Electrical Contacts, 2055, IEEE, Chicago, USA. pp.301-311 '
[3] L. H. Hansen, P. H. Madsen, F. Blaabjerg, H.C. Christensen, U. Lindhardand, K. Eskildsen. 'Generators and power electronics technology for wind turbines', in The 27th Annual Conference of the IEEE Industrial Electronics Society ,201, IECON'01.2001, vol. 3, pp. 2000-2005

- Subsea hub/substation: Collection hub that can contain transformer and switchgear.
- Wind farm power static cable: Connection from the underwater hub to the onshore grid connection point.

Array Layout

The chapter considers the main factors involved in the design of an array layout. Inter cabling configurations are discussed. Individual cabling to shore is dismissed as too expensive although this method has been used for the first four machines to be installed at the MeyGen site. Voltage drop and cable size put a limit on the number of MECs that can be connected together. All the designs defer to a cluster type of arrangement that will depend on a collection hub arrangement. The following arrangements are considered:

- String cluster without redundancy;
- Star radial cluster; and
- Redundant string cluster.

A string cluster without redundancy will be familiar as the type of system used for wind farms. However, while it is easy for the cable to be looped in and out of a wind turbine, doing so on a MEC is much more difficult. This would add complexity and cost to the MEC so a connection box mounted to the seabed to split the cable would be needed. A star radial cluster would involve a single cable connection between each device and a connection hub. This would be more straightforward in terms of cabling and connectors but may be more costly. A redundant string cluster will involve the connection of a large number of units in a string formation with the addition of a return loop. While this provides redundancy it still has the problems of loop connections to the turbine and a larger cable will be required to cope with the additional current rating. The section finishes with a note that the comparison with different models will be driven by economic performance. The book contains a chapter on techno-economics and these will be covered in detail in the next section.

Design Considerations

There is a section on the engineering of grid connection infrastructures. It focuses on floating devices, requiring umbilical cables. It starts with an overview of the qualitative requirements of an ocean energy deployment, which are:

- The infrastructure will be permanent and will require a high design life;
- The motion of the elements of the connecting infrastructure should be limited in order not to affect the cable dynamics;
- The whole structure should be easy to maintain, operate and install;

- The components should have minimum volume and weight and be commercially available; and
- The environmental impact of the structure should be kept to a minimum during its life cycle.

While all of these are admirable goals the book notes that at present many of the systems are purposely designed and it may take some time before the industry focuses in on a reduced range of procedures and components.

Umbilical Cable Requirements

- The section continues to look at connection of umbilical cable to floating devices. It defines the position of the connection point on a number of requirements:
- The motions of the connector should be of limited amplitude to reduce dynamic load on the cable. Ideally connected to the lower part of the structure near to the centre of gravity;
- The cable should be completely immersed during operation and should not oscillate outside of the sea water;
- The connection point should be close to the power generator or converter;
- The connector should be distant from the mooring connection or the extremities of the device to reduce interference; and
- The cable should be easy to maintain and allow for simple access to the MEC.

Once the cable has left the floating device there are a number components and options for connecting the device to the shore. The chapter makes a distinction between umbilical cables, dynamic cables and static submarine cables. Umbilical cables are free floating in the water; to protect this cable at the unit end bending stiffeners are used. These are conical shaped polyurethane mouldings that add local stiffness to the cable at connection points. These are not to be confused with bending restrictors that are placed along the length of the cable and limit the bending of the cable on its cable route from the device to the seabed.

5.2.4 Economics of Ocean Energy Electrical Systems

The chapter notes that since there are no large-scale arrays installed at present, there is some uncertainty as to the overall capex of such projects. It proposes to use figures from the offshore wind industry to inform the electrical infrastructure component of marine projects giving a percentage figure of 20-25%[4]. It also notes that this will be higher for wave and lower for tidal. This reflects the additional umbilical cables required for floating devices.

[4] BVG Associates, A Guide to an Offshore Wind Farm, The Crown Estate, London, UK 2011

Component Cost of a Marine Energy System

A target figure of €4m/MW is given as a cost for marine energy systems giving a total cost for the electrical system of €1m/MW (figures from Crown Estate report)[5]. Table 1 gives figures for the cost of individual components and these are presented below[5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15].

Component	Estimated Cost
Generators*	€ 40-70 kW
Power Converters*	€ 90-110/KW
Power Transformers *	€ 40-60/kW
Switchgear*	€60 -100/kW
*** included in MEC cost**	
Submarine Connectors	Splice Housing €60-100k per connector set (est.)
	Dry Mate Connector €100-200k (est.)
	Wet Mate Connectors €150-250k (est.)
Dynamic Power Cables (MV)	€300-800/m
Submarine Array Cables (MV)	€300-800/m
Submarine Export Cables (HV)	€1000-2000/m
Offshore Substation	Topside €120-150k/MW not including foundation and structure
Onshore Substation	€100-250k/MW

Table 1 Component Estimated Costs

Submarine Cable Cost Model

As can be seen from Table 1, the cost of cable installations is variable. It will be dependent on factors such as fluctuating material costs, complexity of seabed conditions and mobilisation costs. As such, a normalised cable model was developed. This used as a base case a 10kV, $1 \times 3 \times 95\text{mm}^2$ cross linked polyethylene (XPLE) copper conductor cables with a single layer of armouring. This was given a base value of 1 and all other voltage ranges and cable sizes were expressed as multiples of this. A table was provided that gives these values for cable CSA from 35mm^2 to 630mm^2 and 10kV to 132kV.

[5] BVG Associates, A Guide to an Offshore Wind Farm, The Crown Estate, London, UK 2011
[6] D, O'Sullivan and T. Lewis, 'Electrical Machine Options in Offshore floating wave energy converter turbo generators', World Renewable Energy Congress, Glasgow 2008.
[7] D. O'Sullivan and G. Dalton ' Challenges in the grid connection of wave energy devices', 8th European Wave and Tidal Energy Conference Uppsala, Sweden, 2009.
[8] L. Fingersh, M. Hand and A. Laxon , Wind Turbine Design Cost and Scaling Model, National Renewable Energy Laboratory Golden, CO, USA , 2006.
[9] J. Green, A. Bowen, L. Fingershnd , Y. Wan, 'Electrical collection and transmission systems for offshore wind power', Offshore Technology Conference, Houston, TX, USA, 2007
[10] M. Kenny , Electrical Connection Issues for Wave Energy Arrays, Masters thesis , University College , Cork, 2010
[11] P. Djapic and G. Strbac, Cost Benefit Methodology for Optimal Design of Offshore Transmission Systems Centre for Sustainable Energy and Distributed Generation (SEDG) London , UK , 2008
[12] Offshore Design Engineering (ODE) Study of the Costs of Offshore Wind Generation, Department of Trade and Industry (DTI) London, UK, 2007.
[13] P. Hopewell, F. Castro-Sayas and D. Bailey, ' Optimising the design of offshore wind farm collection networks', Universities Power Engineering Conference, Brighton, UK, 2007.
[14] E. Stoutenburg and m Jacobson Optimising Offshore Transmission Links for Marine Renewable Energy Farms, OCEANS, Seattle, WA, USA, 2010.
[15] ESB Networks, Standard Process for Generator Connections Rev 2 ESB Networks , 2012

The costs reduced as the cable size reduced and increased as the voltage and cable size increases.

A candidate array was also presented that made the following assumptions:

- Each MEC is 1MW at Unity Power;
- Each MEC has a 30% Capacity Factor;
- The inter MEC spacing is 400m;
- The water depth is 100m; and
- The export distance is 15km.

MEC Ratings and Capacity Factor

The impact of the MEC rating and capacity factor on the economic model was considered. An example of a 40MW ocean installation was used with cabling costs considered for MEC of 250kW, 500kW, 1MW, 2MW and 4MW. 1MW was used as the base case. The results indicate that for the smaller machines the inter array cost can be up to three times the base case for 1MW machines. For larger machines, the array costs reduce as low as 0.4 times for 4MW machines. It does note, however, that the capex for larger machines will be greater in terms of installation and moorings.

The impact on the capacity factor is also studied with the candidate 40 × 1MW marine farm investigated at 20KV and 33kV. Studies were done at capacity factors of 10% to 60% with the base case of 30% or 12MW. The results show that halving the capacity factor to 15% will double the cost of the farm while doubling the capacity factor will decrease costs by up to 40%. The example of a low capacity factor is given by direct drive WECs which have a high peak to average output ratio. Examples of a high capacity factor are tidal turbines that can achieve capacity factors of 60% at high energy sites.

Submarine Connectors and Other Submarine Electrical Systems

This is a short section that looks at the economics of subsea connectors, junction boxes and switchgear modules. It does not provide much in the way of financial analysis as there are few commercial systems on the market. On the subject of connectors it makes the important point that the cost of installing two connectors per unit (as would be required for a radial circuit) is prohibitively expensive. This is an important consideration in the analysis of preferred array architectures. The section does not go into detail on the subject of junction boxes or undersea substations. It mentions two manufacturers (WavePOD produced by JDR and OPT) but notes that these are expensive and may not be suitable. This is at odds with the other chapters in the report that use these as an integral part of the offshore electrical design.

Cable Installation and Protection

The impact of the environmental conditions on the cable installation is also discussed. It notes that regions of high tidal flows are usually swept clear of sediment and ploughing or jetting cable into the sediment is not possible. It provides examples of the various methods used to protect cables on various UK sites:

- EMEC (armour casing and concrete mattress);
- WaveHub (rock dumping);
- MCT SeaGen (horizontal directional drilling).

As well as cable protection, these sites are challenging in terms of mooring requirements. The use of bend restrictor, stress relievers, scour protectors and flotation modules may also be required. On these sites detailed site surveys will provide an indication of the best routes.

Optimisation of Ocean Energy Electrical System

This section looks at five candidate array architectures four of these are presented below (the double sided ring network example is omitted as this is very similar to the single sided network). The radial network was used as a base and the other networks calculated as follows. The results are presented in Table 2. The method used in calculating the costs is not detailed, but the physical layout is identical for each configuration and the redundant networks are rated for the worst case full load.

