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## Economic Challenges and Optimisation of Ocean Energy Electrical Systems

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## 10 Economics of Ocean Energy Electrical Systems

### 10.1 Economic Challenges and Optimisation of Ocean Energy Electrical Systems (F Sharkey)

#### 10.1.1 Introduction and Components of Ocean Energy Electrical Systems

Ocean Energy Systems are relatively immature and there is limited experience of the costs associated with connecting large scale arrays at present. There is therefore some uncertainty over the overall Capex of such projects. However there is a credible ambition is to bring the costs of ocean energy systems in line with those of offshore wind. There are some similarities and some key differences between offshore wind farms electrical systems and those of offshore wave and tidal farms [1], and with much higher installed capacity the offshore wind industry can be used to inform the ocean energy industry. Electrical systems for offshore wind farms typically cost 20-25% of the overall system Capex [2] and the same is expected for ocean energy farms [3], perhaps a higher proportion for wave farms and lower for tidal farms. Note that this assumes that the overall costs for ocean energy reach similar levels to offshore wind. For early stage arrays the percentage of Capex for electrical systems will be lower as the cost of the actual converters will be much higher.

This Chapter aims to present the expected costs for ocean energy electrical systems and some of the major challenges faced by ocean energy in this area. The Chapter also looks at techno-economic optimisation of array layouts and goes on to explore some potential strategies to reduce the cost of ocean energy electrical systems. The focus is mainly on wave energy electrical systems. However, there are several commonalities to tidal energy electrical systems and the challenges are broadly the same.

Although there are numerous wave energy converter (WEC) and tidal energy converter (TEC) types and there is some variation in the electrical collection and export concepts marine energy converter (MEC) arrays will typically have the following components which are explained in more detail in other Chapters of this book:

- Generators and balance of onboard electrical plant (power electronic Converters, transformers, switchgear etc.)
- Dynamic power cables (floating MEC only)
- Submarine connectors and other submarine electrical systems
- Submarine power cables
- Offshore substations
- Onshore substations and grid connections

There are, of course, some exceptions (such as nearshore WECs with hydraulic transmission) but the components listed above are considered ‘typical’ of an MEC array.

### 10.1.2 Expected Costs for Electrical System Components

So if the target cost of ocean energy systems is that of offshore wind systems [4] and the proportion of that cost for electrical systems is 20-25% of the overall cost then we would expect the following costs for ocean energy electrical systems.

Ocean Energy Target Installed Costs: €4 m/MW [4]

Ocean Energy Electrical Systems Target Costs: €1 m/MW (25% of the above)

Therefore all of the electrical components in the ocean energy system must cost less than €1 m/MW to be comparable to offshore wind. Although the cost of the MEC is expected to come down dramatically as the industry reaches maturity, the cost of the electrical system is predominantly mature at present as it uses mostly mature technologies. There are however some design criteria which will increase the electrical system costs and also some potential strategies for reducing costs which are discussed in later sections.

It is difficult to give actual costs for electrical system components as these are volatile over time and can tend to be project specific rather than generic. However some Euro figures are given below in Table 1 for the major components which may be suitable for preliminary assessments. However they are strictly not suitable for budgeting purpose. They are based on what could be considered 'off the shelf' components and do not cover bespoke or specialist installations.

Table 10.1 Typical Component Cost Ranges for MEC Arrays

Component	Suggested Cost
Generators *	€40-70/kW [4] – [7]
Power Converters *	€90-110/kW [6] - [7]
Power Transformers *	€40-60/kW [6] - [7]
Switchgear *	€60-100/kW [6] - [7]
Submarine Connectors	Splice Housing: €60-100k per connector (est) Dry Mate Connector: €100-200k per connector (est) Wet Mate Connector: €150-250k per connector (est)
Dynamic Power Cables – Medium Voltage (MV)	€300-800/m (est)
Submarine Array Cables (MV)	€300-800/m [4] & [8] - [14]
Submarine Export Cables – High Voltage (HV)	€1000-2000/m [4] & [8] - [14]
Offshore Substation	Foundation and Structure: Unknown Topside: €120-150k/MW (Electrical Plant Only)
Onshore Substation and Grid Connection	Suggested Costs: €100-250k/MW [15]

\* These components are part of the MEC itself (in most cases) therefore they would be included in the MEC cost and not in the 'electrical system' costs. They are included for reference and completeness

### 10.1.2.1 Submarine Cable Cost Model

The cost of submarine power cables is extremely volatile in that there are numerous factors that can affect the overall cost of the cable and its installation; namely materials cost (particularly copper and steel), mobilisation costs (significant for remote sites), seabed conditions (affecting installation method), downtime (determined by prevalent weather) and availability of equipment (determined by market demand). Therefore it is difficult to put a Euro price on cables that will remain relevant across all projects which can be seen by the range shown above in Table 10.1. Another approach is to look at the factors which make up the installed price of a cable and develop a normalised cost model which will be valid with all else being equal in the cost of cables and installation methods across a particular project. This method disregards contract strategies such as bulk purchasing or multi-project which are not possible to model.

By looking at the elements of each factor of the cable cost a normalised cost model can be established. The main factors affecting the cable cost are;

1. The voltage rating of the cable (i.e. the insulation rating/thickness)
2. The cross sectional area (CSA) of the conductor
3. The installation costs

For simplicity we will assume three core cross-linked polyethylene (XLPE) cables with copper conductors and a single layer of armouring for all cases as these are common cables in the offshore wind industry.

As this is a normalised cost model a base case is required to normalise against. The base case will be a 10kV, 1x3x95mm<sup>2</sup> cable. This cable will have an installed normalised cost of 1.0 and all other cables will be represented as a multiple of this. The cost model was developed primarily using the formulae given by Lundberg in [8] and also verified by comparing against numerous sources such as [9]-[14]. The developed normalised costs are shown in Table 10.2.

