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# Offshore Electrical Networks and Grid Integration of Wave Energy Converter Arrays - Techno-economic Optimisation of Array Electrical Networks, Power Quality Assessment, and Irish Market Perspectives

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# Offshore Electrical Networks and Grid Integration of Wave Energy Converter Arrays

*Techno-economic Optimisation of Array Electrical Networks, Power Quality Assessment, and Irish Market Perspectives*

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A thesis submitted for the Doctor of Philosophy
to the Dublin Institute of Technology

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# Abstract

Wave energy is an emerging industry and faces many challenges before commercial wave energy converter (WEC) arrays are installed. One of these challenges is the grid integration of WEC arrays. This includes offshore electrical networks, grid compliance, and access to electrical markets. This must be achieved in a technically viable manner and also at an acceptable cost. As electrical networks are expected to make up a large proportion of the overall WEC array CAPEX, perhaps up to 25%, this area is critical to the long term competitiveness of wave energy.

The objectives of this thesis are to develop technically and economically acceptable electrical network designs for WEC arrays, evaluate voltage flicker issues for WEC arrays and develop design tools to analyse same, and evaluate the market scale for wave energy in Ireland, considering electrical integration issues in both the domestic and export markets.

This thesis presents the optimum design for WEC array electrical networks. By building from the industry state of the art, including offshore wind experience, a comprehensive techno-economic optimisation process is undertaken. This includes optimising the key electrical interfaces between the WEC and the array electrical network, optimising the array network configuration, assessing efficiency of the network, and demonstrating that the network can be achieved at a cost which will allow competitiveness. Some challenges to the economics of WEC array electrical networks and some strategies for improving the economics are presented in this research also. The results provide timely guidance to WEC and WEC array developers.

This research also demonstrates the critical link between voltage flicker emissions from WECs and the primary resource, i.e. ocean waves. Some practical assessment tools for the evaluation of this power quality issue are shown to assist in quantifying the problem. Also the full flicker performance of a candidate WEC is assessed helping characterise this link further.

In this thesis both the domestic and export markets for Ireland's wave energy resource are assessed as, although Ireland has an enviable wave energy resource, it is unclear where the market for this resource lies. This analysis shows that the medium term market for wave

energy in Ireland is an export market. Also, although technically feasible, there is an additional cost for export transmission which must be considered in evaluating export markets.

Some of the critical grid integration issues have been evaluated and addressed in this thesis. Future work is recommended in the areas of weather risk to cable installation at high energy wave sites, evaluating the benefits of shared electrical infrastructure across a range of renewable projects, designing offshore substations for WEC arrays, and quantifying the benefits of the addition of wave energy to the Irish renewable energy mix.

# Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for post graduate study by research of the Dublin Institute of Technology and has not been submitted in whole or part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institute's guidelines for ethics in research.

The Institute has permission to keep, to lend or to copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Signature________________________________________ Date__________________________

Candidate

# Acknowledgements

It is with the utmost pleasure that I submit my PhD thesis. I have undertaken an incredible journey by completing this work and have emerged as a better engineer and more critical thinker. I can't imagine how I would have reached this stage without the help and support of the below people. I simply cannot express my gratitude enough.

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From 2009 to 2011 I was seconded to Wavebob Ltd., a wave energy technology development company. The work that I began with this company contributed massively to this body of research. I would specifically like to thank Andrew Parish, then CEO of Wavebob, and Elva Bannon, for her massive contribution and MatLab expertise.

# List of Abbreviations

| | |
|---|---|
| AMETS | Atlantic Marine Energy Test Site |
| CAPEX | Capital Expenditure |
| CSA | Cross Sectional Area |
| DTS | Distributed Temperature Sensing |
| EHV | Extra High Voltage (380kV or higher) |
| EMEC | European Marine Energy Centre |
| EPDM | Ethylene Propylene Diene Monomer |
| EPR | Ethylene Propylene Rubber |
| EU | European Union |
| FNT | Float Neck Tank |
| HDD | Horizontal Directional Drilling |
| HV(AC) | High Voltage (>100kV) Alternating Current |
| HVDC | High Voltage Direct Current |
| IEC | International Electrotechnical Commission |
| IET | Institute of Engineering and Technology |
| LCC | Line Commutated Converter |
| LCoE | Levelised Cost of Energy |
| LV(AC) | Low Voltage (<1000V) Alternating Current |
| MCB | Miniature Circuit Breaker |
| MV(AC) | Medium Voltage (1kV – 99kV) Alternating Current |
| MW | Megawatt |
| MWh | Megawatt hour |
| O&G | Oil and Gas |

| | |
|---|---|
| OPEX | Operational Expenditure |
| OPT | Ocean Power Technologies |
| OSS | Offshore Sub-station |
| OWC | Oscillating Water Column |
| PMG | Permanent Magnet Generator |
| POC | Point of Connection |
| PTO | Power Take Off |
| RES | Renewable Energy Source |
| RMU | Ring Main Unit |
| ROV | Remotely Operated Vehicle |
| RTTR | Real Time Thermal Rating |
| SCIG | Squirrel Cage Induction Generator |
| SEAI | Sustainable Energy Authority of Ireland |
| SEM | Single Electricity Market |
| SNSP | System Non-Synchronous Penetration |
| VSC | Voltage Source Converter |
| WEC | Wave Energy Converter |
| WTG | Wind Turbine Generator |
| XLPE | Crossed Linked Polyethylene |

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# Chapter 1
# Introduction

## 1.1 Research Problem

The wave energy industry is presently in the advanced stages of single device prototype testing. No commercial arrays of wave energy converters (WECs) have been installed to date. There are numerous plans to develop WEC arrays once the technology has reached suitable maturity and acceptable cost [1]. Ultimately, WEC arrays will need to compete with other equivalent renewable energy sources (RES), a natural benchmark being offshore wind. This entails economic competitiveness and technology competitiveness. Economic competitiveness relates to the capital cost of a plant (CAPEX) and performance, i.e. operational cost (OPEX), availability, and capacity factor. This is sometimes represented as cost per Megawatt (€/MW) or levelised cost of energy (LCoE, €/MWh). Technology competitiveness relates to functionality, scale, resource predictability, grid connectivity and compliance, and market access.

A major challenge for wave energy, and other 'wet' renewables such as offshore wind and tidal energy, is the integration of these renewables into the electrical grid. For offshore wind farms the electrical array and export system can make up 25% of the overall project capital expenditure (CAPEX) [2]. The same proportion, possibly more given inherent challenges outlined in this thesis, is anticipated for wave energy [3]. There are some key differences and additional challenges over offshore wind which must be considered, including electrical connection to floating structures, removal of WECs for maintenance, an inherently harsh marine environment, and lower device ratings. Grid integration for wave energy refers to the generation of grid compliant electrical power, the collection and export of this power from the WEC array to shore, and the connection to a grid which has sufficient market demand for this renewable resource. The focus of this thesis is on this challenge of how WEC arrays can be integrated into the electrical grid technically and cost effectively.

WEC designs are diverse in their designed location and also in how they absorb and convert wave energy. WECs can be located onshore (in a seawall or cliff-face), nearshore (in shallow water, less than 20m depth), or offshore (in deep-water, greater than 75m depth). The focus of this research is on offshore, floating, WECs located in deep-water. In many cases the Wavebob WEC [4] has been used as a candidate device for some analysis in this thesis. This device is outlined in detail in Chapter 4.

This thesis addresses the following key research problems:

- What electrical components are typical of, and what are the design requirements of, a deep-water WEC array?
- What is the techno-economic optimum electrical network design for WEC arrays?
- What economic challenges and potential cost reductions exist for WEC array electrical network designs?
- How can resource induced flicker emissions, which are inherent to the wave energy resource, be evaluated during the WEC design process and how can they be mitigated?
- What is the scale of the domestic Irish market for wave energy and the cost and technical challenges of accessing export market opportunities?

### 1.1.1 Research Objectives

Given the current status of the emerging wave energy industry and the market context in Ireland and the EU, this thesis aims to explore grid integration of wave energy converter arrays. This thesis will outline the development of competitive grid integration solutions for wave energy including addressing electrical network design for WEC arrays, power quality and access to markets of scale.

The primary research objectives of this thesis are outlined below:

- Develop technically and economically acceptable electrical network designs for WEC arrays considering;
    - Economic constraints
    - Array technical requirements
    - Array functional requirements
    - Experience to date from both the offshore wind industry and the wave energy industry
    - Potential strategies for improving economics for WEC electrical networks

- Evaluate voltage flicker issues for WEC arrays and develop design tools to analyse same.
- Evaluate the market scale for wave energy in Ireland, considering electrical integration issues in both the domestic and export markets.

A complementary objective of this thesis is to provide design guidance and tools. This will help technology and project developers understand the implications of design decisions, which impact on grid integration aspects of a project, at an early stage. Early design decisions can lead to adverse implications for the grid integration elements of a project and can affect a project's or technology's commercial viability. These can be decisions made during the design of WECs themselves and also WEC arrays. The objective is to guide decisions to allow wave energy be suitably competitive within the EU market, focussing on the grid integration elements.

### 1.1.2 Novel Academic Contribution, and Technologic Advances in this Thesis

The purpose of original research is to provide novel research and conclusions which will advance the knowledge base in the specific topic. In the previous section the Research Objectives have been outlined. Below some of planned outcomes of this research are presented which represent novel academic contributions to the sector, i.e. have not been previously published, provide particular technologic advances or solutions to technologic uncertainties.

- A holistic approach to optimising WEC array electrical network design including practical functional and commercial requirements
- Demonstration of sensitivity of WEC array electrical network cost to elements such as WEC ratings, capacity factors, inter-WEC spacing.
- Demonstration of methodologies for reducing WEC array electrical network cost to enhance the competitiveness of the industry
- Clearly demonstrating the mechanism by which WEC devices will cause voltage flicker, and demonstration the link between wave resource conditions and flicker severity
- Development of novel, WEC specific, assessment tools for voltage flicker assessment

- Assessment of potential domestic market for wave energy in Ireland, given saturation of renewable energy market by onshore wind.
- Assessment of technical and economic feasibility of wave energy export from Ireland to the UK and France

The above outcomes of this research are novel, resolve technological uncertainties, and are of significant value to the academic body of knowledge. In the Conclusions section of this thesis the success of meeting these outcomes is assessed.

### 1.1.3 Thesis Outline

The thesis initially presents two introductory chapters. This chapter, Chapter 1, develops the context and rationale for the research, and the primary research objectives and methodologies. In Chapter 2 a comprehensive review of literature is undertaken which looks at the body of research that has been undertaken around electrical systems for ocean energy, particularly wave energy. The literature review outlines prior research in particular around the primary research objectives given in Section 1.1.1.

Chapter 3 is a review of the components which make up a WEC array. This introduces the state of the art in the electrical components for both the WEC on-board electrical system and the WEC array electrical network. An understanding of the required components for WEC on-board electrical systems and WEC array electrical networks is required for the analysis in subsequent chapters. Also in Chapter 3 the state of the art from offshore wind electrical network design is introduced to provide context and potential cross-over to WEC array electrical network design. Although not extensive, given the maturity of the industry, any experience with WEC electrical networks from prototype test sites to early stage arrays is also examined in Chapter 3.

Chapters 4 through 7 outline the original research of this thesis. Each of these chapters begins with an introduction of the specific research objective and discusses the methodology for the analysis being undertaken. The analysis and results are outlined in detail in the chapter in a manner that they can be reproduced. In each chapter the results are discussed and the main conclusions are presented.

In Chapter 4 a techno-economic analysis of WEC array electrical network configurations is carried out. This begins by examining the economic and functional requirements of WEC array electrical networks. State of the art electrical network design from the more mature offshore wind industry guides some of the early conclusions in this analysis. However, key differences and distinct challenges for WEC array electrical network designs are introduced and examined. Non-electrical requirements and constraints for WEC array design are evaluated such as array spatial configurations and device output characteristics. Key interfaces between the electrical network and the WEC are identified and some potential options for these interfaces examined.

Chapter 4 continues by evaluating a variety of possible array electrical network configurations from both an economic and functional perspective. The identified key interfaces are also considered. A techno-economic optimisation is undertaken to identify a suitable array electrical network configuration which has the required functionality at an acceptable cost. Chapter 4 concludes by undertaking detailed analysis of the optimised WEC array electrical network and examining voltage levels and efficiency.

In Chapter 5 the economic challenges for WEC array electrical networks are described in detail. The effect that several challenges will have on the WEC array electrical network economics is quantified. Some strategies to improve the economics of the array electrical network are also analysed.

In Chapter 6 the connection between the wave energy resource and voltage flicker emissions is introduced. Some early stage design tools for analysing the potential flicker emission from a WEC are developed. A detailed flicker analysis, in line with international standards, is carried out on a candidate WEC output. Some strategies to mitigate potential flicker emissions are also outlined.

In Chapter 7 the potential market for the large Irish wave energy resource is examined. The domestic market is evaluated in line with renewable energy targets, system constraints and plans in the onshore wind market. Export markets may provide demand for additional renewables and this opportunity is already being explored by some project developers. HVDC technology will enable the access to these markets technically. However, the additional cost of this export infrastructure will challenge the economics of wave energy further. This potential additional cost is evaluated and quantified for a number of scenarios in Chapter 7.

In Chapter 8 the analysis and results from the previous sections are evaluated and discussed. The main conclusions from the original research are presented along with the contribution of the thesis. Any future work which can build on this research is outlined here.

### 1.1.4 Status of the Wave Energy Industry

Wave energy converters have been proposed for over 200 years with some known patents from as far back as 1799 [5]. However since that time only a small number of WEC developers have demonstrated successful prototypes with generated power being exported to the electrical grid [1]. Many more WEC developers, with a variety of technology concepts, have ambitions to develop commercial technology. There have been few commercial applications for wave energy to date, with the most advanced installations being the Pelamis array at Aguçadoura, Portugal and the WaveGen-Mutriku Wave Energy Plant at Mutriku, Spain. These projects are detailed in Section 1.1.5 and some other prototype testing activity is explained Chapter 3.

The available wave energy resource in the UK and Ireland is significant with further potential resource accessible along the western seaboard of continental Europe. The practical accessible resource in some of these areas is shown in Table 1.1. The availability of such a large scale resource has led to the development of large scale project opportunities. This is particularly the case in the UK where capacity for up to 600MW of wave energy projects, and 1000MW of tidal energy projects was leased by The Crown Estate in 2010 [6].

Presently there are opportunities to begin developing projects when the WEC technology has matured and reaches an acceptable cost. Successful prototyping is required to achieve these ambitions with early stage, 'pre-commercial', projects also required to provide a bridging market to larger arrays.

TABLE 1.1 PRACTICAL ACCESSIBLE WAVE ENERGY RESOURCE ON EUROPEAN WESTERN SEABOARD

| Location | Practical Accessible Wave Energy Resource (TWh / annum) | Source |
|---|---|---|
| **Ireland** | 21 TWh | [7] |
| **UK** | 32-42 TWh | [8] |
| **France** | 40TWh | [9] |
| **Norway/Sweden/Denmark** | 65TWh | [10] |

### 1.1.5 Experience and Plans for WEC Arrays

There is little experience available from operational WEC arrays. There are plans for small scale arrays in several countries. However, minimal development has taken place beyond site characterisation activities (surveys, resource measurements, and other consenting activities). Prototyping activity is generally taking place at demonstration facilities (described in Section 3.4). Beyond the current prototyping activities small arrays are expected to be developed initially to further demonstrate the technology and allow larger commercial projects to be progressed. These initial small arrays are expected to be rated at less than 10MW installed capacity. Below is a brief summary of some of the project activities which have taken place or are currently planned in this ‘small array’ category.

Following on from the successful testing of a prototype machine, Pelamis Wave Power secured an order from Portuguese electricity utility Enersis to build the world’s first wave farm off the northwest coast of Portugal at Aguçadoura. The three machine farm had an installed capacity of 2.25MW. The three machines were installed and operated in 2008, generating sustained power to the grid. However, the project ended earlier than planned, with the three machines returning to harbour, due to financial difficulties in Enersis’s parent company, Babcock & Brown. Two main technical issues were encountered. The first affected the foam buoyancy attached to the subsea quick connection system. The second involved the cylindrical bearings of the machine where online instrumentation detected a higher wear rate than was expected. This was discovered to be due to faulty lateral movement of the cylindrical bearing face which was subsequently resolved.

Wavegen have demonstrated a prototype oscillating water column (OWC) device in Islay, Scotland for over a decade with over 75,000 operating hours. Following on from this experience Wavegen installed their first plant at the Mutriku breakwater project at Mutriku, Spain. This project took advantage of plans for a breakwater at Mutriku harbour. Wavegen integrated 16 OWC turbines into the breakwater for a total capacity of ~300kW. This project has been operating since 2011.

Apart from the two projects given above all other demonstration of WEC technology to date would be classified as single device prototyping. There are plans for other small array projects throughout Europe with some examples being shown in Table 1.2.

TABLE 1.2 PLANNED SMALL ARRAY PROJECTS IN EUROPE

| Project | Country | Capacity | Project Developer | WEC Technology |
|---|---|---|---|---|
| **WestWave** | Ireland | 5MW | ESB | TBC |
| **Aegir** | UK | 10MW | Vattenfall | Pelamis |
| **Lewis** | UK | 3MW | Aquamarine Power | Aquamarine Oyster |
| **Bernera** | UK | 10MW | Pelamis | Pelamis |
| **Sotenas** | Sweden | 10MW | Fortum | Seabased |

Ultimately, these projects will be required to provide a bridging market to larger scale projects and further demonstrate the WEC technology for larger commercial projects. As economies of scale cannot be achieved for these projects there will be additional 'out of market' grant funding required to complete these projects. This is a key difference between the economics of early projects in offshore wind and wave energy as WEC technology cannot be proved sufficiently onshore before migrating offshore.

### 1.1.6 The European and Irish Energy Market

In terms of large scale electricity generation market, offshore renewable energy projects must compete with other forms of renewable energy. However, competitiveness must be considered within the context of:

a) Increasing demand for secure and low carbon forms of electricity to meet government targets.
b) Terrestrial constraints to the widespread deployment of onshore wind, hydro and other renewables that are already close to competing with conventional generation.

This has resulted in the introduction of market incentives favouring the importing of renewable electricity from increasingly remote locations back to more densely populated load centres that require it. These incentives are required to overcome the increased costs of the generation technology as well as transmission of electricity over longer distances. Offshore wind is currently the vanguard in this trend and is commercially viable in a number of jurisdictions, including the UK under current incentives of 2 Renewable Obligation Certificates (ROCs) falling to 1.8 ROCs by 2017 [11]. Over 2GW of offshore wind is now operational in the UK alone [11]. There is potential for over 50GW of offshore wind to be further developed under seabed leasing rounds in the UK and it is expected to make a strong contribution to meeting UK renewable energy targets, where there are constraints to onshore developments in densely populated areas of southern Britain. As EU energy markets integrate and renewable targets evolve, such offshore wind opportunities offer the potential to meet the demands of more densely populated regions across Northern Europe.

In the medium term, there are no obvious constraints to offshore wind's expansion though there are risks to accessing the deeper water sites identified to meet future requirements. Renewable UK expects that costs of offshore wind to remain at circa £3m/MW (~€4m/MW[1]) up to 2022 with levelised cost of energy (LCoE) reducing to £130/MWh (~€160/MWh) during that period [12]. This LCoE assumes a project lifetime of 25 years, a 10% return on CAPEX and OPEX, and annual average wind speeds of approximately $10ms^{-1}$. Given the potential scale of offshore wind expansion, in order for other forms of offshore renewable energy to gain significant penetration in the market, they will need to achieve similar or lower cost levels. Furthermore, given that ocean energy is operating in a similar or more severe environment than offshore wind and shares similar marine foundation and transmission costs, it is likely that ocean energy will also require economies of scale similar to offshore wind for long term viability.

### 1.1.7 Competitive Wave Energy

In the context of Ireland and the EU, wave energy must compete against other forms of renewables. Offshore wind is a natural benchmark for competitiveness. Competitiveness in this context does not refer to economic competitiveness alone. Competitiveness of wave energy can be considered in the context of a number of categories, namely;

a) Cost and Performance Competitiveness
  - Capital and operational expenditure (CAPEX and OPEX)
  - Performance – capacity factor and availability (including, and of critical importance, reliability)

b) Technology Competitiveness
  - Functionality – the ability to operate and maintain the plant without adverse safety or environmental effects
  - Scale - available scale

[1] Conversion rate of £1 = €1.25 is assumed

- Public acceptance – allowing available scale to be achieved
- Grid compliance, system stability, and ancillary services (e.g. black start, voltage regulation)
- Diversity – value of diverse energy portfolio
- Energy security - value of indigenous energy sources
- Location – geographic proximity to load centres
- Predictability.

Competitive wave energy must be considered in the context of these categories. This thesis focuses on distinct areas such as electrical networks, power quality and market access which will be a challenge for wave energy competitiveness, both economic and technical.

## 1.2 Wave Energy Introduction

Wave energy is concentrated solar energy. Ocean waves are created by the interaction of the wind with the surface of the sea. Winds, generated by the differential heating of the earth, pass over open bodies of seawater, transferring some of their energy to form waves [13].

The amount of energy transferred from the wind to the waves and hence the energy in the resulting waves depends on a number of factors;

- Wind speed
- Distance of open water over which the wind blows, known as fetch
- Width of an area effected by the wind
- Duration which the wind blows for
- Water depth

The wave climate or 'sea-state' at a particular coastal location is typically made up of two types of ocean wave.

1. Swell: These are waves which were generated by winds some distance from the location and have travelled a long distance with little energy loss.
2. Wind Wave: These are waves which are generated close to the location by local winds.

A regular ocean wave can be represented by a sinusoidal shape with wavelength, height and period. The characteristics of a regular ocean wave are given in Table 1.3 and Figure 1.1.

**TABLE 1.3 CHARACTERISTICS OF A REGULAR OCEAN WAVE**

| Parameter | Symbol | Definition | Unit |
|---|---|---|---|
| **Height** | H | Height between wave crest and trough | m |
| **Wavelength** | $\lambda$ | Length between two consecutive crests | m |
| **Period** | T | Time between two consecutive crests | s |
| **Frequency** | f | 1/T | Hz |
| **Velocity** | V | $\lambda/T$ | m/s |
| **Wave Power** | $P_w$ | $(\rho g^2/32\pi)H^2T$ | W/m |
| | | $\rho$ = seawater density = 1025 $kg/m^3$ | |
| | | g = gravitational acceleration = 9.81 $m/s^2$ | |

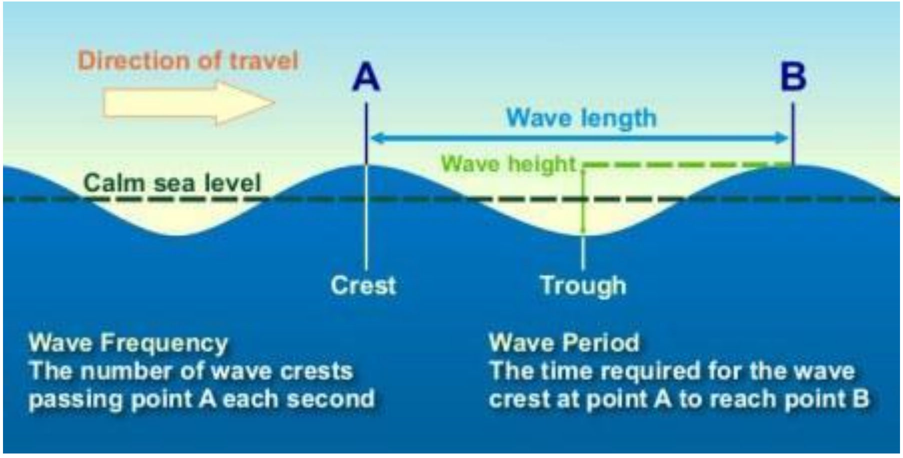



**FIGURE 1.1 CHARACTERISTICS OF REGULAR OCEAN WAVES [14] (COURTESY NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION)**

Regular, sinusoidal, ocean waves are not common in nature and would only really be possible to create in a controlled environment like a wave tank. In a real sea-state there would be a combination of waves with varying heights, periods, and directions. In a given sea-state at a given time these combinations are represented as statistical parameters. Some of these statistical parameters are shown in Table 1.4

TABLE 1.4 STATISTICAL PARAMETERS AND CHARACTERISTICS OF A REAL SEASTATE

| Parameter | Symbol | Definition | Unit |
|---|---|---|---|
| **Water Displacement** | $a_{rms}$ | Root mean square value of the water displacement relative to the mean water level<br>$a_{rms} = \sqrt{\sum y_t^2/n}$<br>$y_t$ = water level at instant t<br>n = mean water level | m |
| **Significant Wave Height** | $H_s$ | $H_s = 4\ a_{rms}$ | m |
| **Zero Crossing Period** | $T_z$ | Average time between upward movements of the sea level through the mean sea level | s |
| **Energy Period** | $T_e$ | $T_e = 1.12\ T_z$ | s |
| **Wave Direction** | θ | Direction of average wave power | (°) |
| **Wave Power** | $P_w$ | $(\rho g^2/64\pi)H_s^2\ T_e$<br>$= 490\ H_s^2\ T_e$<br>ρ = seawater density = 1025 kg/m$^3$<br>g = gravitational acceleration = 9.81 m/s$^2$ | W/m |

### 1.2.1 The Wave Energy Resource

The previous section outlined some of the physical characteristics and parameters that are of importance to wave energy. Wave energy resource in a particular area is normally given in annual average wave power per metre (kW/m), and often in annual theoretical energy and annual practical, accessible energy (TWh). In Section 1.1.4 the practical, accessible energy of some European countries is outlined.

The western seaboard of Europe is in an ideal location for wave energy being at the end of a long, stormy fetch of water (the Atlantic Ocean). In Figure 1.2 the expected annual wave power per metre for Europe is given. This shows Ireland and the UK to be one of the prime locations for wave energy resource in the world.

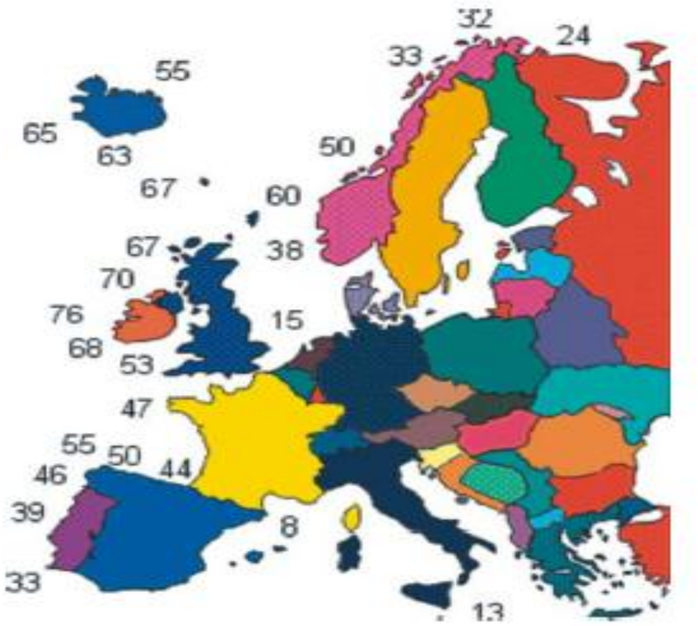



**FIGURE 1.2 EUROPEAN WAVE ENERGY RESOURCE [15]**

The nature of wave energy is that it can have a very high peak to average ratio. This is a huge challenge for the design of wave energy converters as the devices must absorb energy efficiently in lower sea-states and survive extreme sea-states.

### 1.2.2 Conversion of Wave Energy into Electrical Energy

One of the preeminent writers in wave energy, Falnes, states that "a good wave absorber must be a good wave maker" [16]. A design of a wave energy converter must have a wave absorber, which can be a float, flap, oscillating column or other type. See Section 1.3 for more detail on absorber types. The absorber converts the kinetic and potential energy in the wave into another form of energy. Wave energy can be converted via the absorber to mechanical energy, rotational energy, pneumatic energy, hydraulic energy or directly to electrical energy.

Following the absorber a wave energy converter typically has an intermediate system, termed a power take off (PTO) which converts the absorbed mechanical energy to electrical energy. The PTO system can be a hydraulic system, pneumatic system, direct electrical system amongst others. See Section 1.3 for more detail on PTO types. The electrical energy is then connected to the grid through some grid connection infrastructure which comprises offshore electrical collection and transmission and onshore infrastructure to connect to the electrical grid.

The steps in the conversion of wave energy are represented below in Figure 1.3.


**FIGURE 1.3 CONVERSION STEPS OF WAVE ENERGY TO GRID CONNECTED ELECTRICAL ENERGY**

The conversion of wave energy requires a mechanically efficient structure that can absorb and convert wave energy at an appropriate cost. Crucially the device must be capable of surviving the extremes of the ocean environment, not only from wave energy but also from other environmental factors such as temperature and salinity.

WECs can absorb wave energy from different energy modes of the waves through one of the WECs degrees of freedom, or through a combination of multiple degrees of freedom. WECs predominantly absorb energy in heave, surge and pitch. Some WECs also absorb from sway, roll and yaw.

## 1.3 Wave Energy Converters

Wave energy converters are designed to convert wave energy into other forms of energy, normally electrical energy. In this section some broad categories of wave energy converters are introduced with notable examples of each category presented.

The types of power take off (PTO) system typically found in these various categories of WEC are also examined in this section. In Chapter 3 the type of generators for these PTOs is discussed.

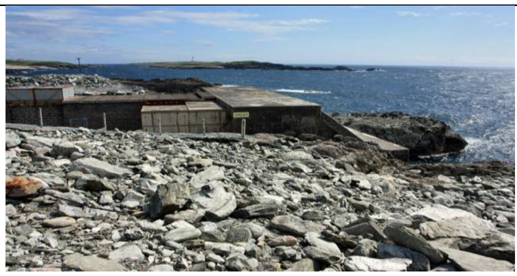
### 1.3.1 WEC Types

There are numerous divergent concepts for WEC devices and it would not be possible to discuss these comprehensively here. WECs can be categorised in a variety of ways, the most common being on the location of the WEC and the absorber type.

#### *1.3.1.1 WEC Location:*

WEC Locations can generally be categorised as onshore, nearshore and deep-water. As outlined in previous sections this thesis focuses on deep-water WECs with electrical transmission. However, some results and conclusions, particularly from Chapters 6 and 7, will also be applicable to certain categories of onshore and nearshore WECs.

**TABLE 1.5 DESCRIPTION AND EXAMPLES OF WECS BY LOCATION**

| | | |
|---|---|---|
| Onshore WEC | WECs are built into the shoreline or a man-made breakwater and so are accessible from land. This type of WEC benefits from 24/7 accessibility and close proximity to electrical networks with the drawbacks of a lower energy resource due to the shallow water next to land, tidal range |  |

| | | |
|---|---|---|
| | issues, and also less scalability due to terrestrial constraints. Onshore devices are predominantly oscillating water column type (see next section) or a variant of a point absorber. Some examples are shown opposite. | <br><br>Top: WaveGen (Courtesy Peter Church), Bottom: Wavestar (Courtesy Sebastian Nils Swiatecki) |
| | | |
| Nearshore WEC | WECs are generally fixed structures in depths less than 25m. These structures are either piled to the seabed or can be held in place with gravity only. Thus this type of WEC can take advantage of the increased surge component in the wave at this depth, more evenly spread directionality, and also shorter transmission distances (and the option of hydraulic or pneumatic transmission). Like onshore devices the resource energy will be lower than in deep-water and tidal ranges will be an issue. Some examples are shown opposite | <br><br>Top: Aquamarine Oyster 800 (Courtesy Aquamarine Power Ltd.), Bottom: Oceanlinx Mk. II (Courtesy Oceanlinx) |
| | | |

| | | |
|---|---|---|
| Offshore WEC | WECs are generally floating, moored devices located in deep-water which, for this thesis, is categorised as deeper than 75m. This type of WEC can take advantage of high energy resource and also the possibility for very large arrays due to large ocean areas. With higher energy comes higher extremes so survivability and accessibility for this type of device will be challenging. These devices will also need extensive electrical systems for collection and export of generated power. Some examples are shown opposite |  Top: Pelamis P2 (Courtesy Pelamis Wave Power Ltd.), Bottom: Wello Penguin (Courtesy Wello Oy) |

### *1.3.1.2 Absorber Type*

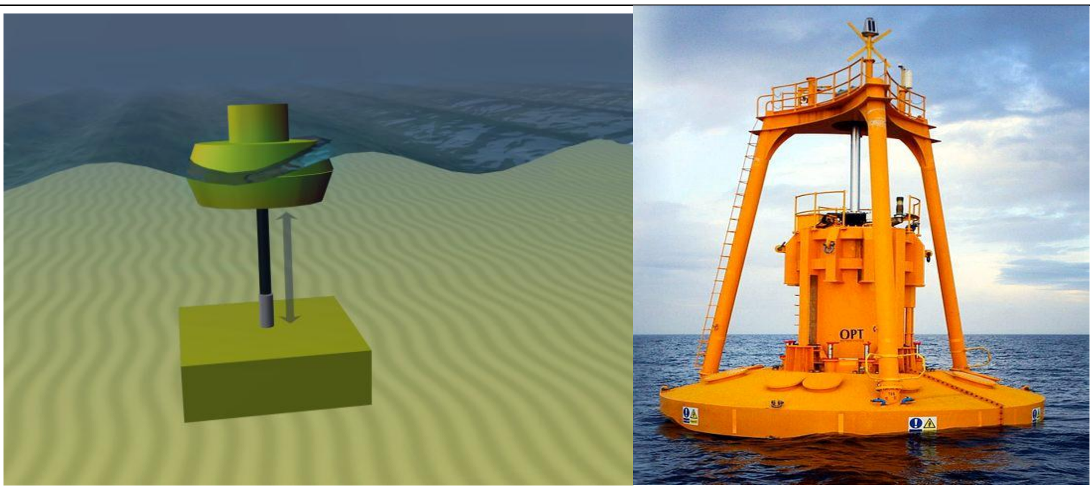
WEC absorber types are relatively divergent and not all WECs can be put into a specific category. Some of the main categories of WEC absorber are introduced in this section.

| |
|---|
| **Attenuators:** Floating devices that are aligned perpendicular to the waves. These devices capture energy from the relative motion of the two arms as the wave passes them |
| An example of an attenuator is the Pelamis device which has multiple sections which articulate along the devices length. The articulated joints capture the wave energy in the pitch and yaw modes. A hydraulic PTO is used within the device. At each joint hydraulic cylinders provide damping force and convert the absorbed mechanical power to hydraulic power. The hydraulic power can be smoothed via accumulators and converted to rotational power via hydraulic motors. These in turn can be connected to electric generators. |


Left: Attenuator Operating Concept (Courtesy Aquaret) and Right: Example (Courtesy Pelamis Wave Power Ltd.)

**<u>Point Absorbers:</u>** Floating structures that can absorb energy from all directions. They covert the motion of the buoyant top relative to the base into electrical power

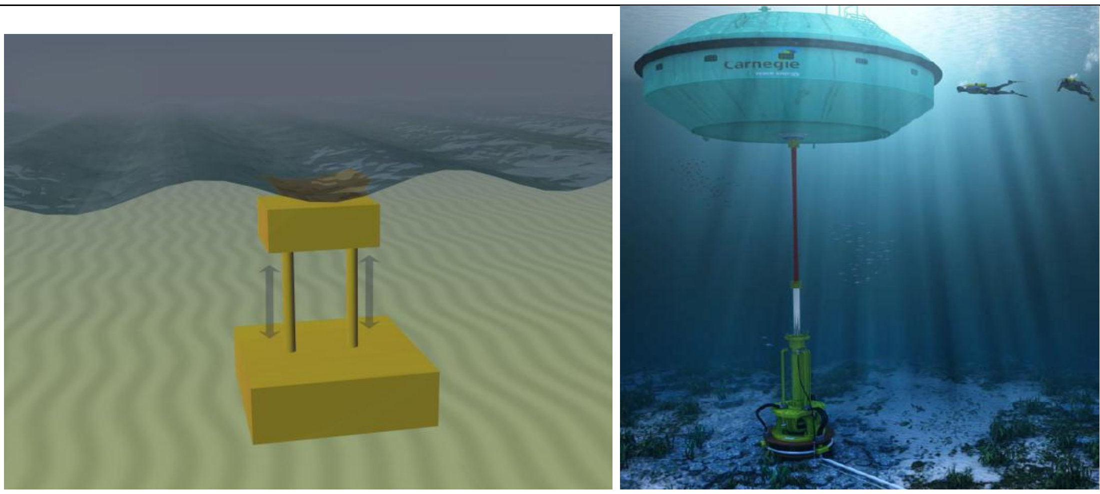
An example of a point absorber is the Ocean Power Technologies (OPT) device which has two bodies which have different natural responses to the wave resource. As a result of the difference responses a relative linear motion between the bodies is induced by the wave resource. A hydraulic PTO is used within the device to capture energy from the relative motion. The hydraulic power can be smoothed via accumulators and converted to rotational power via hydraulic motors. These in turn can be connected to electric generators.