Network Configuration	Relative Cost (array only)	Relative cost (array and export)
Simple Radial Network	1.0	1.0
Single Return Network	2.58	1.39
Single Sided Ring Network	1.8	1.2
Star Cluster Network	1.54	1.13

Table 2 Relative Array Costs

The results show that the simple radial architecture (A) is the most cost effective method with the star cluster (D) second. The study assumes that the redundant cable networks are rated at 100% full load. This could be optimised following some modelling. In addition, it is not clear if connector costs have been taken into account so it may be the case that the star cluster architecture would be cheaper if this factor is taken into account. The section also returns to the subject of subsea connection points and hubs that would be utilised as part of a star cluster configuration. The point is made that the more complex these units are in terms of transformers, switchgear and battery systems, the more chance that a simple fault would render the system inoperable. This could lead to a significant reduction in yield, as the problem is rectified. It also makes the important safety consideration that the switchgear cannot be verified as being isolated and cannot be locked off.

The section discusses the advantages of having a redundant network but concludes that the priority is to keep the cost of electrical network down, so a simple radial network would be preferred. However, this system does not go into detail as to how you would loop in and out of a turbine in a radial network. Having a double set of connectors would be expensive and is unlikely to be include in a standard MEC design.

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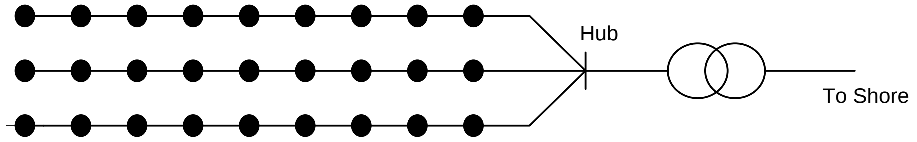


Figure 4 Alternative A: Simple Radial Network

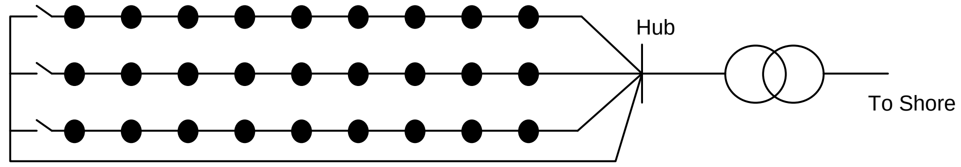


Figure 5 Alternative B: Single Return Network

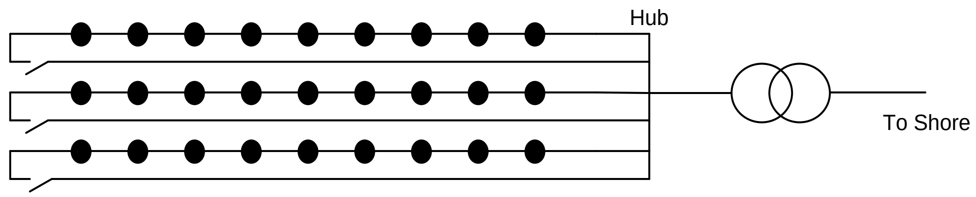


Figure 6 Alternative C Individual Return Network

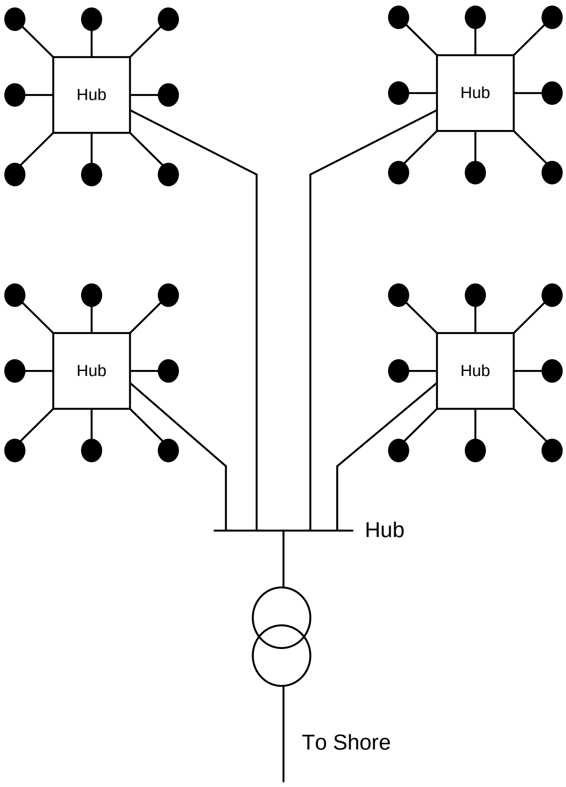


Figure 7 Alternative D Star Cluster Network

5.3 Integrating Wave and Tidal Current Power – IEA – 2011

5.3.1 Introduction

This study is from 2011 and although slightly older appears to be one of the first attempts to look at the large scale integration of wave and tidal power. Like the IET book it covers a wide range of subjects with the final half of the report being dedicated to four case studies.

5.3.2 Generation Characteristics and Conversion

Following the preamble the paper provides a very good overview of the various ways that marine kinetic energy is converted into mechanical energy and then finally to electrical energy. This is a helpful way of looking at the differences in the approach to power take off for wave and tidal devices. For the electrical conversion there is a section on the various types of generators that, unlike the IET book, does not come to any firm conclusions. The section continues to discuss various electrical control and power quality topics in some detail.

5.3.3 Grid Connected Pilot Plants

There is an interesting section that looks at the evidence gained from grid connected power plants over the last 10 years. While it is interesting overview of the variety of devices that have been deployed over the years the section also covers topics such as predictability, dispatchability and capacity factor. The dispatchability section contains a very useful table detailing the various ways that power can be constrained or increased for a number of different devices.

5.3.4 Layout of Devices

This is the most relevant section as far as this study is concerned. It starts off by looking at the issue of large integration from first principles and considers that a layout should consist of:

- Clusters (MV local collection system) to collect the power of several MECs;
- Integration System to collect the energy of these clusters and possibly step it up a voltage level; and
- Transmission System to get the energy to shore.

What is interesting here is, like the IET book, it takes it for granted that the energy from a number of MECs needs to be collected together. For a cluster we can read either a radial network like

Figure 4 or a star cluster like Figure 7. The integration system could therefore be a surface piercing platform or an undersea hub.

The section also provides a useful graphic (a version of which is shown below in Figure 8) of the various consideration that need to be taken into account when designing an offshore layout. This succinctly shows the complexity of designing a marine farm cable layout. The report also adds that there will be additional restrictions on floating devices that will require flexible umbilical cables. It notes that these may limit the voltage to 6kV and that many pilot projects used a reference voltage of 3.3kV. While this may have been the case in 2011 dynamic umbilical cables up to 36kV are commercially available. This 6kV figure does seem to crop up in more recent reports as a perceived limiting factor.

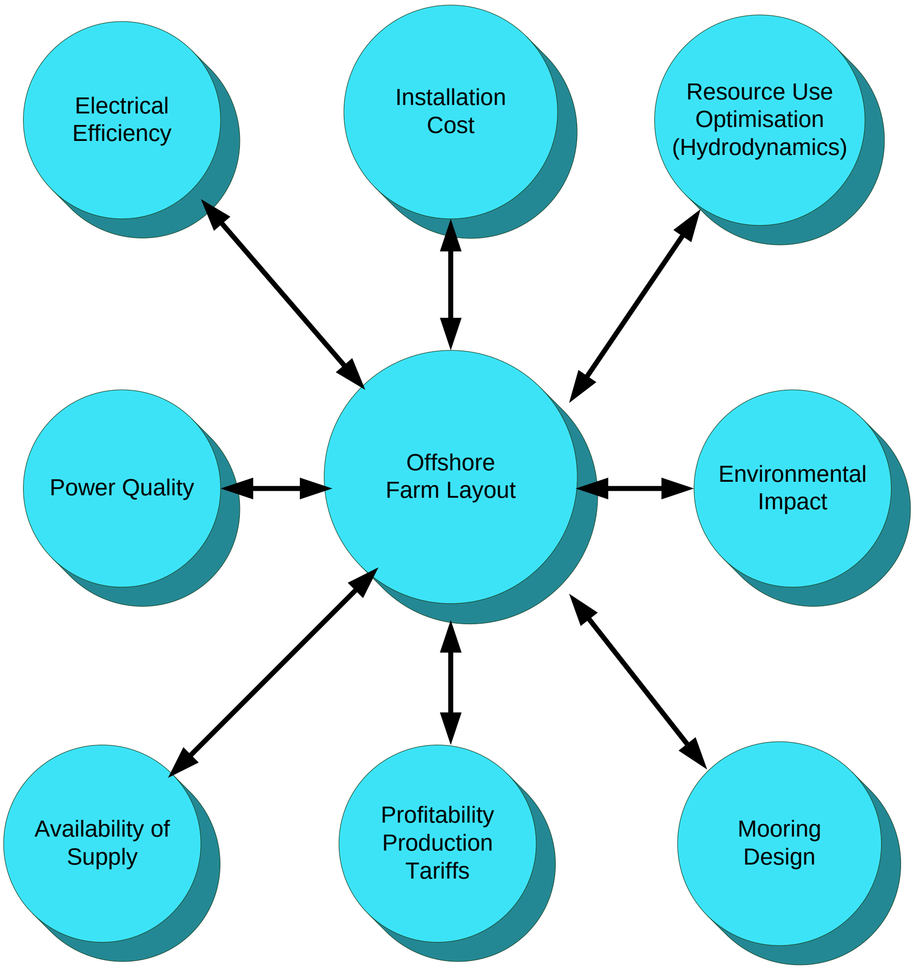


Figure 8 Interaction Diagram for Offshore Marine Farm Layout

Clusters

The report looks at the subject of clustering and covers similar arrangements shown in Figure 4 to Figure 7. As with the IET study it notes that the different arrangements will depend on how important factors such as installation costs, power losses and reliability are to the project. It also notes that there is no difference in cluster architecture between AC and DC networks. The only exception to this would be DC series clusters where machines are connected in series to increase the voltage level.