For example a 33kV, 240mm<sup>2</sup> cable is 58% (1.58/1.0) more expensive than the base 10kV, 95mm<sup>2</sup> cable. Also a 20kV, 500mm<sup>2</sup> cable is 165% (2.25/0.85) more expensive than a 20kV, 50mm<sup>2</sup> cable.

The cost model presented in Table 10.2 will be used for analysis of electrical network options throughout this chapter.

Table 10.2 Installed Cable Normalised Costs

Cable CSA (mm <sup>2</sup> )	Voltage			
	10kV	20kV	33kV	132kV
35	0.79	0.82	0.85	-
50	0.81	0.85	0.88	-
70	0.85	0.89	0.94	-
95	1.00	1.05	1.11	-
120	1.05	1.11	1.18	-
150	1.10	1.17	1.25	-
185	1.25	1.34	1.43	-
240	1.35	1.46	1.58	-
300	1.65	1.80	1.97	-
400	1.80	1.99	2.21	2.79
500	2.00	2.25	2.53	3.25
630	2.25	2.55	2.89	3.75

### 10.1.3 Economic Challenges for Ocean Energy Electrical Systems

There are a number of economic challenges for ocean energy electrical systems which are discussed and analysed in more detail below. Building a business case for early stage arrays will be challenging and it is likely that there will be pressure to reduce the costs of elements such as the electrical system. Therefore there will be a drive towards the least cost option. However designers must be wary to not compromise critical safety and functionality issues with this pressure for minimising cost.

A 'medium' size, 40MW, WEC array is taken from [1] as the candidate array (see Figure 10.1). This candidate array has the following, base case, assumptions:

- Each MEC (node) is rated at 1MW with unity power factor
- Each MEC has a 30% capacity factor
- The inter-MEC spacing is 400m (inter-MEC cables are 400m + twice the depth)
- The water depth is 100m
- The export distance is 15km

This will be used in conjunction with the normalised cable cost model given in the last section in order for an economic analysis to be undertaken.

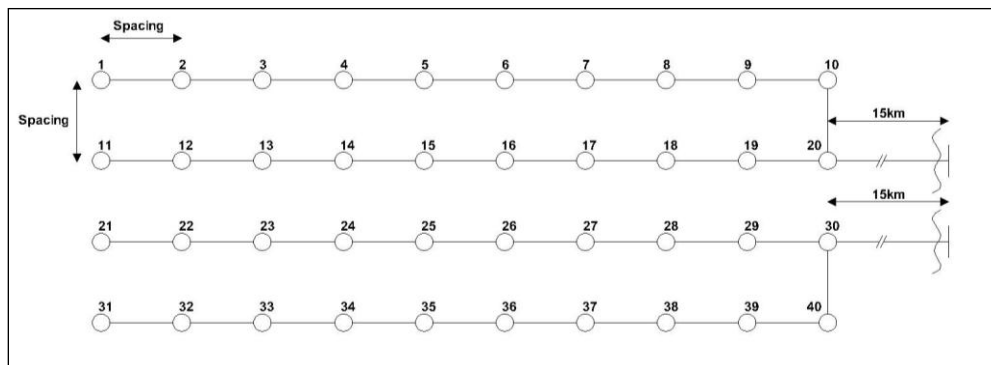


Figure 10.1 Candidate, 40MW, Array

#### 10.1.3.1 Individual MEC ratings:

At the current stage of the industry's maturity there is a trend, both in wave and tidal sectors, towards devices with ratings of ~1MW. Individual device ratings of 1MW are therefore used as the base case in any analysis done. There are of course a number of exceptions to this trend. Offshore wind turbines are mostly rated around 3-4MW with a trend towards higher power units (5MW+). These small MEC unit sizes will present a challenge to the economics of ocean energy electrical systems as each device in an array will require dynamic cables (floating MEC), submarine connectors, and a cable connection to the next device in the array. Naturally the more devices in the array will mean additional cost for the array, certainly on a per MW level.

Just the cost of the dynamic and static submarine cables will be evaluated here. The relative cost of the array (versus the base case) is established for a 40MW array with 250kW, 500kW, 1MW (base case), 2MW, and 4MW individual MEC ratings. The total rating of the array remains at 40MW in all cases, i.e.

the quantity of MECs changes depending on the MEC rating. The array and export voltage is also 20kV in all cases.

The relative cost as a percentage of the base case is shown in Figure 10.2 below. The relative cost is shown for the array only and the full electrical system (i.e. array and export cable). This shows that as expected the relative cost is higher for smaller devices and lower for larger devices. The increase can be as much as 3 times for the array cable costs. It should be noted that the costs do not decrease as much or as exponentially for larger individual devices with decreases to as low as 0.4 times possible for the array cable costs.