Point Absorber Operating Concept and Example (Courtesy Ocean Power Technologies)

**Submerged Pressure Differential:** Devices capture energy from pressure change as the wave moves over the top of the device causing it to rise and fall.

An example of a submerged pressure differential device is the Carnegie CETO device which has a buoyant actuator connected to a hydraulic cylinder on the sea bed. The buoyant actuator will react to the changing pressure differential as the wave resource passed over the device. A hydraulic PTO is used within the device to capture energy from the buoyant actuator. The hydraulic power can be transmitted to shore via high pressure pipelines and converted to electrical power in a hydro-electrical plant.




Submerged Pressure Differential Operating Concept and Example (Courtesty Carnegie Wave Energy Ltd.)

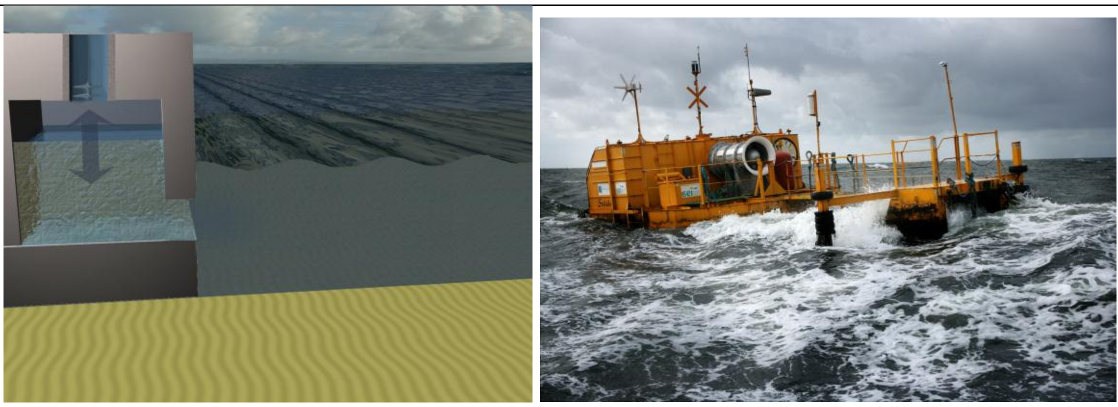
**Oscillating Wave Surge Converters:** Near-surface collectors, mounted on an arm which pivots near the sea bed. The water particles in the waves cause the arm to oscillate and generate power.

An example of an oscillating wave surge converter is the Aquamarine Oyster which has a hinged buoyant flap, connected at the hinge to the sea bed. The buoyant flap reacts to the passing wave resource and hydraulic cylinders connected to the flap capture the energy from the resource. The hydraulic power can be transmitted to shore via high pressure pipelines and converted to electrical power in a hydro-electrical plant. Alternatively an offshore oil-electric PTO can be used to convert to electrical power allowing electrical transmission to shore.

Oscillating Wave Surge Converter Operating Concept and Example (Courtesy Aquamarine Power Ltd.)

**<u>Oscillating Water Column (OWC)</u>** technologies convert the rise and fall of waves into movements of air flowing past turbines to generate power.

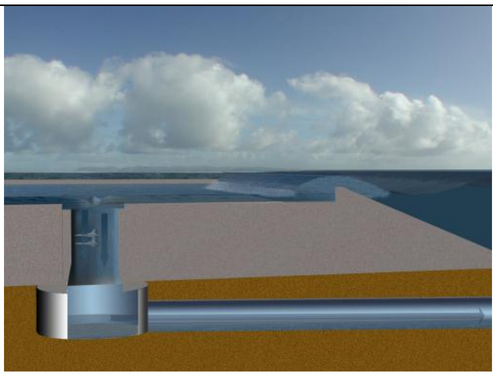
An example of an oscillating water column is the Ocean Energy Buoy which is a floating OWC. The Ocean Energy Buoy captures entrained air in an OWC chamber within the hull of the device. This air is driven in and out of the chamber through a bi-directional air turbine. The air turbine is coupled to a generator which generates electrical power for transmission to shore.



Oscillating Water Column Operating Concept and Example (Courtesy Ocean Energy Ltd.)

**Overtopping** devices have a wall over which waves break into a storage reservoir which creates a head of water. The water is released back to the sea through a turbine to generate power.

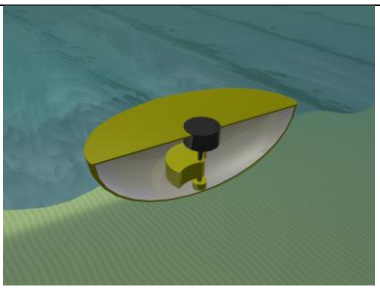
An example of an overtopping device is the Wave Dragon which is a large buoyant structure with a ramp facing the wave resource. The waves overtop, via the ramp, into a reservoir on the structure. The reservoir is then drained, via low-head hydro-electric turbines, back to the sea. The hydro-electric turbines are coupled to a generator which generates electrical power for transmission to shore.



Overtopping Device Operating Concept and Example (Courtesy Erik Friis-Madsen)

**Internal Rotating Mass** Two forms of rotation are used to capture energy by the movement of the device heaving and swaying in the waves. This motion may drive an eccentric weight or a gyroscope causes precession. In both cases the movement is attached to an electric generator inside the device.

An example of an internal rotating mass device is the Wello Penguin which is a large buoyant structure shaped to induce motion in pitch and roll. A large concentric mass is located within the hull of the device and the induced motion causes this mass to rotate. The concentric mass is coupled to a low speed generator which generates electrical power for transmission to shore.




Internal Rotating Mass Operating Concept and Example (Courtesy Wello Oy)

### 1.3.2 Wavebob

This thesis was undertaken with the support of Wavebob Ltd. The Wavebob device is a point absorber type WEC which is under development. During the course of this research the Wavebob device was used as a candidate device for some analysis. In particular the expected generation characteristics and power output time series of the Wavebob device are used in Chapters 4, 5 and 6. Although the Wavebob device was used as a candidate the research is applicable to a wide variety of WEC concepts, in particular deep-water WEC devices. Some of the research may be applicable also to other WEC concepts and potentially for the tidal energy and floating offshore wind industries also.

Further details on the Wavebob device are given in Section 4.3.1.

# Chapter 2

# Literature Review

## 2.1 Introduction

A summary of the academic and industrial literature covering the main research questions of this thesis is presented in this Chapter:

- What electrical components are typical of, and what are the design requirements of, a deep-water WEC array?
- What is the techno-economic optimum electrical network design for WEC arrays?
- What economic challenges and potential cost reductions exist for WEC array electrical network designs?
- How can resource induced flicker emissions, which are inherent to the wave energy resource, be evaluated during the WEC design process and how can they be mitigated?
- What is the scale of the domestic Irish market for wave energy and the cost and technical challenges of accessing export market opportunities?

Literature which focuses on these research questions and topics is presented and critiqued in this Chapter. Any existing research which can be built on, or provides important inputs to the research objectives of this thesis, is highlighted.

The topic of electrical networks and grid integration for WEC arrays has been relatively underexplored in academia until now. There are several reasons for this. Firstly, the main knowledge of this topic lies within WEC technology development companies and the specific electrical systems are often seen as part of the company's intellectual property. This is problematic in itself as it prevents convergence of technology in the industry.

Secondly, the major concentration of the sector has been on prototyping single demonstrator devices to date where the focus is not on economics of large scale commercial installations. Also the electrical infrastructure usually belongs to a third party such as a test site operator.

Thirdly, there is sometimes an assumption that the same offshore electrical networks as offshore wind will be sufficient for WEC arrays. As will be demonstrated in this thesis, while there is some relevant cross-over from offshore wind, there are important differences which must be addressed.

To date the predominant focus of research around electrical systems has been in four distinct areas namely;

- Generators for WECs
- Grid connection issues such as grid code compliance
- Power Quality
- Storage

The main objectives of this thesis relate to these areas and some elements from literature are brought into the research and explored or critiqued. However, the volume of literature in the analysis of electrical network design is comparatively small.

A comprehensive literature review ranging from early stage developments in wave energy through to the most up to date publications has been undertaken to inform the original research in this thesis. Some of the major publications, authors and themes are introduced, evaluated, and critiqued in the subsequent sections.

## 2.2 Notable Publications

At the beginning of this research there was no authoritative publication in the area of electrical systems for ocean energy. In 2013 a comprehensive book, “Electrical Design for Ocean Wave and Tidal Energy Systems”, was published by the Institute of Engineering and Technology (IET) [17]. The author of this thesis is a contributor to this book as shown in Appendix A.

This book is an excellent reference for electrical design issues and brings together the international research community in this area to provide a comprehensive text. Topics covered within the book include; generators, cabling umbilical and array layout, power system interaction, energy storage, control systems, modelling and simulation, and economics.

The IET book is essentially a compilation of a range or researcher's previous publications. The most relevant sections to this thesis are Chapter 3, 'Cabling umbilical and array layout' (P. Ricci and J.L. Media), and Chapter 5, 'Grid integration: part 2 – power quality issues' (A. Blavette and J. MacEnri).

In Chapter 3 of the IET book Ricci et al present potential array layouts but do not undertake a techno-economic analysis and, in fact, refer to the author of this thesis' work as a potential solution for techno-economic evaluation. There is also an evaluation of efficiency for AC transmission schemes which has been conducted in a more comprehensive manner in this thesis, see Chapter 4 of this thesis. Ricci et all present an evaluation of the 'key interfaces' which are outlined in this thesis in Chapter 4. This evaluation, as will be demonstrated in this thesis, makes several assumptions which devalue its contribution; notably the requirement for subsea connection units ('hubs') and also the requirement for fixed platform offshore substations. Ricci et al also conduct an analysis of the requirements for dynamic cables which is a well researched piece of work.

In Chapter 5 of the IET book Blavette et al present a range of power quality parameters and grid code requirements and evaluate their importance to wave and tidal energy converters. This work is relatively high level and does not outline the relationship between voltage flicker and WEC power output appropriately which has been comprehensively presented in Chapter 6 of this thesis.

## 2.3 Generators for Wave Energy Converters

There has been a natural research focus on generators for wave energy converters due to the current development stage of the industry. With wave energy converters there is a variety of concepts for absorbing wave energy and a variety of concepts for converting the absorbed energy to electrical energy as outlined in Chapter 1. Hence there is some interest in generators for a variety of power take off (PTO) systems from hydraulics, air turbines, and water turbines. Linear generators and low speed generators are also a topic of much interest in wave energy due to their attraction in 'direct drive' conversion applications.

During the 1970s, the early days of wave energy system development, there was a focus on generators at the University of Edinburgh as part of the Edinburgh Wave Energy Project [18]. This project investigated generator types for the 'Salter Duck' type WEC.

Presently the leading research in the area of rotary generators for wave energy converters is being undertaken by O'Sullivan [19], [20], [21] with a focus on generators for OWC air turbines. Another prominent researcher in the area is Mueller who examines the technical issues associated with selecting various types of rotary and linear generators [22] and also focusses on generators for 'direct drive' WECs with a particular emphasis on linear generators [23], [24]. Mueller also contributes to studies on the operation of generators with seawater immersed windings [25].

With a predominant focus on linear generators, research undertaken at Uppsala University focusses on the linear generator for the Seabased WEC. Leijon leads the work on developing linear generator based WECs explaining the construction and testing of the linear generator and associated equipment [26], [27], [28], [29]. Leijon is also a prominent researcher of WEC electrical networks and submarine infrastructure, which is particularly relevant to this thesis, as outlined in Section 2.6. There is also a large body of research from Uppsala University on the subject of linear generator construction and testing [30], [31], [32]. The Uppsala/Seabased concept is unique to the wave energy industry and the output of this group certainly represents the primary research in the area of linear generators for wave energy.

Although generators for WECs is not a core research objective of this thesis some generators for hydraulic PTO's and direct drive PTO's are discussed in Chapter 3 and the topic relates somewhat to the overall design of electrical networks for WEC arrays. In particular, the original research on voltage flicker presented in Chapter 6 is an important addition to the knowledge base for PTO and generator selection. PTO design and generator selection is currently undertaken without a accurate reference to voltage flicker impacts of the selection. Therefore, while a PTO may be designed and a generator may be selected which allow for highly efficient conversion of wave energy to electrical energy, this may introduce power quality issues in the form of voltage flicker.

## 2.4 Grid Integration of Wave Energy

The topics of grid connection of WECs and WEC arrays, power quality, and energy storage are interlinked and some researchers address a combination of these topics. In general the focus of literature in these topics is around the effects wave plants will have on the power system. These can be grid integration issues and grid code compliance or can be more focussed on specific power quality issues, specifically steady state voltage control or voltage flicker. In this section the major literature contributions, which have particular relevance to this research, are discussed.

Santos [33], Boehme [34], Khan [35] and Ahmed [36] evaluate the capacity of the grid infrastructure to allow large scale integration of ocean energy. Santos [33] presents a case study of a number of WECs connected to the distribution system and evaluates the steady state voltage effects at a variety of locations on the electrical network. Santos also examines power losses and grid code compliance issues such as low voltage ride through. Santos also presents the smoothing effect on the output power from aggregation effects which are relevant to later discussions in Chapter 6. This work presents relevant studies which would be conducted in a project development (for wind, wave, tidal etc.) so does not provide any insight into the particularities of wave energy on voltage control.

Boehme [34] investigates load flow and constraint issues from the integration of large scale wave and tidal energy in the Orkney Island electrical systems. An optimised load flow is presented to maximise renewable energy resource while remaining within the thermal and voltage limits of the existing power system. This again is a very specific study and provides no insights into any particular impacts of wave energy on the electrical network.

Khan [35] undertakes a load flow analysis to determine the capacity of the Oregon (U.S.A) electrical grid for wave energy, and to identify any potential bottlenecks in the system and optimum points of connection to the system. Again this is a very specific study and provides no insights into any particular impacts of wave energy on the electrical network.

Ahmed [36] investigates the effect of WEC arrays on the system voltage in the UK with some analysis of fixed speed and variable speed generators for WECs. This paper introduces the idea that voltage control will be particularly difficult for direct drive WECs but the analysis is not very detailed into the real relationship between WEC resource and voltage flicker emissions.

O'Sullivan [19] examines some of the challenges to the grid integration of WEC arrays. This paper focuses on areas such as connection charging regimes, use of system charges, grid code compliance and presents a costed case study 20MW wave farm. This paper is a useful overview of some of the regulatory issues associated with grid connection and how they may affect wave energy economics. Blavette and O'Sullivan [37] examine grid compliance issues in more detail and present some control strategies for WECs to ensure compliance. Blavette and O'Sullivan also [38] undertake a case study of grid connected WEC arrays in Ireland with a focus on load flow, steady state voltage limits and grid code compliance. While this work is somewhat relevant to particular project assessment it is routine analysis for connection of renewable generation and does not particularly advance the knowledge of WEC array grid integration.

## 2.5 Power Quality and Energy Storage

The topic of power quality has perhaps the largest volume of literature in the research area of electrical systems for wave energy. The focus is mainly on voltage quality issues caused by the connection of wave energy converters to the electrical grid and areas such as voltage regulation, flicker, and mitigation effects are investigated. One of the solutions to flicker is energy storage which is evaluated by a number of researchers.

Nambiar and Kiprakis et al investigate voltage effects, array configurations effects and other mitigation approaches to power quality [39], [40], [41], [42]. In these papers Nambiar presents a 'wave-to-wire' model which can simulate the power output of a WEC or WEC array with a variety of spatial configuration options. Nambiar evaluates physical spatial aggregation effects from WEC arrays and the mitigation effects this will have on the voltage at the point of connection. Nambiar focusses on the steady state voltage effects and does not address flicker directly. The spatial model that is presented gives physical aggregation effects only and does not consider hydrodynamic interference effects. This research is a useful basis for further assessment but primarily focuses on the control strategies for steady state voltage.

Blavette and O'Sullivan have completed studies around power quality also in areas such as flicker and voltage regulation. Blavette et al [43] present the potential flicker output from a number of OWC type WECs. These WECs exhibit constantly varying power output at twice the resource frequency (as the air flows through the turbine twice per wave period) and due to this cause flicker issues at the point of connection. This was the first publication which correctly linked voltage flicker and wave resource and was followed by a paper from the author of this thesis with similar conclusions. This paper outlines the potential issue with flicker from 'direct drive' WECs and shows that the smoothing expected from other RES sources such as wind turbines may not be seen with WEC arrays.

Blavette [44] also presents a dynamic model for assessment of power quality of both wave and tidal energy converters and highlights some inadequacies in grid codes for ocean energy devices.

The issue of energy storage to mitigate power fluctuations and hence flicker from a wave energy plant is investigated also by Murray [45] and Muthukumar [46], [47] which suggest various energy storage techniques to smooth the output from wave energy arrays to the electrical grid. Murray investigates the use of supercapacitors as a storage medium concluding that lifespan may be an issue. Muthukamar investigates the addition of inertia energy storage to an OWC type WEC concluding that this has a smoothing effect on power fluctuations. Neither researcher consider at the lifetime costs of the storage devices, nor at their impact on overall efficiency.

Blavette and O'Sullivan also present a generic study of storage for mitigation of flicker emissions [48].

Although power quality and flicker have been extensively covered to date it is concluded that the issue has not been simplified sufficiently to feed into the plans of WEC designers. This issue of 'resource induced' flicker has not been explored in as detailed a manner and the sea-states that are likely to cause the greatest flicker issues have not been analysed. A more comprehensive understanding of the voltage flicker issues with WECs would be an extremely valuable addition to the knowledge base.

Therefore, power quality, specifically resource induced flicker, has been included as a research objective in this thesis. The intention is to develop practical, understandable tools for WEC designers to assist in understanding and characterise the flicker issue further. This research is presented in Chapter 6 of this thesis.

## 2.6 WEC Array Electrical Networks

A central research objective for this thesis is the techno-economic analysis of WEC array electrical networks. There is little research on this topic; a gap exists which is addressed in this thesis.

As with electrical generators for WECs, earlier work on WEC array electrical networks was undertaken as part of the Edinburgh Wave Energy Project in the 1970s. This work investigated the electrical networks for connecting multiple ‘Salter Ducks’ together in a ‘spine’ and exporting the power to shore [49], [50]. This work is extremely interesting but there have been huge advances in electrical infrastructure since the 1970s and offshore wind has pioneered the way in this regard as shown in Chapter 3. The drivers of this research, however, are similar; focussing on cost effective electrical network designs.

Ricci has produced and contributed to a number of important papers around electrical networks for WEC arrays. In [51] both HVAC and HVDC export schemes are assessed for large WEC arrays. The cost and efficiency of these schemes are evaluated and presented. Costs for three WEC array electrical networks are calculated (9.75MW, 19.5MW and 48.75MW). Although this is a useful study, no comparison of array configurations is undertaken and the key interface components are not considered. Offshore substations are also required which may present a design challenge for WEC arrays, particularly in deep-water, as outlined in this thesis (see Chapters 4 and 5). In [52] electrical network configuration is introduced as an important factor in the spatial configuration of WEC arrays. Ricci also published one of the more practical analyses of wave energy electrical systems, particularly at the interface level [53]. This looks at a variety of concepts for connecting the devices to the electrical network and is a useful and insightful publication. The major drawback of this work is that it only considers submarine/floating ‘hubs’ as integration and does not consider the practical or economic aspects of using same. In this thesis a strong case is built that submarine ‘hubs’ should not be necessary for WEC array electrical networks. Ricci also contributed to a study on the dynamic performance of a WEC dynamic cable which is of interest, but not central, to this work [54]

Lopez et al present a review of potential WEC array electrical networks with a focus on transmission technology [55]. This gives a comparison of various HVAC and HVDC transmission systems. The array electrical network is assumed to mirror that of an offshore wind farm with some potential solutions proposed within these constraints.

Igic et al examined the potential WEC array electrical network for the Wavedragon WEC [56]. The focus in this study was the possibility of combining the inverter side of the generator power converter into a single unit, i.e. individual WECs would connect together on the DC bus. Similar research has also been conducted for offshore wind but DC aggregation systems have not been shown to be cost effective.

Kenny [57] developed multiple connection schemes for wave energy and endeavoured to build a cost model to compare the various options. This work was a very good baseline for some of the material analysed in this thesis but the methodology was not comprehensive. A review of available technologies was undertaken and these technologies were ‘bolted’ together to develop electrical configurations. No critical analysis was undertaken as to whether these technologies were appropriate in the first instance.

Through Uppsala University and Seabased, Leijon also focussed on wave energy electrical networks for wave farms [58], [59], [60]. The focus of this research is on the linear generator based technology which is at the kW rating and is not wholly applicable to large scale arrays. The focus of the Uppsala research is also on submarine substations and power conversion equipment. The viability of this approach is evaluated further within the work and a strong case made against it.

Outside of academic literature there are some important reports which are relevant to this thesis. The Equimar project is an EU FP7 project which ran from 2008 to 2011 exploring performance, cost and environmental impact of marine energy devices. Deliverable 5.1 was “Guidance Protocols on Choosing of Electrical Connection Configurations” [61]. This deliverable gave a high level view of the issues surrounding the grid integration of marine energy such as grid codes, test site infrastructure, elements of the electrical system, and some possible AC and DC connection configurations. The Equimar work lacked some practical application and did not comprehensively compare the various network configurations. WaveNet [62] also investigated electrical networks but at an early stage in the industry. The current DTOcean project is exploring techno-economics of electrical network configurations in detail but is incomplete at this time.

Finally, there are a number of test centres operational around Europe which offer grid connected ‘berths’ for testing wave and tidal technologies. The most developed of these is the European Marine Energy Centre (EMEC) in Orkney, Scotland. The practical experience in electrical network installation from these test centres is presented in Chapter 3 and referenced throughout the thesis as these locations are the only real deployment of electrical networks to date in the wave energy industry.

From a thorough review of the research literature for electrical networks for WEC arrays it is evident that significant gaps exist. Therefore a comprehensive research thesis on this topic was identified as extremely valuable to the industry and research community. Hence, WEC array electrical networks are the primary focus of the research in this thesis.

## 2.7 Offshore Wind Electrical Networks & Economics

As a much more mature industry, there is a vast amount of literature available which has analysed the electrical network configurations for offshore wind farms. This provides an excellent baseline for the research into electrical networks for WEC arrays, and the body of research is generally more practical and based on real applications and experience. Below is an outline of some useful sources from the large body of available literature.

The state of the art thinking has been summarised in books by Ackermann [63] and Twiddell [64]. From these books it is clear that there has been significant convergence in the design of electrical networks for offshore wind and the industry has moved towards 33kV radial array networks with HVAC export transmission from offshore substations with a more recent move to HVDC export transmission. This has proved the least costly option with all of the required functionality. However, there are characteristics of wave energy which will mean that offshore wind farm electrical systems cannot simply be replicated. Nevertheless, the rationale behind this convergence was used as a guide for wave energy electrical networks.

Although electrical network configuration has converged there are still alternative and new ideas presented in the literature. In [65] some alternative array electrical network configurations for offshore wind are evaluated showing potential benefits from non-radial configurations and additional sectionalising of the electrical protection system, albeit with additional cost. Switching overvoltages, earthing and reliability of various configurations are also evaluated. In [66] HVAC and HVDC configurations are evaluated for the connection of offshore renewables to the grid and an excellent overview of cables and offshore substations is given including some costs. In [67] the cost and performance of the collection and export system for offshore wind farms is examined.

[68], [69], [70], and [71] are excellent review papers covering electrical network redundancy, reliability, losses, and capacity factors for offshore wind.

In the analysis conducted throughout this thesis offshore wind is used as a baseline reference in each case. In particular, the economics of offshore wind served as a useful guideline for economic modelling. Further details on the cross-over areas from offshore wind to WEC arrays are given in Chapter 3.

## 2.8 Array Layout

The spatial layout of WEC arrays is an important factor in understanding the requirements for the electrical network techno-economic analysis. The layout of arrays is a complex topic requiring knowledge of hydrodynamics, wave resource, mooring systems, and control systems amongst others. To develop a full understanding of all these areas would be outside the scope of this research. However some of the relevant literature was reviewed to endeavour to characterise the issue.

C. Fitzgerald [72] outlines the hydrodynamic separation requirements for optimum performance of a WEC array. J. Fitzgerald [73] and [74] assesses the mooring requirements for WEC separation and also evaluates the array spacing for WEC arrays.

Child [75], Ricci [76], and Cruz [77] present array spatial configurations analyses which provide some guidance as to WEC separation requirements. Westphalen [78] demonstrates how the control of WECs within an array can also influence the required spatial configuration. In Chapter 4 the analysis of spatial configuration requirements is used to inform the design of an optimum WEC array electrical network.

## 2.9 Dynamic Rating

Another research objective in this thesis was to apply the emerging technologies in the dynamic or real time ratings area to WEC array electrical networks as a means of improving the economics of these networks. The area of dynamic ratings is predominantly used in the transmission and distribution industry and this was where the literature was concentrated. Some case studies and analysis using dynamic and real time ratings for transmission systems are given in [79], [80], [81], and [82].

## 2.10 Literature Review Summary

From a comprehensive review of the literature it is evident that much of the research in electrical systems for wave energy has been concentrated on the generator and grid connection level including a focus on power quality. There is a lack of in-depth research undertaken on the practical implementation of electrical networks for wave energy arrays. Prominent researchers in this areas are Ricci and Leijon. Ricci's work has been of particular interest in this thesis, and is built upon and improved. Leijon's work is very focussed on the Seabased technology concept and is not as relevant to generic offshore WECs.

There are also gaps in the existing research on power quality issues, particularly voltage flicker. Blavette in particular has advanced the research in this topic significantly. However, particular value to the knowledge base can be added by better characterising voltage flicker in relation to WEC power output, and by providing practical tools for assessing voltage flicker at the design stage,

Therefore, the main objectives of this thesis have gaps in the knowledge base and provide significant scope for novel and original research. This practical, industrial, thesis is aimed at filling these knowledge gaps and will be a valuable addition to the industry's knowledge base. At the present time the industry is developing from prototype testing towards commercial projects. This thesis, its results, and conclusions will be timely in this regard.

# Chapter 3

# State of the Art in WEC Array and Offshore Wind Electrical Networks

## 3.1 Introduction

In Chapter 2 the academic literature and industrial research was reviewed and this shows the body of relevant knowledge relating to the research questions and objectives of this thesis. While the academic literature is critical there is also practical, industrial experience from both the wave energy and offshore wind industry that must be reviewed and critiqued in order to meet the research objectives of this thesis.

This chapter introduces the components in the on-board electrical system of a Wave Energy Converter (WEC) and also the components required within a WEC array electrical network. The state of the art in electrical network design from both the emerging wave energy industry itself and the more mature offshore wind industry are outlined also.

On-board the WEC the major components are introduced such as the electrical generators, switchgear, and power transformers.

Within the WEC array electrical network major components are also introduced including the dynamic power cables, submarine power cables, submarine cable connectors, and offshore and submarine substations. Each of these components is described, and from industry experience and any state of the art developments, the available options for these components are introduced.

Although there is limited experience in the development of electrical networks for WEC arrays there has been some demonstration of electrical network designs at WEC test sites in Europe and some early stage projects. These electrical networks are, at present, the only in service demonstrating some of the required components. Therefore, an understanding of these applications will benefit the research in this thesis.

In the offshore wind industry there is vast experience of design of electrical networks which have converged allowing specific installation vessels, installation procedures and interface designs to be used for any large offshore wind farm. With larger offshore wind farms being developed further from shore there is a move to HVDC export systems to allow for the large power and long transmission distances. The wave energy industry can learn from the offshore wind industry in order to achieve early convergence in the design of WEC array electrical networks and, as a consequence, cost reduction.

## 3.2 WEC On-Board Electrical Systems

Within the wave energy converter device itself electrical components are required to convert mechanical power to electrical power, condition the generated power to grid compliant requirements, step up the voltage for export, provide auxiliary supplies, isolation for maintenance, and electrical protection from faults.

### 3.2.1 Generators

An electrical generator is required to convert captured mechanical power into electrical power. The selection of a generator for a WEC depends on the type of power take off (PTO) system. Environmental factors and grid code compliance must also be considered. For example in the case of a hydraulic PTO the generator would be coupled to a rotating hydraulic motor. In the case of a direct drive PTO this could be a linear generator or rotary generator coupled via a mechanical linear to rotary conversion system such as a rack and pinion.

#### *3.2.1.1 Generator Types*

There are numerous types of electrical generator which are used in various WEC designs. Within the power system all large thermal and hydroelectric power plants use synchronous generators and these have certain characteristics that support the operation of large electrical power systems. The majority of wind turbines use double fed induction generators to allow for variable speed operation but there is a move to direct drive generators, particularly offshore, to allow for the removal of the gearbox from the wind turbine, which can be a major source of failures and maintenance. Even within the different types of generator there are different subtypes and even still variations on the subtypes, mostly in construction or flux linkage type.

The selection of a generator for a WEC is a complex task. Some of the main types and subtypes of generator are given in Table 3.1. Some more details on these various types of generators can be found in [63].

**TABLE 3.1 MAJOR TYPES AND SUBTYPES OF ELECTRICAL GENERATORS FOR WAVE ENERGY**

| Generator Type | Generator Subtype |
|---|---|
| **Synchronous** | **Field Wound with Static Excitation** |
| | **Field Wound with Brushless Excitation** |
| | **Field Wound with PMG Excitation** |
| | **Permanent Magnet Field** |
| **Asynchronous** | **Squirrel Cage Induction** |
| | **Wound Rotor Induction** |
| | **Double Fed Induction** |
| **Permanent Magnet Generators** | ***See Synchronous – Permanent magnet*** |
| **Switched Reluctance Generators** | |
| **DC Generators** | |
| **High Voltage Generator (Powerformer)** | |

Table 3.1 applies to rotary machines but can also apply to linear generators with permanent magnet and switched reluctance being two relatively common types of linear generator in the literature.

In the following section the type of generator for several distinct PTO cases are discussed briefly. This gives a cross section of the type of generator which would be required for a given PTO at various stages of development.

#### *3.2.1.2 Directly Connected SCIG with Hydraulic PTO*

The choice of generator for a prototype WEC with a hydraulic PTO, and all pre-commercial, one-off hydraulic PTO prototypes would be a fixed speed squirrel cage induction generator (SCIG) with power factor correction capacitors. This type of generator is cheap, robust and simple to connect to the electrical grid, but for large scale applications may not comply with grid code requirements. Therefore, it is only a suitable generator solution for prototype devices. A schematic of a SCIG connection to the electrical grid is shown in Figure 3.1. The Pelamis P2 prototypes (see Section 1.3.1.2) utilises this generator configuration.

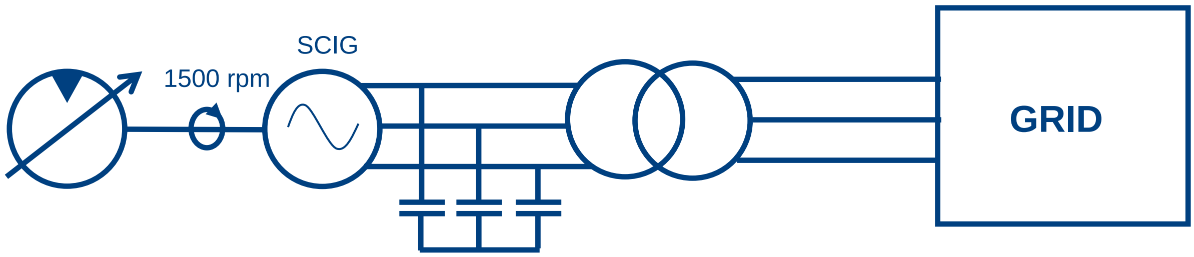



FIGURE 3.1 HYDRAULIC PTO WITH SCIG CONNECTION SCHEMATIC

However this type of generator would not comply with elements of the grid codes particularly low voltage ride through and reactive power control requirements which would be required for larger installations. Also, operating a conventional variable displacement hydraulic motor in this configuration may result in low efficiencies.

#### *3.2.1.3 Variable Speed SCIG with Hydraulic PTO*

Since commercial projects would require compliance with grid codes and high efficiency a direct connected SCIG would not be suitable for these applications.

Using conventional variable displacement hydraulic motors as the prime mover, high efficiencies could be obtained by allowing for variable speed operation which is controlled to maximise the efficiency of the hydraulic system. This is an area which needs further study. Such an arrangement would operate in a similar fashion to 'maximum power point tracking' in wind [63].

If a variable speed generator is required the simplest and most robust solution would be a squirrel cage induction generator with back to back converter. The power electronic converter converts the variable frequency AC power from the SCIG to fixed voltage and frequency for synchronising with the grid, as shown in Figure 3.2. A synchronous generator could also be used here giving some benefits (such as a simpler rectifier); however the SCIG is considered simpler than a synchronous generator, i.e. no excitation or brushgear requirements. The Aquamarine Oyster (see Section 1.3.1.1) onshore hydroelectric plant uses this generator configuration, albeit with a water hydraulic Pelton wheel turbine.

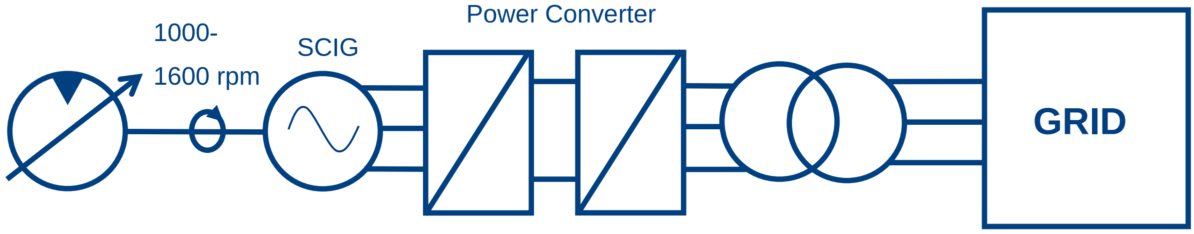



**FIGURE 3.2 HYDRAULIC PTO WITH SCIG AND POWER CONVERTER CONNECTION SCHEMATIC**

However, the use of axial piston type digital displacement (DD) hydraulic motors such as those developed by Artemis Intelligent Power [83] could achieve high efficiencies in the hydraulic system at fixed speed and use conventional synchronous generators, as shown in Figure 3.3. Brushless synchronous generators may be more suitable to the marine environment. This would comply with the requirements of the grid codes and also remove the need for a power electronics converter for interfacing with the grid.