Integration Configurations

The report also looked at various integration architectures which are presented in Figure 9 to Figure 12. Option A is a direct connection of each device to shore. To date the only cluster installed in the UK is at the MeyGen site in Orkney where the four MECs are connected to shore individually. Option B is where the whole site is connected via a single cable. Option C provides for individual sets of clusters connected to shore. Option D is a hybrid of B and C. The report provides a comparison between the four options which are reproduced below in Table 3. This seems to reiterate the point made in the IET study that the style of layout will vary depending on the size and location of the marine farm.

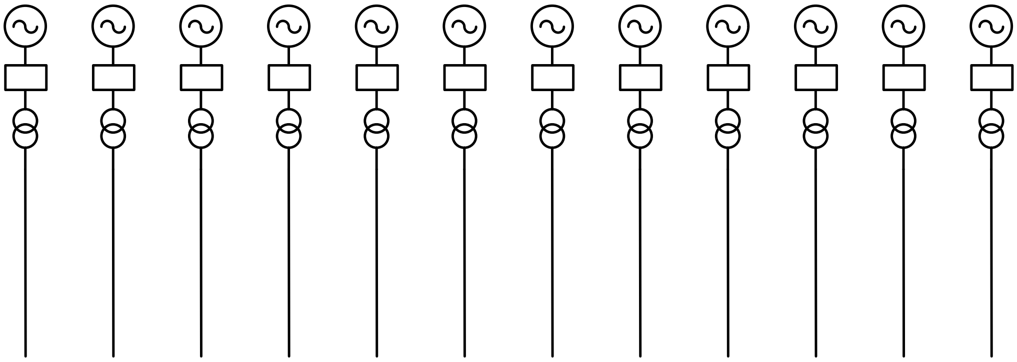


Figure 9 Option A Direct Connection

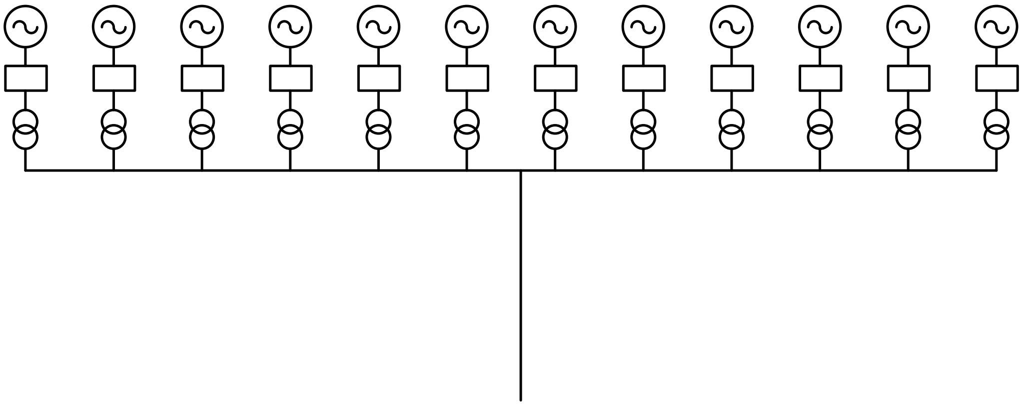


Figure 10 Option B Single Cluster Connected by Single Power Cable

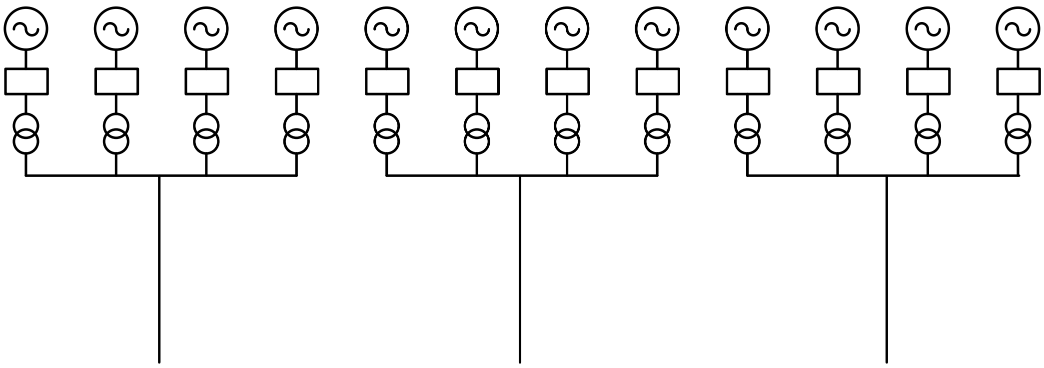


Figure 11 Option C Several Clusters Independently Connected

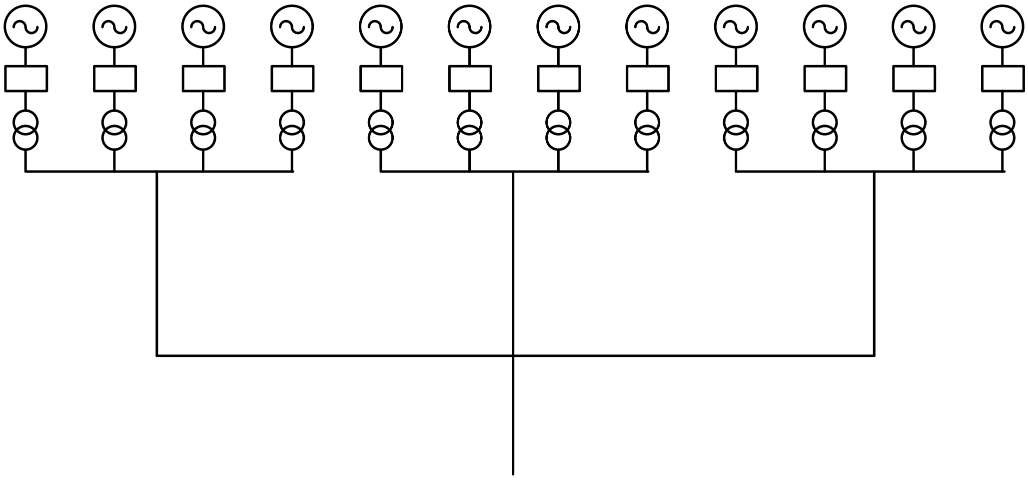


Figure 12 Option D Hybrid Connection

Concept	Configuration A	Configuration B	Configuration C	Configuration D
Pros	Very high availability; Low losses; Very simple configuration	Very low installation cost; Simple maintenance	High availability	Low installation cost
Cons	High installation cost; Numerous connections onshore necessary	Low availability; May imply high losses	Numerous connections onshore necessary	Difficult to find faults; Complex system
Possible Installation Option	Very small farms close to grid	Small farms with low risk	Large farms with high risk	Large farms with low risk

Table 3 Evaluation of Integration Configurations

Transmission Voltage

The requirement to transmit electrically to shore is discussed. The report takes distance as the key factor in deciding in transmission voltage. Near to shore devices will be connected at medium voltages while large offshore farms will require the voltage to be stepped up. HVDC systems are discussed. A review of the emerging (in 2011) VSC technologies is presented. As well as presenting the example of a large AC clustered DC connected marine farm it also presents a number of DC clustered DC connected options.

5.3.5 Generators

The relevant section of this report looks at generators and electrical systems. What is interesting about this section is that it attempts to provide some typical generation configurations. These are grouped into 5 types:

- CV1 Squirrel cage asynchronous coupled to AC cluster grid with back to back converter;

- CV2 Squirrel cage asynchronous coupled to AC cluster using step up AC transformer;
- CV3 Permanent magnet synchronous coupled to a DC grid using as galvanic insulated (transformer coupled) AC/DC converter;
- CV4 Slip ring doubly fed induction generator coupled to an AC cluster grid; and
- CV5 Permanent magnet synchronous coupled to an AC grid using a frequency controller.

While some of these are at present theoretical (DC generating machines) or may not be practical (DFIG machines) this is a useful exercise. The wind turbine industry has, over the years, been able to define turbines as types A to D. As the marine energy industry matures it would be useful to have a universal system that classed machines in terms of electrical conversion.

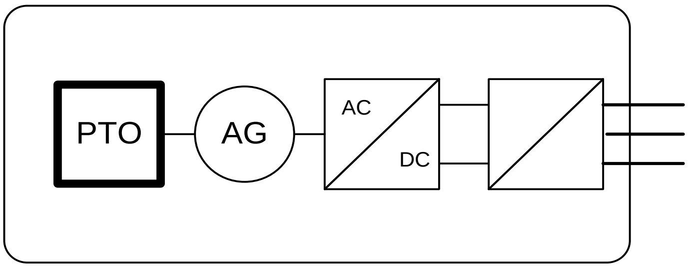


Figure 13 Generator Type CV1

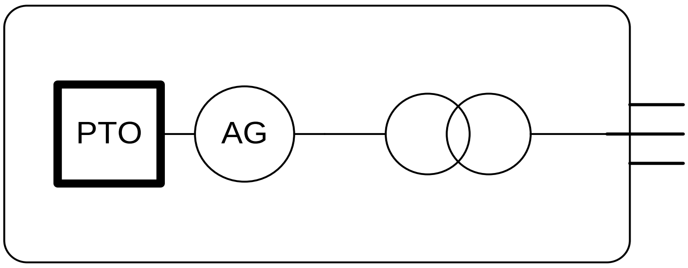


Figure 14 Generator Type CV2

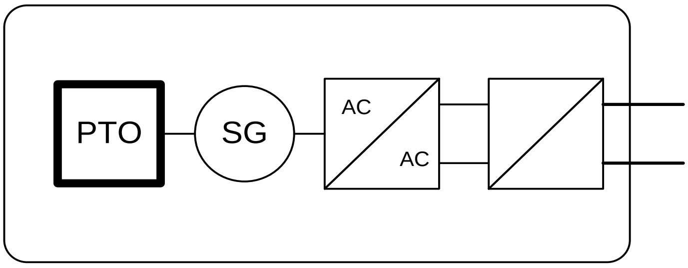


Figure 15 Generator Type CV3

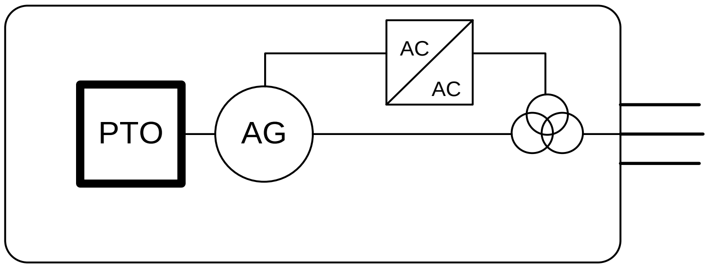


Figure 16 Generator Type CV4

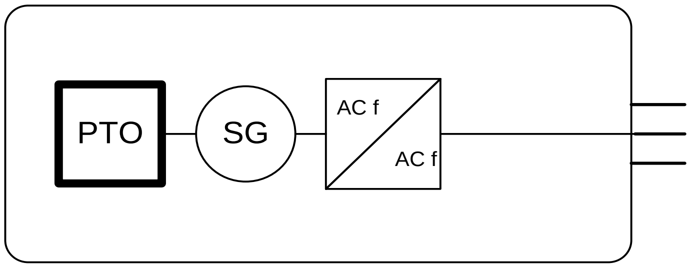


Figure 17 Generator Type CV5

5.4 State of the Art Assessment and Specification of Data Requirements for Electrical System Architecture – DT Ocean Report – 2014