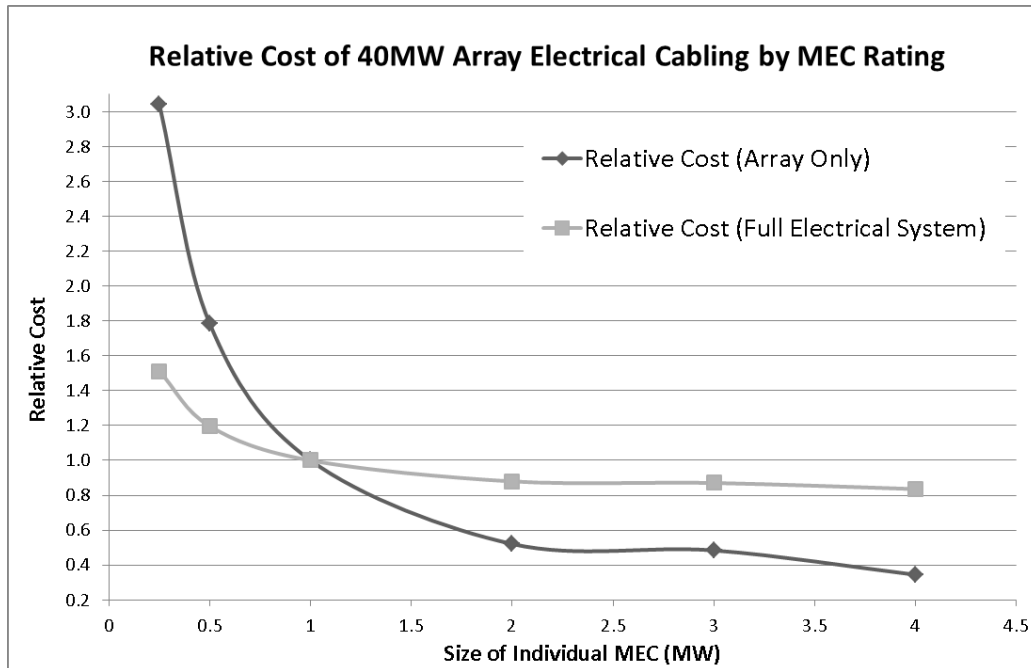


Figure 10.2 Relative Cost of 40MW array electrical cabling based on device rating

The focus here is on the electrical system only however it is worth noting that lower MEC ratings will increase other elements of Capex such as installation, moorings etc.

#### 10.1.3.2 Device Capacity Factor:

The capacity factor of offshore wind turbines is typically in the region of 30-40% [16] depending on turbine type, location, yearly wind speed etc. Given the variety of wave and tidal energy devices available it is unclear what capacity factors these devices will have. For 'direct drive' wave energy converters the capacity factor could be very low, <20%, due to a high peak to average output ratio. Conversely some tidal turbines may achieve capacity factors of over 60% at high energy sites.

The relative cost of the array electrical network (versus the base case) is established for the candidate array with capacity factors of 10%, 20, 30% (base case), 40%, 50% and 60%. The overall average output of the array remains at 12MW (base case 40MW x 30%) in all cases but the peak power output changes with the capacity factor.

The relative cost as a percentage of the base case is shown in Figure 10.3 below. The relative cost is shown for the full electrical system only (i.e. array and export cable). This is because capacity factor effects both array and export systems. The relative cost is assessed at two voltage levels (20kV and 33kV). This shows that as expected the relative cost of the electrical network is higher for devices with lower capacity factor and lower for device with higher capacity factor. Halving the capacity factor from 30% to 15% would almost double the cost of the electrical network. Doubling the capacity factor from 30% to 60% would decrease the costs by up to 40%.

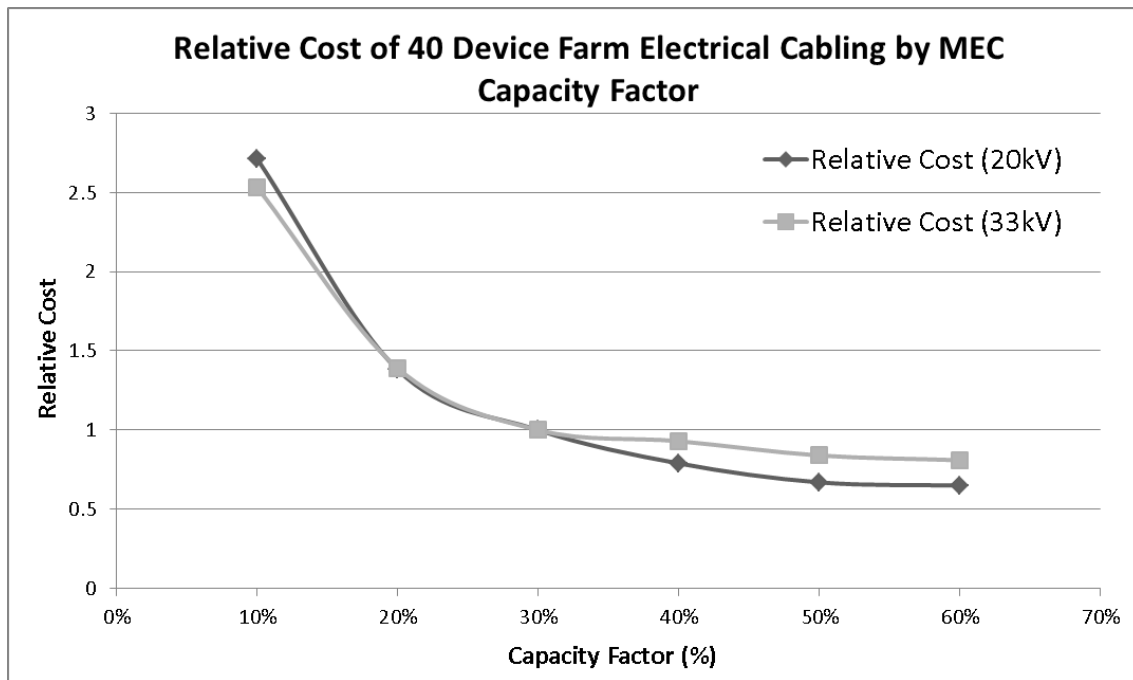


Figure 10.3 Relative Cost of 40 device array electrical cabling based on device capacity factor

### 10.1.3.3 Submarine Connectors and Other Submarine Electrical Systems:

In offshore wind farms the cables are routed, through J-tubes, straight into the turbine tower. This is not the case with ocean energy arrays as the devices are required to be removed for maintenance on a regular basis. This presents a number of issues, including redundancy in the electrical network, which is discussed in the next section. For floating MECs there will be a connection required between the dynamic cable and the static cable. In some cases there will be a requirement for the device to be quickly and repeatedly connected and disconnected from the electrical network, although more so at prototype stage. Therefore some type of connector is required. These connectors are discussed in Chapter 3.