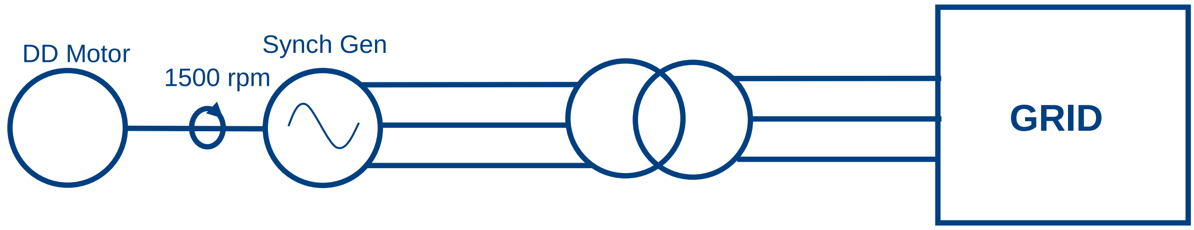



**FIGURE 3.3 DIGITAL DISPLACEMENT HYDRAULIC PTO WITH SYNCHRONOUS GENERATOR CONNECTION SCHEMATIC**

In the case of variable and fixed-speed, other generator options could be explored but would not give any major benefits over those selected here. No current working WEC prototypes use this configuration.

#### *3.2.1.4 Linear Direct Drive PTO*

Another type of direct drive PTO which has been considered for many WEC concepts is a linear direct drive PTO. This PTO uses a linear generator to convert the linear motion directly to electrical power.

Linear generators operate under the same principle of rotary generators, only instead of the electromagnetic flux being cut by an angular rotation motion it is cut by a linear motion. Essentially the linear generator is a section of rotary generator with a very large radius or a rotary generator rolled out flat.

Linear generators have long been of interest to the ocean energy community with a number of pilot projects and seagoing devices already tested. In particular they lend themselves very well to point absorber type WECs as the linear reciprocal motion can be converted to electrical power.

As with rotary generators there are various types of linear generators. The most developed are permanent magnet linear generators and switched reluctance linear generators. Again there are a variety of subtypes of each of these generators with a particular emphasis on the construction of the stator and translator of the generator

There are a number of potential benefits of using a linear generator such as having less mechanical parts (within the overall WEC) and high wave to wire efficiency. However, there are also several drawbacks as the technology is relatively immature, the machines can be extremely large due to low speed operation (in comparison to a rotary equivalent) and there are mechanical challenges in bearings and linear guidance systems. Issues with power quality also exist with this concept as detailed in Chapter 6.

A linear generator requires a power electronic converter interface with the grid. This allows the variable frequency, variable voltage output from the linear generator to be converted to a fixed frequency, fixed voltage output to the electrical grid. Figure 3.4 shows a typical connection schematic for a linear generator PTO WEC. The Seabased WEC concept (see Figure 3.16) uses this generator configuration.

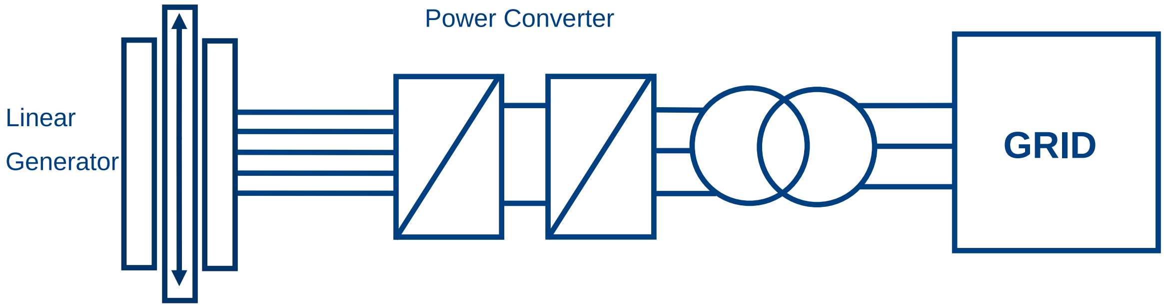



FIGURE 3.4 LINEAR GENERATOR WITH POWER ELECTRONIC CONVERTER CONNECTION SCHEMATIC

#### *3.2.1.5 Implications for WEC Array Electrical Network Design*

The type and configuration of the WEC electrical generator can have an impact on the design and economics of the electrical network for a WEC array.

Firstly, the type of generator and PTO can directly affect the capacity factor, i.e. peak to average output power ratio, of a WEC device. As detailed in Chapter 5 this has an impact on the economics of the WEC array electrical network. The type of PTO and generator may also effect the potential flicker emissions as outlined in Chapter 6.

Secondly, the type of generator may affect the fault level within the WEC array electrical network. The fault level is a design condition for the cable rating within the electrical network and so this could have adverse economic impacts also.

### 3.2.2 Switchgear and Protection

As with any electrical system there is be a requirement for protection and isolation which will come in the form of LV and MV switchgear and protection relays. There are numerous requirements for switchgear and protections systems on a WEC device including but not limited to the below;

- Generator Protection and Circuit Breaker
- Transformer Protection and Circuit Breaker
- MV Switchgear for coupling devices (at array scale)

- Auxiliary Switchgear
- Consumer Units (MCBs)
- DC Consumer Units (MCBs)

The auxiliary switchgear and consumer units are simple equipment used in standard industrial applications and require no further mention here.

The generator protection is likely to be low voltage (LV <1000V) due to the size of the generators. Medium voltage switchgear shall be required to connect multiple devices together in an array.

#### *3.2.2.1 Implications for WEC Array Electrical Network Design*

The MV switchgear within a WEC array electrical network allows for isolation for installation, maintenance, or post faults. The MV switchgear will also operate in the event of a fault. These are crucial functions to the operation of the WEC array and the MV switchgear is identified as a 'key interface' and explored in detail in Chapter 4. Whereas in offshore wind the MV switchgear is always located in the wind turbine itself there may be a rationale for separating this from the WEC within WEC arrays. However, separating the MV switchgear from the WEC device may also present challenges both economically and technically. In Chapter 4 this is analysed in detail.

### 3.2.3 Transformers

Because of the present power rating of WECs it is likely that they will generate at low voltage (LV) within the WEC itself. However in order to export the generated power to the electrical system the voltage level will have to be stepped up via a transformer to medium voltage (MV). This facilitates both the transmission from the WEC to shore and also the connection to the local electrical grid. A transformer is therefore required to step up the voltage from LV to MV.

#### 3.2.3.1 Transformer Types

The subject of power transformers is a comprehensive topic but in general transformers can be classified in a number of ways:

- Insulation Medium
- Cooling Method
- Vector Group

Due to the environment within which the WEC is located, the critical issue for transformer selection for WEC devices is the insulation medium. There are three main insulation mediums for power transformers, shown in Figure 3.5:

- Dry Type (E.g. Cast Resin or Open Wound ('dip and bake'))
- Oil Filled
- Synthetic Fluid Filled

**FIGURE 3.5 LEFT TO RIGHT: DRY TYPE, OIL FILLED AND SYNTHETIC FLUID FILLED (COURTESY PELAMIS WAVE POWER LTD.) TRANSFORMERS**

#### 3.2.3.2 On-board Transformers

The main requirement for an on-board transformer would be to step the voltage up for transmission. The voltage would be stepped up from LV to MV. Typical MV voltage levels (sometimes country specific) are 10kV, 11kV, 20kV, 33kV & 38kV. Typical LV generator voltage levels are 400V, 415V, 480V and 690V. The choice of voltage is dependant on equipment ratings and the overall design of the WEC array electrical network.

Another function of the transformer would be to step the voltage up or down for supply of on-board auxiliary loads. This would be a low power transformer (10's of kW) so would be considered a relatively minor piece of plant.

Oil filled transformers would most likely be unsuitable due to the environmental risks of an oil spill or potential fire risks. More likely are Dry Type and Synthetic Fluid Filled.

Dry type transformers use a solid dielectric such as cast resin as insulation around the core and windings. Therefore heat losses are dissipated directly to the air meaning a large surface area is required. These transformers are simple and robust; however they usually require an additional housing as power parts are generally exposed. As the transformer is air cooled it is possible that this housing will require air conditioning of some type which could mean that the transformer is exposed to the saline atmosphere. This type of transformer is simple and robust but the additional requirements may make it challenging for installing within the WEC itself. There is considerable experience in the use of dry type transformers in the marine industry.

Synthetic Fluid Filled transformers are especially useful where there is an environmental or fire concern such as within a building, train tunnel or on an offshore platform. The silicon based synthetic fluid is used as the dielectric and cooling medium so a tank is also required and therefore they appear identical to an oil filled transformer. The synthetic fluid would have a high fire point (>300°C), high moisture tolerance, and be environmentally biodegradable. Midel 7131 is an example of this fluid (www.midel.com). A synthetic fluid filled transformer is used in the Pelamis device. It has the advantages of an oil filled transformer in that it is self contained (no housing required) and could be water cooled to avoid air ingress into the dry compartments.

#### *3.2.3.3 Implications for WEC Array Electrical Network Design*

The transformers within a WEC array electrical network shall increase the voltage to a suitable level for export. Whereas in offshore wind the transformer is always located in each wind turbine itself there may be a rational for separating this from the WEC within WEC arrays. However, separating the transformer from the WEC device may also present challenges both economically and technically. In Chapter 4 this is analysed in detail.

## 3.3 WEC Array Electrical Components

Within the WEC array electrical components are required to connect the WECs together in an array electrical network and export the generated power to shore and into the electrical grid. These components are described in this section.

### 3.3.1 Submarine Cables

In order to transmit the power from the WEC to the electrical grid a submarine cable is required between the WEC(s) and the shore. Deep-water WEC arrays require dynamic submarine cables from the floating WEC(s) to the seabed and static submarine cables from the WEC locations to the shore based substation. A submarine cable connector is required to connect the dynamic cable to the static cable and allow for multiple connection and disconnection activities.

#### *3.3.1.1 Submarine Power Cables*

Submarine power cables can be considered a well developed technology. They have been used for decades for transmitting power to islands and offshore rigs, interconnecting countries, and more recently have seen extensive use in offshore wind farms.

Submarine power cables use similar technologies to onshore power cables although they have a higher rating against water ingress, normally provided with additional water barriers. Normally they must be armoured to allow for potential impacts from fishing equipment or anchorage and to protect the cable during installation. For deep-water installations dual armouring may be required which are helically wound in opposition to give torque balance in the cable. This means that no twisting of the cable occurs whilst the cable is suspended in the water column during installation.

The type of cable used for submarine power connections has changed over the decades but the industry standard in offshore wind is now XLPE insulated cables mainly due to lower cost manufacturing processes and low dielectric losses. EPR insulated cables are also used in some projects.

Three core cables are preferable where possible as this allows for a simpler, cheaper installation process. For larger power applications three single core cables may be required due to the required current carrying capacity. Three single cores also allows for cheaper redundancy as a fourth single core cable can be installed as a redundant phase where a second full three core cable is required for redundancy in a three core application.

A fibre optic cable can be installed within the submarine power cable to allow for communications. Figure 3.6 shows the typical construction of a medium voltage XLPE submarine power cable. The fibre optic cable is not shown but would be installed within the filler (8)

**Medium-voltage submarine cable, XLPE insulated**

Typical design of a medium-voltage submarine cable with a maximum voltage up to 36 kV

**Type: 2XS2YRAA**

1. Conductor: copper, circular stranded compacted, longitudinal water-tight by filling with a sealing compound (optional)
2. Conductor screening: extruded semi-conductive compound
3. Insulation: XLPE
4. Insulation screening: extruded semi-conductive compound
5. Screen: copper tapes
6. Separator: plastic foil
7. Sheath: PE
8. Fillers: polypropylene strings
9. Binder tapes
10. Bedding: polypropylene strings
11. Armour: galvanized round steel wires
12. Serving: hessian tapes, bitumi-nous compound, polypropylene strings, lime wash


**FIGURE 3.6 TYPICAL THREE CORE MEDIUM VOLTAGE SUBMARINE CABLE [84]**

### *3.3.1.2 Dynamic Power Cables*

Dynamic Cables (sometimes referred to as risers or umbilicals) are a specialised type of submarine power cable that connect the electrical system on the floating WEC to the static cable on the seabed. The dynamic cable is designed for the rigorous duty of being suspended in the water column and undergoing the cyclic forces which are induced by the movement of the WEC.

As shown in Figure 3.7 the dynamic cable configuration can vary. The free hanging catenary is the simplest configuration but there will be loading on the full cable and scour issues at the touchdown. It is expected that the lazy wave configuration will be used for WEC dynamic cables as this avoids touchdown scour issues and also allow for the movement (vertical and horizontal) of the WEC.

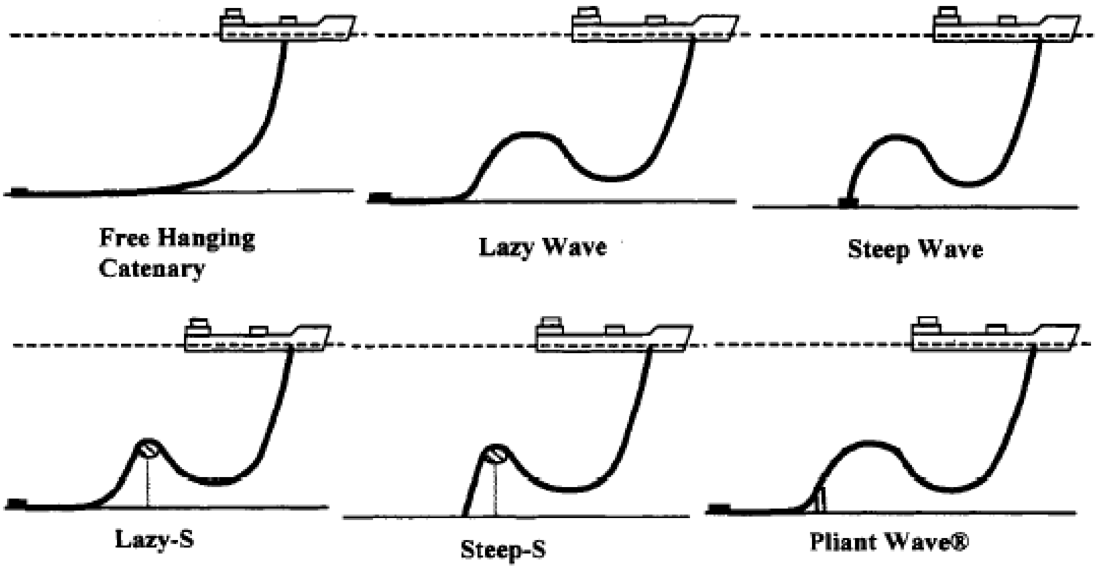



**FIGURE 3.7 POTENTIAL CONFIGURATION FOR DYNAMIC CABLES [85]**

Dynamic cables are very similar in construction to static cables and one must note that all power cables experience dynamic loading during installation. There are three main differences between a static submarine cable and a dynamic submarine cable, namely;

- Dynamic cables typically require two layers of concentrically wound armour which provides torque balance in the cable (i.e. avoids inducing radial twisting in the cable)
- A specific modelling and design process is required for dynamic cables and type testing in some cases
- Accessories such as bend restrictors, floatation modules, scour protection and stress relievers are required to protect the cable at key locations

The conductor itself may also be finely stranded to allow for flexibility. The number of loading cycles a dynamic cable may experience during its lifetime will be perhaps 10 million or more. Specialist companies, such as JDR Cables, have expressed confidence in their analysis tools to allow the cable survive the rigorous duty expected.

Figure 3.8 shows a cross section of a 3.3kV, 6 x 60mm$^2$ cable which was developed by JDR Cables for the OPT Powerbuoy. This shows the dual armouring, finely stranded copper conductors (and two conductors per phase) and fibre optic cables in the central filler. The insulation material chosen is ethylene propylene diene monomer (EPDM) rubber in this case which has good flexibility properties.

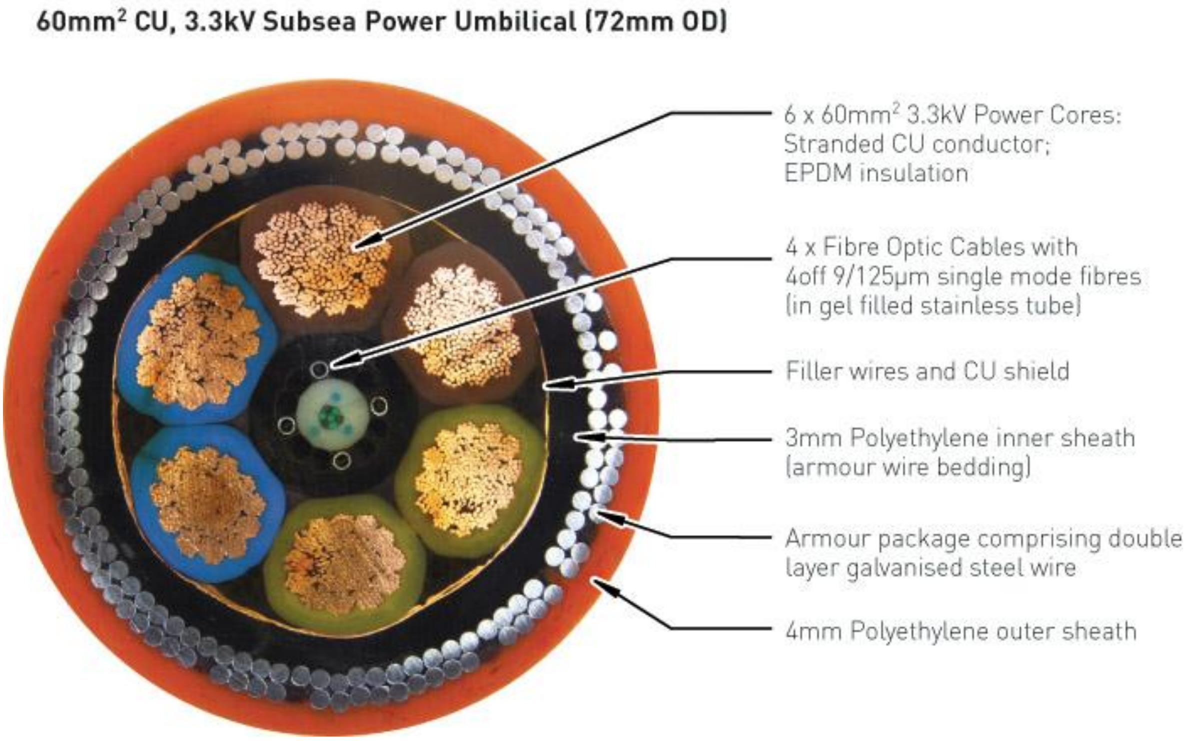



FIGURE 3.8 DYNAMIC CABLE CROSS SECTION (COURTESY JDR CABLES)

#### *3.3.1.3 Cable Installation and Connection*

Methods for cable installation and post protection are well established in offshore wind and outlined in Section 3.6. In general WEC arrays will be able to use the same methods. However, there are some different installation requirements and risks for WEC arrays which should be noted.

Firstly, offshore WEC arrays are likely to be in deep-water, at least 75m depth. Presently, as outlined in Section 3.6 most offshore wind farms are located in depths of 10-30m. This presents an additional challenge for installation particularly where any diving activities are required.

Secondly, the weather risk associated with installation contracts for WEC arrays will be large. In general offshore wind farm sites have been selected to be in relatively benign sites to reduce the weather risk. WEC array sites will be in high energy areas such as the western European seaboard. This is necessary for energy yield from the WEC arrays but is a challenge to the installation of submarine cables.

Thirdly, offshore WECs are floating structures, unlike wind turbines. This means that a dynamic cable is required to allow cable connection while the WEC moves freely to absorb energy. The devices must be connected to these dynamic cables, most likely at the site itself. The dynamic cables also have to be connected to the static submarine cable (see next section). These areas have also been identified as 'key interfaces' and are explored in detail in Chapter 4.

### 3.3.2 Submarine Connectors

The dynamic cable is a specialised cable and so is only used for the connection between the WEC and the seabed where the dynamic cable is connected to a static submarine cable. Therefore a connection needs to be made between the two types of cable. There is also a possibility that a cable may be required to connect to a submarine component such as a hub or substation. There are a variety of submarine cable connection options but they broadly fall into four categories

1. Splice Connection (Figure 3.9) – A permanent splice/joint is made to join the dynamic cable to the static cable. This could be done during cable manufacture. If the cable is to be separated again it would require the joint being physically cut.

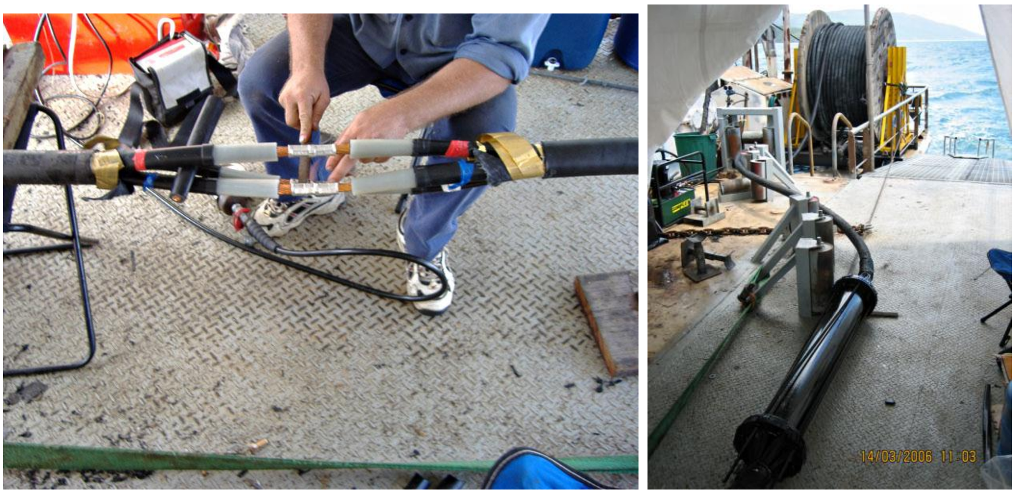



FIGURE 3.9 SUBMARINE POWER CABLE JOINT ASSEMBLY (COURTESY WARDOPERATIONS.COM.AU)

2. Splice Housing (Figure 3.10) – A splice is made in a prefabricated housing. In this case the two ends of the dynamic and static cable would be lifted onto a work vessel and the splice made over a number of hours. The connection is then lowered onto the seabed. The splice can be undone and the cable capped with a similar procedure.

FIGURE 3.10 J&S LTD. SPLICE HOUSING (COURTESY J&S LTD)

3. Dry-Mate Connection (Figure 3.11) – A connector is prefabricated in two parts and the dynamic and static cables are spliced into either part during fabrication or on site. Once the two parts of the dry-mate connector are spliced they can both be lifted onto a work vessel and the connection made in a number of hours. The connection can then be lowered onto the seabed. The connection can be lifted and opened / closed numerous times without any further cable jointing work required

**FIGURE 3.11 DRY MATE CABLE CONNECTORS. LEFT (COURTESY HYDROGROUP), RIGHT (COURTESY MACARTNEY)**

4. Wet-Mate Connection (Figure 3.12) – Like the dry mate connector this is a re-usable connector, however it is located on the seabed. The connection can be opened / closed numerous times on the seabed, however most likely requires the use of a dynamic positioning class vessel.

**FIGURE 3.12 MACARTNEY 11KV WET-MATE CABLE CONNECTOR (COURTESY MACARTNEY)**

The connectors are generally expected to be more expensive and require more expensive installation processes going from 1-4 above. Most of the connectors have been developed up to 10-11kV, with some already available up to 36kV.

Connectors can be considered an expensive but necessary component of a WEC array electrical network so a system design that keeps the use of these connectors to a minimum will prove less costly and so may be desirable. This is detailed in Chapter 4.

### 3.3.3 Submarine Electrical Equipment

There is some interest in the use of submarine electrical equipment as aggregation points, or hubs, in WEC array electrical networks. While this technology has been developed for wellhead systems in the Oil and Gas (O&G) industry it is not certain what, if any, role this may play for wave energy systems.

Some WEC developers and component suppliers have developed submarine electrical hubs which form part of their WEC array electrical network design concept.

Submarine electrical systems, specifically submarine switchgear may be unsuitable for wave energy systems due to the expected costs (both CAPEX and OPEX) of such a system and the safety systems required within power plants of any type.

#### *3.3.3.1 Oil and Gas*

There have been several applications for submarine electrical systems developed for the oil and gas industry. These systems are specifically developed for wellhead production where it is more economical to install the wellhead equipment on the seabed than on a fixed or semi-fixed rig. Companies such as Siemens, ABB, GE-Vetco Gray have developed submarine transformers, switchgear, variable speed drives, submarine cable connectors, and motors for these wellhead systems.

These technologies may be suitable for the wave energy industry but there are several issues which must be considered and evaluated before the crossover of technology can occur.

- The cost of this type of equipment is likely to be high as the O&G industry economics are fundamentally different to offshore renewables.
- The design requirements are extremely onerous as this equipment is expected to operate in very deep water (>1km). However, some elements of the technology may be expected to cross over to wave energy.
- Active electrical components (switchgear, relays, and power electronics) require maintenance. The cost of recovering the submarine equipment for maintenance may outweigh any benefits accrued from its use.

- Electrical safety is critical to the operation and maintenance activities of any power plant. Guidance given by the renewables industry in the UK [86] state that "*Machinery must be fitted with means to isolate it from all energy sources. Such isolators must be clearly identified. They must be capable of being locked if reconnection could endanger persons. Isolators must also be capable of being locked where an operator is unable, from any of the points to which he has access, to check that the energy is still cut off*". What this means is that the point of isolation should be locked open and the applied earths should be locked on. This would be extremely impractical and difficult to achieve in the case of submarine switchgear and is an important consideration in the design of the plant.

Therefore although the equipment is of interest it may not be cost effective to use in WEC array electrical networks and has maintenance and safety issues associated with it.

#### *3.3.3.2 Ocean Energy*

Some WEC developers and component suppliers have developed systems specifically for use in WEC array electrical networks. These systems have mostly been developed by WEC developers in response to the research problems addressed in this thesis. Component suppliers have also responded to demand from WEC developers. However, it is unclear whether they have considered the practical and long term commercial implications of the use of these technologies. Some examples are shown below.

### 3.3.3.2.1 MacArtney MV Submarine Switchgear Hub

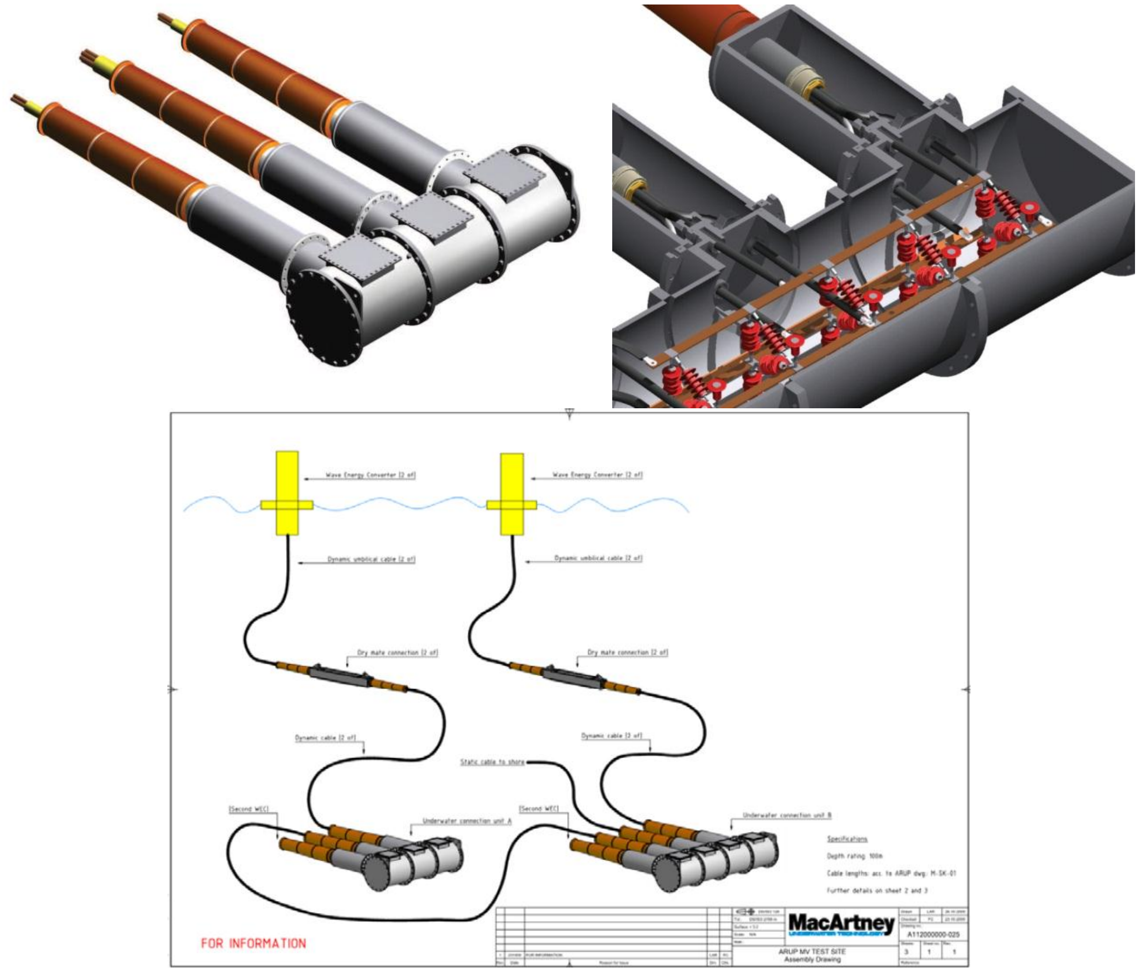



**FIGURE 3.13 MACARTNEY MV SUBMARINE SWITCHGEAR CONCEPT (COURTESY MACARTNEY)**

As shown in Figure 3.13, this is an active device with on-board circuit breakers/disconnectors which allow for the WEC to be teed off from the circuit, i.e. it acts as a ring main unit (RMU). The advantage of this system is that a radial circuit can be kept live while a WEC is maintained or removed, as it can be switched at the submarine switchgear. This is at concept stage only by MacArtney and has not been developed further. Projected costs are in the region of €215k per hub with installation costs (including foundation, deployment vessels and mooring lines) estimated at approx. €1m [57].

MacArtney also have other 'passive' solutions such as inline connectors, Y-connectors and Y-splitout junction boxes (left to right respectively in Figure 3.14)

FIGURE 3.14 PASSIVE OPTIONS FROM MACARTNEY (COURTESY MACARTNEY)

### 3.3.3.2.2 OPT Underwater Substation Pod

Ocean Power Technologies (OPT) have specifically developed a bespoke underwater substation pod (USP) for their Powerbuoy devices. The design allows for several (up to 10 for the device shown in Figure 3.15) 150kW WECs to be connected to the USP at relatively low voltage (3.3kV). The outputs of the devices are connected together and stepped up to a higher medium voltage (11-15kV) for transmission to shore.

The details of the USP are proprietary but it is evident that the device uses relatively standard switchgear and transformer assemblies and installs them in a watertight housing and frame for installation on the seabed. This is an interesting concept and the current design by OPT means that one USP is be required for every 10, 150kW, devices.

FIGURE 3.15 OPTS UNDERWATER SUBSTATION POD – 1.5MW CONSTRUCTION AND TEST DEPLOYMENT (COURTESY OCEAN POWER TECHNOLOGIES)

### 3.3.3.2.3 Seabased Underwater Substation

Seabased developed an underwater substation to collect and condition the power from three linear generator based WECs and step the voltage up to MV for transmission to shore. The current device is rated for relatively low power, approx. 100kVA. Seabased are developing higher power units for initial projects. Their overall electrical system concept is for multiple small linear generator based WECs connected to intermediate submarine substations, Low Voltage Marine Substations (LVMS), and several LVMS's connected to a Medium Voltage Marine Substation (MVMS). This is shown in an artist's impression in Figure 3.16.

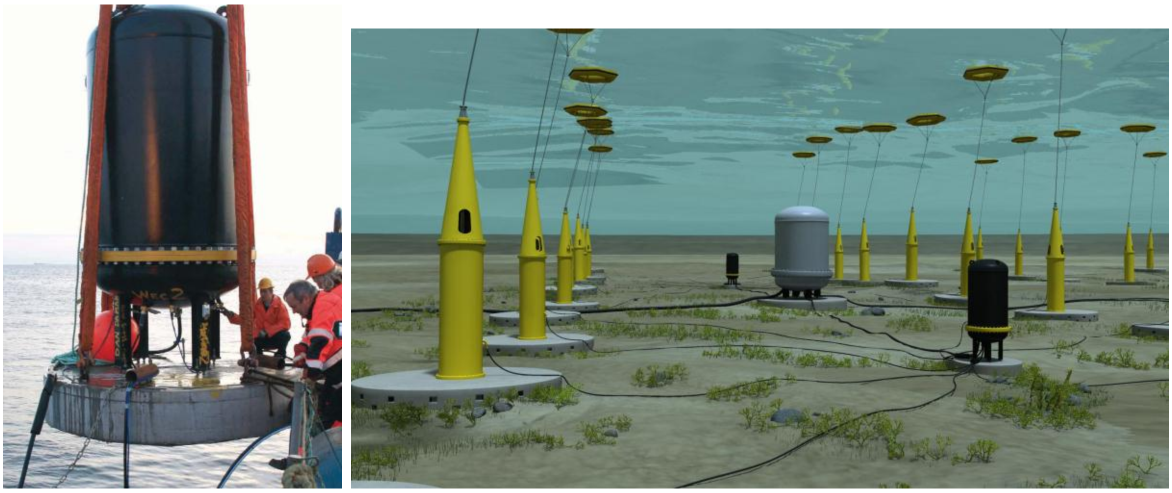


FIGURE 3.16 SEABASED SUBSTATION INSTALLATION PHOTO AND ELECTRICAL SYSTEM CONCEPT (COURTESY SEABASED.COM)

#### 3.3.3.2.4 Wavehub

The Wavehub test site in Cornwall, UK is a wave energy test facility with four test berths grid connected at 11kV (see more details in Section 3.4.3). The four test berth cables are joined together at the 'Wavehub', a submarine connection box, and a single cable (albeit with 6 cores) is connected to the shore substation and into the national grid at 33kV.

The 'Wavehub' could be considered a passive device as it is simply a junction box to split the single cable from shore into four individual circuits to the test berths. There are no switching components in the device. The device was deployed in 2011 but has yet to be utilised by any WEC, see Figure 3.17.

FIGURE 3.17 WAVEHUB CONNECTION DEVICE (COURTESY WAVEHUB.CO.UK)

### 3.3.4 Offshore Substations

Offshore substations are generally required for wind farms with capacities of >100MW and long transmission distances to shore (>25km). Offshore substations are large platform mounted structures which connect the output of various wind turbine circuits and step the voltage level up to HV (typically 132kV) for transmission to shore. These are huge structures (typically 1500 tonnes +) and have complicated systems on-board such as MV switchgear, power transformers, HV switchgear, protection relays, auxiliary AC and DC systems, fire fighting and sometimes accommodation.

However they are located in areas of shallow water (<30m) and it is anticipated that the cost of fixed foundation structures for these in deep water (>100m) will be prohibitive. There are other options such as semi-submersible or spar type platforms.

Another suggested option is to house the entire substation on the seabed. This gives the same access, maintenance and safety problems as any other active electrical component on the seabed.

## 3.4 WEC Test Sites and Electrical Infrastructure

There are a number of active and planned grid connected test sites for WEC prototype demonstration in Europe. The most active of these is the European Marine Energy Centre (EMEC) in Orkney, Scotland which has seen the bulk of both wave and tidal technology demonstration over the last decade.

Although grid connected test sites are primarily designed for WEC prototyping, there is the additional benefit of demonstration of the grid integration infrastructure and measurement of power quality. Critically, however, the economics rationale for electrical systems for test sites is not be as challenging as those for commercial projects.

An outline of some of the existing and planned wave energy test sites is given in this section. This includes details of the electrical network within the test site, cable installation, cable accessories, submarine connectors and operational experience if appropriate.

### 3.4.1 European Marine Energy Centre (EMEC)

EMEC has been in operation since 2003 and provides grid connected wave and tidal facilities, scale test sites, site monitoring and office facilities to WEC developer clients. At the Billia Croo wave test site EMEC provides seven grid connected berths, 5 offshore and 2 nearshore.