5.4.1 Introduction

DT Ocean was a European collaborative project funded by the European Commission under the 7th Framework Programme for Research and Development. It aimed to accelerate the industrial development of ocean energy power generation knowledge, and to provide design tools for deploying the first generation of MEC arrays. The report is from Work Package 3.1. Unlike the two previous studies discussed, this looks in detail at the state-of-the-art in the various components required for the construction of an offshore MEC array electrical network. It also presents some new research into techno–economic modelling. This looks at using the power generation of MECs as an input into the design of offshore electrical networks. The section on electrical layout and description of clusters and arrays is based on the work of the previous report so will not be covered here. In addition, there is a section on power storage which is not covered.

5.4.2 Transmission Cables

This section covers the use of cables; it makes the initial distinction between transmission cables and umbilical cables. This distinction is important in looking at the cost of various array architectures. High voltage (HV) submarine cables are in common usage so are easy to model. Medium voltage submarine cables are not commonly used and are currently subject to testing. The report notes that MV cables are useful for small marine farms and notes that the WaveHub project is 20MW connected at 33kV at a distance of 26km (this is the rating of the grid connection and the distance from the WaveHub to the grid connection point). A cost model is presented which is based on a 2003 wind farm study[16]. The report notes that there is little scientific literature on this subject, which may point to a suitable area for further research.

Cable types are presented, focusing on the conductors, insulation and screen. How these are affected by the marine environment is discussed as is cable protection. The issues caused by shipping are presented (53% of failures) as are some of the mitigation methods (burying, concrete bags/mats). The issues caused by strong tides are not covered.

5.4.3 Umbilical Cables

There is a section covering umbilical cables which the report splits into static (fixed to the seabed) and dynamic (floating). The report notes the experience of the oil and gas industry and notes the Norwegian Norsok standards are a useful source of guidance on the requirements of subsea umbilical cables. It lists the following relevant requirements:

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

The report notes that umbilical cable fixed devices will be static and that the cable ratings will be determined by the use of J tubes and how the cables enter the structure. Floating devices present challenges to the design of umbilical cables. These will have to resist the forces due to waves, currents and the motion of the MEC. It notes that the oil and gas platforms are static, so the MEC-induced forces would present an additional strain on a cable. The results of a study into the hydrodynamics of different flexible umbilical configurations were presented. This study considered three methods of managing umbilical cables (Free hanging, Lazy Wave and Sleep Wave, the latter two using buoyancy devices). It concluded that most mechanical failures occurred at the attachment, hanging off point of the umbilical cable to the device. The section

[16] S. Lundberg, 'Performance Comparison of Wind Park Configurations' Technical Report, Chalmers University, 2003.

also presents a table first used in the 2011 IEA report which notes the limit of 6kV on umbilical cables. As noted in the IEC report, these types of cables are now available up to 36kV.

5.4.4 Connectors

Both wet and dry mate connectors are discussed with pros and cons presented and a list of eight manufacturers is presented. The section does not present any analysis of the difference between the types of connectors but presents some examples of different types (hydro group for dry mate, MacArtney for wet mate). An example of a J&S repair joint is also presented.

5.4.5 Ancillary Equipment

This covers components such as bend stiffeners, bend restrictors and marking buoys. These are used on umbilical cables to restrict movement and minimise damage. They are in common use in the oil and gas industry

Bend Stiffeners

Bending stiffeners add local stiffness to a cable. They are used when a cable connects to a marine device, cable end or a connection box. They work by limiting the bending radius under a defined tension and angle combination. They tend to be manufactured for specific applications and are made of polyurethane elastomer. As noted in the previous section, the main area of failure for these cables is at the MEC end. This suggests that there may be improvements that can be made to bend stiffeners to improve this situation.

Bend Restrictors

Bend restrictors are used along the length of a cable were the external forces on the cable could cause it to exceed its bending radius. These work by using a number of interlocking elements that articulate when under an external load. At a certain point, the elements will lock and the external force will be applied to the bend restrictor rather than the cable. These bend restrictors can also be used to add buoyancy to cable when it is used in lazy or sleep wave configuration.

5.4.6 Hubs

The use of hubs to collect electrical energy for multiple MECs will be central to any future large-scale deployment of marine energy. This section provides an overview of those currently in use or in development.

Subsea Hubs (no switchgear or transformers)

These are the simplest types of undersea connections available and can be thought of as a waterproof bus bar. Two examples are presented, the WaveHub by JDR which is used at the demonstration site of the same name and the MacArtney modular hub. Both devices can operate to voltages up to 33kV, with the JDR device taking up four connections and the

MacArtney three. Both devices are watertight with the cable terminations taking place inside the unit.

Subsea Substations (switchgear and transformers)

Subsea substations address a number of issues such as collection, voltage transformation and protection in one package. However, as the report notes, there are none in operation for a marine energy array. The report notes the Schneider, GE and Siemens all have offerings for the oil and gas industry. OPT has a prototype 1.5MW 11kV module specifically for marine energy array applications. Subsea substations present an option when looking at possible marine farm array architectures. This will probably be the case for large near shore tidal arrays where getting planning permission for a surface piercing substation not be possible.

- Cost: As noted in the IET study, the electrical plant may be around 25% of the total cost of the project. In the short-term, these substations are likely to be purpose built so are likely to be expensive.
- Reliability: A subsea substation would act as a single point of failure for multiple units. If it was servicing a number of units these would all be out of action until the substation could be raised to the surface and fixed. In the future, these substations would have to be designed with a high degree of redundancy in order to be viable. The Schneider website notes that a five year maintenance free cycle is the goal.
- Safety: Issues around isolation of circuits using undersea substations need to be addressed. It is standard safety practice when working on a circuit that it is physically isolated and locked out with an identifying label attached (so called lock out, tag out). In a subsea substation this will not be possible and work will have to be done on developing failsafe system of remotely locking out circuits that meets agreed safety standards.

Subsea Transformers

A possible alternative to a subsea substation is standalone subsea transformers. These are manufactured by ABB and can be fully immersed at depth without the need to be sealed in a barometric chamber. They are mainly used as step down transformers for use with underwater plant but could be used as a step up transformer as a more cost effective alternative to a subsea substation.

Surface-Piercing Hubs

The paper covers the use of surface-piercing substations and their use for large offshore marine energy array at distances of greater than 5km from the shore. Examples from the offshore wind industry are used. Due to the cost of using subsea equipment, the use of surface piercing or floating hubs to house as much plant as possible will likely be the best option for offshore marine energy arrays as long as planning and environmental conditions allow.

5.4.7 Power Generation as Input to the Design of the Offshore Electrical Network

This section looks at developing methods of estimating the power output of individual WECs and TECs and subsequently, arrays. The aim is to be able to predict the energy output of the marine energy array over its lifetime and use this to predict the LCoE of a particular project. A similar approach is used in the wind industry, where wind data are used to produce a typical yield for a farm. For TECs, varying annual current speed needs to be taken into account, as well as the use of any speed control (such as blade pitching) that will be used as a device. For WECs, the two parameters that impact the power output are wave height (H) and the mean zero crossing wave period (T). Examples of measurements of these are presented. In addition to the energy input to the MEC, the inherent losses of the power conversion are also considered. The results of this study feed into the final DT Ocean as explained below.

5.4.8 DT Ocean Further Work

This report details the findings of WP3.1 which is an early deliverable of the DT Ocean project. The final deliverable will be WP7 which is described by DT Ocean as:

The main goal of WP7 is the development of a multi-objective suite of tools that will provide quantitative criteria for the design and analysis of ocean energy arrays. This global package will integrate the models and algorithms developed within the individual Work Packages into a common interface.

When it is released, this will likely provide a core resource for the analysis and design of future marine farm networks.

5.5 Power Conversion Systems for Tidal Power Arrays - ABB - IEEE Conference Paper 2014

5.5.1 Introduction

This paper follows on from the previous study ABB, which is being reviewed as part of WP2. This favoured a ± 7.5kV DC architecture that uses a wound field synchronous generator with a passive rectifier. At present, such a machine has not been manufactured but the method used for evaluation and the number of options considered is valid. The paper sets the scene by limiting the networks to TECs of 1MW. It also uses the fact that 26 of the 30 sites in the UK are less than 10km from shore and less then 80m in depth, this limits the maximum transmission voltage to 33kV. The section on main power train electrical architectures are split into three classes as detailed below. It is assumed that the generators are 690V and the TECs are 1MW. The items of plant are considered are the TEC, the hub and the substation.