However, as these connectors are a requirement for ocean energy electrical systems, which does not exist in offshore wind, they will naturally add to the overall cost of the system. In some cases, where a radial circuit it used (see next section), there will be a requirement of two connectors per device. As mentioned in 10.1.2 the electrical system will need to cost less than €1m/MW. Also in 10.1.2 it is shown that electrical connectors could cost anywhere from €60-€250k per installed connector. Naturally if we do not want to exceed the threshold of €1m/MW then 2 x €250k per connector is not feasible, i.e. €0.5m/device on connectors alone. So, although wet-mate connectors may increase the functionality of

the device, they may be unfeasibly due to cost in the medium term. Either way submarine connectors will be required and it is a matter of trying to balance the cost with the functionality of the connector. This is explored further in the next section.

There are other potential submarine electrical systems which could be utilised in MEC arrays. These could be simple junction boxes (such as 'Wavehub'), submarine switchgear modules (such as OPT's Undersea Substation Pod), or more complicated 'submarine substations' in place of platform based substations. It is not clearly understood what the potential costs of these components would be, however these would on the whole represent additional costs over the traditional offshore wind farm electrical system. It is highly likely that such systems would be expensive to build, install and maintain and costs would be in the millions of Euro. There are also practical functional and safety concerns with such systems. Submarine electrical systems have been successfully installed in deepwater oil and gas fields; however the economics are not comparable to ocean energy, and so these systems may not be suitable.

#### ***10.1.3.4 Cable Installation and Protection:***

The cable costs given in 10.1.2.1 are based on the assumption that a standard installation method can be used, ploughing or jetting the cable into the seabed sediment. In truth every site is different but the seabed is predominantly rocky along the western seaboard of the UK and Ireland, and areas of high tidal flows are likely to be swept clear of most sediment. These conditions present extremely challenging cable laying conditions and expensive installation and protection methods must be used such as rock trenching, rock dumping, armour casings, concrete mattresses or horizontal directional drilling [17]. These methods could more than double the cost of the cable installation and so are huge challenges to the sector. A high number of installed wave and tidal facilities have required these measures such as;

- EMEC (armour casings and concrete mattresses)
- Wavehub (rock dumping)
- MCT SeaGen (horizontal directional drilling)

The careful selection of sites with sufficient sediment may allow the avoidance of expensive cable installation methods and this may go hand in hand with mooring requirements for wave energy arrays.

There is also a challenge in the protection of dynamic power cables as this will require numerous additional components such as bend restrictors, stress relievers, floatation module and scour protection. Again this will add to the cost of the electrical system however this is expected to be relatively modest.

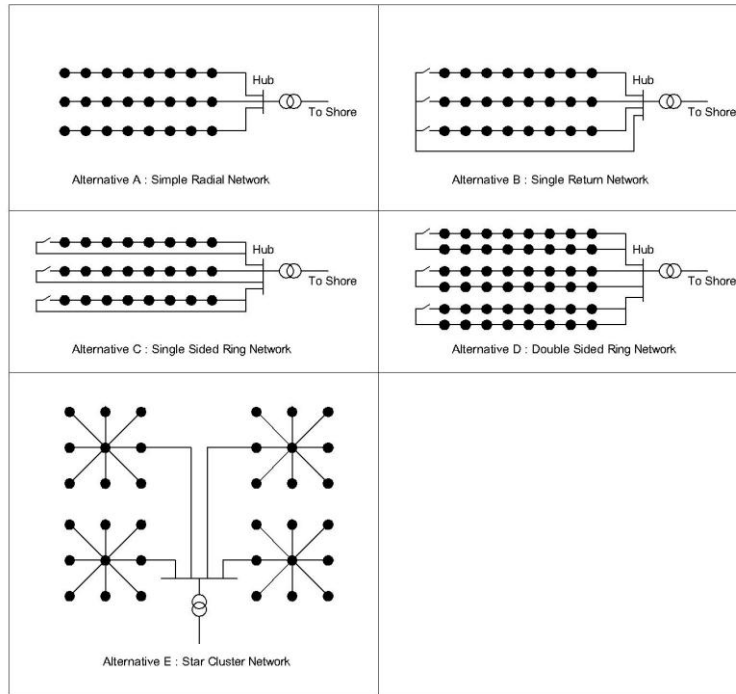
### **10.1.4 Techno-Economic Optimisation of Ocean Energy Electrical Systems**

This section examines at some of the issues above and considers the optimal electrical network configuration for an MEC array based on the technical and economic aspects.

#### ***10.1.4.1 Optimal Array Electrical Configuration:***

One major factor in the cost and functionality of the electrical system is the configuration of the MEC array electrical network. There are a variety of alternative configurations as shown in Figure 10.4 below. For MEC arrays some proposals have been made for submarine 'hubs' which could act as an aggregation point in a star network. These are discussed further in section 10.1.4.3





*Figure 10.4 Alternative Network Configurations*

We can evaluate the candidate wave farm using the alternative configurations as shown in Figure 10.4 under a number of criteria.

The following assumptions are made in addition to those shown in Section 10.1.3:

- The physical grid layout of the devices is assumed to be maintained at all times, for all configurations
- Redundant circuits are assumed to be rated for worst case full load, i.e. they are 100% redundant.
- No bespoke equipment such as submarine switchgear is considered at this stage and all switching operations are assumed to be contained within the MEC or in the onshore substation.