Figure 3.18 shows the layout of the wave test facility at EMEC. Each offshore berth is connected by an 11kV submarine cable to shore. Offshore berths are located in approximately 50-70m water depth and are 2km from shore. The nearshore berths are grid connected onshore as the devices using these berths, Aquamarine Power and Seatricity, utilise hydraulic transmission to shore.

The 11kV cables have 50mm$^2$ conductors, dual steel armouring, pilot signal cables, and fibre optic communications cables. The power cables are laid on the seabed from the offshore berths to around 15m water depth. From here they are protected with ductile iron cable protectors until they enter a trench at the shoreline. They are then connected to a local 11kV substation which is connected to the Orkney electrical grid. There are facilities at the substation to operate the cables at other voltages than 11kV, e.g. Pelamis connect their devices at 6.6kV at EMEC requiring a transformer onshore to step up the voltage to 11kV.

The offshore power cables are capped at the berth with one half of a submarine splice housing, or connector, manufactured by J&S. WEC developers must connect a dynamic cable from their WEC to the other half of the splice housing and make the final connection between the two halves of the connector during WEC installation at the berth. The submarine connector in use in EMEC is shown in Figure 3.19.

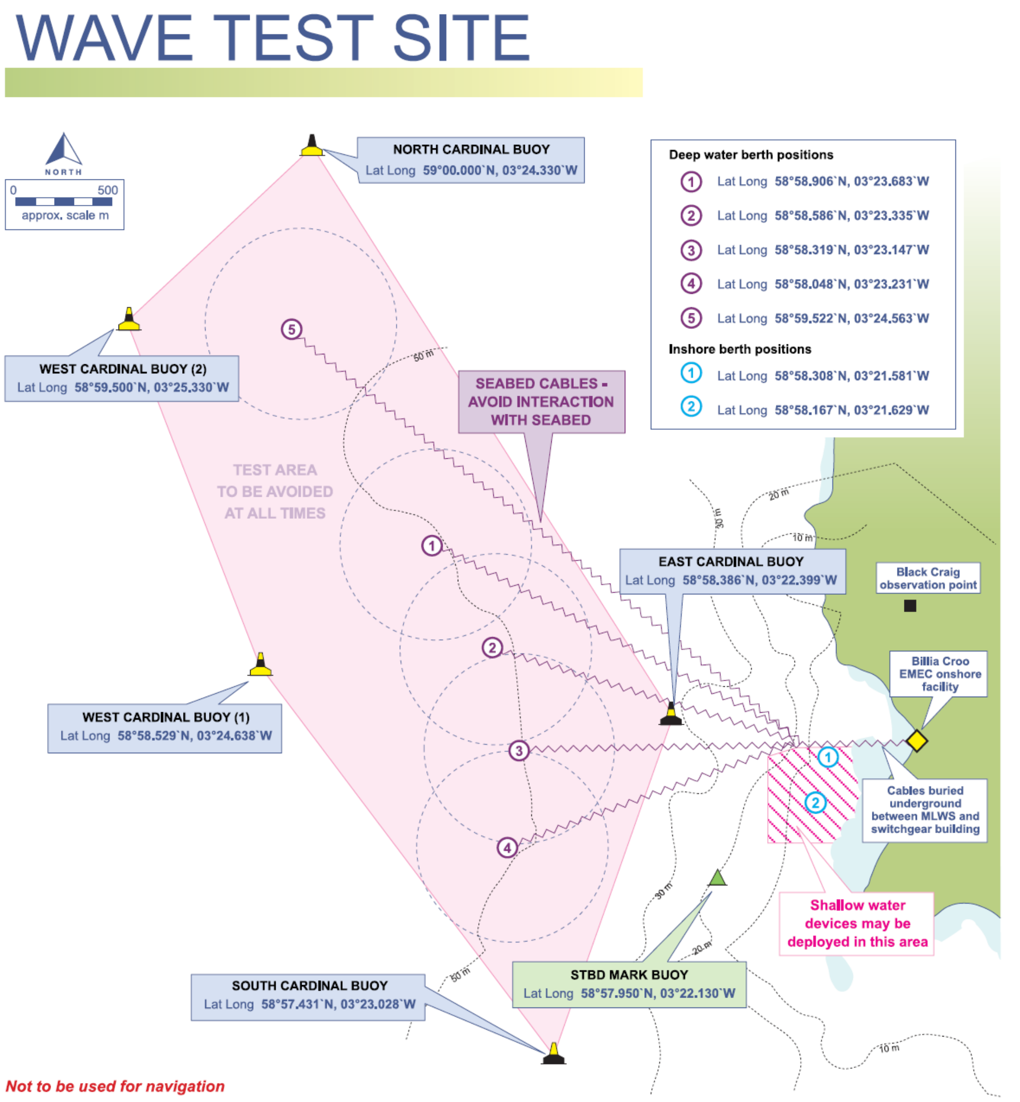



FIGURE 3.18 EMEC WAVE TEST SITE SCHEMATIC (SOURCE: EMEC.ORG.UK)

FIGURE 3.19 J&S SUBMARINE SPLICE HOUSING / CONNECTOR IN USE AT EMEC (COURTESY J&S LTD.)

EMEC is considered an extremely successful test site with multiple wave and tidal devices prototyping at the site. The performance of the electrical system has been good with lessons being learned in the protection of power cables and the use and reliability of submarine connectors. EMEC have also developed guideline documents including a grid connection guidance document [87].

### 3.4.2 Atlantic Marine Energy Test Site (AMETS)

The Sustainable Energy Authority of Ireland (SEAI) is planning a grid connected test site, AMETS, off Annagh Head, near Belmullet, Co. Mayo, Ireland. AMETS will allow the testing of pre-commercial WEC prototypes in extreme Atlantic conditions. SEAI are in the advanced stages of securing a foreshore lease and planning permission for offshore and onshore elements of the project.

AMETS plans to have two separate test areas, or berths. A deep-water berth (Test Area A) will be located in 100m water depth and an intermediate depth berth (Test Area B) will be located in 50m water depth. The deep-water berth is located around 16km from shore and the intermediate berth is located around 6km from shore. Four 10kV submarine cables will be installed to these berths, two to each berth. These four cables will be routed to a substation at the head of Belderra Strand where they will be connected to a 10kV substation and subsequently to the Irish electrical grid at 20kV. Some details of the proposed test site are shown in Figure 3.20.

As AMETS has yet to be built the final details of the offshore electrical system, such as cable specification and submarine connectors, are not finalised. AMETS will provide a facility that experiences some of the most extreme conditions expected in the Atlantic for WEC arrays. AMETS will provide an important proving ground for later stage WEC prototypes.

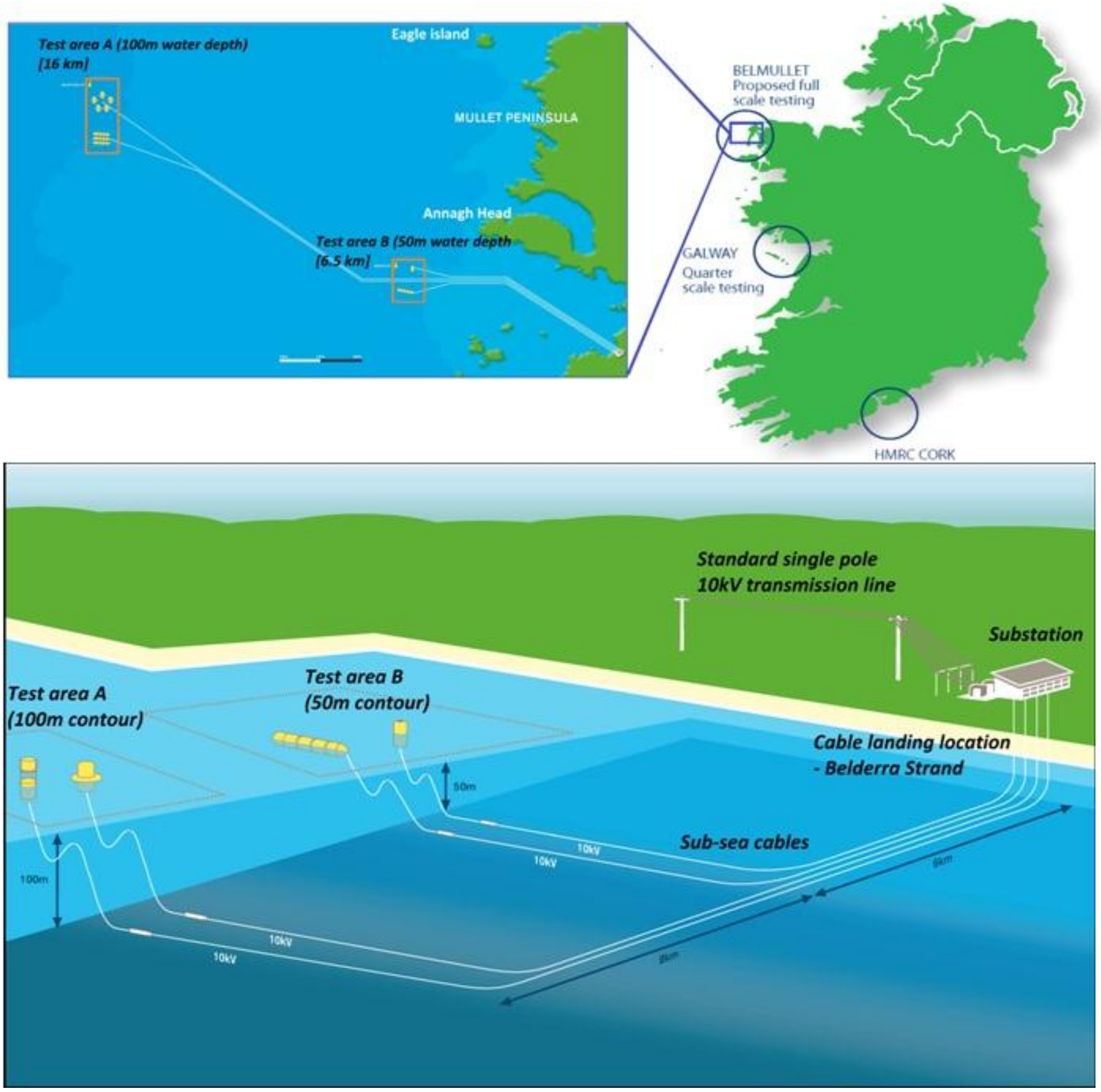



FIGURE 3.20 SCHEMATIC SHOWING DETAILS OF AMETS TEST SITE (SOURCE: SEAI.IE)

### 3.4.3 Wavehub

Wavehub is a wave energy test site located off Hayle, on the Cornwall Coast in southwest England. It consists of an electrical 'hub' on the seabed 16km from shore. The hub is connected to an onshore substation by 25km of 33kV power cable, which is operated presently at 11kV. From the onshore substation the site is connected to the electrical grid. From the hub four berths are served, each in approximately 50m water depth with a capacity for 4-5MW. If operated at 33kV Wavehub has the capacity for up to 50MW within the existing infrastructure. A schematic of the site is shown in Figure 3.21.

Wavehub has a unique design compared to other existing and planned test sites in that a bespoke connection unit, the Wavehub, is used as an aggregation point for multiple berths and was designed and built by JDR Ltd. The main power cable is a 33kV, 6-core, armoured cable supplied by JDR Ltd. This cable allows two power circuits to operate within the same cable. These two circuits are connected to independent, isolated busbars in the wavehub unit. Each busbar feeds two of the four available berths via 300m tails. At the end of each tail is an 11kV dry-mate connector supplied by Hydrogroup. The wavehub unit and the 11kV dry-mate connector are shown in Figure 3.22.

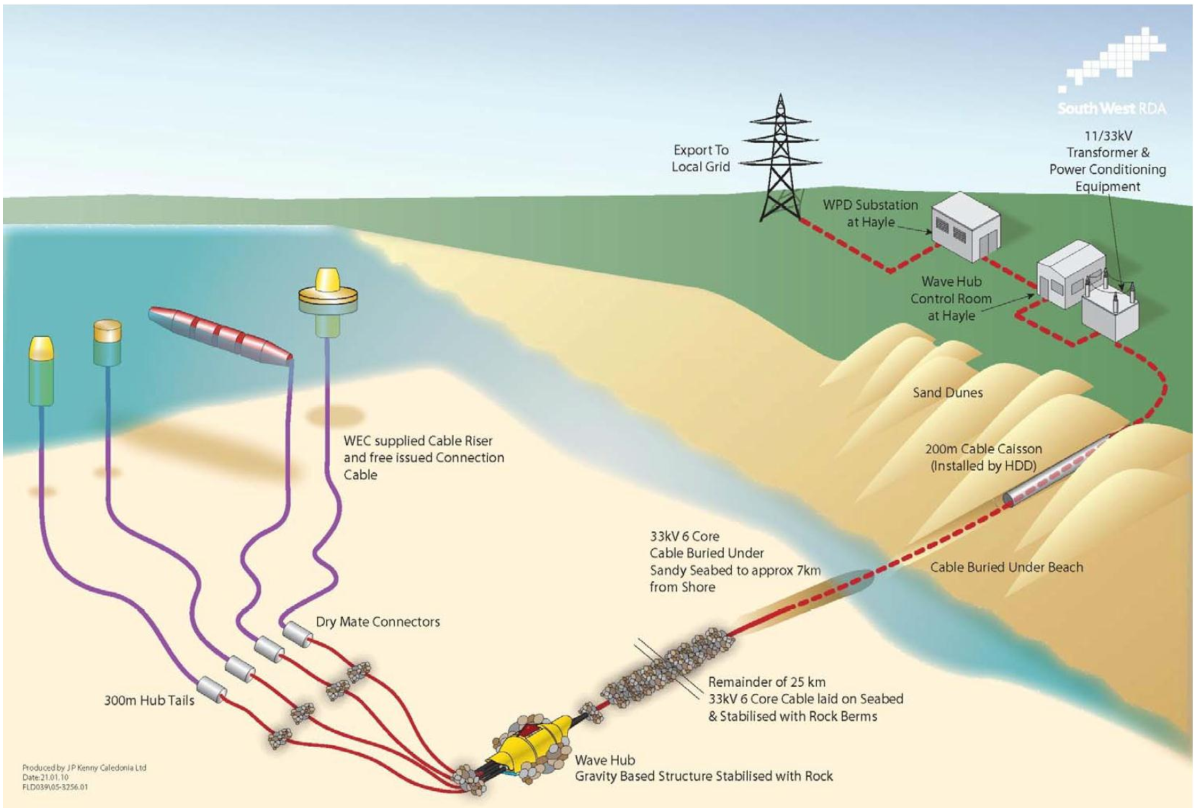



**FIGURE 3.21 SCHEMATIC SHOWING DETAILS OF WAVEHUB SITE (SOURCE: WAVEHUB.CO.UK)**

FIGURE 3.22 WAVEHUB UNIT DURING INSTALLATION (L) AND HYDROGROUP DRY-MATE CONNECTOR (R) (COURTESY WAVEHUB AND HYDROGROUP)

Although installed since 2010, Wavehub has not had any WEC prototype deployed at the site at the time of writing. They have, however, had a number of WEC developers expressing interest and designing prototypes for the site. More recently Wavehub have begun to focus on offshore floating wind testing opportunities as an alternative use for the site.

### 3.4.4 Other Test Sites

Beyond the UK and Ireland there are a number of other wave energy test sites planned around Europe.

#### *3.4.4.1 Biscay Marine Energy Platform (BiMEP)*

The Biscay Marine Energy Platform (BiMEP) is being developed by Ente vasco de la Energía (EVE), a Basque government body. The site is located off the coast from Armintza, Bizkaia, Spain. BiMEP has a total capacity of 20MW with four 13kV power cables connected from an onshore substation to offshore 'hubs' which can feed multiple devices. The exact design of the cables and these 'hubs' is not available at this time. A schematic of the planned test site is given in Figure 3.23.

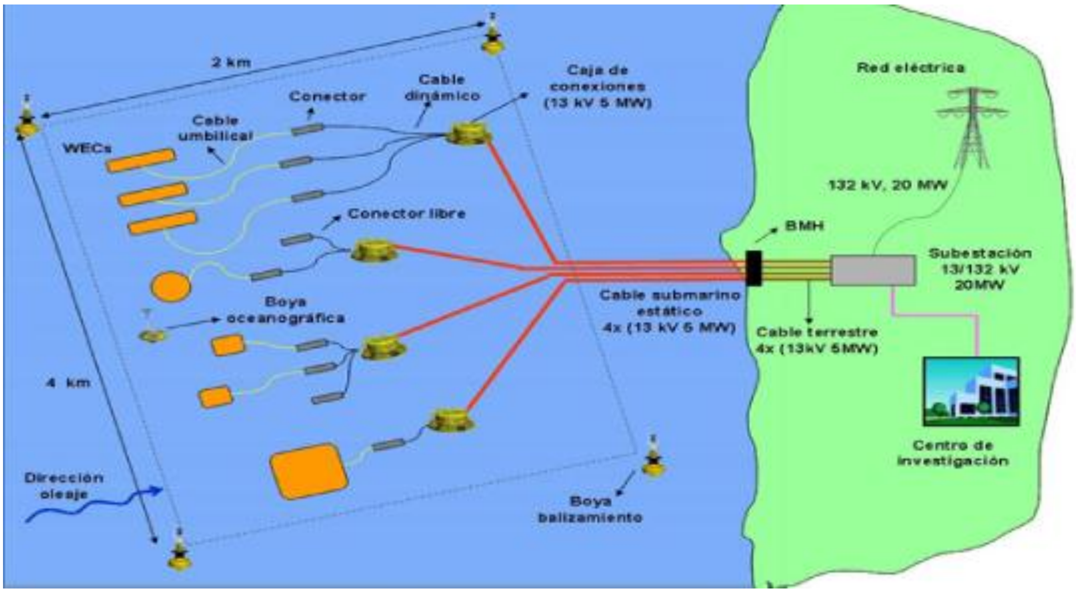



FIGURE 3.23 SCHEMATIC SHOWING DETAILS OF BIMEP TEST SITE [53]

### *3.4.4.2 Site D'experimentation en Mer (SEM-REV)*

SEM-REV is a grid connected wave energy test site off the western coast of France. The site is located off the coast of Guérande, France and is operated by Ecole Centrale de Nantes. The test berth location is in approximately 35m water depth. Berths are connected to the grid with a single power cable rated for 8MW. Other details of the cable are not available at present. It is anticipated that this cable can service up to four WEC prototypes within the test site area. A schematic of the site and cable route is shown in Figure 3.24.

SEM-REV has not hosted any WEC prototype testing to date although it has only been grid connected for approximately one year. There is ongoing wave resource and environmental monitoring and it is also being considered for the testing of floating offshore wind prototypes.

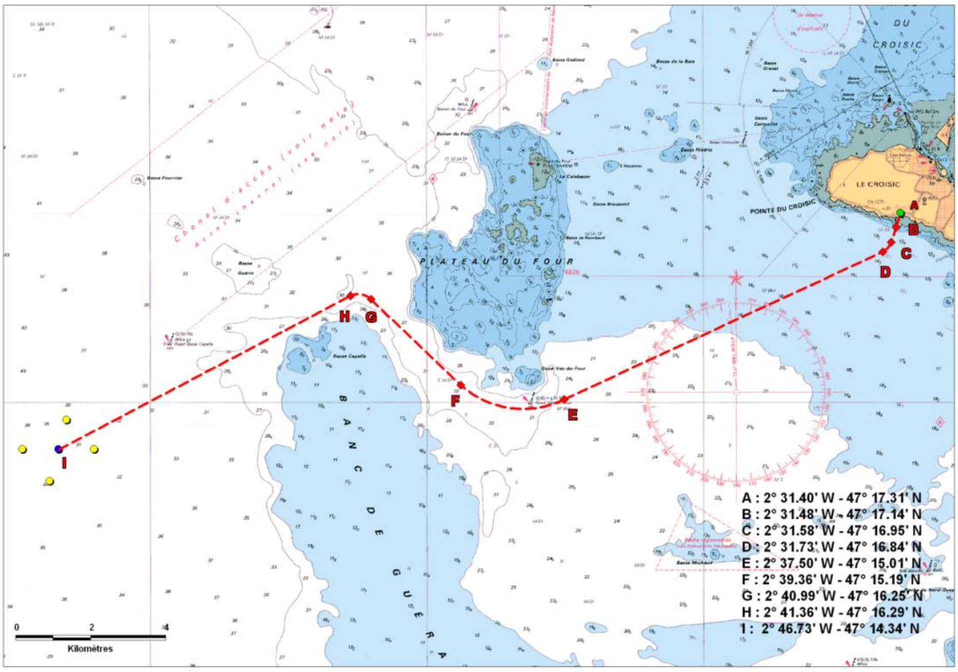



**FIGURE 3.24 SCHEMATIC OF SEM-REV TEST SITE LOCATION AND CABLE ROUTE (SOURCE: SEMREV.FR, ECOLE CENTRALE NANTES)**

### *3.4.4.3 Pilot Zone / Ocean Plug*

In Portugal a test site for ocean energy has been proposed for a number of years. The Pilot Zone, which is being developed by electrical utility REN, extends to 320km$^2$ of leased area off the coast north of Nazare, Portugal. The location of the project is shown in Figure 3.25.

The test site is expected to be developed in phases with the first phase consisting of four 3MW berths connected at 15kV. Later, commercial phases are envisaged at the site up to 250MW. The first phase is expected to have two, 'interwoven' cables from the shore to the site area. From here the cables will be split into four individual links to the four 3MW berths. Exact details of the connection scheme are not available at this time.

The project has obtained a concession (lease) for 45 years for the project area. Projected timelines for the pilot zone are phase one by 2013; however some delays are anticipated at this time.

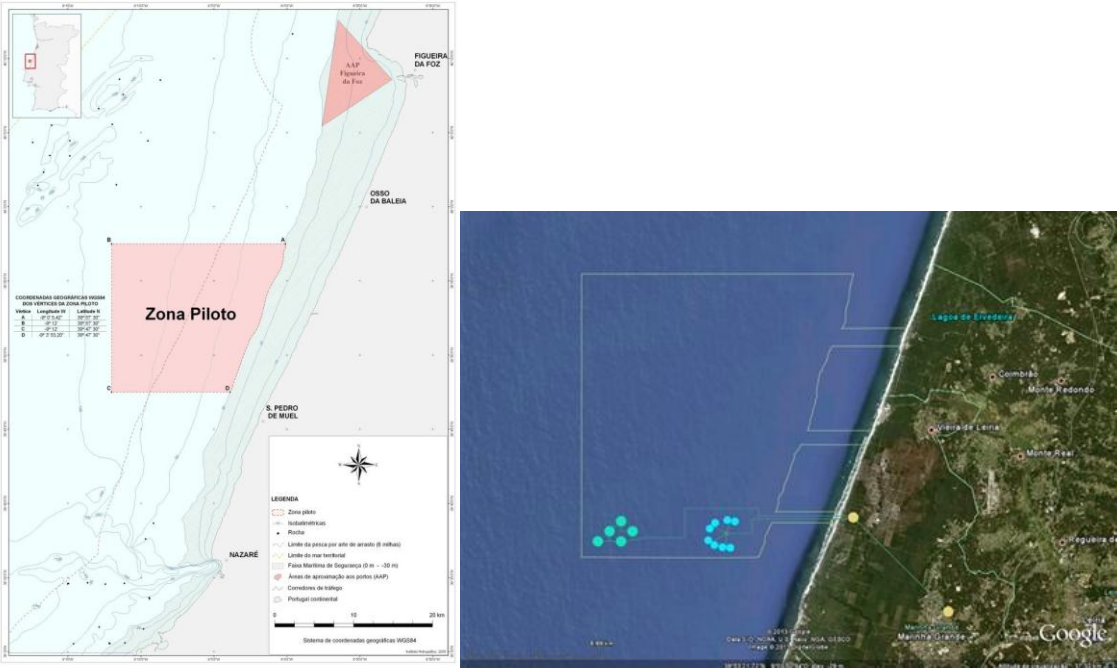



FIGURE 3.25 SCHEMATIC OF PILOT ZONE LOCATION (SOURCE: REN.PT, OCEANPLUG.COM)

## 3.5 WEC Prototype Electrical Infrastructure

There has been limited testing conducted of WEC arrays but there is experience from prototype testing which utilised electrical infrastructure. There are also conceptual designs which have been developed to various levels of detail. The knowledge from these electrical infrastructure demonstrations and concepts is important to this thesis.

### 3.5.1 Aguçadoura Wave Farm

Pelamis tested three 750kW prototype WECs at the Aguçadoura site in Portugal. The electrical infrastructure was pre-existing at this site from a previous WEC demonstration by AWS-Ocean Energy in 2004. It has subsequently been used for the Windfloat, a floating wind demonstration project.

The site has a single 10kV, 150mm$^2$ power cable connected from the offshore berth to an onshore substation. The cable is operated at 6.6kV for Pelamis and Windfloat, while the onshore substation connects to the local grid at 15kV.

Pelamis connected the three prototypes together in a radial circuit with dynamic cables between the devices and to the static cable. This is shown schematically in Figure 3.26. Pelamis use a wet-mate connection system which is part of their mooring connection concept as detailed in Section 4.4.1.

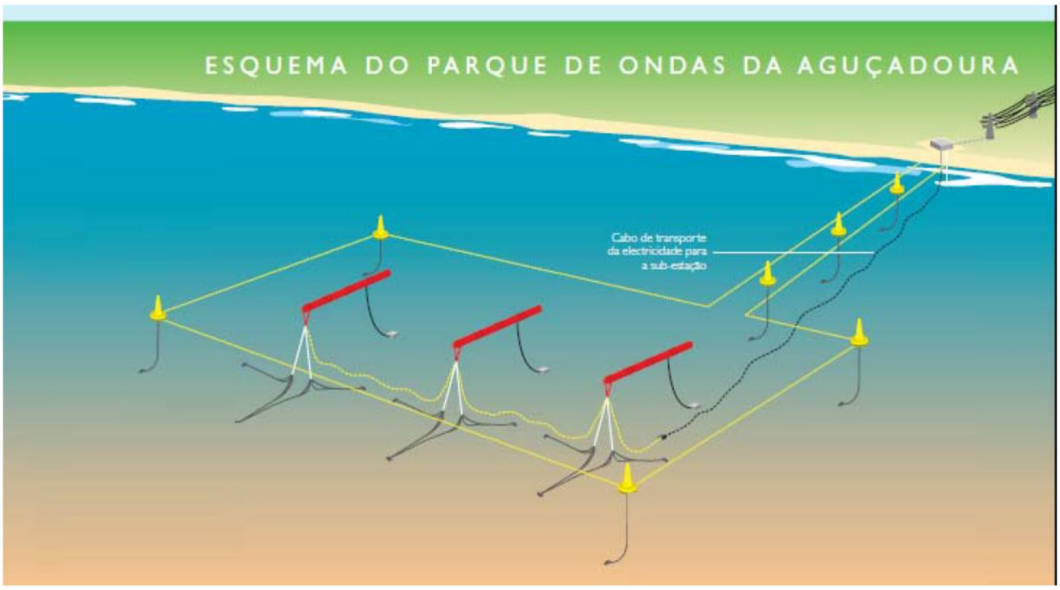



**FIGURE 3.26 SCHEMATIC REPRESENTATION OF PELAMIS ELECTRICAL NETWORK AT AGUÇADOURA (COURTESY PELAMIS WAVE POWER)**

### 3.5.2 AW Energy at Peniche

AW Energy deployed a nearshore WEC at Peniche in Portugal in 2012. This 300kW 'Waveroller' generates power on-board via a hydraulic PTO. The device is connected to shore via a low voltage 1kV cable operating at 690V. The WEC is located in the nearshore regime so the cable is approximately 1km in length.

### 3.5.3 Seabased at Lysekil

Seabased are a spin-out company from Uppsala University which develop linear generator based WECs. Some detail is given in Section 3.3.3.2.3. They have operated a test site at Lysekil since 2002 and have deployed numerous test prototypes. They have also installed an underwater substation which houses power electronic converters and low voltage switchgear. This low voltage marine substation (LVMS) is shown in Figure 3.27 along with schematics for large LVMS and MVMS.

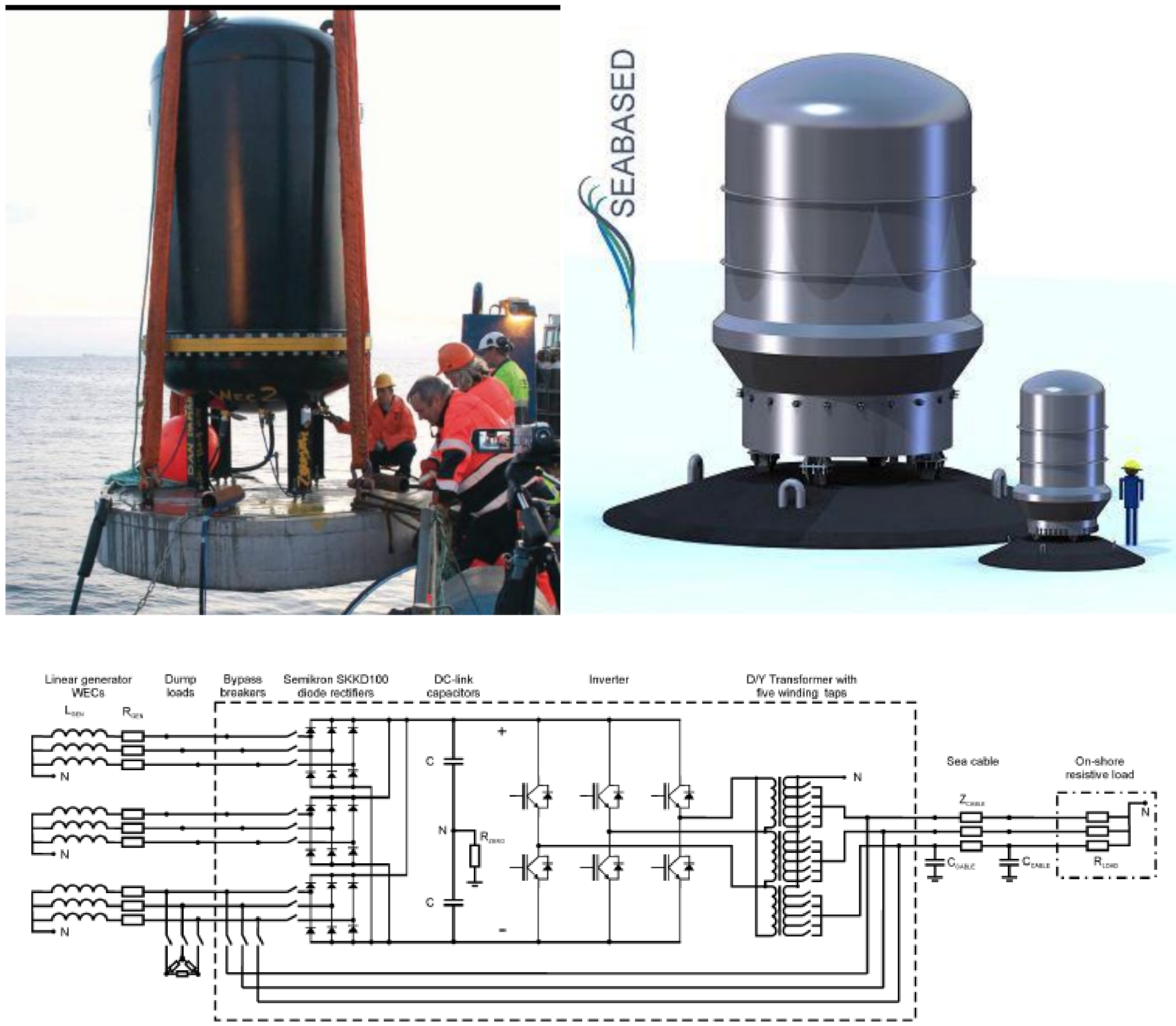



**FIGURE 3.27 SEABASED LOW VOLTAGE MARINE SUBSTATION (LVMS) SHELL AND FOUNDATION (TOP LEFT), MEDIUM VOLTAGE (MVMS) AND LVMS (TOP RIGHT) AND ELECTRICAL SCHEMATIC (BOTTOM) (SOURCE: SEABASED.COM)**

The Seabased electrical system concept includes multiple low power linear generator WECs connected at low voltage back to a LVMS. For example there may be 25 x 25kW generators connected to a single LVMS. The LVMS conditions the generated power and steps up the voltage. Multiple LVMS then connect to a MVMS and so the power can be aggregated and converted to medium voltage for connection to shore and into the electrical grid. This tiered electrical system is a fundamental part of the Seabased concept for WEC arrays and is a relatively unique approach in the industry.

### 3.5.4 Ocean Power Technologies

From 2009 to 2011 Ocean Power Technologies (OPT) had a grid connected 40kW prototype operational in Oahu, Hawaii, USA. This site is owned by the US Marine Corps and consists of a single 11.5kV submarine cable connection to the Oahu electrical grid. The test site is located in 30m water depth.

OPT have developed a number of solutions for their technology including an Undersea Substation Pod (USP). The USP allows several WECs to connect at low voltage to the USP for aggregation where the voltage can be stepped up to medium voltage for transmission to shore. A 1.5MW USP is shown in Figure 3.28 and OPT plan for larger 5MW versions in the future. In this way OPT have a similar electrical network concept as Seabased however ultimately plan for larger individual devices (up to 0.5MW at present).

FIGURE 3.28 OPT'S UNDERSEA SUBSTATION POD (USP) INTERIOR SWITCHGEAR (L) AND INSTALLATION (R) (SOURCE: OCEANPOWERTECHNOLOGIES.COM)

## 3.6 Offshore Wind Electrical Networks and Transfer to WEC Arrays

Offshore wind is a useful knowledge base for understanding the electrical networks for WEC arrays. There are some applicable areas of transfer between the two, particularly with the optimal configuration of WEC array electrical networks and installation processes. There are also some key differences, particularly around the interface between the WEC and the electrical network. This section outlines the potential areas of transfer and key differences.

### 3.6.1 Offshore Wind Electrical Networks

Offshore wind farms have been commercially developed since the first, Vindeby Wind Farm, was developed in 1991 off the coast of Lolland, Denmark. The main driver for going offshore was for increased wind speeds and site availability [63]. Early offshore wind farms utilised identical turbines to onshore wind farms although the components were ‘marinised’ and the foundation designs altered to allow for installation at sea. The electrical system would also be identical to onshore wind farms with array cabling linked to a substation (initially onshore and subsequently offshore) and connected to the electrical grid.

These early wind farms were built on shallow water sandbanks with typical water depths <5m. Transmission distance to shore would also have been small (<5km). As larger offshore wind farms were built they were pushed into deeper water areas further from shore with offshore wind farms typically being installed presently in water depths of >20m with transmission distances of >30km. Some of the characteristics of the world’s largest offshore wind farms, as of 2013, are shown in Table 3.2.

The electrical network of a large offshore wind farm essentially consists of two stages. There is a medium voltage (MV) array collection system, which is subsequently connected to an offshore substation. This offshore substation steps the voltage up to high voltage (HV) for export to shore. In the case of a HVDC connection the offshore substation has a converter which converts the stepped up voltage from AC to DC.