5.5.2 Main Power Train Electrical Architecture

The architectures are split into three classes; variable frequency, fixed frequency and DC collection. The base architecture consists of a nacelle, an aggregation hub and a substation. The generator and the transformer are always in the nacelle but the converter and can be split into machine side and grid side and located in any of these three locations. The variable frequency architecture has the nacelle fitted with a transformer to step to 6.6kV but has no power converter in the nacelle. The HV power converter will be placed either in a substation, in a hub or a combination of both. Fixed frequency collection has a low voltage converter and a step up transformer in the nacelle. DC collection favours a transformer, a wound field generator and a passive converter in the nacelle. The argument for using the passive converter is that the reliability of MV active converters is not satisfactory. Eleven candidate arrangements are presented. The report then looks at the number of variants that can apply to these eleven arrangements. This is done by considering:

- Moving aggregation points;
- Moving some of the power equipment into a separate subsea enclosure;
- The location of the hub (floating or submerged); and
- Locating the substation onshore or offshore.

This provides many options and the report presents a two-step method to approach this.

5.5.3 Comparison of Architectures

To down select all the candidate architectures, a ‘figure of merit’ calculation was carried out on all the candidate arrangements using the following approach:

- Identify the cost of individual components including fixed, mechanical and civil cost of hubs and platforms;
- To account for installation, maintenance and downtime costs apply a penalty factor according to where it is installed. The report suggests 2 for offshore, 5 for subsea; and
- Once all the costs are estimated they can be summed and the results compared.
- A shortlist can be drawn up containing all the architectures that have up to 50% higher cost of the least cost architecture. The six favoured candidates using this method are listed below in order of their lowest capex first:
- A fixed frequency class unit with a squirrel cage or permanent magnet generator. Power conversion is done with a transformer and full converter in the nacelle.
- A variable frequency class unit with a squirrel cage or PM generator. A transformer in the nacelle would feed a converter in a surface piercing hub. Eight of these line side converters could feed into a single grid side converter i.e. eight units could be handled from one hub.
- A DC class unit with a wound field generator. A passive rectifier and a transformer would be situated in the nacelle. This would feed a subsea collector converter in that could connect up to 11MW of generation.

- A DC class unit with a wound field generator. A passive rectifier and a transformer would be situated in the nacelle. This would feed an onshore substation where it would be converted to AC.
- A DC class unit with a wound field generator. A passive rectifier and a transformer would be situated in the nacelle. This would feed a surface piercing substation where it would be converted to AC and transmitted to shore.
- A variable frequency class unit with a squirrel cage or permanent magnet generator. A transformer is situated in the nacelle with full conversion at the substation.

6 Further Work

6.1 Introduction

One of the aims of this report was to provide background information that would inform the following work. Below is a list of some of the points to be considered when going forward with a preferred electrical array design.

6.2 Standard Generating Voltage

It would be helpful for the industry to adopt a standard generating voltage as this is one of the best routes for driving down costs. From the survey it looks like most devices operate in the range of 6.6kV to 11kV. There will definitely be an optimal range of voltages that are high enough for the current produced to allow for a manageable cable size but also low enough so that it can be handled by commercially available wet and dry mate connectors which are currently limited to operate at around 6 to 8 kV. The next constraint is how far offshore voltages of 6.6kV to 11kV can transmit before the losses become unacceptable and a higher voltage is required. All of these constraints will be considered in the third report.

6.3 MECs are Getting Larger

The brief for this project and the models used in literature consider a turbine size of 1MW. The survey shows that companies are now increasing the size of the machines up to the 1.5 to 2MW range. Both Scotrenewables and OpenHydro have made a jump from 250kW demonstration platforms to 2MW devices with a view to commercial production. In discussion, with the developers it was decided to extend the project brief to take in devices up to 2 MW.

6.4 AC vs. DC

The majority of the devices surveyed produce AC power. DC generation is being prototyped by a few manufacturers. Nautricity is proposing a passive converter arrangement while Albatern have a DC device in development. While DC generation offers some interesting benefits in the aggregation of the output of multiple units MVDC networks are still in their early stages of development at distribution level voltages. They will require offshore demonstrator projects to take place before they are deployed commercially. It was decided in the context of these studies to concentrate on MV DC networks.

6.5 Hubs and T off Connectors

The use of hubs and T off connectors will be central to the development of any future array architecture. When considering radial arrays much of the existing literature does not consider how an array cable will loop in and out of each MEC in the array. Given the expense of wet mate connectors, it is not cost-effective to have two on each MEC so the availability of T off connectors will need to be investigated. The same situation exists for subsea hubs, which will be needed for developing star topologies. Having a four berth hub installed at WaveHub, demonstrates that the technology has reached a suitably high level to be considered ready for commercial roll out.

6.6 Planning Permission and Visual Impact

Surface piercing or floating platforms for converter plant may be the preferred option for MECs at distance from shore, as they provide the easiest access for maintenance and repair. However, it may be difficult to get planning permission for surface piercing platforms closer to shore. This means the design of near shore arrays may have to consider whether the power conversion needs to take place onshore or on the MEC. .

6.7 Far Offshore Arrays and Offshore Transmission Owner

As well as considering the connection of close-to-shore TECs, this project will also consider connecting wave devices at distance from shore. In the case of a 200MW WEC array, this may mean that the most economical way to connect to the mainland is using a cable operating at 132kV AC (or possibly HVDC). At this voltage level, the transmission asset will need to be sold on to an Offshore Transmission Owner (OFTO) to operate. The role of the OFTO is outlined in the Connection Use of System Code (CUSC) and the UK Grid Code, both produced by National Grid. This will lead to a situation where a design will need to conform to a similar pattern to those used in current offshore wind farm design. This arrangement does not promote the use of any novel or prototype architecture as these would prove risky to potential buyers of the OFTO transmission asset.

6.8 Floating MECs and Umbilicals

Floating MECs (either WEC or TEC) will require a dynamic umbilical cable to connect them to the subsea electrical architecture. Umbilical cables are in use by the oil and gas industry but tend to be used for static devices. There will be some crossover for cable connections with the use of tension leg platforms (TLP) for floating wind turbines. These TLPs will also be subject to the movement of the ocean and will need power connections at similar voltages and currents as WECs.

Appendix 1 MEC Manufacturers

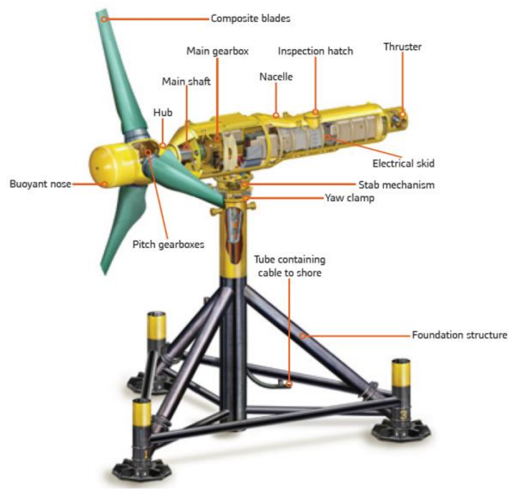
The following device manufacturers were approached and asked to provide details of their devices.

Company	Device Name	Website
Alstom	Oceade 18	http://www.alstom.com/products-services/product-catalogue/power-generation/renewable-energy/ocean-energy/tid
Andritz Hydro Hammerfest	HS1000	http://www.andritz.com/hydro/hy-others-andritz-hydro/pf-detail?productid=9197
Aquamarine Power	Oyster	http://www.aquamarinepower.com/
Atlantis Resources	AR1500	http://atlantisresourcesltd.com/about-atlantis.html
Carnegie	CETO	http://www.carnegiewave.com/
Nautricity	CoRMat	http://www.nautricity.com/tidal-energy/
Nova Innovation	Nova 30/100	http://www.novainnovation.co.uk/index.php/first-power
Schottel	STG 50	http://www.schottel.de/news-events/news/news-detail/?tx_ttnews[tt_news]=252&cHash=61c8acd9173c11a7438d8867
Scot Renewables	SR2000	http://www.scotrenewables.com/
Seatricity	Oceanus 2	http://seatricity.com/
MCT	SeaGen	http://www.marineturbines.com/SeaGen-Products/SeaGen-S
Tidal Energy Limited	DeltaStream	http://www.tidalenergyltd.com/
Tocardo	T-X	http://www.tocardo.com/
Blue Water	Blue-Tec	http://www.bluewater.com/new-energy/force/
OpenHydro		http://www.openhydro.com/company.html
Voith Hydro	HyTide 1000	http://voith.com/en/products-services/hydro-power/ocean-energies/tidal-current-power-stations--591.html
Wello Oy	Penguin	http://www.wello.eu/en/

Table 4 Device Manufacturers and their Devices

Appendix 2 MEC Details

Company: **Alstom***	
Model: **Oceade 18**	
Power Output	1.4MW
Output Voltage	6.6kV
Type	Tidal
Maintenance Interval	2 Years

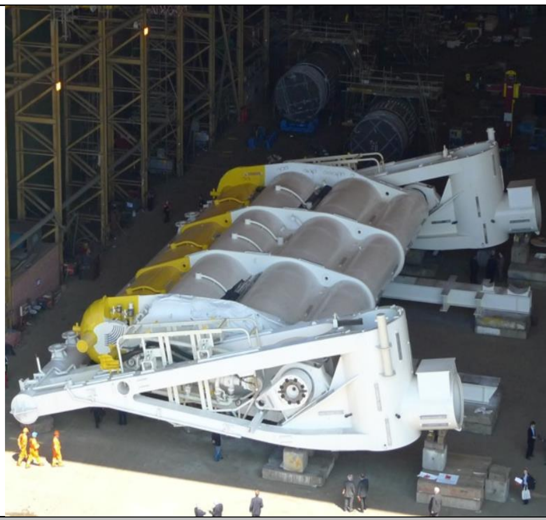


Physical Description of Device
The device consists of 2 sections. The tripod support structure is permanently mounted to the seabed. The nacelle and blade structure is buoyant and is lowered into position and attached to the support structure. The unit is a horizontal 3 bladed turbine, with variable pitch control.
Conversion of Marine Kinetic Energy to Mechanical Energy
The unit consist of a 3 blade, pitch controlled rotor with an epicyclic gearbox.
Conversion of Mechanical Energy into Electrical Energy
The rotor is pitch controlled and the gearbox is connected to an induction generator. The turbine can operate over a wide range of flow speeds.
Description of Electrical System
The induction generator is fed through a fully rated frequency converter. This in turn is fed into a transformer that steps up the voltage to 6.6kV. The nominal frequency is 50Hz.
Power Take Off
Power take off is via a cable permanently attached to the support structure. This contains a stab plate containing wet mate connectors. This stab plate contains a 6.6kV 3 phase power connector and a data connector. This allows for the nacelle to be detached for servicing. The output voltage is limited by the rating of the wet-mate connector.
Control, Data and Aux Power Requirements
Auxiliary power is derived inside the device from the main circuit power. The power is used for the control system, cooling pumps and yaw system. Communication is by fibre optic cable which connects to the unit using a separate wet mate connector.
Current Commercial Installation or Demonstrator Project
500kW and 1MW turbines have been tested at the EMEC. 1MW unit has exported in excess of 1GWh of energy.