*Cost (Relative to (A))*

Table 10.3 shows the relative cost of the array only, and the array and export cabling for the various alternative configurations detailed in Figure 10.4. This shows that the Radial network is the least cost solution from an array configuration perspective. This is primarily due to additional cabling required for the proposed alternatives. Also, in order to allow redundancy and bi-directionality in some of the circuits, the cross sectional area (CSA) of some of the cables must be increased thus increasing cost. The Star Cluster Network (E) shows an relative cost of 1.54 with the existing physical grid layout. It is expected that with optimisation of the Star Cluster Network this could be on par with the Radial network for cost; however the electrical cost may only be one optimisation factor for the selection of physical layout.

<b>Network Configuration</b>	<b>Relative Cost (Array Only)</b>	<b>Relative Cost (Array and Export)</b>
Radial Network (A)	1.0	1.0
Single Return Ring Network (B)	2.58	1.39
Single Sided Ring Network (C)	1.8	1.2
Double Sided Ring Network (D)	1.69	1.17
Star Cluster Network (E)	1.54	1.13

Table 3 - Cost of Alternative Array Network Configurations

### *Installation*

The radial network would allow the simplest installation with multiple short cable runs. The installation process for the alternative array configurations may be more complex involving additional and longer cable runs and possible cable crossings.

### *Operation*

The radial circuit has no redundancy in the array network meaning that in the event of a fault during normal operations all upstream MECs in the circuit will be disconnected from the system. All of the alternatives offer some level of redundancy in the circuit which has been shown to increase availability of the overall array [18].

### *Maintenance*

A unique characteristic of deepwater wave farms is that individual WECs will require removal for routine and non-routine maintenance. Similar to the comments in 'Operation' above a radial circuit would have no redundant circuit. The alternative configurations would be more suitable to overcome this but there are solutions to overcome the lack of redundancy in radial circuits. These solutions are discussed below.

### *Isolation and Protection*

How the individual MECs and array cables are isolated is an important consideration for safe operation of a MEC array. The operation of a radial circuit is well understood where any MEC or cable can be simply isolated by switching out the connection at either side. More complicated switchgear and isolation systems may be required for the alternative networks.

What can be concluded from the above discussion is that the simple radial network appears to be the most advantageous in terms of cost; however the radial network is less suitable where redundancy is required. In reality, as shown in Section 10.1.2, the cost of the electrical system would need to be kept as low as possible, therefore any other technical or functional considerations may not be valid. Thus radial networks are selected here as the most suitable array network configuration for MEC arrays.

This has proven the case with offshore wind farms, with radial networks being used in all offshore wind farm array configurations and few wind farms having any redundancy in the electrical system. However with offshore MEC arrays we have the issue of removal of MECs in the circuit which needs to be resolved. This can be done with a number of options including;

1. 'Standby' or 'dummy' MECs to 'slot' into place.
2. A system for temporarily 'bridging' the gap left by the MEC in the electrical circuit.

3. Submarine switchgear allowing continued operation of the infield circuit (see next section)

It is likely that that option 2 here would be the least cost solution to this issue.

#### ***10.1.4.2 Key Electrical Interfaces:***

If the MEC array network configuration is to be a radial network then the key interfaces between the MEC and the radial network need to be optimised. This means achieving a balance between the functionality of these interfaces and cost.

These key interfaces are categorised as;

1. Dynamic cable to MEC interface
2. Dynamic cable to static cable interface
3. MEC MV switchgear interface
4. Offshore substation

There is certain functionality required at the key interfaces between the electrical system and the MECs including the following;

- Multiple connection / disconnection of the MEC
- Initial cable installation
- Electrical protection
- Electrical isolation (and earthing)
- Cable hull penetration
- Circuit continuity (i.e. redundancy)

Although the maximum functionality in the key electrical interfaces would be desirable, the cost of the key interfaces must also be minimised. The expected costs may limit the functionality that can be viably achieved in the key interfaces. The Key interfaces are not outlined in any more detail here but a techno-economic optimisation can be found in [19].

#### ***10.1.4.3 Other Bespoke Solutions:***

The focus here has been on offshore MEC arrays with radial array networks. Other bespoke solutions have been proposed which all fall into a general category of submarine 'hubs' utilising star cluster type network configurations.

These hubs in general collect the generated power from several MECs and condition it for transmission to shore. These hubs can contain one or all of the below equipment:

- Power electronic converters
- Low Voltage (LV) & MV switchgear
- Power transformers
- Energy storage solutions
- Battery chargers and auxiliary systems

Although these are not explored in detail here there are several major challenges that must be overcome in order to make these types of solutions viable. They are the same challenges that apply to larger submarine offshore substations. These challenges are outlined here for information only:

- Access to complicated equipment such as power electronic converters, digital protection relays, battery chargers etc. would be required in the event of even a simple fault. This operation alone would be a huge cost.
- There are safety implications with having a point of isolation and earthing in a location where it can not be verified or locked out.
- The practicalities of connecting multiple LV and MV cables to a submarine hub are onerous. This would require multiple expensive mate-able connector and/or remotely operated vehicles (ROV) operations.
- The potential construction and installation costs of a submarine hub are very large and there is little experience here apart from the oil and gas industry.
- There are other, less technically and economically challenging options for electrical connection schemes which should be explored first.

### **10.1.5 Cost Reduction of Ocean Energy Electrical Systems**

The purpose of this section is to explore strategies to reduce the Capex of the electrical network of MEC arrays, i.e. to maximise the value of the electrical network asset with particular emphasis on the cabling system. This in turn will reduce the overall Capex of MEC arrays. As shown in Section 10.1.3 increasing MEC capacity factor or increasing the unit rating will reduce the electrical system Capex.

There are a number of other strategies which are explored in this section in order to achieve this increase in the value from the MEC array electrical network.