**TABLE 3.2 CHARACTERISTICS OF OFFSHORE WIND PROJECTS UP TO 2012 (SOURCE: 4COFFSHORE.COM AND DEVELOPER WEBSITES).**

| Name | Turbines | Capacity | Year | Distance from Shore / POC | Max Water Depth | Inter Array | Offshore Substation | Shore Connection | AC / DC | # Cables to Shore |
|---|---|---|---|---|---|---|---|---|---|---|
| London Array | 175 | 630MW | 2012 | 53km | 25m | 33kV | Yes (2) | 150kV | HVAC | 4 |
| Greater Gabbard | 140 | 504MW | 2012 | 45km | 32m | 33kV | Yes | 132kV | HVAC | 3 |
| Thornton Bank II | 30 | 184MW | 2012 | 39km | 28m | 33kV | Yes | 150kV | HVAC | 1 |
| Sherringham Shoal | 88 | 316MW | 2012 | 22km | 22m | 33kV | Yes | 132kV | HVAC | 2 |
| Ormonde | 30 | 150MW | 2012 | 43km | 22m | 33kV | Yes | 132kV | HVAC | 1 |
| Walney Phase 2 | 51 | 183MW | 2012 | 44km | 30m | 33kV | Yes | 132kV | HVAC | 1 |
| Walney Phase 1 | 51 | 183MW | 2011 | 43km | 28m | 33kV | Yes | 132kV | HVAC | 1 |
| Thanet | 100 | 300 MW | 2010 | 11km | 25m | 33kV | Yes | 132kV | HVAC | 1 |
| Rosand 2 | 90 | 207MW | 2010 | 4km | 10m | 33kV | Yes | 132kV | HVAC | 1 |
| Robin Rigg | 60 | 180MW | 2010 | 10km | 9m | 33kV | Yes | 132kV | HVAC | 1 |
| Gunfleet Sands | 48 | 172MW | 2010 | 7km | 15m | 33kV | Yes | 132kV | HVAC | 1 |
| Donghai Bridge | 34 | 110MW | 2010 | 10km | 10m | 35kV | No | 35kV | MVAC | 1 |
| Vänern | 10 | 30MW | 2010 | 7km | 22m | 33kV | No | 33kV | MVAC | 1 |
| Horns Rev 2 | 91 | 209 MW | 2009 | 15km | 17m | 33kV | Yes | 150kV | HVAC | 1 |
| Ryll Flats | 25 | 90MW | 2009 | 8km | 12m | 33kV | No | 33kV | MVAC | 3 |
| Alpha Ventus | 12 | 60MW | 2009 | 45km | 33m | 30kV | Yes | 150kV | HVAC | 1 |
| Lynn and Inner Dowsing | 54 | 194MW | 2008 | 5km | 18m | 33kV | No | 33kV | MVAC | 6 |
| Princess Amalia | 60 | 120MW | 2008 | 23km | 24m | 22kV | Yes | 150kV | HVAC | 1 |
| Lillgrund | 48 | 110MW | 2008 | 10km | 8m | 33kV | Yes | 138kV | HVAC | 1 |
| Kemi Ajos | 10 | 30MW | 2008 | 11km | 7m | 20kV | Yes | 110kV | HVAC | 1 |
| Thornton Bank I | 6 | 30MW | 2008 | 28km | 27m | 33kV | Yes | 150kV | HVAC | 2 |
| Burbo Bank | 25 | 90MW | 2007 | 7km | 8m | 36kV | No | 36kV | MVAC | 3 |
| Egmond aan Zee | 36 | 108MW | 2006 | 10km | 18m | 34kV | No | 34kV | MVAC | 3 |
| Barrow | 30 | 90MW | 2006 | 27km | 20m | 33kV | Yes | 132kV | HVAC | 1 |
| Kentish Flats | 30 | 90MW | 2005 | 8.5km | 5m | 33kV | No | 33kV | MVAC | 3 |
| Nysted | 72 | 166MW | 2004 | 8km | 12m | 33kV | Yes | 132kV | HVAC | 1 |
| Scroby Sands | 30 | 60MW | 2004 | 2.5km | 15m | 33kV | No | 33kV | MVAC | 3 |
| Arklow Bank | 7 | 25MW | 2004 | 10km | 5m | 38kV | No | 38kV | MVAC | 1 |
| North Hoyle | 30 | 60MW | 2003 | 7km | 11m | 33kV | No | 33kV | MVAC | 2 |
| Samsø | 10 | 23MW | 2003 | 4km | 13m | 30kV | No | 30kV | MVAC | 1 |
| Horns Rev 1 | 80 | 160MW | 2002 | 14km | 17m | 36kV | Yes | 150kV | HVAC | 1 |
| Mittelgrunden | 20 | 40MW | 2001 | 3.5km | 6m | 30kV | No | 30kV | MVAC | 1 |

What can be seen from Table 3.2 is that up to 2012 the majority of offshore wind farms were installed less than 15km from shore and in less than 20m water depth. As the installed capacity and distance from shore increased there was a requirement for offshore, platform based, substations in order to step the voltage up to HVAC (>100kV) for transmission to shore. Since 2010 there is a trend for offshore wind farms with much longer transmission distances (up to 50km) and in deeper water (around 30m). This has meant offshore wind farms with multiple offshore substations and/or multiple HVAC connections to shore. With larger transmission distances and greater capacity some wind farms are developing HVDC transmission systems such as the Borwin (400MW) and Helwin (576MW) HVDC connection projects [88]. There are also development projects on deep-water wind farms [89] and floating wind turbines [90].

For smaller wind farms, closer to shore, it is possible to export the power at MV either through a single or multiple connections. The change to HV export and offshore substations generally occurs at 100MW or >10km from shore. The change to HVDC generally occurs around the 300MW capacity or >100km from shore but is typically dictated more by distance. These ranges are not fixed and a final decision is made on a case by case basis but these general trends in the configuration of offshore wind farms are shown in Table 3.3.

TABLE 3.3 TRENDS IN ELECTRICAL NETWORKS FOR OFFSHORE WIND FARMS

| Array Capacity | Distance to Shore | Inter Array Voltage | Shore Connection Voltage | Offshore Substation |
|---|---|---|---|---|
| < 30MW | 0-10km | MVAC | MVAC (Single Connection) | No |
| 30-100MW | 0-10km | MVAC | MVAC (Multiple Connections) | No |
| 30 -100MW | >10km | MVAC | HVAC | Yes |
| 100-300MW | 0-100km | MVAC | HVAC | Yes |
| 300MW+ | 0-100km | MVAC | HVAC (Multiple Connections) | Yes (Multiple possible) |
| 300MW+ | 100km+ | MVAC | HVDC | Yes (Converter) |

### 3.6.2 Array Configuration and Protection

As seen in Table 3.2, offshore wind farms have a MVAC array network, typically 20-36kV, with the majority >30kV. The array network configuration of different wind farms varies but is, in the majority of farms, a series of radial circuits connected back to a central location (either onshore or offshore), such as that illustrated in Figure 3.29. The cables in each radial are tapered in size towards the radial extents and this is viewed as the best way to minimise cable costs [64] and give flexibility in operation. Some actual single line diagrams are shown of Horns Rev, North Hoyle and Thanet wind farms in Figure 3.30. North Hoyle is unusual in that the network has some redundancy built into the design which is discussed in Section 3.6.3. Thanet shows a more optimised forked radial configuration which has a centrally located offshore substation and multiple forked radials which minimises the cost of the electrical network.

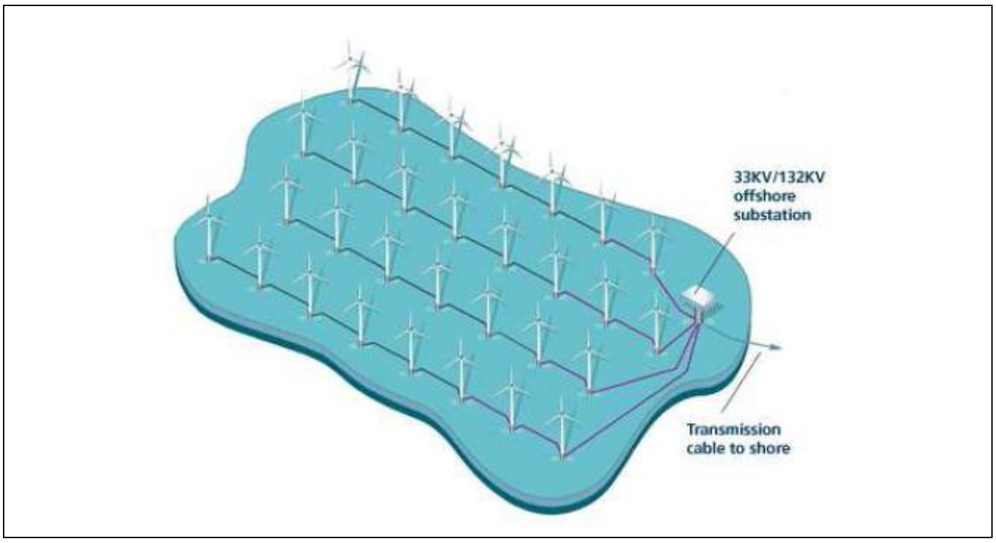



FIGURE 3.29 TYPICAL OFFSHORE WIND FARM ELECTRICAL ARRAY CONFIGURATION (COURTESY ABB)

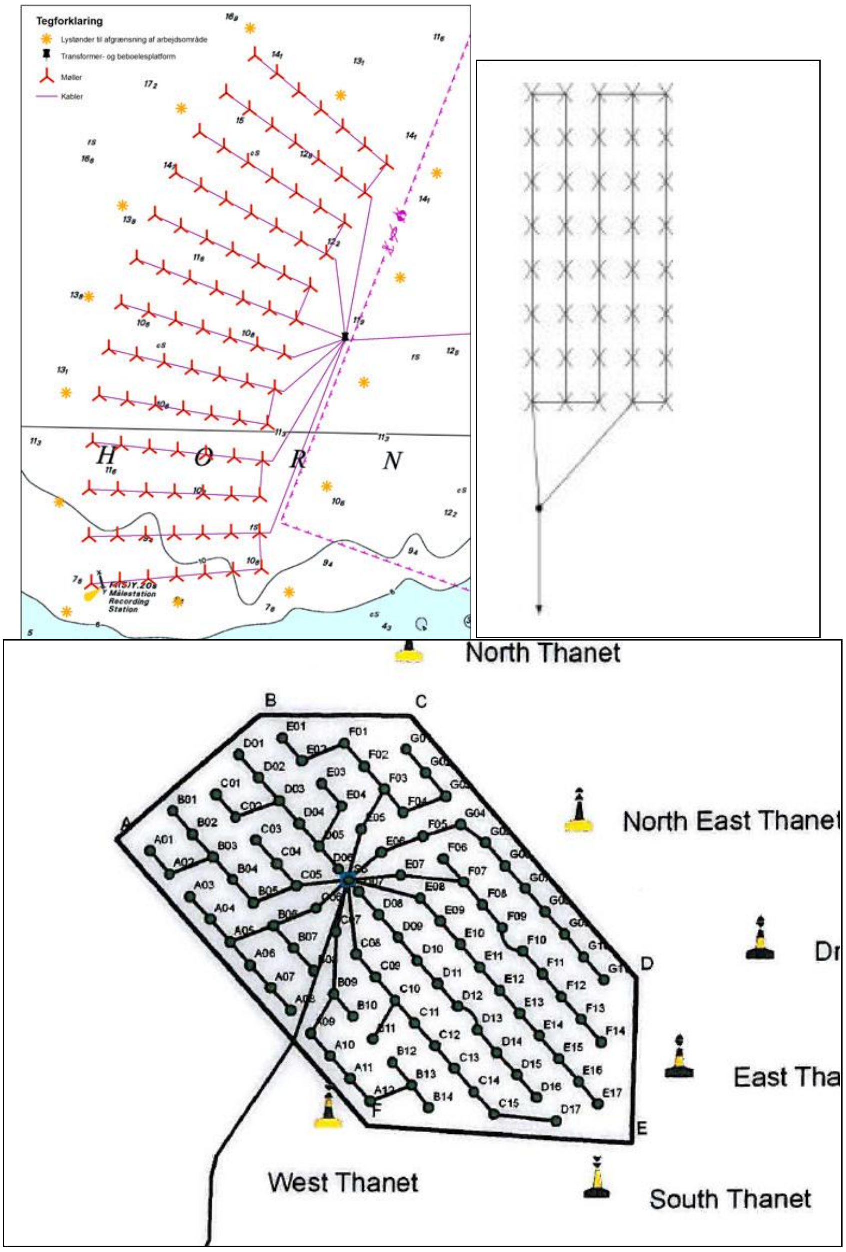



**FIGURE 3.30 OFFSHORE WIND FARM ELECTRICAL SCHEMATICS: HORNS REV (TOP LEFT, COURTESY DONGENERGY.DK), NORTH HOYLE (TOP RIGHT) AND THANET (BOTTOM, COURTESY VATTENFALL.CO.UK)**

Typically a wind turbine is connected (either directly or through a gearbox) to an LV generator of various types. The LV generator has an LV contactor to allow connection or disconnection from the grid during run-up and shutdown. The voltage is stepped up to MV via a transformer located either in the nacelle or in the base of the tower. The MV transformer is connected to the array network via either a switch-fuse or a circuit breaker depending on the transformer rating, a circuit breaker being typically employed above 2MVA capacity [91].

In most cases the connection to the cable is done through a simple switch disconnect with a cable earthing facility although in some cases a direct connection to the cable from the busbar is employed, sometimes a combination of the two (see Figure 3.32) to reduce cost. Some typical connection arrangements are shown in Figure 3.31.

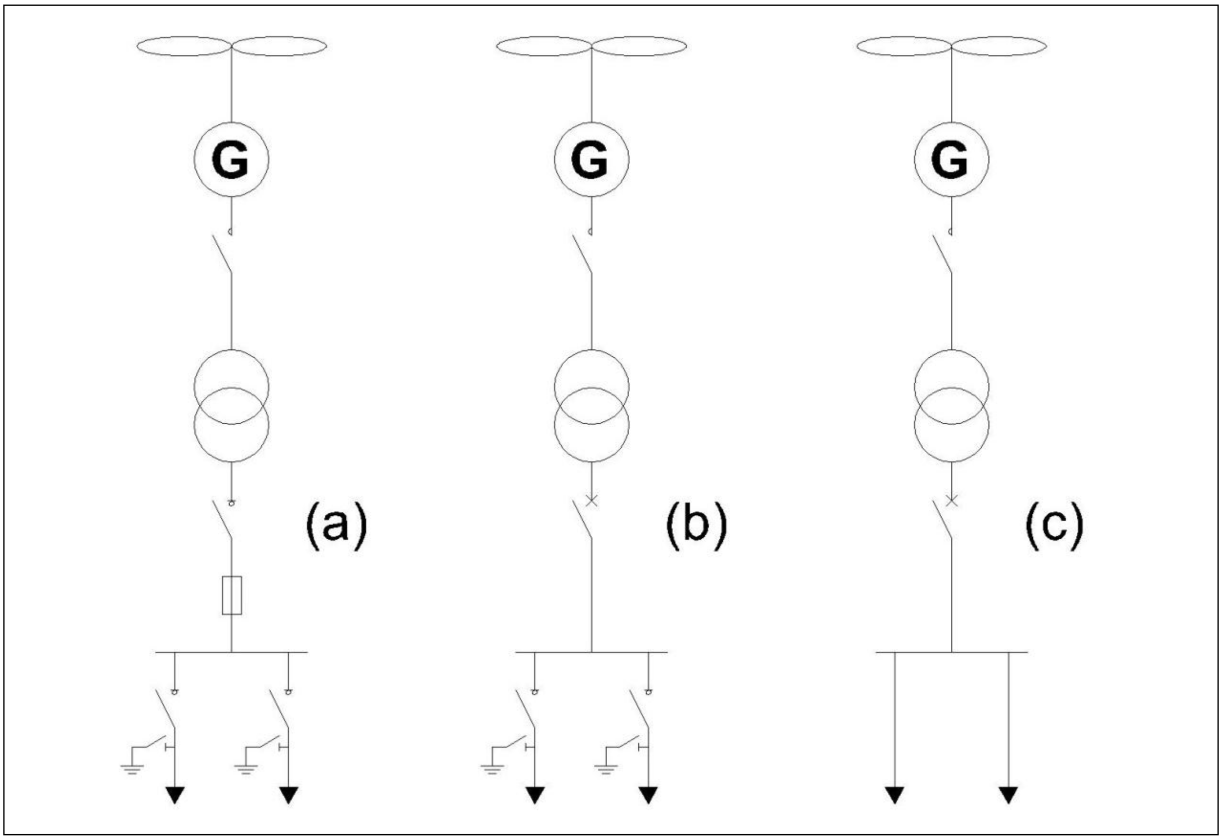



FIGURE 3.31 TYPICAL GENERATOR AND SWITCHGEAR ARRANGEMENTS FOR OFFSHORE WIND.

| | |
|---|---|
| Figure 3.31 (a): | Transformer protection: MV switch fuse |
| | Cable connection: switch-disconnect. |
| Figure 3.31 (b): | Transformer protection: MV circuit breaker |
| | Cable connection: switch-disconnect. |
| Figure 3.31 (c): | Transformer protection: MV circuit breaker |
| | Cable connection: direct connection. |

In the event of a cable fault the cable is protected by the MV fuse or circuit breaker. This disconnects the wind turbine generator and the circuit breaker at the substation (i.e. the beginning of the radial) thus disconnecting the fault from the electrical grid. The cable switch-disconnects are used for isolating (and earthing) a cable for maintenance, and post fault.

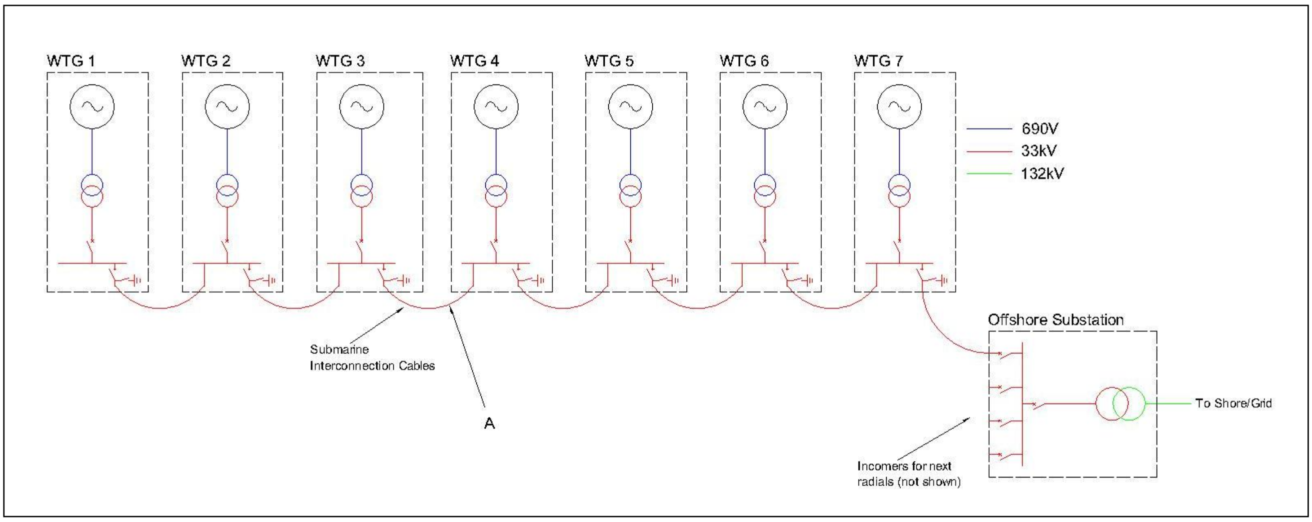



**FIGURE 3.32 TYPICAL CONNECTION FOR OFFSHORE WIND FARM RADIAL**

For example in Figure 3.32, (which shows a combination of cable switch disconnect and direct connection) if a fault occurred at point 'A' on the submarine cable between WTG3 and WTG4, the main circuit breaker at the offshore substation connected to WTG7 would open and the generators (1-7) would be disconnected from the network. The faulty cable would be isolated by opening the cable switch in WTG4. Then the radial could be re-energised from the offshore substation, however only WTG 5, 6 & 7 could generate as the radial circuit is now broken until the cable can be repaired. This results in lost generation capacity and is an inherent weakness of radial network configurations. Also as the generators are all disconnected for the fault at point 'A', there is also lost generation during the reconfiguration of the radial after the fault. In order to overcome this some redundancy and sectionalising have been proposed.

### 3.6.3 Redundancy and Sectionalising

Yang et al concluded [68] that with reasonable investment in redundancy the reliability of an offshore wind farm improves. Ackermann presents a selection of layouts for offshore collector systems [63] introducing different redundancy concepts, shown in Figure 3.33.

Redundancy in the circuit can be achieved in a variety of ways, the simplest being the connection of two radials together at their extents. However, this means that each radial must (in a worst case scenario) carry the additional rated power from the other radial, meaning a requirement for larger cables in both radials. Therefore the increased security and reliability comes at the expense of additional, larger cables and switchgear. A compromise can be achieved by not rating the redundant cabling at full capacity and curtailing generation to the circuit limit should that limit occur while the alternative circuit is in place. This allows a reduction in cable size in the redundant circuit. To date the vast majority of offshore wind farms have employed a simple radial circuit with no redundancy, this being viewed as the most economical option.

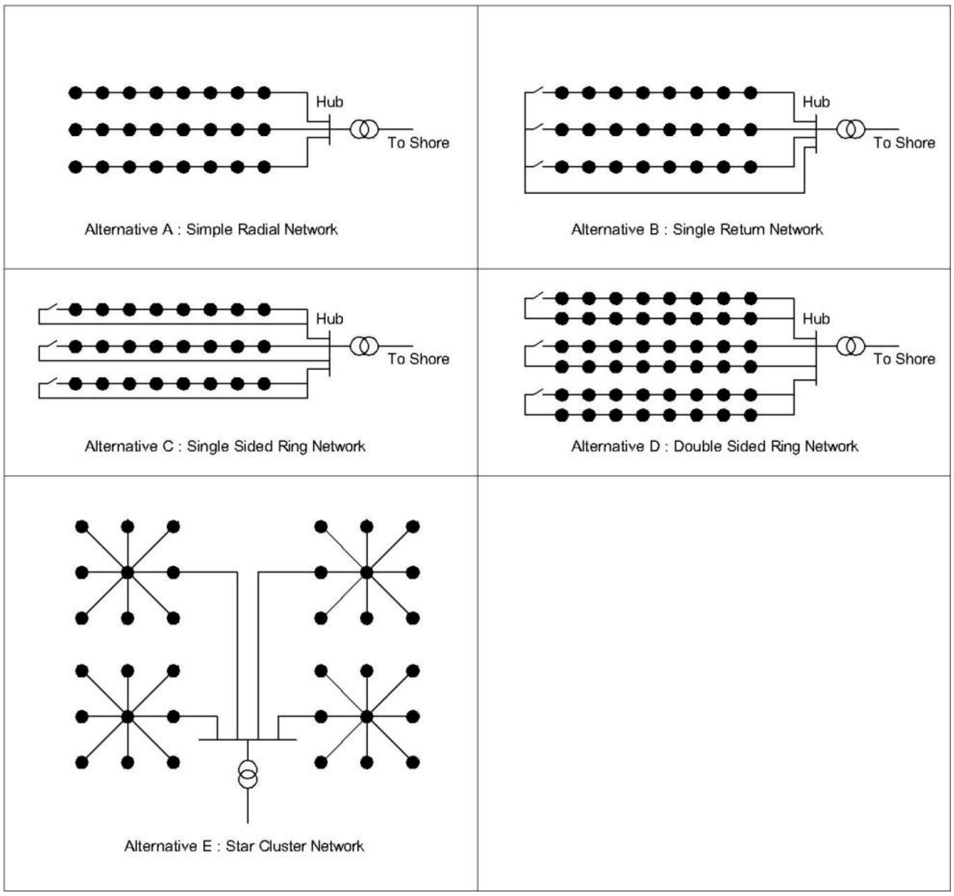



**FIGURE 3.33 REDUNDANCY CONCEPTS FOR OFFSHORE WIND FARM ARRAYS**

In [65] Franken et al establish that increased availability can be achieved using redundant circuits, however this availability can be increased further given a sectionalising approach to protection. Franken et al conclude that the equivalent of up to 2 wind turbines generated annual energy can be saved with the addition of redundancy and sectionalising. This was based on a 160MW wind farm (40 x 4MW Turbines).

### 3.6.4 Submarine Cable Installation

The method of cable installation in an offshore wind farm has developed rapidly with the evolution of the industry and there are now custom built vessels for this purpose. The total cable installation consists of the following steps (considering a wind farm with offshore substation)

**1.** Transmission cable shore end operation
**2.** Transmission cable to offshore substation installation
**3.** Transmission cable pulling into offshore substation
**4.** Array cable installation
**5.** Array cable pulling into turbine bases
**6.** Array cable pulling into offshore substation

This is completed with a combination of ships, barges, ROVs, ploughs, and divers. From a WEC array perspective steps 1, 2 and 4 would be identical as to an offshore wind farm, although there will be some site specific constraints and peculiarities. Therefore the areas of interest are steps 3 and 5.

Step 3: This involves the pulling of the cable using a pull wire into the substation through a j-tube. The cable is installed up to a point adjacent to the substation base and extra cable is played out onto the seabed (to allow for connection into the substation). The cable is then cut and a pulling nose fitted to the cable end. From the offshore substation a pull wire is passed down the j-tube where it is picked up (by ROV or diver.) and connected to the cable pulling nose. The cable is then winched up into the offshore substation where it is prepared for termination to the switchgear.

Step 5: This involves the pulling of the cable using a pull wire into the wind turbine base through a j-tube. The cable is installed up to a point adjacent to the wind turbine base and extra cable is played out onto the seabed (to allow for connection into the wind turbine). The cable is then cut and a pulling nose fitted to the cable end. From the wind turbine a pull wire is passed down the j-tube where it is picked up (by ROV or diver) and connected to the cable pulling nose. The cable is then winched up into the wind turbine where it is prepared for termination to the switchgear.

For the cable installation, the use of specialist vessels and equipment is critical. The cable installation and protection depends on numerous factors including the location, seabed conditions, and expected marine traffic. The cable installation process cost can typically be higher than the cable cost itself [66], sometimes a multiple of the cable cost.

There are several possible methods of cable installation which are briefly outlined below:

1. Cable installation on seabed: This is the simplest installation procedure whereby the cable is laid onto the seabed and simply kept in place by its own weight. This would rarely be used for power cables in offshore wind farms as the cables are subject to damage by currents, trawlers, anchorage and marine life. It is used in very deep water for long distance communications cables.
2. Pre trenching and installation: This method involves trenching before the cable is installed and then installing the cable into the trench and closing the trench. This procedure is not normally utilised in offshore wind farms.
3. Cable installation and post installation trenching: This method involves the cable being installed on the seabed. Following installation the cable is trenched and buried to a specified depth. The trenching and burial is normally undertaken by an ROV using a jetting system. This is the normal procedure for installing short lengths of cable in shallow water such as the infield cables in an offshore wind farm.
4. Combined cable installation and burial: This method involves the cable being installed on the seabed, trenched and buried simultaneously. The trenching and burial is undertaken with a plough which is towed behind the cable installation vessel. This

is the normal procedure for installing long lengths of cable in shallow water such as the transmission cable to shore in an offshore wind farm.

5. Cable installation and post protection: This method involves the cable being installed on the seabed. Following installation the cable is protected using rock dumping or concrete mattresses. This is suitable for where the seabed conditions do not permit burial or where the cable must cross over another cable/pipe.
6. Cable installation and pre protection: This method involves some mechanical protection being installed on the cable as it is installed. This protection could be some ducting system like Uraduct. This is used for specialised protection application such as the touchdown point where the cable enters the wind turbine J-tube and may be subject to scouring.
7. Horizontal Directional Drilling: This method involves HDD from shore to a connection point. A duct is then inserted into the HDD hole and the cable is drawn through the duct. The length of the HDD is limited to a few km so it is not practical for offshore wind farms. It has been used for tidal energy devices due to the high currents in the area of installation.

Array cabling is normally installed using method 3 whereby the cable is laid and subsequently buried. Method 5 or 6 may be used for the exposed part of the array cable around the J-tube to reduce scour or cable damage at the J-tube entrance.

Export cabling is normally installed using method 4 whereby the cable is laid and simultaneously buried. Method 5 or 6 may be used for the exposed part of the cable around the J-tube (at the offshore substation) to reduce scour or cable damage at the J-tube entrance.

The shore end of the cable is normally floated to shore, using buoyancy modules, and then buried after installation by excavators or by ROV to the low water line.

The main section of the cable is installed by a cable plough. The cable plough can start to install the cable from the high water line. The plough is pulled behind the cable lay vessel and simultaneously cuts a trench and lays the cable in this trench. There are two types of cable plough, displacement and non displacement. Displacement ploughs cut a large trench and lay the cable in the trench which is subsequently backfilled. Non-displacement ploughs cut a small slice into the seabed with a blade like ‘shear’. The cable is simultaneously fed into this slice and immediately buried as the slice naturally closes in. Ploughs can bury cables in a larger variety of seabed soils than jetting ROVs including hard clays and loose shale or stones.

### 3.6.5 Offshore Substations

For wind farms with capacities of >100MW or sometimes transmission distances of >10km an offshore substation is required to step up the MV array voltage to HV for export. This reduces export losses and export cable sizes. It is not practical that the voltage could be stepped up to HV in each of the turbines. In order to collect the power from the radials in the wind farm and step it up to HV an offshore substation is required.

An offshore substation typically contain the following components:

- MV Switchgear for collection of the array power
- Oil Filled Step Up Transformer to step the voltage up to HV for connection to shore
- Fire and Blast Protection for Transformer
- HV Switchgear for protection and isolation of transformer and HV export cable
- Line Reactors
- Protection and Metering Relays
- Auxiliary and Emergency Power Systems
- Accommodation Quarters and Workshop facilities
- Medical and Rescue Equipment
- Helipad

For HVDC systems the offshore substation also contains the converter to convert the voltage from HVAC to HVDC for export. HVDC offshore substations are significantly larger and heavier as a result.

HVAC offshore substations are delivered as a single unit and can weigh over 2000t and have an area of up to 800m$^2$. Typically a single HVAC offshore substation would be rated for a maximum of 500MW.  For large wind farms multiple substations are required each with their own export cable to shore giving some redundancy to the export system.

HVDC offshore substation can weigh more than 10,000t and are beyond the capability of most heavy lift vessels.  These platforms must be self installing structures which are floated to site and jacked up into position.  HVDC offshore substations up to 690MW are installed with individual platforms up to 900MW in planning.

Offshore substation foundations can be similar to that for an offshore wind turbine although with a different load pattern.  For small offshore substations a monopile foundation is suitable.  For large offshore substations distributed piles or a jacket foundation is more suitable.  For very large HVDC offshore substation the foundation must self install as no heavy lift is possible for this scale of substation.  Some photos of offshore substations are shown in Figure 3.34.

**FIGURE 3.34 OFFSHORE SUBSTATIONS (FROM TOP LEFT CLOCKWISE) – BARROW (2006, 450T, 90MW, COURTESY WIKICHOPS), SHERRINGHAM SHOAL (2011, 875T, 316MW), BORWIN BETA (HVDC – SELF INSTALL) (2014, 10,000T, 800MW, COURTESY WAERFELU).  DOLWIN BETA (HVDC – SELF INSTALL) (2014, 20,000T+, 900MW, COURTESY STEN DUELAND)**

### 3.6.6 HVDC Transmission for Offshore Wind

The first HVDC links of significant scale were developed in the 1970s and the transmission technology has developed significantly in the intervening decades. HVDC systems do not suffer from reactive losses and so are more suitable for long distance, however as they require a converter station at both ends they are expensive relative to HVAC and therefore they are only economical for large capacities/distances. HVDC links were initially used to connect remote generators (such as hydroelectric stations) to load centres, interconnecting countries, and also connecting systems of different frequencies (such as the south and north of Japan). In recent years, however, they have gained attention for connecting large offshore wind farms due to the increasing capacity and export distances for planned wind farms.

HVDC systems can be broken into two categories, LCC (Line Commutated Converter) and VSC (Voltage Source Converter)

LCC Systems have the advantage that they have a long and proven track record with most HVDC systems installed in the world being LCC based. They have the disadvantage of requiring a large footprint due to the component size and also requiring a very stable AC grid at both ends to operate. For offshore wind farms this can mean a diesel generator or StatCom (Static Compensator) is required to support the offshore grid in times of low wind. LCC systems have an overall efficiency of 97-98%.

The basic LCC system uses monopole transmission, i.e. a single cable is used with the sea as the return path. This reduces system cost but has other negative effects such as electrochemical reactions on other subsea services such as gas pipelines, electro-chlorination and navigation impact on ships. This is not normally acceptable so a monopole with a separate of integrated return path is normally used for monopole configurations (see Figure 3.35). The other option is to use a bipole configuration which requires two separate HVDC cables but allows a larger voltage across the two poles, as one is positive and the other is negative.

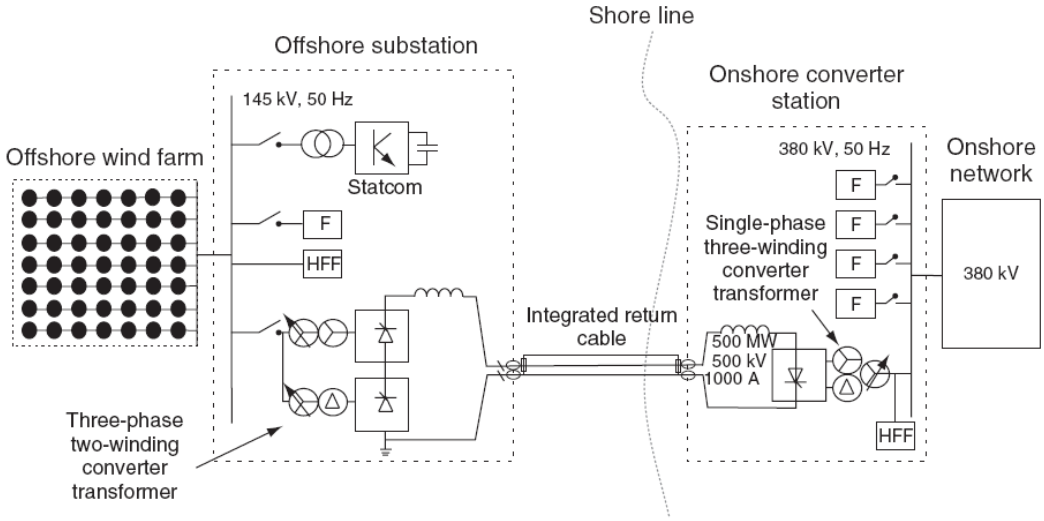



**FIGURE 3.35 LINE COMMUTATED CONVERTER (LCC) HVDC TRANSMISSION SCHEME [63]**

VSC Type HVDC Transmissions have become more popular for low and medium power transmission systems since the development of high power IGBTs in the 1990s. Using IGBTs means that pulse width modulation (PWM) can be used to convert DC to AC rather than LCC techniques.

VSC Systems require a bi-polar cable network and normally operate at lower voltage than LCC systems due to ratings of IGBTs and XLPE cables. VSC systems are less efficient than LCC systems with typical efficiencies of 90-95%.

An example of a HVDC system installed for an offshore wind farm is the BorWin Alpha platform which is rated for 400MW. This uses the ABB HVDC-Light VSC system and all other offshore wind farm HVDC connections (installed and planned) use VSC systems.

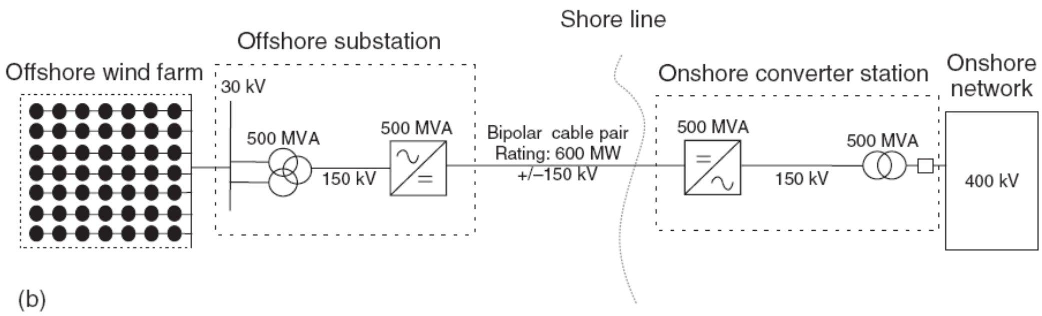



**FIGURE 3.36 VOLTAGE SOURCE CONVERTER (VSC) HVDC TRANSMISSION SCHEME [63]**

The choice of when to use HVDC over HVAC depends on numerous factors including the overall cost of the solution. However the predominant factors are the capacity of the wind farm and the distance to shore. The likely transmission concept for a combination of these two factors is shown in Figure 3.37. As can be seen any offshore wind farm with an installed capacity over 400MW or a distance of greater than 100km from shore would be considered a candidate for HVDC transmission. In reality any wind farm with a transmission distance of greater than 100km would need to have a capacity greater than 400MW for a variety of other economic reasons. The choice between HVAC and HVDC at the extents of these limits will be down to cost and efficiency.