<table>
<tr><td colspan="2">Company: Andritz Hydro Hammerfest</td><td rowspan="7">Image not available</td></tr>
<tr><td colspan="2">Model: HS1000</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Power Output</td><td>1MW</td></tr>
<tr><td>Output Voltage</td><td>MV</td></tr>
<tr><td>Type</td><td>Tidal</td></tr>
<tr><td>Maintenance Interval</td><td>5 years</td></tr>
<tr><td colspan="3">Physical Description of Device</td></tr>
<tr><td colspan="3">The device is a horizontal axis turbine. It consists of a permanent tripod base that is gravity fixed to the seabed. The nacelle can be raised and lowered using a crane.</td></tr>
<tr><td colspan="3">Conversion of Marine Kinetic Energy to Mechanical Energy</td></tr>
<tr><td colspan="3">Power take off is via a 3 blade variable pitch rotor.</td></tr>
<tr><td colspan="3">Conversion of Mechanical Energy into Electrical Energy</td></tr>
<tr><td colspan="3">The company literature does not mention a gear box but it is assumed that the rotor is connected to the generator via gearbox. The variable pitch blades will allow the torque on the generator to be varied.</td></tr>
<tr><td colspan="3">Description of Electrical System</td></tr>
<tr><td colspan="3">The literature makes note of an induction generator (hence the assumption of a gearbox). As the unit is being used for the MeyGen project and power conditioning is on land it is assumed that the unit induction generator produces MV and there is no power conditioning or voltage transformation taking place on the unit.</td></tr>
<tr><td colspan="3">Power Take Off</td></tr>
<tr><td colspan="3">The diagrams in the company literature show that power take off is via a connector at the rear of the nacelle. The description of the installation process suggests that the power cable is connected to the unit prior to it being lowered onto the seabed support structure.</td></tr>
<tr><td colspan="3">Control, Data and Aux Power Requirements</td></tr>
<tr><td colspan="3">Not known.</td></tr>
<tr><td colspan="3">Current Commercial Installation or Demonstrator Project</td></tr>
<tr><td colspan="3">Pre commercial trial of 1MW machine at EMEC 2012.</td></tr>
</table>

Company: **Aquamarine Power ***

Model: **Oyster**



Power Output	Circa 800kW
Output Voltage	8kV
Type	Wave
Maintenance Interval	Annually

Physical Description of Device
Near shore device fixed to the seabed with a hinged buoyant flap that uses the surge component of the wave to generate energy. The first prototype used to pump water under pressure to a generator on land. A revised design using a Bosch Rexroth WavePOD unit for power conversion is being planned.

Conversion of Marine Kinetic Energy to Mechanical Energy
The motion of the buoyant flaps operates the hydraulic cylinder of the WavePOD. The energy can be stored in accumulators and produce smoothed out power to the hydraulic motors. The hydraulic motors are controlled to produce fixed frequency and variable torque.

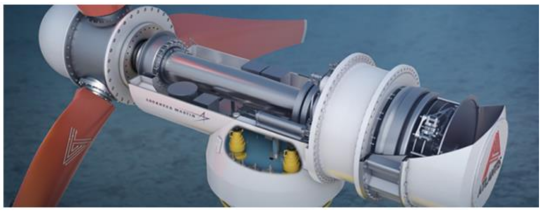
Conversion of Mechanical Energy into Electrical Energy
Hydraulic motors are used to drive the electrical generators. These are squirrel cage induction generators. Each module is rated at 150kW and a series of these modules will be stacked up to build up the desired power rating.

Description of Electrical System
The motors generate at 690V and are stepped up to 8kV using an onboard transformer in the WavePOD. The generators are held at grid frequency using hydraulic swash plate motors to control speed and vary torque. A number of devices are then aggregated together at an offshore substation and stepped up to 33kV. An onshore substation will include power electronics and active power storage in parallel to provide grid support.

Power Take Off
Power take off is via a 3 phase wet mate connector. This is connected to a short length of oil filled cable with is terminated into a connection box adjacent to each machine.

Control, Data and Aux Power Requirements
Auxiliary power is 24V provided by a step down transformer when the unit is connected to the grid. Alternative power is by 24V batteries topped up by using a 24V generator powered by a hydraulic motor. Data connection is currently by fibre through wet mate connector but will be replaced by a fibre to Ethernet connector terminated inside the connection box and then wired using a subsea Ethernet cable to the machine.

Current Commercial Installation or Demonstrator Project
A hydraulic model installed at EMEC produced the equivalent of 800kW. The machine is in 13m water 500m from shore.

Company: **Atlantis***	
Model: **AR1000 -1500**	

Power Output	1MW -1.5MW
Output Voltage	MV
Type	Tidal
Maintenance Interval	6.25 years

Physical Description of Device

The turbine is a horizontal axis turbine. It consists of a tripod base and a nacelle that can be lowered via a crane from a dynamic positioning vessel. The foundations can be gravity base, monopole, or pinned structure.

Conversion of Marine Kinetic Energy to Mechanical Energy

The machine as a 3 blade fixed rotor design and is able to yaw by 360 degrees.

Conversion of Mechanical Energy into Electrical Energy

Variable pitch hub, low speed shaft, integrated 2 stage epicyclic gearbox and a permanent magnet generator. The variable pitch blades will work to maintain optimum tip speed up to rated power. Once at rated power the unit will operate at a constant average speed with the pitch control limiting power.

Description of Electrical System

Generator is a MV permanent magnet generator generating at MV. There is no transformer on the device and power conversion is handled onshore.

Power Take Off

Power take off is via a wet mate cable management system that also handles auxiliary power and fibre optic. The connection occurs automatically as the nacelles is lowered onto the base.

Control, Data and Aux Power Requirements

Controller is situated offshore and communication is via a fibre optic cable. Auxiliary power is derived externally via a subsea cable. Both connect to the unit via the cable management system.

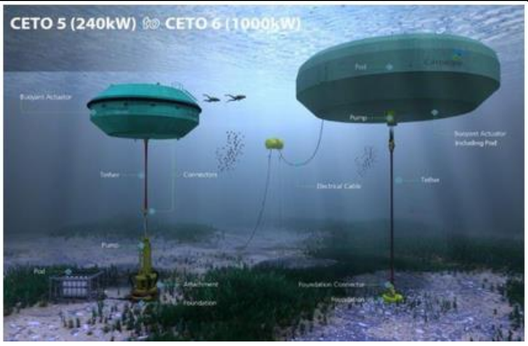
Current Commercial Installation or Demonstrator Project

The drive train was tested at EMEC and NAREC and the AR1500 unit will be installed for the MeyGen project.
The company also produces the AS140 which is a ducted 3 blade turbine suitable for shallow waters and run of river applications.

Company: **Carnegie ***

Model: **CETO 5 and 6**

Power Output	240kW (1MW)
Output Voltage	11 to 22kV
Type	Wave
Maintenance Interval	1 to 3 Years



Physical Description of Device

The device is anchored to the seabed using either a pile foundation or gravity base structure. The selection is dependent on seabed composition, array size as well as local manufacturing and offshore logistics capabilities. The device is easily removed by disconnecting the electrical umbilical, disengaging the foundation connection and towing back to the quayside. Maintenance events involving disconnection at the foundation are expected to occur between once per year and every three years.

Conversion of Marine Kinetic Energy to Mechanical Energy

Energy is extracted by the waves acting on a buoy or Buoyant Actuator (BA) connected to a hydraulic cylinder which is nominally pressurised such that it opposes the buoyancy force of BA. This renders the BA neutrally buoyant in still water. As the waves move the BA up and down, a differential pressure is created in the hydraulic system which drives a hydra-electric conversion device.

Conversion of Mechanical Energy into Electrical Energy

The drive train consists of a number (between 3 and 6) of hydraulic motor – generator sets which deliver electrical power to individual power electronics modules. This module consists of an Active Front End (AFE), a DC bus and an Inverter. The control system instructs the module to set the speed or torque of the generator which in turns controls the pressures in the circuit.

Description of Electrical System

The electrical system consists of five 200kW inductive generators connected to a variable speed drive (VSD). The variation in speed of the generator is controlled by the variable displacement hydraulic motor and the active front end of the VSD will ensure a steady frequency and voltage.

Power Take Off

Power take off from the device is via a wet mate connector attached to an umbilical cable. This cable is connected to the seabed into a fixed connection box via a dry mate connector.

Control, Data and Aux Power Requirements

Control is from a PLC onshore and transmitted via a redundant fibre optic network through the umbilical and connecting to the device using a wet mate connector. Auxiliary power requirements are 240VAC and 24VDC and are sourced internally.

Current Commercial Installation or Demonstrator Project

Three devices are planned to be installed as a demonstrator project. Location: 12km west of Garden Island, Western Australia. Size: 3MW total, 11kV or 22kV.