1. Less than 100% rating based on statistical data
  - Based on the idea that a MEC arrays rarely output 100%
2. Dynamic rating based on environmental data
  - Based on the idea that cable rating change depending on the environmental conditions
3. Dynamic rating based on real time measurement
  - Based on the idea that actual cable ratings can be measured in real time

These strategies are outlined briefly below and more detailed analysis can be found in [20]

#### ***10.1.5.1 Less Than 100% Rating Based on Statistical Data:***

It could be assumed that an array of MECs would rarely reach 100% output based on resource availability and MEC reliability. This leads to the possibility that the electrical export system could be rated at less than 100% of 'nameplate' rating. In this case the rating will mean that the cable is under-rated when the MECs do reach maximum output simultaneously, leading to either output curtailment or a combination of one of the other techniques described in this section. However any loss in energy may be offset by the savings gained from using a lower rated cable.

A small MEC array is modelled so that the effect of <100% rating of the cabling can be evaluated. The proportion of time (and generated energy) when the cable limits are exceeded is calculated. The effect on the annual energy yield of the array can be established and it can be seen whether this is offset by the savings in the Capex of the electrical network.

A small array of devices is examined to assess the possibility of lowering the rating of some of the cables thus realising cost savings. For simplicity a 5-WEC array is considered here. It should be noted that, unlike the candidate wave farm (Figure 10.1), the physical spatial arrangement of the devices is considered here. All WECs are considered identical and interference between WECs, either destructive or constructive, is not taken into account. Interference is an area of significant interest to the wave energy industry; however it is not considered to be sufficiently developed to be included in this study.

In order to avoid simultaneous operation the array layout is staggered so that some devices will be out of phase with others regardless of the angle of incidence. This means that the 5 WECs may not react simultaneously to the oncoming wavefront, although there may be a combination of wave period and approach angle that allows this to occur. This array is shown in Figure 10.5

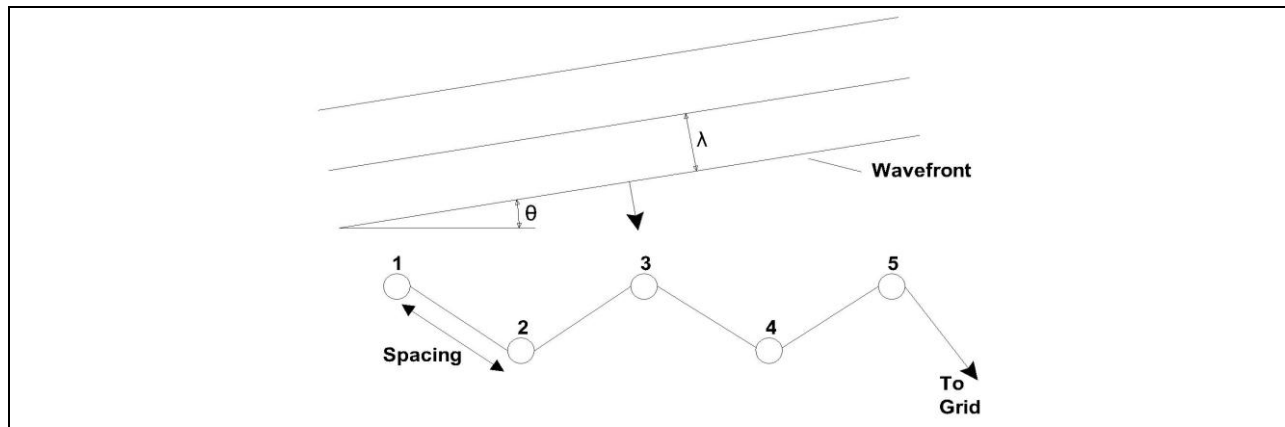


Figure 10.5 Concept of Array for Analysis ( $\theta$  = angle of incidence,  $\lambda$  = wavelength)

Focussing on the export cable only (5-Grid), reducing the cable CSA from  $95\text{mm}^2$  to  $70\text{mm}^2$  would reduce the export capacity from 5MVA to 4.15MVA or 83% of the rated array output. From the normalised cost model in Section 10.1.2.1 this will give a saving of 15% for the export cable. The time series output from the five devices is assessed to see if or when the overall output exceeds 4.15MVA. This will allow a cost benefit analysis to be carried out to see if the potential savings outweigh the possible loss of annual energy from the array.

This showed that the 5-WEC array reached 100% output (5MVA) for 3.2% of the year. The output was >83% (i.e. >4.15MVA) for 6.2% of the year and this contributed to 2.98% of the overall annual energy production. So if the export cable capacity was reduced from 5MVA to 4.15MVA a saving of 15% of the cable cost would be made, however this would result in a 2.98% energy curtailment per annum. A breakeven analysis will show if this curtailment can be justified based on the proposed saving.

#### *10.1.5.2 Dynamic Rating Based on Environmental Data:*

The current carrying capacity (ampacity) of power cables is calculated according to IEC60287 [21]. The maximum permissible continuous current is based on the maximum conductor operating temperature as defined by the cable manufacturer. For XLPE insulated cables this temperature is typically 90°C. The cable must dissipate heat during normal operation so the maximum permissible current is calculated based on the thermal properties of all of the components of the cable (insulation, screens, sheaths, filler, armour, and serving), the cable geometry and the thermal properties of the surroundings.

The current ratings given in submarine cable specifications use assumed values for the ambient conditions and surroundings such as those given below;

- Ambient temperature of 20°C
- Sheaths bonded at both ends and earthed
- Burial depth of 1 metre
- Thermal resistivity of surroundings of 1 Km/W

The ambient temperature, burial depth and thermal resistivity of the surroundings are somewhat within the control of the designer. These vary over time and over the length of the cable route. Therefore the maximum permissible current will vary also.