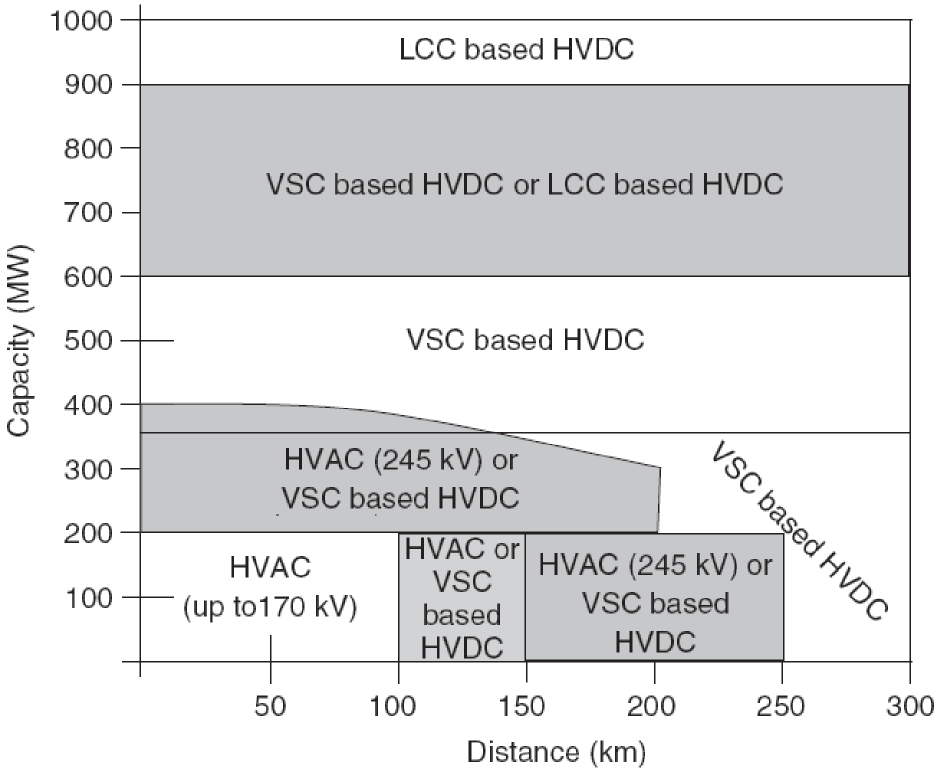



**FIGURE 3.37 TRANSMISSION CONCEPTS BASED ON DISTANCE (TO SHORE) AND CAPACITY OF OFFSHORE WIND FARMS [63]**

There are still risks associated with the availability of these HVDC systems as they introduce numerous additional ‘active’ electrical systems which have multiple failure modes.

### 3.6.7 Efficiency of Offshore Wind Collection and Transmission Systems

In [92], [70]& [93] the active power losses and efficiency of offshore wind farms are evaluated and it is shown that up to 98% efficiency can be achieved for certain theoretical configurations, however 96-97% is more typical for the majority of offshore wind farms which have a similar electrical configuration as shown in Figure 3.29.

## 3.7 Crossover and Differences between Offshore Wind Farms and WEC Array Electrical Networks

There is certainly a crossover of knowledge possible between offshore wind farm and WEC array electrical network design. This is particularly so in the selection of optimal network configuration, export solutions for various scales of WEC arrays, submarine cable installation processes, and offshore substation design.

Offshore wind farms electrical network configurations have converged on radial designs. More recently optimisation programmes are used to give the most efficient and lowest cost electrical network and locate the offshore substation for same. The rationale for radial networks is primarily economic as the literature has shown that redundant network configurations would increase availability.

Cable installation procedures and vessels for offshore wind will, for the most part cross over to WEC arrays. WEC array sites, as will be shown, may be in deeper water and more energetic locations. This is a challenge for WEC array electrical networks which is discussed in Chapter 5.

The export solutions for a range of offshore wind farm capacities and transmission distances (Table 3.3) will be relevant to WEC array electrical networks and this is reflected in Chapter 4.

There are key differences between offshore wind farm and WEC array electrical network design. These are outlined briefly below and solutions to deal with these are presented in later sections.

1. At present the majority of WEC prototypes are rated around 1MW. This is a lower rating than a typical offshore wind turbine which is rated around 3-4MW

with larger turbines in development. Smaller individual WEC ratings will present challenges for the economic design of WEC array electrical networks

2. WEC designs are divergent unlike offshore wind turbines, which are almost all three bladed, horizontal axis. This can mean that a generic solution for WEC array electrical networks will be more challenging until such time as WEC technology designs converge.
3. Some ‘direct drive’ WEC concepts have a high peak to average output power ratio, i.e. a low capacity factor. This presents challenges for the economic design of WEC array electrical networks and also may cause power quality issues (See Chapters 5 and 6)
4. The water depth at potential WEC array sites is likely to be much deeper than offshore wind sites which presents challenges for offshore substation foundation design and also for submarine cable installation.
5. In order to access deeper water depths the export distance to shore may be greater for WEC arrays. This is geographically dependent.
6. Unlike offshore wind farms, in WEC arrays the devices require removal from site for maintenance activities. This requires connection and disconnection functionality but also may break the electrical circuit for upstream devices.
7. WECs are not fixed structures like offshore wind turbines and therefore require dynamic cable connections to the electrical network
8. The array spatial configuration for WEC arrays is driven by different factors than that of an offshore wind farm.
9. As WEC array sites are high energy wave sites the installation and protection of submarine cable systems will be challenging
10. WEC technology is not proven onshore, as is the case with offshore wind. Therefore smaller initial WEC arrays are expected which will be economically challenging.

In the next Chapter the state of the art technologies for WEC arrays and the crossover knowledge from offshore wind will be utilised to undertake a techno-economic optimisation of WEC array electrical networks

## 3.8 Conclusion

Electrical network design for WEC arrays is a novel research problem but is critical to the delivery of cost effective WEC arrays. An understanding of the electrical components and systems on-board the WEC devices, within the WEC array electrical network, and any experience from WEC test sites or WEC prototypes is invaluable for developing a techno-economic analysis of future WEC array electrical networks. Some of these electrical networks for test sites and prototypes may have developed sub-optimally and show signs of divergence in configuration, components and concept.

The offshore wind industry is relatively mature and electrical network designs have converged. There is certainly opportunity for cross-over of knowledge from offshore wind to wave industries. However, the differences and novel challenges which WEC array electrical networks present must be acknowledged and addressed.

There are key differences between offshore wind and WEC array electrical networks. These differences are primarily in the areas of device ratings, site characteristics, maintenance strategies and around the key interfaces between the WEC and the electrical network. Optimising these key interfaces to allow for the required functionality but at an acceptable cost is explored in the next chapter.

# Chapter 4

# Techno-economic Analysis of Electrical Networks for WEC Arrays

## 4.1 Introduction

There is minimal experience in the wave energy or utility industry of designing and installing electrical networks for WEC arrays, with the closest comparison being offshore wind farms. The offshore wind industry has developed to the stage that very large wind farms (>500MW) have been installed, with larger projects in development. There is some potential knowledge transfer from offshore wind to WEC array electrical network design as outlined in Chapter 3. It has been shown also, in Chapter 3, that there are some key differences between the array electrical network requirements of both offshore wind and wave, which require original designs to be developed.

In this chapter, a techno-economic analysis of electrical networks for WEC arrays is undertaken. Critical design factors, constraints, and assumptions are examined by considering WEC array layout factors, economic and performance targets, and key interfaces between the WEC and the array electrical network.

### 4.1.1 Technical, Functional and Economic Factors

Techno-economic analysis must consider the economic, technical and functional factors in the context of the cost competitiveness of the entire solution. These are listed below but outlined in detail in the subsequent sections.

- Economic factors include:
    - Capital cost of equipment
    - Installation costs
    - Operational costs
    - Decommissioning costs

- Technical factors include:
    - WEC ratings
    - Capacity factor
    - Array Scale
    - Site characteristics (water depth, distance to shore)
    - Array spatial layout
    - Key interfaces
- Functional factors include:
    - Connection and disconnection for installation and maintenance
    - Continuity of network during maintenance and faults
    - Safe operability
    - Electrical protection

The factors given above must be considered when optimising the design of the electrical network for WEC arrays. A balance must be struck between a technically superior solution and one which is economically competitive. For WEC test facilities, such as those described in Section 3.4, the balance is in favour of technically superior solutions as there is less commercial pressure on the electrical network design.

The scale of the array being evaluated must also be considered. One challenge for WEC arrays is that the technology is novel and cannot be proven onshore. Therefore it is likely that smaller arrays, perhaps less than 10MW, will be required initially. Early offshore wind projects took proven onshore technologies into the offshore environment and therefore did not require small initial wind farms to prove the technology. These smaller arrays will challenge the economics further as economies of scale cannot be achieved.

### 4.1.2 Methodology

As outlined there are many factors which must be considered for a techno-economic analysis of WEC array electrical networks. The methodology for optimisation is outlined below and in Figure 4.1 and ensures that all design requirements, constraints and assumptions are considered in the development of optimal electrical networks for WEC arrays.

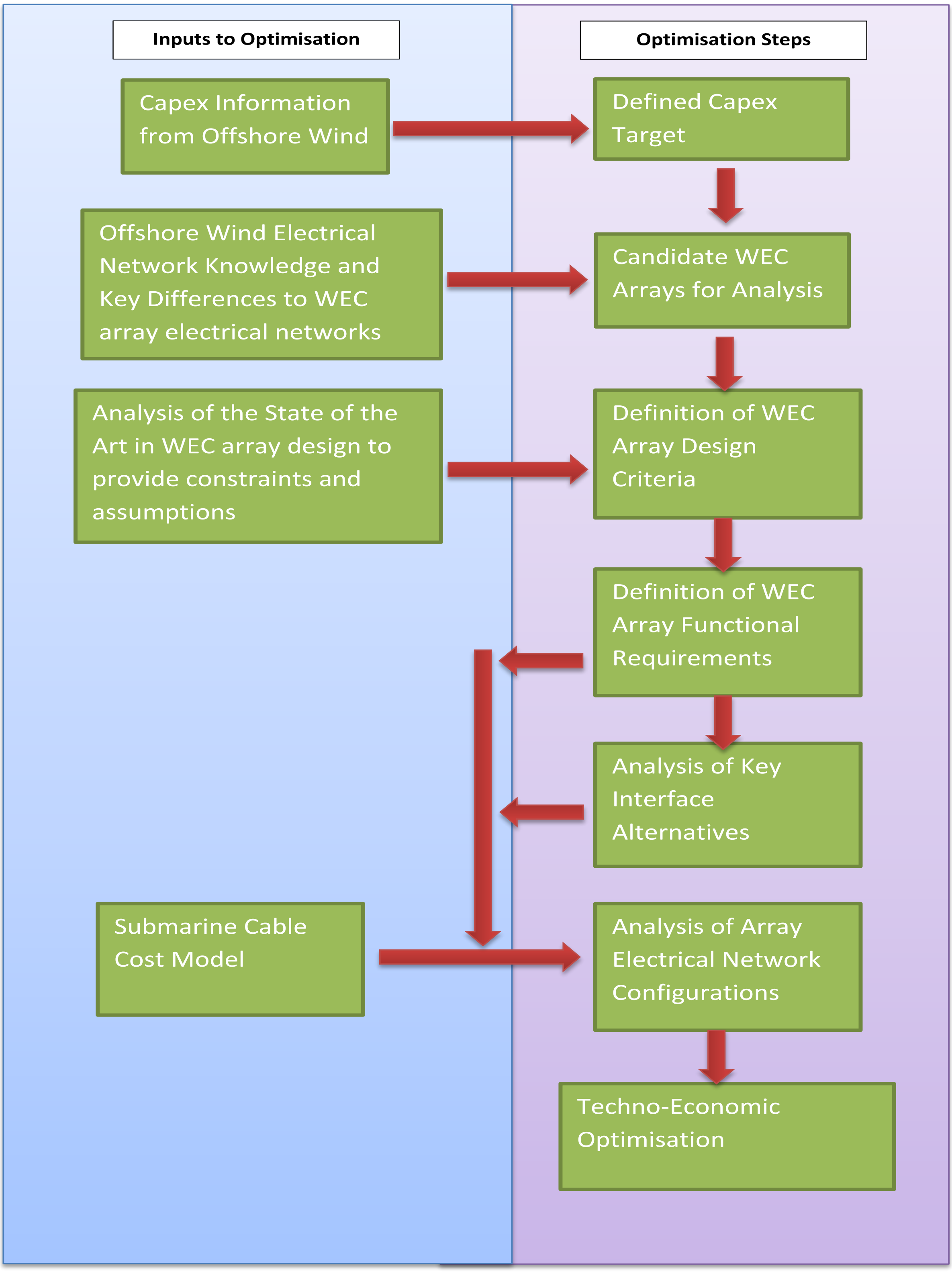



**FIGURE 4.1 GRAPHICAL REPRESENTATION OF TECHNO-ECONOMIC OPTIMISATION PROCESS**

The first step is to analyse wave energy in the European market context to understand what the competitive costs for wave energy are. From this the available, or target CAPEX for electrical systems can be estimated. This target cost guides the optimisation process from an economic aspect.

An analogue to WEC array electrical networks is the evolution of electrical networks for offshore wind, which was analysed in Chapter 3. This examined how designs converged and the driving factors behind this convergence. Importantly, while analysing where offshore wind can cross over to wave energy, the key differences have been identified between the two. Solutions which allow for these key differences while acknowledging crossover areas will be critical to the optimisation process.

The technical and functional factors which are outlined briefly in Section 4.1.1 are analysed in detail. This provides an understanding of the characteristics of a WEC array in terms of array spatial layout, device separation, water depth, distance from shore, WEC nameplate ratings, and capacity factors amongst others. Some assumptions must be made here to allow for an optimisation process, and these are outlined.

The functional requirements and constraints as outlined in Section 4.1.1 are analysed in detail. Examples include installation requirements, operational requirements, maintenance requirements, and protection/safety requirements.

Critical design elements are the key interfaces between the WEC and the array electrical network. Components at these interfaces can fulfil connection and disconnection functions, in addition to protection functions. The components at the key interface include submarine connectors, switchgear, and hull penetrations. These are critical but potential high cost components. There are a variety of potential methods for realising these components and these methods are also analysed in the context of the overall WEC array electrical network cost and functionality.

Using all the analyses from the previous steps, a techno-economic optimisation of the array electrical network can be undertaken, and suitable designs evaluated from an economic, technical and functional perspective. This allows an optimised design to be selected for further analysis.

The optimised electrical network design can be evaluated for efficiency at various voltage levels, with efficiency calculated over the annual output of a typical WEC allowing the annual energy losses to be calculated for a typical array.

Throughout this chapter the techno-economic optimisation and subsequent evaluation is undertaken using a combination of statistical analysis, frequency domain analysis, time domain analysis, and economic modelling. In some cases some subjective analysis of alternatives is undertaken under predetermined criteria.

## 4.2 Wave Energy Cost Breakdown and Target Cost

Electrical systems for offshore wind farms can typically cost 20-25% of the overall system CAPEX [2], and the same is anticipated for commercial WEC arrays [3]. For pre-commercial arrays the percentage of CAPEX for electrical systems will be lower as the cost of the actual converters will be much higher. Renewable UK [12] expects investment costs of offshore wind to remain at circa £3m/MW (~€4m/MW) up to 2022 with levelised cost of energy (LCoE) reducing to £130/MWh (€160/MWh) during that period.

As outlined in Chapter 1 wave energy must be competitive with other comparable renewable energy sources if it is to obtain a significant market. So if the target cost of WEC arrays is that of offshore wind farms and the proportion of that cost for electrical systems is 20-25% of the overall cost then the following costs for WEC array electrical systems would be expected. This assumes that similar capacity factors can be achieved for wave farms as for current offshore wind farms.

| | |
|---|---|
| Wave Energy Target Installed Costs: | €4 m/MW [12] |
| WEC Array Electrical Systems Target Costs: | €1m/MW (25% of the above) |

Therefore the electrical system in the WEC array must cost less than €1m/MW to be comparable in cost to offshore wind. Although the cost of the WEC is expected to come down dramatically as the industry reaches maturity, the cost of the electrical elements are predominantly mature at present as mature technologies are expected to be utilised. There are however some design criteria which may increase the electrical system costs and also some potential strategies for reducing costs which are discussed in Chapter 5.

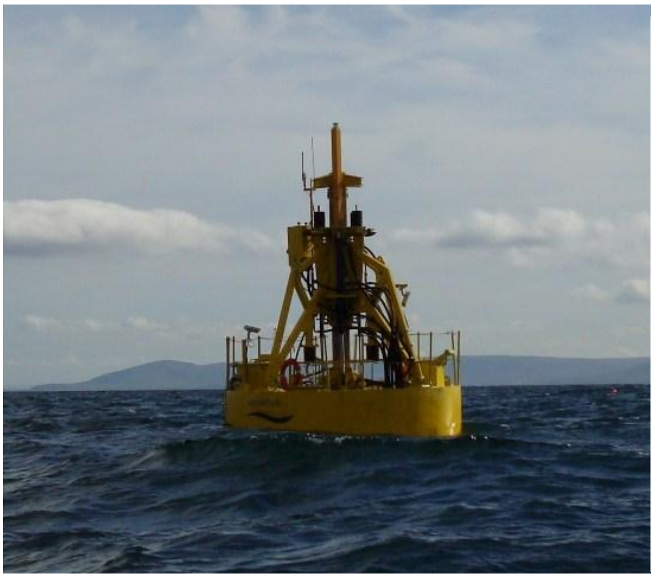
The challenge, and objective of this section, is to design a WEC array electrical network which can provide the required functionality within the technical and economic constraints outlined.

## 4.3 WEC Array Design Considerations, Constraints and Assumptions

To facilitate the techno-economic analysis of WEC array electrical networks this section outlines major design considerations, technical constraints and working assumptions for the WEC array. This information, coupled with the state-of-the-art knowledge from offshore wind electrical network design shown in Section 3.6, allows the development of a credible outline and roadmap for wave energy converter arrays. The following sections describe important factors in this optimisation.

### 4.3.1 The Wavebob Wave Energy Converter

The WEC used as a candidate for part of this research is the Wavebob device shown in Figure 4.2. However, the results and conclusions are generally applicable to any deep-water floating WEC. The results may also be somewhat applicable to other types of WEC, floating offshore wind and tidal energy converter arrays.



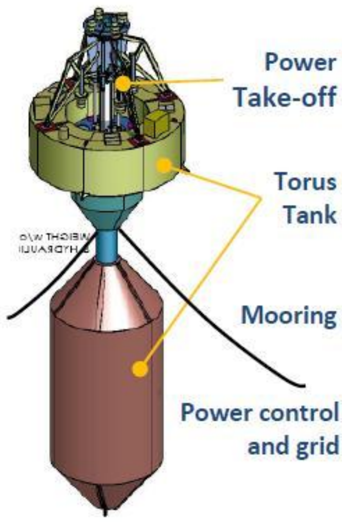



FIGURE 4.2 1:4 SCALE WAVEBOB DEVICE IN GALWAY BAY (L) AND DEVICE DRAWING (COURTESY WAVEBOB LTD.)

The Wavebob device is a self reacting point absorber type WEC [4]. The device is made up of two main structures, the torus and the float-neck-tank (FNT), connected by a power take off (PTO) system. This device has been tested at various scales up to 1:4 scale.

A full scale device was planned for deployment off the west coast of Ireland[2]. The general characteristics for the full scale Wavebob device are given below.

Geometry: Torus Diameter: 22m, Height: 65m, Freeboard: 20m

Design water depth: >100m

Device Electrical Rating: 1MW

### 4.3.2 Site Locations

The full scale Wavebob device is designed for operation off the west coast of Ireland in >100m water depth. The 100m contour off the west coast of Ireland is shown in Figure 4.3. The 100m contour mostly lies between 10km and 25km from the nearest landfall depending on the location. Areas of counties Mayo, Galway and Kerry have landfall within 10km of the 100m contour and may be utilised in the first deep-water arrays, although there will also be an emphasis on the availability of grid connection capacity, which may be better in some locations. Later arrays can be expected to be more than 20km from landfall.

[2] In 2013 Wavebob was put into administration and the technology development has not continued as planned

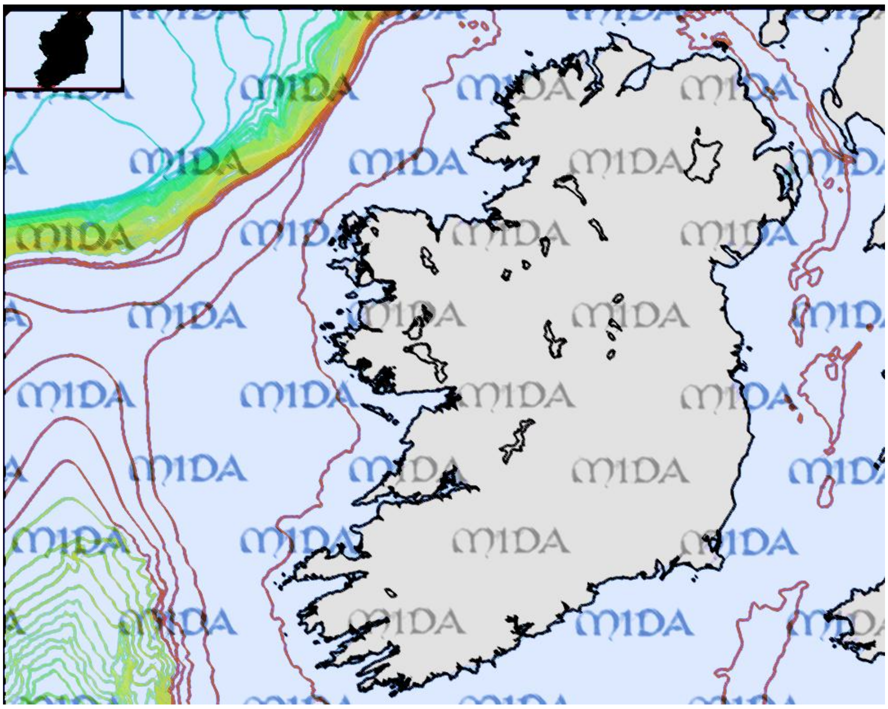


FIGURE 4.3 100M DEPTH CONTOUR (FIRST RED LINE OFF THE WEST COAST OF IRELAND) [SOURCE MIDA]

### 4.3.3 Resource and Generation Distribution

To understand the generation characteristics of the Wavebob WEC off the west coast of Ireland the scatter diagram from the Belmullet test site off the coast of Mayo, Ireland is analysed in detail and the Wavebob frequency domain model is utilised. The scatter diagram is shown in Figure 4.4. The scatter diagram shows the occurrences (in the case below 10,000) of significant wave height, $H_s$, and wave period, $T_p$, over a particular period (typically one year). The scatter diagram characterises the resource at a particular site.

**Bulmullet Scatter Diagram: Number of Occurrences (total = 10,000)**

| Significant WaveHeight, Hs [m] \ Wave Period, Tp [s] | 5.54 | 6.12 | 6.71 | 7.29 | 7.88 | 8.46 | 9.04 | 9.63 | 10.21 | 10.79 | 11.37 | 11.96 | 12.54 | 13.12 | 13.71 | 14.29 | 14.88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0.5** | - | - | - | - | 5 | - | - | 14 | - | 14 | 9 | - | - | 5 | 9 | - | - |
| **1.0** | 14 | 9 | 5 | 14 | 5 | 23 | 18 | 32 | 64 | 18 | 73 | 60 | 41 | 9 | 9 | - | 9 |
| **1.5** | 9 | 46 | 14 | 28 | 60 | 92 | 119 | 110 | 115 | 110 | 73 | 64 | 23 | 14 | 23 | - | 5 |
| **2.0** | - | 5 | 14 | 37 | 37 | 96 | 119 | 156 | 161 | 165 | 156 | 83 | 23 | 28 | 28 | 5 | 9 |
| **2.5** | - | - | - | 18 | 46 | 78 | 124 | 156 | 193 | 206 | 183 | 92 | 69 | 64 | 28 | - | - |
| **3.0** | - | - | - | 5 | 14 | 78 | 106 | 119 | 165 | 206 | 174 | 133 | 55 | 46 | 32 | 18 | 5 |
| **3.5** | - | - | - | - | - | 14 | 64 | 101 | 170 | 197 | 239 | 170 | 78 | 92 | 9 | 9 | - |
| **4.0** | - | - | - | - | - | - | 5 | 32 | 87 | 106 | 206 | 165 | 124 | 60 | 50 | 9 | 5 |
| **4.5** | - | - | - | - | - | - | 5 | 23 | 69 | 106 | 202 | 202 | 106 | 133 | 41 | 23 | - |
| **5.0** | - | - | - | - | - | - | - | - | 23 | 55 | 119 | 151 | 161 | 55 | 41 | 32 | 14 |
| **5.5** | - | - | - | - | - | - | - | - | - | 23 | 55 | 106 | 161 | 92 | 28 | 18 | 5 |
| **6.0** | - | - | - | - | - | - | - | - | - | - | 5 | 55 | 83 | 92 | 50 | 23 | 14 |
| **6.5** | - | - | - | - | - | - | - | - | - | - | - | 28 | 46 | 64 | 50 | 28 | 5 |
| **7.0** | - | - | - | - | - | - | - | - | - | - | - | 14 | 32 | 37 | 60 | 37 | 14 |
| **7.5** | - | - | - | - | - | - | - | - | - | - | - | - | 9 | 23 | 46 | 23 | 18 |
| **8.0** | - | - | - | - | - | - | - | - | - | - | - | - | 5 | 14 | 18 | 14 | 9 |
| **8.5** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 9 | - | 9 |
| **9.0** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 5 | 5 | - |
| **9.5** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 5 | - | - |
| **10.0** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

**FIGURE 4.4 BELMULLET SCATTER DIAGRAM [94]**

Using this scatter diagram and a frequency domain simulation model of the Wavebob device, the distribution of the annual generated power for the Wavebob device at the Belmullet site is determined. Two results of interest are shown in Figure 4.5 and Figure 4.6.

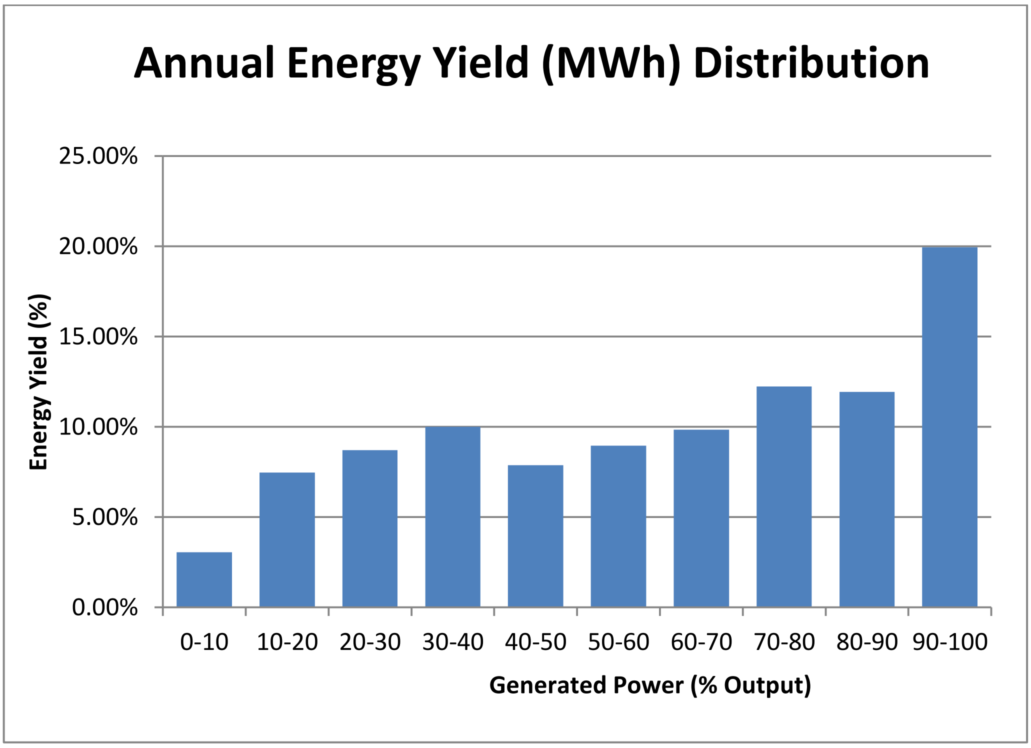



**FIGURE 4.5 WAVEBOB AT BELMULLET - ANNUAL DISTRIBUTION OF ENERGY YIELD BY % OUTPUT**

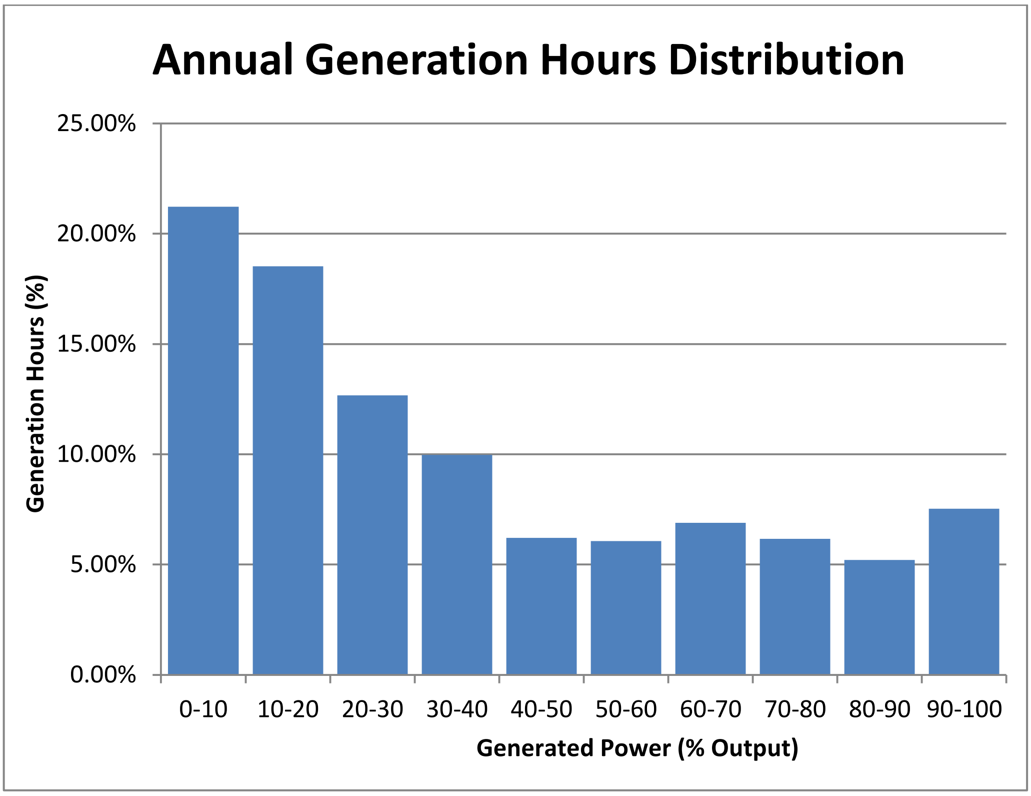



**FIGURE 4.6 WAVEBOB AT BELMULLET - ANNUAL DISTRIBUTION OF GENERATION HOURS BY % OUTPUT**

Figure 4.5 and Figure 4.6 illustrate the generation characteristics of the Wavebob WEC at the Belmullet site. It can be seen, in Figure 4.5, that ~45% of the annual energy yield is produced when the WEC generates above 70% of the rated power. Also, in Figure 4.6, it can be seen that the WEC generates below 70% of rated output for ~80% of the year. Therefore ~45% of the energy comes from ~20% of the operation time.

An understanding of this variability allows the calculation and optimisation of the efficiency of the WEC array electrical network in Section 4.7.

### 4.3.4 Array Spatial Configuration

The spatial configuration of an array of WECs will be determined from a number of factors, including:

1. Maximising energy capture and reducing destructive interference
2. Minimising the overall area used by the array and taking account of local bathymetry

3. Mooring footprint and installation requirements
4. Marine operations such as vessel access for deployment and maintenance
5. Reduction in electrical losses and cable costs

The spatial configuration and device interaction of WEC arrays is a critical research topic for wave energy. C. Fitzgerald and Thomas [72] reference the q-factor, which is the ratio of the absorbed energy by a single device versus the absorbed energy from the same device operating within an array, i.e. its ‘array efficiency’. Where q > 1 constructive interference is taking place within the array; where q < 1 destructive interference is taking place. Ricci et al. conclude [76] that device performance becomes practically independent for spacing larger than four radii of the absorber in question. However, this is for a single row array. This is contradicted by Westphalen et al [78] who show that for irregular waves negative interference occurs up to approx. 15 diameters of the device.

On the issues of array capture efficiency, J. Fitzgerald calculates [73] that for an ‘intermediate efficiency’ array the minimum spacing for an array of 1.5MW devices, 6 devices deep, would be 225m. This rises to 525m for arrays which are 14 devices deep. J. Fitzgerald and Bergdahl also conclude on the issue of moorings [74] that with a typical mooring scope (mooring line length to water depth ratio) of 5:1 in 50m of water the mooring would have a footprint of approximately 300m diameter for a catenary configuration with surface buoy. It can be envisaged that for 100m of water this footprint would be double, therefore approximately 600m. There are many dependants in mooring design and Wavebob have assessed vertically loaded suction anchors which would reduce the mooring footprint in 100m deep water to approximately 150m diameter, although it is unclear whether the seabed conditions required for this type of mooring will be readily available on potential sites.

One also has to consider the requirements of different vessels to operate within the array, both for device deployment and for mooring, cable and maintenance activities.

It can be seen that there are multiple views on the spatial configuration given different criteria. For an array electrical network the shorter distance is preferable from an electrical efficiency and economic perspective. However, given the requirement for dynamic cables, enough space between devices must exist to allow for the dynamic cable configuration.

From a review of the literature it is established that for capture efficiency the required spacing in 100m depth water for an absorber with a 22m diameter can range from 44m – 525m between absorbers, and is dependant on the ‘depth’ of the array, i.e. how many rows of devices there are. For mooring installation the required spacing can range from 75-300m, and is dependant on what type of mooring can be deployed given the seabed conditions at the site. It could be envisaged that, given a requirement for catenary moorings, the spatial requirement for resource capture would become prominent only in arrays with more than 6 rows, but only if vertically loaded mooring solutions are not possible which is not the topic of this thesis.

It is proposed that the linear separation between devices in arrays to be evaluated in this work are **200m, 300m and 400m**. This allows for closely- to widely-spaced arrays and still consider the movement of vessels within the array.

### 4.3.5 Generators

The type of generator in the WEC has an impact on the short circuit level within the network. The short circuit level may in turn affect the design requirements for the cables within the network. Networks containing generators which contribute a higher level of fault current may have higher short circuit fault levels meaning that the cable capacities may need to be increased to cater for this. From [95] the fault currents (in per unit (p.u.)) to be expected for the generators being examined are;

- Synchronous (Fixed Speed): Up to 6 p.u.
- Induction (Fixed Speed): Up to 6 p.u.
- Power Electronic Converter Interfaced (Variable Speed): 1-2 p.u.

It can be seen that power electronic connected generators have a lower short circuit contribution, and this will be desirable for limiting short circuits current within the array. However, this is not the only consideration when selecting a generator so any offset in cost must be assessed as part of a holistic design of the generator for the WECs within the array.