Company: **Nautricity**	
Model: **CoRMat**	
Power Output	500kW
Output Voltage	Not known
Type	Tidal
Maintenance Interval	Not known

Physical Description of Device
This is a novel horizontal axis tidal generator that is buoyant and floats in the water. It is buoyant and can be tuned to sit at a particular point in the water column. It is then tethered in position. The tidal flow will keep the device in the optimal orientation.
Conversion of Marine Kinetic Energy to Mechanical Energy
The device consists of two contra rotating rotor systems one with three blades and the other with four.
Conversion of Mechanical Energy into Electrical Energy
The contra rotating rotors form an axial flux generator using permanent magnets. There is no gearbox.
Description of Electrical System
The device solely consists of the sea water cooled axial flux generator. There is no power conditioning or voltage transformation.
Power Take Off
Power take off is at the rear of the device in the same location as the tether.
Control, Data and Aux Power Requirements
There does not seem to be any requirement for data or auxiliary power.
Current Commercial Installation or Demonstrator Project
The company has tested a unit at EMEC and have given themselves a technology readiness level (TRL) of 6 -7. They have a project under their own development (as Argyle Tidal) in the Mull of Kintyre, Scotland.

Company: **Nova Innovation**		Image not available
Model: **Nova 100**		
Power Output	100kW	
Output Voltage	Not known	
Type	Tidal	
Maintenance Interval	Not known	

Physical Description of Device
A horizontal axis tidal generator fixed to a tripod on the seabed.
Conversion of Marine Kinetic Energy to Mechanical Energy
The rotor has 3 fixed blades.
Conversion of Mechanical Energy into Electrical Energy
The rotor will drive a generator, it is not clear if the unit has a gearbox.
Description of Electrical System
It is not known what type of generator is used but the relatively small size of the nacelle suggests that there is no power conditioning or voltage transformation on the machine. This would have to happen on land.
Power Take Off
Not known.
Control, Data and Aux Power Requirements
Not known.
Current Commercial Installation or Demonstrator Project
A 30kW device is installed in North Yell, Shetland and is used to power an ice house. Five Nova 100 units are to be installed as part of the Shetland Array in Bluemull sand.

Company: **OpenHydro**	Image not available
Model:	
Power Output	2MW
Output Voltage	Not known
Type	Tidal
Maintenance Interval	Not known

Physical Description of Device
Open Hydro is an open centre 16M diameter tidal turbine fitted to a gravity base.
Conversion of Marine Kinetic Energy to Mechanical Energy
The unit is a toroid shaped device with the tidal flow passing through the middle of the device and rotating the blades.
Conversion of Mechanical Energy into Electrical Energy
The mechanical rotor in the centre of the toroid structure rotates in the tidal stream.
Description of Electrical System
The device uses a permanent magnet generator. The stator is situated in the outer toroid, with the rotor on the outer rim of the spinning mechanical rotor in the middle of the device. The test device at EMEC had power conversion situated on the unit.
Power Take Off
Not known.
Control, Data and Aux Power Requirements
Not known.
Current Commercial Installation or Demonstrator Project
A 6m diameter machine (shown in the photo) was tested at EMEC. Two 2MW machines will be installed at the FORCE test site in Nova Scotia, Canada.

Company: **Schottel ***	
Model: **STG**	
Power Output	85kW
Output Voltage	440V
Type	Tidal
Maintenance Interval	Not known

Physical Description of Device
This is a small horizontal axis turbine intended as a multi-use device for marine energy devices. It comes as a standalone unit ready for integration into marine energy platforms. Schottel have their own Triton S40 platform.
Conversion of Marine Kinetic Energy to Mechanical Energy
The unit has 3 fixed pitch blades mounted to a hub that is connected to a 2 stage planetary gearbox via a slow speed shaft and bearing. The unit is sea water cooled.
Conversion of Mechanical Energy into Electrical Energy
The device is fitted with a 4 pole 85kW rated asynchronous generator. This has a rated frequency of 74Hz and a power factor of 0.86.
Description of Electrical System
The individual generators do not have any power conditioning or power transformation. This will be done on the platform upon which the devices are mounted.
Power Take Off
Connection is via dry mate connector at the rear of the unit.
Control, Data and Aux Power Requirements
There are no power or data requirements.
Current Commercial Installation or Demonstrator Project
In use on the Triton Device (see next section) and on other platforms.

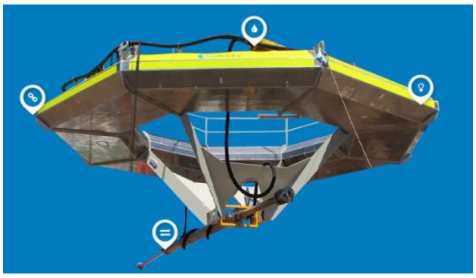
Company: **Tidal Stream ***		Image not available
Model: **Triton S40**		
Power Output	2.5MW	
Output Voltage	13.8kV (Variable)	
Type	Tidal	
Maintenance Interval	Not known	

Physical Description of Device
The Triton S40 uses 40 of the Schottel STG turbines. These are mounted on 4 cross bars attached to 2 spar buoys. Two tether arms connect these buoys to a gravity base. The tether arms are hinged so that the whole structure can move into the tidal stream. The spar buoys can be tilted to the horizontal position for access to the individual turbines.
Conversion of Marine Kinetic Energy to Mechanical Energy
Each individual turbine has 3 fixed pitch blades mounted to a hub that is connected to a 2 stage planetary gearbox via a slow speed shaft and bearing. The unit is sea water cooled.
Conversion of Mechanical Energy into Electrical Energy
The device is fitted with 40 4 pole 85kW rated asynchronous generators. Each has a rated frequency of 74Hz and a power factor of 0.86.
Description of Electrical System
Each turbine is connected to its own inverter. 10 of these inverters are then connected to a common DC bus and then to a frequency converter. These are located in one of the spar buoys. Four of these converters then feed into a cast resin transformer. Internal voltages are in the range of 400-500VAC and the HV voltage can be changed to whatever is required.
Power Take Off
The aggregated and conditioned power is transmitted via cable down one of the tether arms to a slip ring device. The gravity base comes pre-fitted with an export cable and a dry mate connector that is then connected to a dry mate subsea connector.
Control, Data and Aux Power Requirements
Auxiliary power is generated on the unit. Data is provided by a fibre optic cable along with the power cable. A redundant Wi-Fi/ Radio connection is also provided.
Current Commercial Installation or Demonstrator Project
Location: Bay of Fundy, Nova Scotia, Canada. Size and Connection Voltage: 2.5MW grid ready power at 13.8kV.

<table>
<tr><td colspan="2">Company: Scotrenewables</td><td rowspan="4">Image not available</td></tr>
<tr><td colspan="2">Model: SR 2000</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Power Output
Output Voltage
Type
Maintenance Interval</td><td>2MW
6.6kV
Tidal
Not known</td></tr>
<tr><td colspan="3">Physical Description of Device</td></tr>
<tr><td colspan="3">The Scotrenewables device is a floating platform tethered to the seabed. It has 2 arms that extend under the device each containing a generator. These arms can be moved up into the main body of the device to store the generators during transport or harsh weather conditions. The device shown above is the 250kW version but a 2MW version will be deployed in the near future. The unit can passively yaw around its mooring connection.</td></tr>
<tr><td colspan="3">Conversion of Marine Kinetic Energy to Mechanical Energy</td></tr>
<tr><td colspan="3">For the 250kW machine the counter-rotating rotors are fixed pitch and each have a diameter of 8m.</td></tr>
<tr><td colspan="3">Conversion of Mechanical Energy into Electrical Energy</td></tr>
<tr><td colspan="3">Each rotor drives a separate gearbox and a variable-speed electrical generator within sub-surface nacelles.</td></tr>
<tr><td colspan="3">Description of Electrical System</td></tr>
<tr><td colspan="3">The generator power is transmitted via cable to the hull for power-conditioning through variable speed drives. A transformer then steps up the voltage to 6.6kV for export to shore via a wet-mate electrical connector and subsea cable. All equipment is housed onboard the floating structure.</td></tr>
<tr><td colspan="3">Power Take Off</td></tr>
<tr><td colspan="3">Power take off for the 250kW device is via a wet mate connector. It is assumed that this situation will be the same for the 2MW device.</td></tr>
<tr><td colspan="3">Control, Data and Aux Power Requirements</td></tr>
<tr><td colspan="3">Not known.</td></tr>
<tr><td colspan="3">Current Commercial Installation or Demonstrator Project</td></tr>
<tr><td colspan="3">The SR 250 unit was tested at EMEC and testing of the SR 2000 will take place at EMEC prior to commercial release.</td></tr>
</table>

Company: **Seatricity***

Model: **Oceanus 2**



Power Output	170kW
Output Voltage	Not known
Type	Wave
Maintenance Interval	2 years

Physical Description of Device

The Oceanus is a floating wave device tethered to the seabed.

Conversion of Marine Kinetic Energy to Mechanical Energy

The PTO is a double acting linear hydraulic ram connected to a float on one side and a tether to a reaction block on the seabed. Tidal height difference is taken up by the length of stroke built into the pump which is 9m for the Oceanus 2 prototype. The behaviour of the devices is controlled through the back pressure in the common pipeline, the higher the pressure the larger the retraction force on the devices.

Conversion of Mechanical Energy into Electrical Energy

The device transports pressurised water at 70bar onshore to where it feeds a pelton turbine which is connected to a generator.

Description of Electrical System

As the generator is housed in an onshore switch room, power conversion and transformation can be chosen to suit local grid voltages and connection requirements.

Power Take Off

Via high pressure pipelines.

Control, Data and Aux Power Requirements

No electrical connection on the device. There is a battery powered isolation valve to disconnect a faulty device from the array pipeline. The unit also has solar/battery powered navigation lights.

Current Commercial Installation or Demonstrator Project

There is a prototype Oceanus 2 unit to be installed at Wave Hub, England.