By focussing on our candidate wave farm (Figure 10.1) and in particular the export cables which would be 400mm<sup>2</sup> for 20kV and 150mm<sup>2</sup> for 33kV, we can evaluate the effect of lowering the cable CSA.

Focussing on the west coast of Ireland, Figure 10.6 shows that the seawater temperature varies seasonally from approx 6-15°C. Also the air temperature for the land based portion of the cable is important and this is shown in Figure 10.7 and varies seasonally from approx 3-17°C although with some extremes. This implies that the cable ampacity will vary throughout the year due to ambient temperatures.

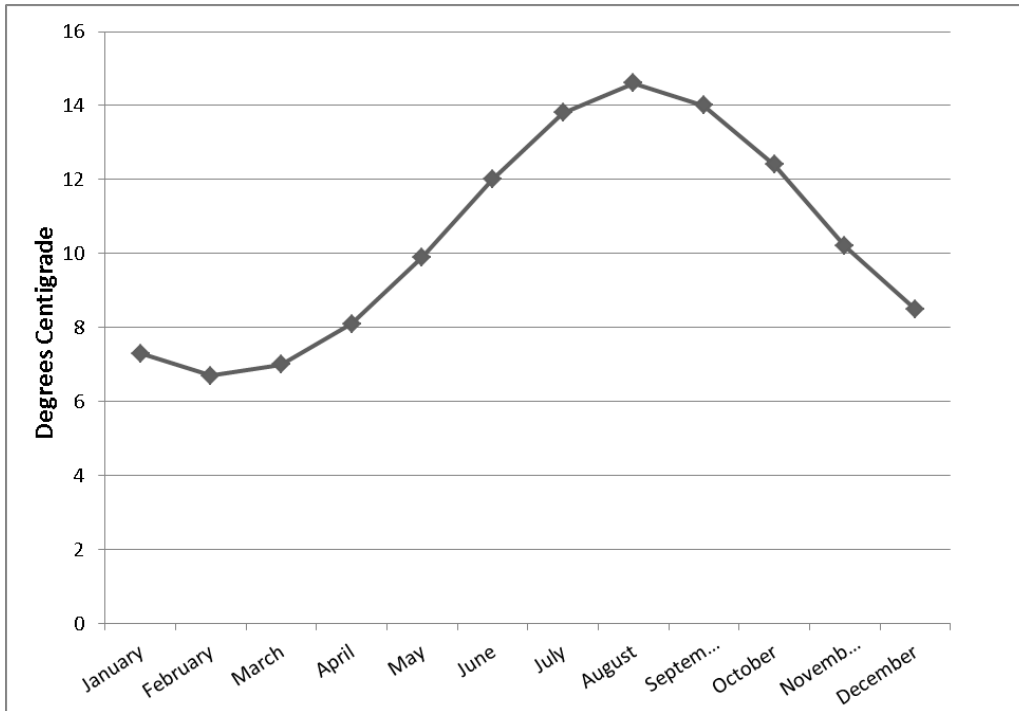


Figure 10.6 Average Monthly Seawater Temperature at Malin Head 1961-1990 (source: Met Eireann)

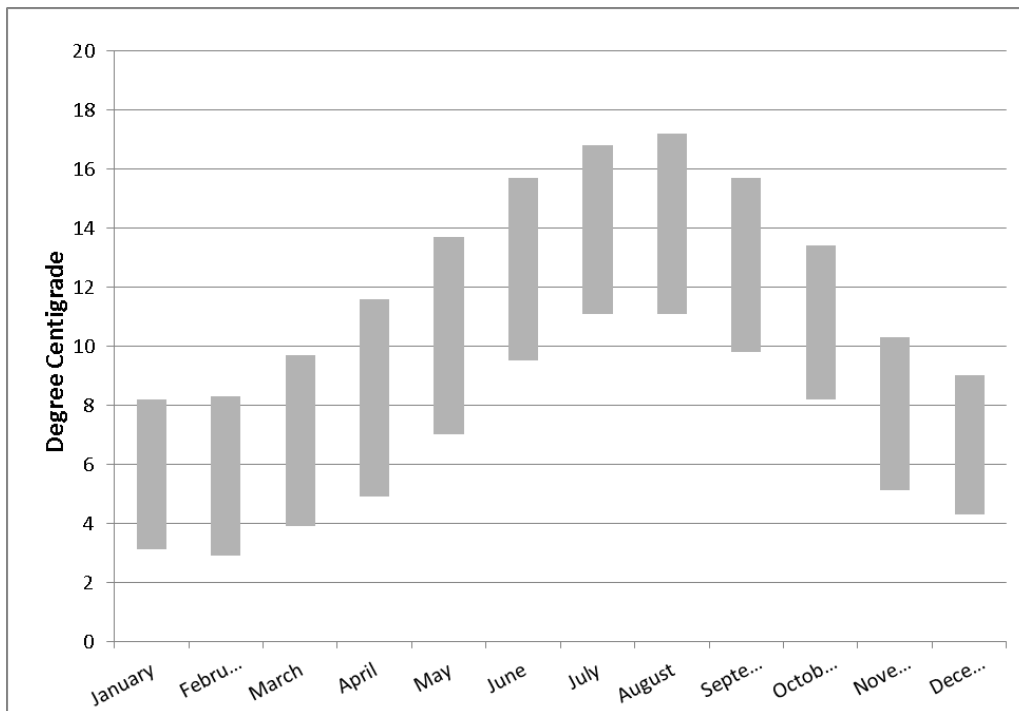


Figure 10.7 Average Monthly Air Temperature Range at Belmullet 1961-1990 (source: Met Eireann)

It is assumed for this analysis that the worst thermal resistivity along the route is 1.0 Km/W and that the burial depth is 1.0 m along the entire cable route. From this information we can show the available and required ampacity across the year for the selected cable and the next lowest cable CSA. The air

temperature is used for the calculation as it has higher extremes than the seawater temperature and the land section of the submarine cable would be expected to be a “bottleneck” as a result.