### 4.3.6 Dynamic Cables

Dynamic cables fundamentals are outlined in Chapter 3. The use of dynamic cables for WEC has been confined to prototypes and early stage arrays, typically rated for <2MW and around 10kV. There are some examples of high power umbilicals in the offshore oil and gas industry. In the oil and gas industry up to 3 x 500mm$^2$ have been installed (Maari Field) and up to 115kV (Gjoa platform).

Two important considerations for the network configuration study are the maximum CSA of cable that can be used at a given voltage and the maximum amount of umbilicals that can be connected to a single WEC. For the purposes of this research it is assumed that the maximum CSA is 3 x 500mm$^2$ up to 90kV and the maximum amount of umbilicals is four (4) (unless a star cluster configuration is utilised)

### 4.3.7 Target Electrical Network Efficiency

The only revenue which the WEC array operator receives is for the power delivered at the actual POC (Point of Connection). This is at the shore based substation. Therefore it is important to reduce active power losses within the array and export electrical network. From [92] it can be seen that the electrical network efficiency of an offshore wind farm could be as high as 98% given a certain configuration, however this is based on a 6km transmission length which is not possible for offshore WEC arrays in Ireland. For the purposes of this study a minimum required efficiency of 96% is targeted.

The electrical network efficiency is defined further by regarding it as an annual average efficiency rather than a maximum instantaneous efficiency. The efficiency of the WEC array electrical network changes as the output of the individual devices varies. As a WEC array owner does not get paid for instantaneous power delivered (MWs) but for energy delivered (MWh) they are concerned with the average annual network efficiency, $\eta_{network}$.

### 4.3.8 Availability

The only revenue the WEC array owner receives is for energy delivered, although there are some market changes occurring across Europe where ‘system services’ could also deliver revenue for WEC array owners. There will be periods of planned maintenance where a device is removed for overhaul. Forced outages must be kept to a minimum and this also applies to the electrical network. In later sections options for increasing the availability and security of the electrical network are introduced and evaluated. The potential economic impact of these options on the electrical network is also assessed.

### 4.3.9 Cable Losses

There are three sources of losses in AC power cables, namely:

1. Conductor Losses ($I^2R$ losses)
2. Dielectric Losses (Capacitive losses)
3. Sheath/Armour Losses (Induced Losses in the cable sheath and armour)

#### *4.3.9.1 Conductor Losses*

Conductor losses (Ohmic losses) are dependant primarily on the conductor material (copper or aluminium), cross sectional area, and operating temperature. The conductor losses are simply $I^2R$ losses, i.e. a function of the cable current (I), the cable a.c. resistance ($R_\theta$) and the number of cores (n), i.e.:

$$W_c = n \times I^2 \times R_\theta$$ **EQUATION 4.1**

The losses in aluminium cables are higher due to the higher resistance, however the costs of aluminium cables is significantly (up to 6 times) lower. No proximity effects are considered.

#### *4.3.9.2 Dielectric Losses*

Dielectric losses are losses caused by the inherent capacitance of power cables. They depend on the construction of the cable and the operating voltage. They are a product of the capacitance of the cable (C), the system frequency (ω), system voltage ($U_o$), and the dielectric power factor (tanδ), i.e.:

$$W_d = n \times \omega \times C \times U_o \times \tan\delta$$ **EQUATION 4.2**

Dielectric losses are insignificant at medium voltage but can be much larger for long distance HVAC cables [70]. For long HVAC cables the losses can be compensated by inductive reactance at either or both ends (or distributed along the length). Dielectric losses are included in our calculation of losses as some cables are HVAC. From IEC 60287 tanδ is 0.004 for XLPE cables below 36kV, and 0.005 for XLPE cables above 36kV. These values are used in the analysis.

#### *4.3.9.3 Sheath & Armour Losses*

The losses caused by induced currents in the sheath and armour are highly dependent on numerous factors such as the bonding arrangement, sheath and armour material, physical construction of the cable, and core arrangement. The mechanism of the losses is different for the sheath and the armour.

From [96], power losses in the sheath, $\lambda_1$ consist of losses caused by circulating currents, $\lambda_1^{'}$, and eddy currents, $\lambda_1^{''}$, i.e.:

$$\lambda_1 = \lambda_1^{'} + \lambda_1^{''}$$ **EQUATION 4.3**

or

$$W_S = I^2 R_S \left( \frac{X_m^2}{R_S^2 + X_m^2} + \left[ \frac{3\omega^2}{R_S^2} \left( \frac{d_m}{2S} \right) \times 10^{-8} \right] \right)$$ **EQUATION 4.4**

where $R_S$ = sheath resistance

$X_m$ = mutual reactance

$d_m$ = mean diameter of sheath

$S$ = distance between cable centres

Power losses in the armour, $\lambda_2$, consist of losses caused by circulating currents, $\lambda_2^{'}$, and, for magnetic amour, hysteresis, $\lambda_2^{''}$, i.e.

$$\lambda_2 = \lambda_2^{'} + \lambda_2^{''} \quad \textbf{EQUATION 4.5}$$

However, as explained in [97], the sheath losses in three-core cables may be ignored when the sheaths are bonded at both ends and earthed at one end. Also, armour losses are shown to have very little significance as a proportion of overall losses. All cables are considered to be three-core here and hence the sheath and armour losses are not calculated, although their existence is acknowledged.

### 4.3.10 Cable Selection and Calculation

Using the equations in Section 4.3.9 the efficiency of the WEC array electrical network can be calculated. Power factor is considered to be unity for all calculations.

Cabling is not be the only component in the power collection and transmission system; transformers and compensating equipment may also be required amongst other components. Typical efficiency ratings for the transformers and compensating equipment are used in the calculations. However, in [70] it is shown that the cabling causes 87% of the losses in a typical HVAC transmission system with offshore and onshore transformer and compensation. Therefore, cable losses represent the majority of overall losses in the system.

There are other important factors such as short circuit studies, protection coordination and load flow analysis which feed into the electrical network design. These factors are discussed in this chapter but not calculated.

### 4.3.11 Cable Parameters

For the MVAC cables the data shall be, for the most part, obtained from the Nexans submarine power cable brochure [84], supplemented where necessary with cable data obtained from [97]. Current carrying capacity is calculated according to [98] and the following assumptions:

- Max conductor temperature at continuous load 90°C
- Frequency 50Hz
- Max Ambient Temperature 20°C
- Screens bonded at both ends and connected to earth
- Cable Burial Depth 1.0 m
- Thermal Resistivity of Surroundings 1.0 K.m/W

For the HVAC cables the data shall be, for the most part, obtained from the ABB XLPE submarine cable systems brochure [99] and supplemented where necessary with cable data obtained from [97]. From [99] the same installation characteristics are used as the MVAC cables above.

#### 4.3.12 Cable Cost Model

In order to accurately compare the economics of the electrical networks and potential cost reductions in the electrical network capital expenditure (CAPEX), reliable costs must be established for the submarine cables in the network.

Modelling the cost of submarine cables accurately is extremely challenging but a representative tool for this task is critical to the objectives of this thesis. The cost model developed in this section is based on the best available information at the time of publication. It is not considered practical to develop a cable cost model which is 100% accurate in all circumstances. Therefore, the cost model developed is considered sufficiently accurate to establish relative, 'order of magnitude' comparisons of electrical network configurations. However, there are potential sources of error in the cost model, and some assumptions and simplifications have been made to enable the development of a cost modelling tool, specific for WEC array electrical network configuration. The source information for the cost model, assumptions, potential sources of error, and simplifications are outlined below for clarity.

The cost of submarine 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. Therefore, it is difficult to put a price on cables that will remain relevant. Another approach is to look at the factors which make up the installed price of a cable, and develop a normalised cost model which is sufficiently accurate for a wide range of array configurations. The following assumptions, simplifications, and potential sources of error should be noted.

- All cables are assumed to be 3-core XLPE cables with copper conductors and a single layer of armouring. This type of cable is common in the offshore wind industry.
- All cables are considered to be installed in ideal conditions for cable burial; i.e. soft clays, sands or mud where installation can be conducted with low cost methods such as ploughing.
- Additional protection of the cable with rock dumping or other means is not considered.
- Contract strategies like bulk purchasing or a multi-project purchasing approach are not considered.
- No economies of scale for purchasing are considered; e.g 500m of cable is considered to cost the same per metre as 50km of cable.
- No economies of scale for installation are considered; e.g the installation of 500m of cable is considered to cost the same per metre as 50km of cable.
- Installation vessel type is not considered; i.e. the availability of various installation vessels, speed of installation, and cost of same.
- The cost model does not consider the cable installation location and the proximity to manufacturing facilities, and suitable port facilities.
- The cost model does not consider the metocean conditions or time of year at the installation site which could significantly impact potential installation down time.
- No reactive compensation equipment is considered in the costs.

#### *4.3.12.1 Cable Cost Components*

The normalised cost model was developed primarily by using the formulae given by Lundberg in [100] which was validated and then calibrated against numerous sources such as [67], [57], [101], [102], [103], [104] and [105]. Even within these sources there is inconsistency and disagreement and so some compromise is needed to develop a single normalised cost model. This is described in the next section.

#### *4.3.12.2 Evaluation and Calibration of the Lundberg cost model*

Lundberg developed a cost model for evaluation of wind farm electrical network costs [100]. The cost model developed by Lundberg is specifically based on the power capacity of the submarine cable, i.e. it is a cost by capacity model. Lundberg developed formula to match the trend of cable costs available across a range of projects. The formula developed by Lundberg are reproduced below.

$$Cost_{AC} = A_p + B_p \times e^{\left(\frac{C_p S_n}{10^8}\right)}$$ **EQUATION 4.6**

Where:

| | |
|---|---|
| $Cost_{AC}$ | Cost of the cables (SEK/km) |
| $A_p$, $B_p$, $C_p$ | Cost constants |
| $S_n$ | Rated power of the cable (VA) |

Note that this does not include an estimated installation costs of 2400SEK/m for all submarine cables.

**TABLE 4.1 COST CONSTANTS FROM LUNDBERG**

| Rated Voltage | $A_p$ ($10^6$) | $B_p$ ($10^6$) | $C_p$ |
|---|---|---|---|
| **10kV*** | 0.154 | 0.57 | 11 |
| **22kV** | 0.284 | 0.583 | 6.15 |
| **33kV** | 0.411 | 0.596 | 4.1 |
| **132kV** | 1.971 | 0.209 | 1.66 |

*extrapolated

Using the above formula and cost constants the Lundberg the installed costs for submarine cables across a range of voltages and cross sectional areas (CSA) are calculated. The results are presented in Euro (exchange rate of 1SEK – €0.11) in Table 4.2.

TABLE 4.2 EURO INSTALLED SUBMARINE CABLE COSTS DERIVED FROM LUNDBERG

| Cable CSA ($mm^2$) | Current Carrying Capacity (A) | 10kV | 20kV | 33kV | 132kV |
|---|---|---|---|---|---|
| | | | Cost / m | | |
| **35** | 168 | €367.29 | €386.97 | €406.40 | €524.31 |
| **50** | 201 | €372.90 | €393.65 | €414.21 | €530.11 |
| **70** | 245 | €380.94 | €403.32 | €425.62 | €539.07 |
| **95** | 292 | €390.31 | €414.70 | €439.17 | €550.45 |
| **120** | 330 | €398.52 | €424.78 | €451.28 | €561.25 |
| **150** | 368 | €407.35 | €435.70 | €464.51 | €573.73 |
| **185** | 413 | €418.66 | €449.83 | €481.78 | €591.03 |
| **240** | 475 | €435.93 | €471.66 | €508.77 | €620.27 |
| **300** | 564 | €464.57 | €508.49 | €555.05 | €676.32 |
| **400** | 627 | €487.99 | €539.12 | €594.16 | €729.12 |
| **500** | 699 | €518.43 | €579.55 | €646.54 | €807.15 |
| **630** | 777 | €556.48 | €630.95 | €714.19 | €919.58 |

There are a number of potential sources of error which should be highlighted about the Lundberg model. Firstly, the model was developed from 2003 costs so is over a decade old and arguably dated. Therefore, the Euro (or SEK) costs may not be accurate today, or into the future. Secondly, the model uses a fixed installation cost for all cables, regardless of the size of the cable. To address these potential source of error the following steps are taken to 'recalibrate' the cost model.

The installation costs are removed for now and the costs are normalised. For this normalised cost model a base case is needed. This base case will be a 10kV, $95mm^2$ cable. This cable has a normalised installed cost of 1.0 with all other cables referenced against this base cost.

Once normalised the relative components costs are examined. The main components affecting the cable cost are:

1. The voltage rating of the cable (i.e. the insulation rating)
2. The cross sectional area (CSA) of the conductor
3. The installation costs (which are not considered in Table 4.3 but are added to the normalised costs later)

The relative costs identified from the Lundberg model are then recalibrated based on more up-to-date costs from [67], [57], [101], [102], [103], [104] and [105] which also include variable installation costs.

In Table 4.3 the normalised relative costs of submarine cables only, with installation costs removed.

TABLE 4.3 NORMALISED SUBMARINE CABLE (EXCLUDING INSTALLATION) FROM LUNDBERG MODEL

| Cable CSA ($mm^2$) | 10kV | 20kV | 33kV | 132kV |
|---|---|---|---|---|
| | Normalised cost (/m) | | | |
| **35** | 0.80 | 0.97 | 1.14 | 2.16 |
| **50** | 0.85 | 1.03 | 1.21 | 2.21 |
| **70** | 0.92 | 1.11 | 1.31 | 2.29 |
| **95** | 1.00 | 1.21 | 1.42 | 2.39 |
| **120** | 1.07 | 1.30 | 1.53 | 2.48 |
| **150** | 1.15 | 1.39 | 1.64 | 2.59 |
| **185** | 1.25 | 1.52 | 1.79 | 2.74 |
| **240** | 1.40 | 1.71 | 2.03 | 2.99 |
| **300** | 1.64 | 2.02 | 2.43 | 3.48 |
| **400** | 1.85 | 2.29 | 2.77 | 3.94 |
| **500** | 2.11 | 2.64 | 3.22 | 4.62 |
| **630** | 2.44 | 3.09 | 3.81 | 5.59 |

To calibrate this according to the first two relative cost components described above, i.e. voltage rating and CSA the Lundberg normalised cost model is presented in Table 4.4 and Table 4.5 with relative costs based on Voltage rating only, and on CSA only respectively.

TABLE 4.4 NORMALISED LUNDBERG MODEL (VOLTAGE ONLY – 10KV BASE)

| Cable CSA ($mm^2$) | 10kV | 20kV | 33kV | 132kV |
|---|---|---|---|---|
| | Normalised cost (/m) | | | |
| **35** | 1.00 | 1.21 | 1.42 | 2.70 |
| **50** | 1.00 | 1.21 | 1.42 | 2.61 |
| **70** | 1.00 | 1.21 | 1.42 | 2.49 |
| **95** | 1.00 | 1.21 | 1.42 | 2.39 |
| **120** | 1.00 | 1.21 | 1.43 | 2.32 |
| **150** | 1.00 | 1.21 | 1.43 | 2.26 |
| **185** | 1.00 | 1.22 | 1.44 | 2.20 |
| **240** | 1.00 | 1.22 | 1.45 | 2.15 |
| **300** | 1.00 | 1.23 | 1.48 | 2.12 |
| **400** | 1.00 | 1.24 | 1.50 | 2.13 |
| **500** | 1.00 | 1.25 | 1.53 | 2.19 |
| **630** | 1.00 | 1.26 | 1.56 | 2.29 |

TABLE 4.5 NORMALISED LUNDBERG MODEL (CSA ONLY – 95MM$^2$ BASE)

| Cable CSA ($mm^2$) | 10kV | 20kV | 33kV | 132kV |
|---|---|---|---|---|
| | Normalised cost (/m) | | | |
| **35** | 0.80 | 0.80 | 0.80 | 0.91 |
| **50** | 0.85 | 0.85 | 0.85 | 0.93 |
| **70** | 0.92 | 0.92 | 0.92 | 0.96 |
| **95** | 1.00 | 1.00 | 1.00 | 1.00 |
| **120** | 1.07 | 1.07 | 1.07 | 1.04 |
| **150** | 1.15 | 1.15 | 1.15 | 1.08 |
| **185** | 1.25 | 1.25 | 1.26 | 1.15 |
| **240** | 1.40 | 1.41 | 1.42 | 1.25 |
| **300** | 1.64 | 1.67 | 1.71 | 1.46 |
| **400** | 1.85 | 1.89 | 1.94 | 1.65 |
| **500** | 2.11 | 2.18 | 2.26 | 1.93 |
| **630** | 2.44 | 2.55 | 2.68 | 2.34 |

Recalibrating the Lundberg model with more up to date references is challenging as references often contradict each other (and themselves), and are normally derived from specific project costs, which by their nature have project specific cost information. Also insufficient detail in terms of voltage rating, CSA and installation conditions is common. The range of costs given is also relatively limited. From the selected references in [67], [57], [101], [102], [103] , [104] and [105] the cost information has been extracted and is presented in Table 4.6. Colour coding is added where voltage information is available for MV cables.

**TABLE 4.6 SUBMARINE CABLE COST (€) INFORMATION FROM SELECTED REFERENCES**

| CSA | [67] | | [67] | | [103] | | [105] | |
|---|---|---|---|---|---|---|---|---|
| **MV** | Cable | Installation | Cable | Installation | Cable | Installation | Cable | Installation |
| 35 | | | | | | | | |
| 50 | | | | | | | 200 | 160 |
| 70 | | | | | | | | |
| 95 | 114 | 140 | 341 | 140 | | | 200 | 160 |
| 120 | | | | | 258 | 140 | | |
| 150 | 171 | 140 | 370 | 140 | | | | |
| 185 | | | | | | | | |
| 240 | | | | | | | | |
| 300 | | | | | 354 | 140 | | |
| 400 | 286 | 140 | 457 | 140 | | | | |
| 500 | | | | | | | | |
| | | | | | | | | |
| **HV** | | | | | | | | |
| 240 | | | | | | | | |
| 300 | | | | | | | | |
| 400 | | | | | 450 | 140 | | |
| 500 | | | | | | | | |
| 630 | 567 | 140 | 645 | 140 | 578 | 140 | | |

| | [102] | | [57] | | [101] | | [104] | |
|---|---|---|---|---|---|---|---|---|
| **MV** | Cable | Installation | Cable | Installation | Cable | Installation | Cable | Installation |
| 35 | | | | | | | | |
| 50 | | | | | | | | |
| 70 | | | | | | | | |
| 95 | | | | | | | | |
| 120 | | | 155 | 160 | | | | |
| 150 | | | | | | | | |
| 185 | | | | | | | | |
| 240 | | | | | | | | |
| 300 | 315 | 227 | | | | | | |
| 400 | | | | | | | | |
| 500 | | | 490 | 600 | | | | |
| | | | | | | | | |
| **HV** | | | | | | | | |
| 240 | | | | | | | | |
| 300 | | | | | | | | |
| 400 | | | | | | | | |
| 500 | | | | | | | | |
| 630 | | | 560 | 600 | 330 | 225 | 385 | 190 |

| | |
|---|---|
| | 10kV |
| | 20kV |
| | 33kV |

In Table 4.6 the variability in absolute, €, costs from different references can be observed. Therefore the absolute costs are not utilised. However, any relative cost information which can be taken from Table 4.6 is critical in recalibrating the Lundberg model. Using this information the Lundberg model is repopulated based on actual relative costs (for both Voltage CSA) available from the selected references. In Table 4.8 and Table 4.11 the repopulated cells are highlighted in yellow. It must be acknowledged that even with eight references there was a wide range of values for some of the relative costs. Also, a significant repopulation of the Lundberg model was not possible.

However, two observations were made. Firstly, the relative costs based on voltage from the Lundberg underestimate the relative cost of increasing voltage. Also this is somewhat CSA dependant unlike the Lundberg model. Secondly, the relative costs based on CSA from the Lundberg underestimate the relative cost effect of increasing CSA.

TABLE 4.7 REPOPULATED NORMALISED LUNDBERG MODEL (VOLTAGE ONLY – 10KV BASE)

| Cable CSA ($mm^2$) | 10kV | 20kV | 33kV | 132kV |
|---|---|---|---|---|
| | Normalised cost (/m) | | | |
| 35 | 1.00 | 1.21 | 1.42 | 2.70 |
| 50 | 1.00 | 1.21 | 1.42 | 2.61 |
| 70 | 1.00 | 1.21 | 1.42 | 2.49 |
| 95 | 1.00 | 1.21 | 1.42 | 2.39 |
| 120 | 1.00 | 1.21 | 1.43 | 2.32 |
| 150 | 1.00 | 1.21 | 1.43 | 2.26 |
| 185 | 1.00 | 1.22 | 1.44 | 2.20 |
| 240 | 1.00 | 1.22 | 1.45 | 2.15 |
| 300 | 1.00 | 1.23 | 1.48 | 2.12 |
| 400 | 1.00 | 1.7 | 1.50 | 2.13 |
| 500 | 1.00 | 1.25 | 1.53 | 2.19 |
| 630 | 1.00 | 1.26 | 1.56 | 1.89 - 4.9 |

TABLE 4.8 REPOPULATED NORMALISED LUNDBERG MODEL (CSA ONLY – 95MM² BASE)

| Cable CSA ($mm^2$) | 10kV | 20kV | 33kV | 132kV |
|---|---|---|---|---|
| | Normalised cost (/m) | | | |
| 35 | 0.80 | 0.80 | 0.80 | 0.91 |
| 50 | 0.88 | 0.85 | 0.85 | 0.93 |
| 70 | 0.92 | 0.92 | 0.92 | 0.96 |
| 95 | 1.00 | 1.00 | 1.00 | 1.00 |
| 120 | 1.07 | 1.07 | 1.07 | 1.04 |
| 150 | 1.15 | 1.15 | 1.1 – 1.5 | 1.08 |
| 185 | 1.25 | 1.25 | 1.26 | 1.15 |
| 240 | 1.40 | 1.41 | 1.42 | 1.25 |
| 300 | 1.64 | 1.67 | 1.5 | 1.46 |
| 400 | 1.85 | 1.89 | 1.3 – | 1.65 |

| | | | | |
|---|---|---|---|---|
| | | | 2.5 | |
| **500** | 2.11 | 2.18 | 2.26 | 1.93 |
| **630** | 2.44 | 2.55 | 2.68 | 2.1 |

Taking account of the above observations the Lundberg model is recalibrated in the following section. What is also observed from the cost references is a general increasing installation cost for larger CSA/Voltage cables. This is also built into a recalibrated Lundberg model.

#### *4.3.12.3 Recalibrated Normalised Cost Model*

From the observations of the sources of error in the Lundberg model, and the observations on a repopulated model and a range of cost references, a recalibrated Normalised Cost Model is proposed. This normalised cost model is developed by using the relative trends demonstrated in the Lundberg model and adjusting these based on the observations from a range of cost references. Where contradictory observations are made some judgement must be applied. Also, a lot of extrapolation must be undertaken to populate the normalised cost model fully.

As outlined in the previous section, each component of the cable cost is evaluated and a normalised cost model is established. The main components affecting the cable cost are:

4. The voltage rating of the cable (i.e. the insulation rating)
5. The cross sectional area (CSA) of the conductor
6. The installation costs

1. <u>The voltage rating of the cable (i.e. the insulation rating)</u>

The insulation rating of the cable determines the permissible operating voltage of the cable. For MVAC cables there is an expected increase in price between the different voltage ratings, i.e. the cable itself is more expensive due to a higher level of insulation required. As more insulation is required for larger CSA cables this cost is expected to vary with CSA also. The increase in cost as a result of an increase in voltage rating is relatively small compared to the other components. Table 4.9 shows the proposed normalised costs that are applied to the cables here.

**TABLE 4.9 NORMALISED COSTS FOR CABLES BASED ON VOLTAGE RATING**

| Voltage | Lundberg Normalised Cost | Normalised Cost |
|---|---|---|
| **10kV** | 1 | 1 |
| **20kV** | ~1.2 | 1.07-1.2 (CSA dependant) |
| **33kV** | ~1.4 | 1.15-1.42 (CSA dependant) |
| **132kV** | ~2.4 | 1.9-2.0 (CSA dependant) |

2. The CSA of the conductor

The CSA of the conductor determines the permissible operating current of the cable. As the cable conductor is made up of copper the cable cost is sensitive to the CSA of the conductor and a larger cable also requires more steel armouring, more insulation and other materials. Therefore the cable cost is expected to be particularly sensitive to the CSA. However, a doubling of CSA is not expected to double the cost of the cable. Table 4.10 gives the proposed relative normalised costs of different CSAs of cable.

TABLE 4.10 NORMALISED COSTS FOR CABLES BASED ON CSA

| CSA ($mm^2$) | Lundberg Normalised Cost | Normalised Cost |
|---|---|---|
| **35** | ~0.8 | 0.78 |
| **50** | ~0.85 | 0.82 |
| **70** | ~0.92 | 0.9 |
| **95** | 1 | 1.0 |
| **120** | ~1.07 | 1.1 |
| **150** | ~1.15 | 1.2 |
| **185** | ~1.25 | 1.3 |
| **240** | ~1.4 | 1.5 |
| **300** | ~1.6 | 1.8 |
| **400** | ~1.9 | 2.1 |
| **500** | ~2.2 | 2.5 |
| **630** | ~2.5 | 3 |

3. <u>The installation costs</u>

The installation costs in this case include mobilisation and demobilisation costs, vessel costs, standby costs, installation of the cable itself, termination and testing of the cables, onshore installation and termination. These costs can be highly volatile as they are dependent on vessel availability, location of project, weather conditions during the installation, proximity of port facilities, seabed conditions, and equipment issues. It can also be stated that the vessel required will vary for the length and CSA of a given cable to be installed, and a larger cable presents more difficult handling and installation issues, therefore making that cable installation more expensive. Longer cables may require jointing between single lengths which is considered to be factored into the cost.

Therefore, with all else being equal on the site, normalised costs for installation are proposed which are primarily based on the cable CSA. For simplicity, cables are grouped together in CSA ranges. These are given in Table 4.11.

**TABLE 4.11 NORMALISED COSTS FOR CABLES BASED ON INSTALLATION**

| CSA Range ($mm^2$) | Lundberg Normalised Cost | Normalised Costs |
|---|---|---|
| **35-70** | 1 | 0.8 |
| **95-150** | 1 | 1 |
| **185-300** | 1 | 1.2 |
| **300+** | 1 | 1.5 |

Total normalised costs for all submarine cables used in this research is shown in Table 4.12. This is also shown graphically in Figure 4.7. These normalised costs are used for the economic analysis throughout this section. For comparison the normalised Lundberg cost model and the normalised cost model developed for this research are shown together in Figure 4.8.

TABLE 4.12 NORMALISED COSTS FOR SUBMARINE CABLES.

| Installed Cable Cost | | | | |
|---|---|---|---|---|
| | Voltage | | | |
| Cable CSA ($mm^2$) | 10kV | 20kV | 33kV | 132kV |
| 35 | 0.79 | 0.82 | 0.85 | 1.38 |
| 50 | 0.81 | 0.85 | 0.88 | 1.42 |
| 70 | 0.85 | 0.89 | 0.94 | 1.5 |
| 95 | 1.00 | 1.05 | 1.11 | 1.6 |
| 120 | 1.05 | 1.11 | 1.18 | 1.7 |
| 150 | 1.10 | 1.17 | 1.25 | 1.8 |
| 185 | 1.25 | 1.34 | 1.43 | 1.91 |
| 240 | 1.35 | 1.46 | 1.58 | 2.12 |
| 300 | 1.65 | 1.80 | 1.97 | 2.45 |
| 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 |

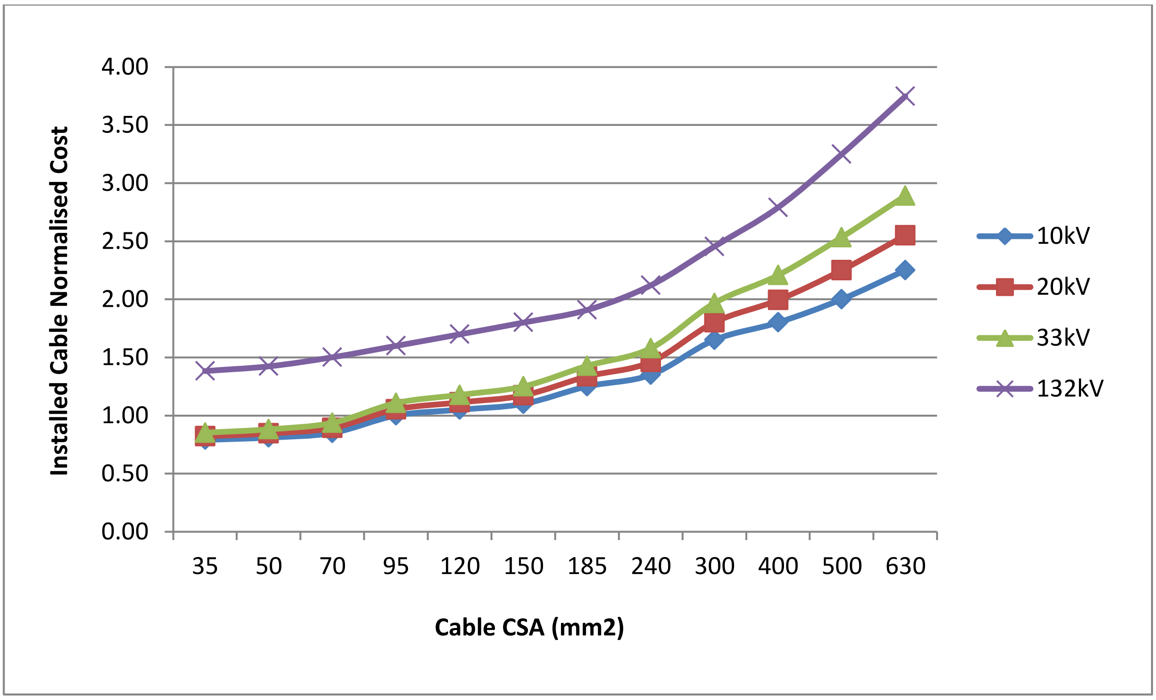



FIGURE 4.7 INSTALLED NORMALISED CABLE COST BY VOLTAGE AND CSA

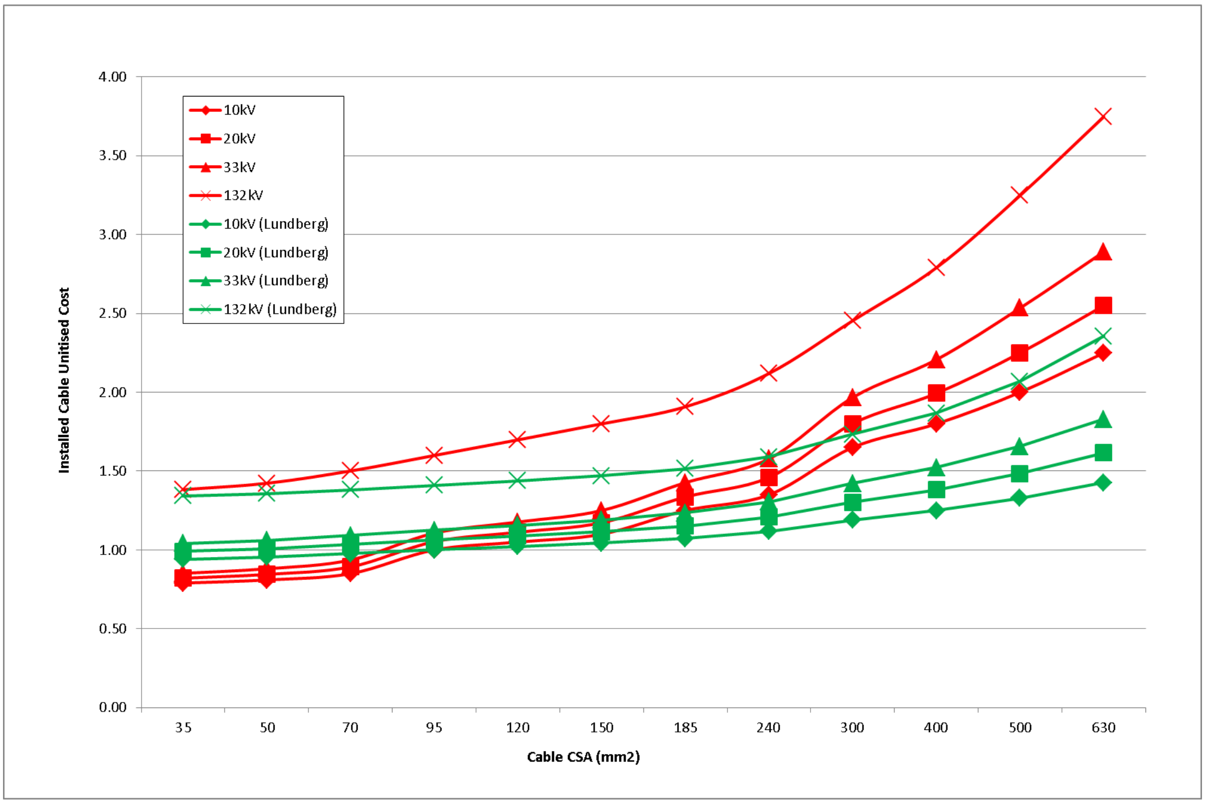



FIGURE 4.8 COMPARISON OF LUNDBERG MODEL AND RECALIBRATED MODEL

**Example:**

As outlined in the previous sections, at a normalised cost of 1.0, a 10kV, 95mm$^2$ cable is the base case for the normalised cable cost model. The following calculation shows what the difference is between a 33kV, 240mm$^2$ cable and the base case:

Total Normalised Cost = $(1*1.5^{(1)}*(1.1468*1.1373)^{(2)}) + 1*1.2^{(3)})/2$

Total Normalised Cost = 1.58

**Note:**

(1) Difference between 95mm$^2$ and 240mm$^2$ cable cost

(2) Difference between 10kV 240mm$^2$ and 33kV 240mm$^2$ cost

(3) Difference between 95mm$^2$ cable installation and 240mm$^2$

This shows that a 33kV, 240mm$^2$ cable is 58% more expensive than a 10kV, 95mm$^2$ cable. Therefore if the installed cost of a 10kV, 95mm$^2$ cable is €350/m then a 33kV, 240mm$^2$ cable costs €553/m.

#### 4.3.13 WEC Array Capacity

No commercial projects are in the latter stages of planning at this time. Therefore, the ‘typical’ rated capacity of a WEC array is uncertain. It is likely that some smaller ‘pre-commercial’ WEC arrays will be required to provide a bridging market to commercial projects. By looking at the constraints and the information from the offshore wind industry the following three stages of development are anticipated.

1. Small scale arrays (pre-commercial demonstrators)

**TABLE 4.13 CHARACTERISTICS OF SMALL SCALE ARRAYS**

| | |
|---|---|
| **Capacity:** | 1-10MW |
| **Distance from shore:** | 10-15km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 1 |

2. Medium scale arrays (commercial)

**TABLE 4.14 CHARACTERISTICS OF MEDIUM SCALE ARRAYS**

| | |
|---|---|
| **Capacity:** | 10-100MW |
| **Distance from shore:** | 10-15km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 2 or more |

3. Large scale arrays (commercial)

**TABLE 4.15 CHARACTERISTICS OF LARGE SCALE ARRAYS**

| | |
|---|---|
| **Capacity:** | 100MW+ |
| **Distance from shore:** | 15-25km |
| **Transmission voltage:** | HVAC |
| **Number of transmission connections:** | 1 |

For the purposes of this thesis three hypothetical WEC arrays are chosen for detailed analysis.