Company: **MCT**		Image not available
Model: **SeaGen S**		
Power Output	1.2 to 2 MW	
Output Voltage	Not known	
Type	Tidal	
Maintenance Interval	Not known	

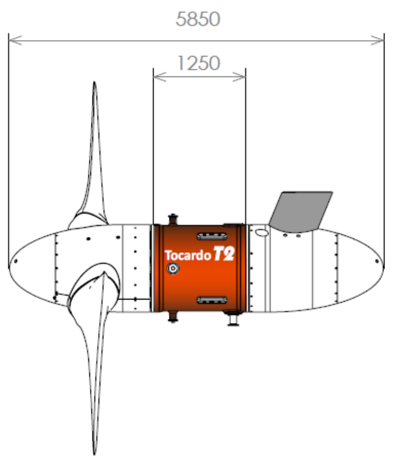
Physical Description of Device
The device consists of a vertical structure mounted to the seabed with a horizontal arm that houses the 2 nacelles. The horizontal arm can move up the vertical structure out of the water so that the nacelles and blades can be serviced.
Conversion of Marine Kinetic Energy to Mechanical Energy
A set of 3 blade pitch controlled rotors are fitted to each nacelle. Each nacelle can pitch by 180° to make most efficient use of the tidal flow. Rated power is achieved at tidal flows faster than 2.4m/s. The 16m blade device can produce 1.2MW (total) while the 20m blade increases this to 2MW.
Conversion of Mechanical Energy into Electrical Energy
The axial flow rotors drive a generator in each nacelle via a gear box.
Description of Electrical System
The company's website makes a point of noting that the device is fully grid compliant. It is assumed that the device consists of a full converter and step up transformer.
Power Take Off
From the diagrams on the website it is assumed that the device is permanently connected and that the cable is able to loop in and out of the device.
Control, Data and Aux Power Requirements
It more than likely that the auxiliary power is derived from the internal transformer.
Current Commercial Installation or Demonstrator Project
Commercial turbine installed at Strangford Lough in Ireland.

Company: **Tidal Energy Limited ***		
Model: **DeltaStream**		
Power Output	400kW to 3MW	
Output Voltage	6.6kV	
Type	Tidal	
Maintenance Interval	2 years	

Physical Description of Device
The Delta Stream is an upstream horizontal axis turbine. It is mounted on a triangular steel structure that acts as a gravity base. The photo above shows the 400kW prototype which is one corner of the triangle. The nacelle is fixed but in future designs will be removable, the power of each generator will also be increased to 1MW.
Conversion of Marine Kinetic Energy to Mechanical Energy
The device has 3 fixed blades and an active yaw.
Conversion of Mechanical Energy into Electrical Energy
The device is fitted with a 1.74 planetary gearbox and the rotor is connected directly to the gearbox. The high speed shaft is connected to the generator. On the prototype version there is a clutch mechanism to protect the gearbox from electrical failure.
Description of Electrical System
The generator is an induction machine that generates 400kW at 6.6kV with a speed of 700rpm. Power is fed directly to shore and there is no power conditioning or transformation on the device. This is all done onshore.
Power Take Off
Power take off is via a 6 way dry mate connector with 3 cores dedicated to 6.6kV export power and 3 cores for 6.6kV import power. Wet mate connectors will be used for future models with removable nacelles.
Control, Data and Aux Power Requirements
Auxiliary power is from the mainland at 6.6kV and is transformed down to 400V on the device. The burden is 14.5kW. Data is via a single mode fibre optic cable.
Current Commercial Installation or Demonstrator Project
The 400kW prototype is waiting to be installed at Ramsey Sound in Pembrokeshire, England. There is a 1.2MW 11kV connection with WPD which will accept the full 1.2MW three turbine unit.

Company: **Tocardo** *

Model: **T Series**



Power Output	98/200/520kW
Output Voltage	400V
Type	Tidal
Maintenance Interval	Not known

Physical Description of Device

Similar to the concept of the Schottel generators these are standalone units that are designed to be integrated into suitable submarine structures. The units come in 3 sizes T1/ DD700, T2/ DD1000 and T3/DD1600 rated at maximum outputs of 98kW, 250kW and 520kW respectively. At present these devices are intended for run of river or near shore applications and a T4 machine that will generate in excess of 1.5 MW is in development.

Conversion of Marine Kinetic Energy to Mechanical Energy

The units have twin blades that come as uni–directional, bi-directional and fixed pitch.

Conversion of Mechanical Energy into Electrical Energy

The units are fitted with 20 pole permanent magnet direct drive variable speed generator. There is no gearbox.

Description of Electrical System

Each turbine is fitted with a solid state AC-DC-AC IGBT drive. The unit operates at connects at 400V. It is not clear if the T4 unit will produce power at a higher voltage.

Power Take Off

Not known.

Control, Data and Aux Power Requirements

Not known.

Current Commercial Installation or Demonstrator Project

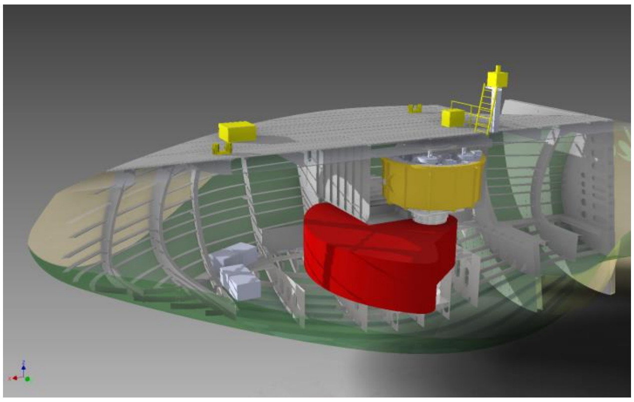
100kW unit operating for 6 years in Den Oever Holland, 1MW array of T200 units at Oosterschelde storm barrier. Units have also been shipped to Nepal for run of river applications.

<table>
<tr><td colspan="2">Company: Voith Hydro</td><td rowspan="7">Image not available</td></tr>
<tr><td colspan="2">Model: HyTide 1000</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Power Output</td><td>1MW</td></tr>
<tr><td>Output Voltage</td><td>Not known</td></tr>
<tr><td>Type</td><td>Tidal</td></tr>
<tr><td>Maintenance Interval</td><td>Not known</td></tr>
<tr><td colspan="3">Physical Description of Device</td></tr>
<tr><td colspan="3">3 blade horizontal axis turbine. Unit is fixed in the tidal stream and does not yaw.</td></tr>
<tr><td colspan="3">Conversion of Marine Kinetic Energy to Mechanical Energy</td></tr>
<tr><td colspan="3">3 blade fixed pitch rotor with bi-directional operation.</td></tr>
<tr><td colspan="3">Conversion of Mechanical Energy into Electrical Energy</td></tr>
<tr><td colspan="3">The unit has no gearbox but a direct drive permanent magnet motor.</td></tr>
<tr><td colspan="3">Description of Electrical System</td></tr>
<tr><td colspan="3">It is not clear if there is any power conditioning of voltage transformation done on the machine.</td></tr>
<tr><td colspan="3">Power Take Off</td></tr>
<tr><td colspan="3">The promotional video on the website shows a power connection operation taking place in a box at the rear of the machine. This seems to take place as an automated stab plate arrangement. It is not clear if this is done using wet mate connectors.</td></tr>
<tr><td colspan="3">Control, Data and Aux Power Requirements</td></tr>
<tr><td colspan="3">Not known.</td></tr>
<tr><td colspan="3">Current Commercial Installation or Demonstrator Project</td></tr>
<tr><td colspan="3">1MW prototype machine installed at EMEC.</td></tr>
</table>

Company: **Wello Oy***

Model: **Penguin**

Power Output	500kW – 1MW
Output Voltage	11 kV
Type	Wave
Maintenance Interval	12 months, onsite-maintenance



Physical Description of Device

This device looks like a rather irregularly shaped boat with 28 meters length and 15 meters width. It has a 7 metre draft and sits 2 meters proud of the water. It is tethered to the seabed and connected to the grid with 11 kV subsea cable.

Conversion of Marine Kinetic Energy to Mechanical Energy

Asymmetric shape of the floating device is used to capture the movement to a spinning rotator inside the device. Power is fed directly from the rotator to generator using the same shaft.

Conversion of Mechanical Energy into Electrical Energy

The rotating mass is directly connected to a permanent magnet generator, rated 1.2MW.

Description of Electrical System

Components inside the device are; generator, converters and transformers. The transformer converts the generator voltage to grid voltage i.e. 11 kV.

Power Take Off

Not known.

Control, Data and Aux Power Requirements

The control and automation system inside the device uses internal 220/380V circuit.

Current Commercial Installation or Demonstrator Project

Full scale prototype (500kW unit) used at the EMEC since 2012. All the components inside the device are still original without need to replace.

Appendix 3 Consultation Questions

The following is a list of the questions asked in the questionnaire sent out on 18/02/2015.

	Device Mechanical Properties
1	How does the device convert wave/tidal energy to electrical energy?
2	Describe the drive chain.
3	How is the device anchored to the seabed and how is it removed for servicing? What is the expected number of maintenance events per annum?
	Device Electrical Properties
4	What is the output voltage and power of the device?
5	Please describe the generator used. (Type, Size and Output Voltage)
6	Does the speed of the generator vary as a function the energy delivered to the device? Does the voltage and/or frequency of the output vary with speed?
7	Is the generator connected to any power electronics? Are they located on the device or elsewhere? Please provide details.
8	Is there a step up transformer situated in the device? If so please provide details.
9	What are the short circuit characteristics of the device at the output terminals
10	What are the auxiliary power requirements of the device? Please provide figures for voltage and power
11	How adaptable is your electrical design. Can it operate over a range of output voltages
	Power Take-Off and Data
12	Describe how the power cable connects to the unit
13	How is auxiliary power derived, internally or externally? If externally how does it connect?
14	Does the device contain a controller? Does it communicate to the mainland? If so how (copper, fibre or radio)?
15	Does the unit use wet mate connector technology to connect main, auxiliary and data cables to the device?
16	If wet mate connector technology is not used is this something that would be considered if it was more economical. If so is the device capable of being fitted with these types of connectors.
	Additional Data
17	Is your device installed in a commercial or demonstrator project? Please give details including: Location Size and Connection Voltage Number of MWh generated
18	If a number of devices were connected together as a marine farm how will the active power and reactive power be regulated (to comply with UK and European grid codes)

Table 5 Consultation Questions

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