Figure 10.8 shows the results of the seasonal adjustment for a 20kV system. Based on the adjustment of the seasonal temperatures alone we can show that a 300mm<sup>2</sup> cable is more suitable for this application. The output of the array almost reaches the ampacity limit in the summer months; however this is only when the output of the array is 100%. Thus by understanding the environmental data the cable CSA may be decreased from that using the assumed values.

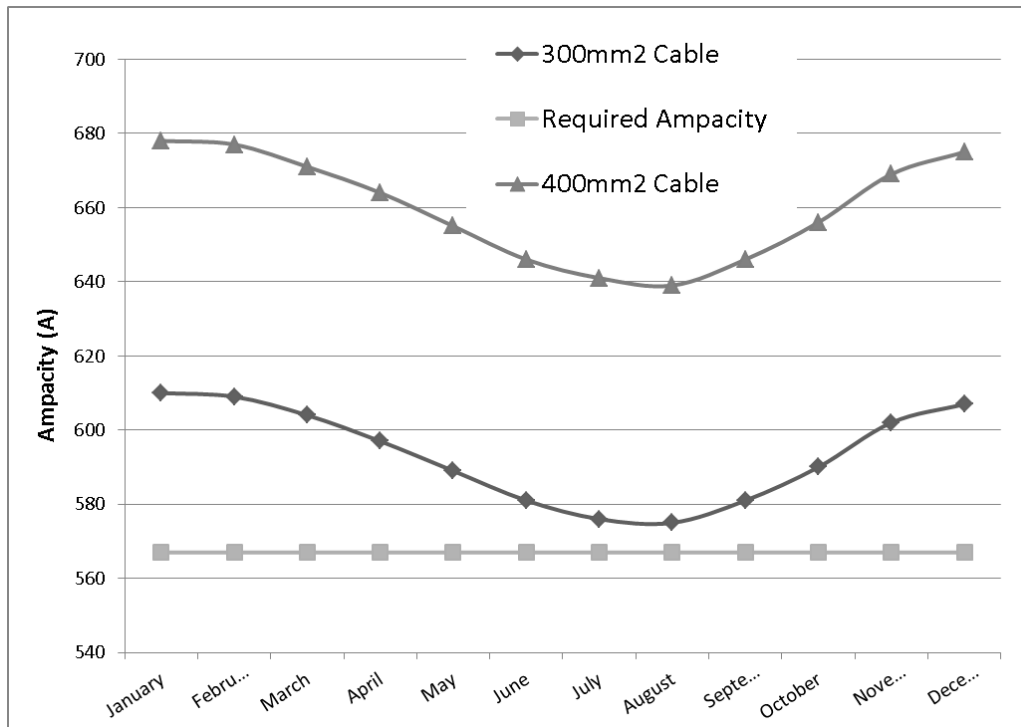


Figure 10.8 - Seasonal Ampacity of 20kV Cables

For the 20kV array the reduction in cost of the export cable by reducing the cable from 400mm<sup>2</sup> to 300mm<sup>2</sup> would be approx 10%. This saving only considers the export cable. Further savings to the overall electrical system costs could be made by reducing the inter-array cables CSA, particularly those nearest the export side, using the same method.

### 10.1.5.3 Dynamic Rating Based on Real-Time Measurement:

Dynamic or real-time thermal rating (RTTR) systems have been developed in order to utilise the ‘headroom’ available in transmission assets to increase the capacity at a given location. These systems monitor the environmental conditions (such as temperature, humidity etc.) and/or measure/model the temperature of the conductors themselves to allow dynamic constraints to be set on the system. This has been shown to allow 10-30% increased capacity over the static thermal rating of overhead lines [22].

To date this has been utilised successfully, with varying levels of complexity, on transmission systems in a number of countries. It has also been utilised for offshore wind farm export cables [23].



These measurement technologies ensure that an accurate figure of the cable ampacity is maintained at all times thus allowing the cable asset to be utilised to its actual full permissible rating when required. Similar to the above methodology in the previous section, this would give greater accuracy and confidence regarding the actual maximum current rating at any given time.

The methodology in the previous section above carries a certain amount of risk as there may be times when the air temperature is significantly higher than the average for a given month. Therefore the system is normally designed for extremes to introduce a factor of safety.

In order to remove this risk real time measurement may be utilised to ensure that the ampacity of the cable is calculated in real time and the cable is never at risk of becoming overloaded. This can be done by simply measuring the ambient temperatures at several locations along the route and using a model of the cable to calculate ampacity. However this does not give actual real-time data about the conductor temperature and simply gives a calculated ampacity at a given time. More complex distributed temperature sensing (DTS) systems which measure the actual temperature of the conductor across the entire cable route will allow a very high degree of certainty in the loading at a given time.

DTS systems can use fibre optic technology which through a combination of back scattered light intensity and time domain reflectometry can measure the temperature to one metre resolutions in cables up to 30km in length [23][24]. This can give a temperature profile of the entire length of the cable thus allowing accurate loading of the cable, i.e. accurate dynamic ampacity ratings, and identification of hotspots along the route. While the DTS fibre optic cable can be installed after cable manufacture, it is preferable to install the sensing cable during manufacture as this will improve response time and makes the system integral to the power cable.

Such a real time system would allow the operator to use the strategies given in this paper with full confidence that the power cable asset will be maintained within safe limits. It also means that any output curtailment will be kept to an absolute minimum. Naturally such a system will increase the costs of the installation but this would be expected to be a marginal increase.

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