**WEC Array 1** - Small scale array (pre-commercial demonstrator)

TABLE 4.16 CHARACTERISTICS OF WEC ARRAY 1

| | |
|---|---|
| **Capacity:** | 10MW |
| **Distance from shore:** | 12km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 1 |

**WEC Array 2** - Medium scale array (commercial)

TABLE 4.17 CHARACTERISTICS OF WEC ARRAY 2

| | |
|---|---|
| **Capacity:** | 40MW |
| **Distance from shore:** | 15km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 2 |

**WEC Array 3** - Large scale array (commercial)

TABLE 4.18 CHARACTERISTICS OF WEC ARRAY 3

| | |
|---|---|
| **Capacity:** | 150MW |
| **Distance from shore:** | 20km |
| **Transmission voltage:** | HVAC |
| **Number of transmission connections:** | 1 |

In the context of this thesis these three WEC array scenarios represent the stages in the development of WEC arrays. This is a similar development path taken to the development of large commercial offshore wind farms so it can be reasonably assumed that WEC arrays will also develop in this manner.

## 4.4 Key Electrical Interfaces

Before optimising the electrical network configuration the key electrical interfaces between the array electrical network and the WEC need to be analysed. These key interfaces are one of the important differences between offshore wind and WEC array electrical networks outlined in Chapter 3. These key interfaces between the WEC and the electrical network also form part of the overall techno-economic optimisation process, and a balance between the functionality of these interfaces and cost is required.

These key interfaces are detailed in later sections but are identified as:

1. Dynamic Cable to WEC interface
2. Dynamic Cable to Static Cable interface
3. WEC MV Switchgear interface
4. Offshore Substation

There is a level of functionality required at the key interfaces between the electrical system and the WECs. In this section these interfaces are considered from the required functionality within the electrical system. The required functionality includes the following:

- Multiple Connection / Disconnection of the WEC
- Initial Cable Installation
- Electrical Protection
- Electrical Isolation (and earthing)
- WEC/Cable Hull Penetration
- Circuit Continuity (i.e. redundancy)

Various types of WEC will lend themselves better to some of the presented options than others. The focus here, as already outlined, is on a generic offshore floating WEC array.

Although maximum functionality in the key electrical interfaces would be desirable, the cost of the key interfaces must also be minimised. Some relative costs are indicated in these sections based on information from [57] and other various sources. The costs are indicative only but are expected to be sufficiently accurate for the techno-economic optimisation undertaken in Section 4.6. The expected costs may limit the functionality that can be viably achieved in the key interfaces. The balance of cost and functionality is important and an optimal solution is developed in Section 4.6.

### 4.4.1 Dynamic Cable to WEC Interface

The method by which the dynamic cable is connected to the WEC is of critical importance to the deployment and retrieval strategy of the WEC array. Some developers have already considered this, with Pelamis developing a proprietary connection system so the cable can be connected automatically to the device as it is latched to its moorings [106]. OPT have developed a floating connection system in cooperation with JDR cables so the cable can be connected without a diver/ROV to the WEC. It is possible that the main method for connection / disconnection is to use the submarine connector as detailed in Section 4.4.2.

The system used for the interface between dynamic cable and the WEC should be simplistic in order to avoid lengthy offshore operations, and flexible in order to allow for quick connection / disconnection. It should also be noted that for commercial projects the WECs should ideally remain on station for long periods of time between maintenance so reliable operation after long periods is required also.

If the system is designed so that the cable can be pre-installed at the site and brought into the device during deployment, this could allow for the dynamic to static cable connection to be made during manufacture of the cable, thus reducing the requirement for submarine cable connectors and hence reducing cost. This is discussed further in the next section.

Some possible dynamic cable to WEC connection schemes are shown for a generic floating WEC device in Figure 4.9 and the options shown are evaluated.

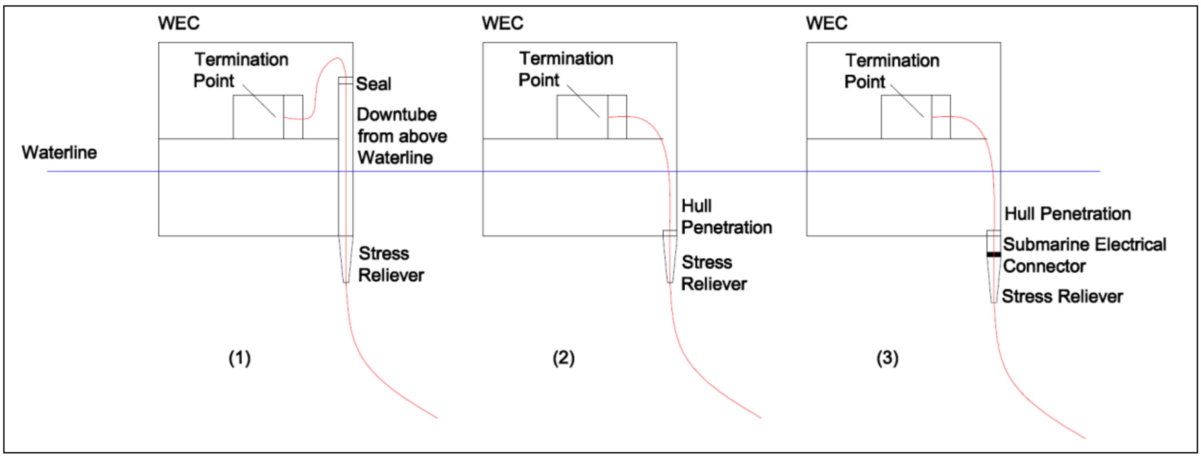



FIGURE 4.9 DYNAMIC CABLE / WEC INTERFACE OPTIONS FOR WEC

(1) Cable routed above the waterline and through a 'downtube' to the bottom of the WEC. The downtube could be internal or external to the WEC hull. A stress reliever would be required at the bottom of the downtube to avoid stress, kinking or cable damage. If properly designed this system could allow the cable to be drawn into the device on site and the cable terminated within the WEC, similar to an offshore wind turbine connection. This process may be difficult to achieve on a floating WEC. This would mean that when the cable was disconnected from the device it would need to be capped before it is left disconnected in situ.

(2) Cable routed directly out through a hull penetration. This would involve a submarine hull penetration including a stress reliever and seals, in order to maintain hull integrity. This would mean that the dynamic section of cable would need to be connected during onshore construction and transported to the site where it would be connected to the static section of cable already installed.

(3) Cable routed directly out through a hull penetration with a submarine connector. This would involve a submarine hull penetration including a stress reliever and seals in order to maintain hull integrity. On the 'wet' side of this penetration one half of a submarine connector would be fixed to the hull. This would mean that the dynamic section of cable, with the other half of a submarine connector, would need to be connected on site during installation. This could be by diver, ROV, or an automated system. Pelamis use a system similar to this for connection of their mooring and power cable simultaneously [106].

Table 4.19 gives indicative relative costs of the various options presented. The relative costs shown here and in Sections 4.4.2 and 4.4.3 are indicative only, as there is no available cost information to allow comparison. The least cost option is likely to be (1) where no hull penetration and sealing is required. Option (2) would require hull penetration and (3) requires a submarine connector which gives rise to the increase in relative cost.

TABLE 4.19 INDICATIVE RELATIVE COSTS FOR WEC TO DYNAMIC CABLE INTERFACE

| Option | Relative Cost |
|---|---|
| **(1)** | **1.0 (Base Case)** |
| **(2)** | **1.5** |
| **(3)** | **2.5** |

### 4.4.2 Dynamic Cable to Static Cable Interface

The method by which the dynamic cable is connected to the static cable is also of critical importance to the deployment and retrieval strategy of the WEC array. There are multiple options for submarine connectors which differ primarily in the ease and speed of connection, and as a result, cost. Further detailed descriptions are given in Section 3.3.2. Submarine connectors can be broadly separated into the categories given below.

#### *4.4.2.1 Non-'Mate-able' Connector*

Permanent/Factory Cable Splice: This is a permanent splice between two cables. This is the type of splice that is regularly used in factories or in cable repair operations. Once the splice is made it cannot be separated without cutting the cable. This type of connection can only be done in very dry and controlled conditions. The cost of these connectors is expected to be approximately €30,000-40,000 per unit.

#### *4.4.2.2 'Mate-able' Connector*

Splice Housing: This is a 'mate-able' splice which can be separated and re-connected. The connector is essentially a housing in which a temporary cable splice can be made. This type of connection is undertaken on board a service vessel. The cost of these connectors is expected to be approximately €75,000-100,000 per unit.

Dry-Mate Connector: This is a 'mate-able' connector which can be separated and re-connected numerous times. The dry-mate refers to the fact that this type of connection can only be undertaken outside of the water on-board a vessel. The cost of these connectors is expected to be approximately €100,000-150,000.

Wet-Mate Connector: This is a ‘mate-able’ connector which can be separated and re-connected numerous times. The wet-mate refers to the fact that this type of connection can be undertaken under water on the seabed. The cost of these connectors is expected to be approximately €200,000-300,000.

The system for interfacing dynamic cable and the static cable should be simplistic in order to avoid lengthy offshore operations, and flexible in order to allow for multiple quick connections / disconnections. Some possible dynamic cable to static cable connection schemes are shown for a generic floating WEC in Figure 4.10.

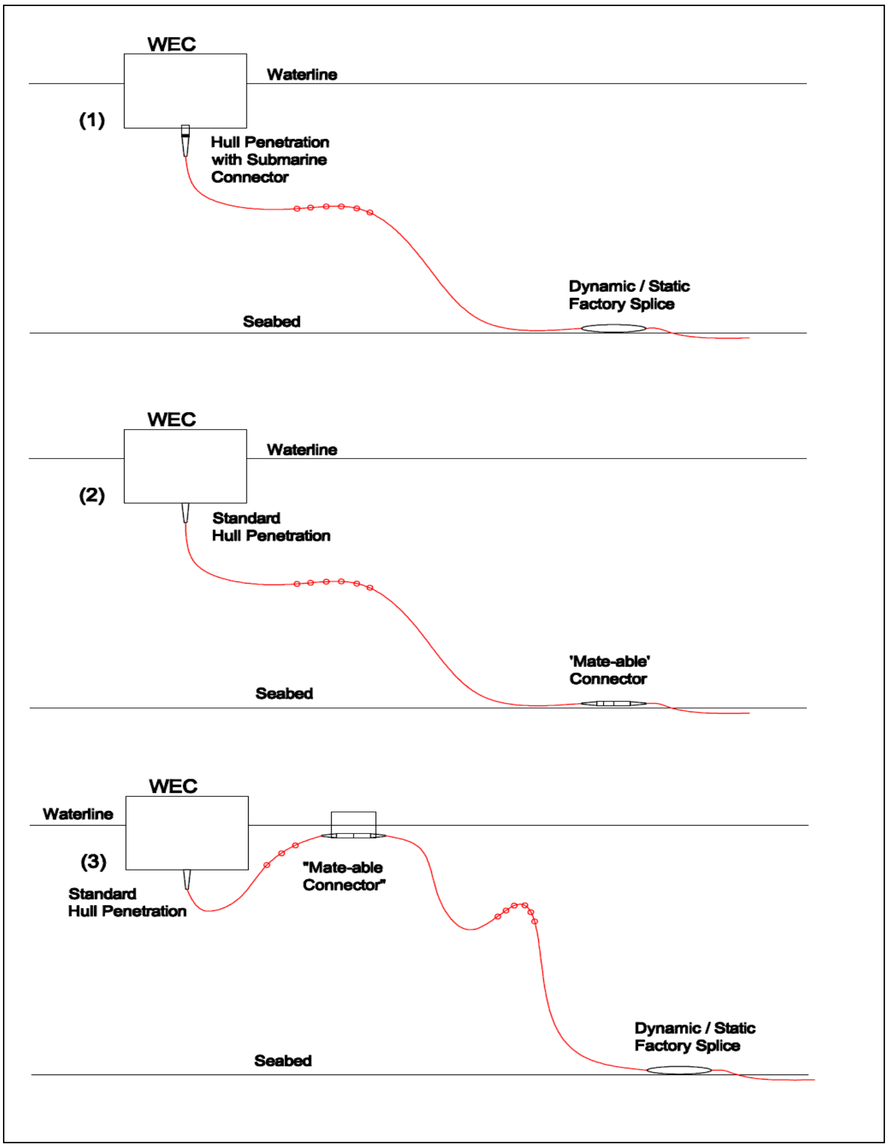



**FIGURE 4.10 DYNAMIC / STATIC CABLE CONNECTION OPTIONS FOR WEC**

(1) As per option (3) in Figure 4.9, a mate-able connector would be installed at the hull penetration. This connector would serve a dual purpose as a hull penetration and cable connector. From the connector the dynamic cable is configured in a lazy-wave to the seabed where it is connected to the static cable through a permanent/factory splice. The splice between the static and dynamic cable could be made onshore during cable manufacture to allow for a simpler installation process. This option however may require diver, ROV activities, or an automated connection system.

(2) From the WEC standard hull penetration (option (2) in Figure 4.9) the dynamic cable is configured in a lazy-wave to the seabed where it is connected to the static cable through a

mate-able connector such as those outlined in Section 4.4.2. This option could also be used with option (1) in Figure 4.9 where the cable is routed directly into the WEC on site without the need for a mate-able connector (the dynamic/static cable interface could be a permanent splice).

(3) From the WEC a short length (~50m) of dynamic cable is connected to a floatation module containing a mate-able connector. This floatation module may be part of the WEC mooring system if a clash between cable and mooring line can be avoided. From the floatation module the dynamic cable is configured in a lazy-wave to the seabed where it is connected to the static cable through a factory made joint such as that described in option (1) above. The short length of dynamic cable to connect to the floatation module would also be pre-installed before deployment.

Table 4.20 gives indicative relative costs of the various options presented. The least cost option is (1) where the submarine connector forms part of the WEC to dynamic cable interface and the dynamic to static cable interface is the lowest cost splice connection. Option (2) would be slightly more expensive depending on the type of 'mate-able' connector used. Option (3) would be the most expensive depending on the connector used.

**TABLE 4.20 INDICATIVE RELATIVE COSTS FOR DYNAMIC CABLE TO STATIC CABLE INTERFACE**

| Option | Relative Cost |
|---|---|
| **(1)** | **1.0 (Base Case)** |
| **(2)** | **1.2 – 2** |
| **(3)** | **1.3 – 2.5** |

### 4.4.3 WEC MV Switchgear Interface

In order to connect the WECs in a radial circuit, MV switchgear is required for protection of the WEC electrical system and cables, and also for isolation purposes. A similar switchgear arrangement to offshore wind farms is required in a WEC array.

If submarine switchgear is employed this can be coupled with a mate-able connector system. Submarine switchgear systems have been developed by Siemens [107], ABB [108], GE Vetco Gray [109], MacArtney [110] and OPT [111]. With the exception of MacArtney and OPT these have been predominantly designed for offshore Oil and Gas applications where the economics are of a different order of magnitude to offshore energy generation. Hence they are designed for extreme deep-water operation (>1000m).

Some possible switchgear configuration schemes are shown for a generic floating WEC device in Figure 4.11.

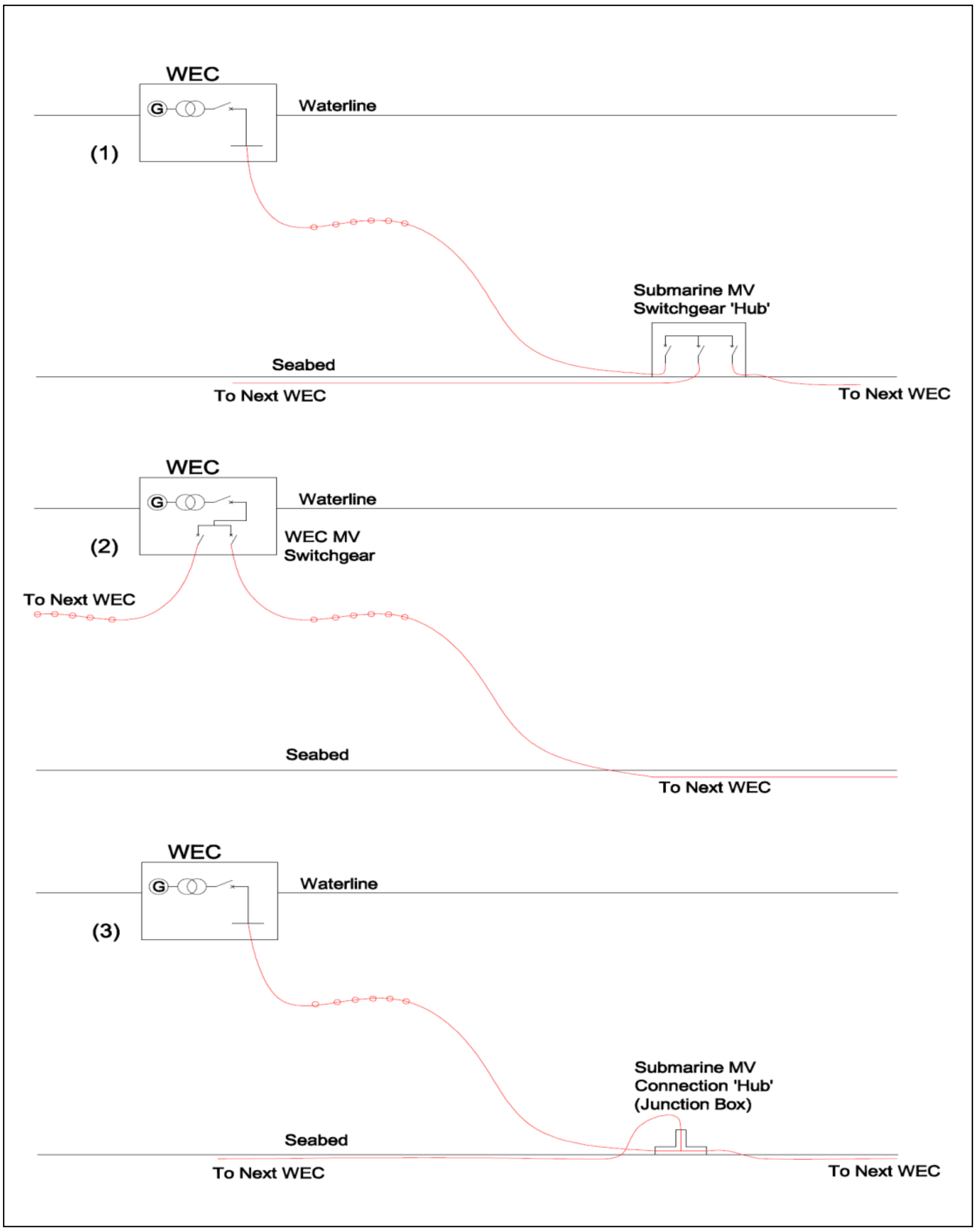



**FIGURE 4.11 SWITCHGEAR OPTIONS FOR FLOATING WEC**

(1) From the onboard transformer a dynamic cable is connected (optionally with an onboard MV circuit breaker) to a submarine switchgear unit (‘hub’), which includes a protection circuit breaker for the WEC electrical system and dynamic cable, and switch disconnects for isolation of the cable section. In this way all protection and isolation functions are done within the subsea module, which would contain protection relays also. This has the advantage of only one dynamic cable being required for connection to the WEC, but has issues with regard to electrical safety and maintenance of submarine electrical equipment. Connectors would also be required to be added to the switchgear unit to allow a connection / disconnection function also.

(2) From the onboard transformer a cable is connected to onboard switchgear, which includes a protection circuit breaker for the WEC electrical system, and switch disconnects for isolation of the dynamic and static cable sections. This system would require two dynamic cables for WECs connected in a radial network.

(3) From the onboard transformer a cable is connected to onboard switchgear, which includes a protection circuit breaker for the WEC electrical system and dynamic cable, and switch disconnects for isolation of the cable section. One dynamic cable is connected to a ‘T’ connector on the seabed (submarine connection ‘hub’). This means that only one dynamic cable is required for devices connected in arrays. However, to isolate the dynamic cable section, the entire circuit (including all WECs on the radial) must be switched out and isolated.

Table 4.21 gives indicative relative costs of the various options presented. The least cost option is (2) where the switchgear is contained within the WEC itself although this requires two dynamic cables per WEC. Option (3) is the next most expensive due to the requirement for additional submarine connectors and a submarine ‘T’ connector. Option (1) is considered the most expensive due to the requirement for additional submarine connectors and submarine switchgear.

TABLE 4.21 INDICATIVE RELATIVE COSTS FOR DYNAMIC CABLE TO STATIC CABLE INTERFACE

| Option | Relative Cost |
|---|---|
| **(1)** | **3 – 5** |
| **(2)** | **1.0 (Base Case)** |
| **(3)** | **2 – 3** |

### 4.4.4 Offshore Substation

In offshore wind farms, an offshore substation would be required for arrays over 100MW or those located further than 10km from shore, as these are considered the breakeven points where the cost of the substation is less than the cost of multiple MV connections. Also important in the consideration of an offshore wind farm is the voltage for connecting to the grid, which would normally be HV (>100kV) for large generators.

There are at least 20 offshore substations installed on existing offshore wind farms with further projects in development or construction. These substations are normally installed in up to 35m water depth. More detail on offshore wind substations can be found in Chapter 3.

As offshore WEC arrays are likely be located in 100m water depth, although the required offshore substation 'topside' will be identical, the type of foundations typically used in offshore wind farm substations will not be practical, i.e. monopile, tripod and gravity-base. Jacket structures have also been used for 'deep-water' sites such as in [89]; however this is still only 45m depth. Much deeper jacket structures have been deployed in the oil and gas industry so the technology is feasibly, yet potentially adds a large additional cost to the project. So the choices for an offshore substation in 100m water depth would be the following:

- Deep-water jacket or compliant-tower type structure such as that in use for oil platforms. This additional cost will change the breakeven point between multiple MV connections and a single HV connection.
- Strategically locating the WEC array in proximity to a <50m water depth location and locating the offshore substation at a midpoint between the WEC array and the shore

- Building the substation on a floating platform such as the semi-submersible, tension leg or spar type structures in use for oil platforms
- Locating the offshore substation on the seabed

The choice of substation design will be a matter of cost and feasibility. The technologies in use for oil platforms are well proven but the economics of O&G is very different than that for offshore WEC arrays so may prove too expensive for use in this industry. Locating the offshore substation on the seabed would solve the foundation platform issue; however, this has only been achieved on a small power scale and also in the O&G industry. There would be the same access, maintenance, and safety concerns for this equipment if this was the case. Sites that have a shallow water location in the vicinity could possibly be utilised but the economics of the longer MV cables may outweigh the benefits of this approach. Essentially, a cost benefit analysis must be undertaken on this aspect and this will not be undertaken accurately until such time as a project at this scale is in development.

It is very likely that the cost of the foundation for a deep-water offshore substation would be significantly higher than that of a foundation in 0-40m water depth. The full cost would include the construction and installation including potentially expensive deployment vessels. The topside of the substation would be approximately the same cost, although some increase in protection may be necessary to deal with wave loading and installation may also be more expensive. Therefore it is very likely that the breakeven point for an offshore substation for a WEC array will be higher than 100MW. It is currently difficult to establish what the exact breakeven point will be as there are numerous variables in a cost model but detailed financial models of a specific large wave energy project could establish this.

### 4.4.5 Submarine Hubs and Substations

Other bespoke solutions have been proposed which all fall into a general category of ‘submarine hubs’ utilising star cluster type network configurations. Star clusters are considered as a potential network configuration in Section 4.5. The proposed submarine hubs in general collect the generated power from several WECs and condition it for transmission to shore. These hubs can contain one or all of the below equipment:

- Power Electronic Converters
- LV & MV Switchgear

- Power Transformers
- Energy Storage Solutions
- Battery Chargers and Auxiliary Systems

The hubs may also be completely passive such as the Wavehub (see Section 3.3.3.2.4 for details). In this case they are acting as a junction box for the aggregation of power from several WECs.

Although these 'hubs' are not evaluated 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 (Section 4.4.4). These challenges are outlined here for information only:

- Access to complicated equipment such as power electronic converters, digital protection relays, and battery chargers would be required in the event of even a simple fault. This operation alone would result in a large operational cost.
- There are safety implications from having a point of isolation and earthing in a location where it can not be verified or secured (locked out). Some detail on this is provided in Section 3.3.3.
- The practicalities of connecting multiple LV and MV cables to a submarine hub are onerous. This would require multiple expensive mate-able connectors and/or ROV operations.
- The potential construction and installation costs of a submarine hub are very large and there is little experience here apart from in the oil and gas industry.
- There are other, less technically and economically challenging, options for electrical connection schemes which should be explored first.

## 4.5 Array Electrical Network Configuration Evaluation

The array network configuration is a major factor in the cost and functionality of the array electrical network. There are a variety of possible configurations as shown in Figure 4.12. For WEC arrays some proposals have been made for submarine 'hubs' which could act as an aggregation point in a star network. These are discussed in Section 4.4.5 and star cluster networks are analysed in this section.

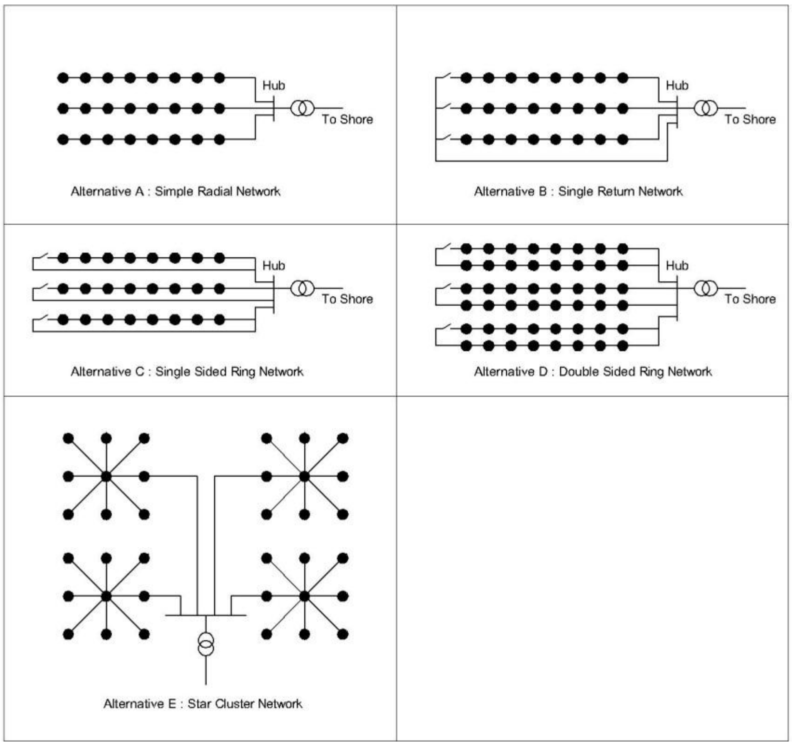



**FIGURE 4.12 POSSIBLE NETWORK CONFIGURATIONS**

In order to evaluate the possible configurations a candidate array, WEC array 2, is selected from Section 4.3.13. This candidate WEC array is evaluated using the alternative configurations as shown in Figure 4.12 under a number of economic and functional criteria.

- Economic:
    - This considers the increase in the cable cost (relative to configuration (A)) by a change in the configuration. Costs are taken from Section 4.3.12. A physical grid layout is considered for all electrical configurations to calculate the cable lengths and hence costs.
- Functional
    - Installation: This considers the complexity of the cable laying operation compared to a simple radial network scenario. Aspects such as the cable laying duration and complication are considered.

- Operation: This considers the effect of the configuration on the operation of the WEC array, in particular its availability.
- Maintenance: This considers the ease of maintenance of WECs within the arrays and the loss of energy when WECs are removed from the array.
- Protection: This considers the location of protection equipment and the ease of installation and maintenance of same.

The following assumptions are made in addition to those given in Section 4.3:

- 20kV voltage level is considered for all cases in this section.
- Each WEC (node) is 1MW in all cases with unity power factor.
- For simplicity only 400m inter-WEC spacing is considered here.
- A physical grid layout of the devices is assumed to be maintained, with the exception of the optimised star-cluster layout.
- 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 in the economic calculations.
- All switching operations are assumed to be contained within the WEC or in the onshore substation.

### 4.5.1 Simple Radial (A)

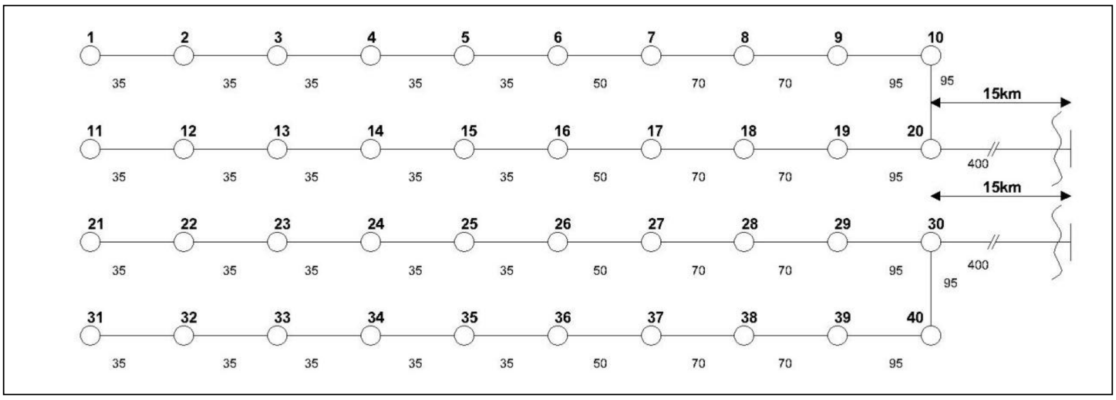



**FIGURE 4.13 SIMPLE RADIAL CONFIGURATION (NUMBERS BELOW INTER-WEC CABLES DENOTE CSA)**

As shown in Figure 4.13 this is the simplest configuration, and as outlined in Chapter 3 this has shown to be the most cost effective for offshore wind farms. In the case of the failure of an array cable there is no redundant circuit. Thus all generators upstream of the fault cannot keep generating. This is the main disadvantage of a radial configuration. Another disadvantage is that WECs require two connections to the array electrical network and some may require three.

**Radial Configuration (A)**

| Criteria | | |
|---|---|---|
| Economic | Cost | 1.0 (base case) |
| Functional | Installation | Simplest installation with the fewest cable routes. Two cable connections to each WEC may increase cost. |
| | Operation | Does not allow for continued generation upstream in the case of a faulty infield circuit. |
| | Maintenance | Loss of generation during WEC off-station maintenance. |
| | Protection | All protection functions possible. No submarine switchgear. |

The radial configuration's main advantage is that it has the lowest cost. The main disadvantage is that in the eventuality of an array cable failure or WEC removal for maintenance, all upstream WECs lose the network connection to the grid, and revenue may consequently be lost.

### 4.5.2 Single Return Ring (B)

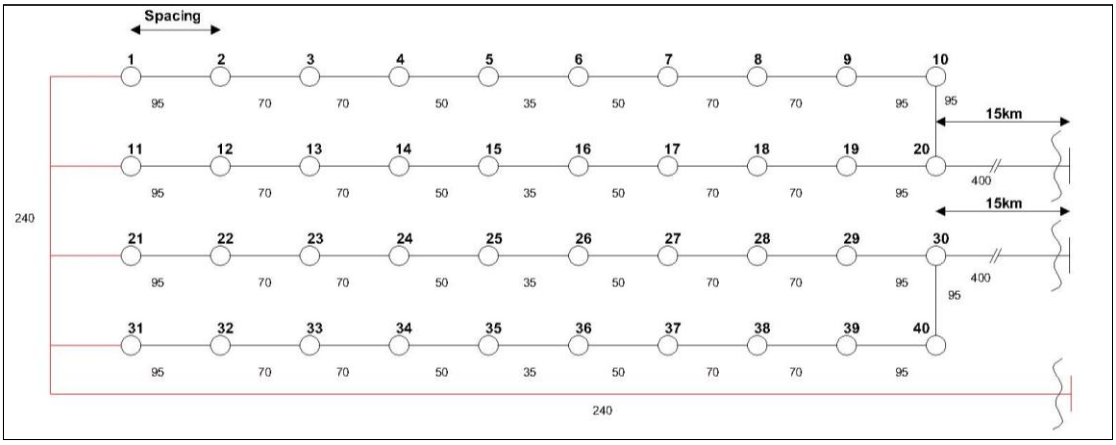



**FIGURE 4.14 SINGLE RETURN RING CONFIGURATION (NUMBERS BELOW INTER-WEC CABLES DENOTE CSA)**

As shown in Figure 4.14 this configuration gives an alternative circuit to shore in the case of a fault within the array network or the removal of a WEC. Thus all generators can keep generating once the circuit is reconfigured. The redundant circuit in this case would be rated to carry the power of one radial. The radial cables' capacity would need to be increased to allow for the bi-directionality of this circuit.

| Single Return Ring Configuration (B) | | |
|---|---|---|
| Criteria | | |
| Economic | Cost | 2.58 x (A) |
| Functional | Installation | No more difficult than (A), however it will require additional time for redundant circuits. This configuration may influence physical layout as the array ends may need to be in close proximity. |
| | Operation | Allows for continued generation in the case of a faulty array or export circuit. Also allows for the failure of one of the main export cables with continued (although curtailed) generation. |
| | Maintenance | Allows for WEC off-station maintenance with no loss of generation. |
| | Protection | All protection functions possible. No submarine switchgear. |

The single return ring allows the availability of a redundant circuit in case of array or export cable failure or WEC removal thus overcoming the disadvantage of the simple radial circuit. This comes at a high cost, as potentially the electrical network cost is 258% of the cost of the radial configuration.

### 4.5.3 Single Sided Ring (C)

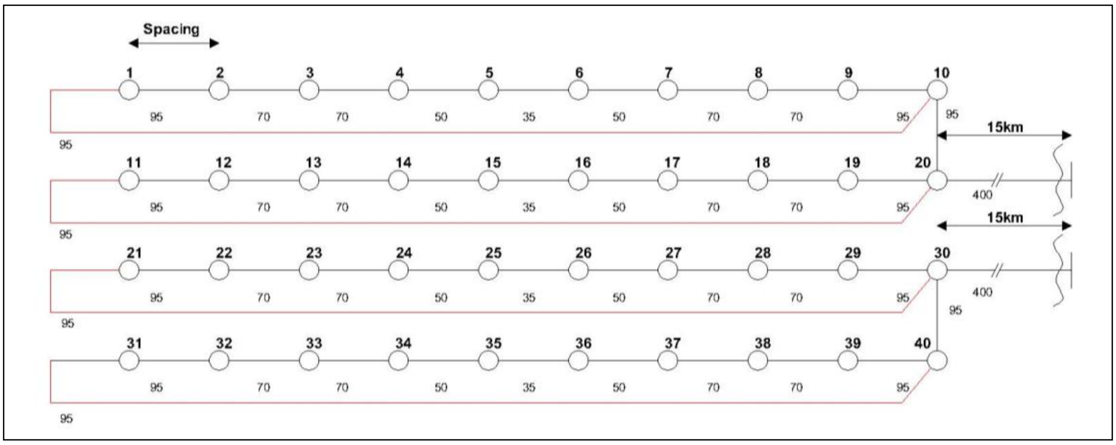



**FIGURE 4.15 SINGLE SIDED RING CONFIGURATION (NUMBERS BELOW INTER-WEC CABLES DENOTE CSA)**

As shown in Figure 4.15 this configuration gives an alternative circuit for each radial in the case of a fault of an array cable of WEC removal. This is connected to the beginning of the radial and not to the shore. Thus all generators can keep generating once the circuit is reconfigured. The redundant circuit in this case would be rated to carry the power of one radial. The radial cables' capacity would need to be increased to allow for the bi-directionality of this circuit.

**Single Sided Ring Configuration (C)**

| Criteria | | |
|---|---|---|
| Economic | Cost | 1.8 x (A) |
| Functional | Installation | May be difficult to accurately run cable circuits in close proximity to each other. Additional time will be required for redundant circuits. |
| | Operation | Allows for continued generation in the case of a faulty array circuit or WEC removal. |
| | Maintenance | Allows for continued generation in the case of a faulty array circuit or WEC removal. |
| | Protection | All protection functions possible. No submarine switchgear. |

The single sided ring configuration overcomes the disadvantage of the radial configuration with less additional cost than the single return ring. The cost of this configuration is still 180% of the radial. There are multiple additional cables required within the array, which may be difficult to install within an array with small inter device separation.

### 4.5.4 Double Sided Ring (D)

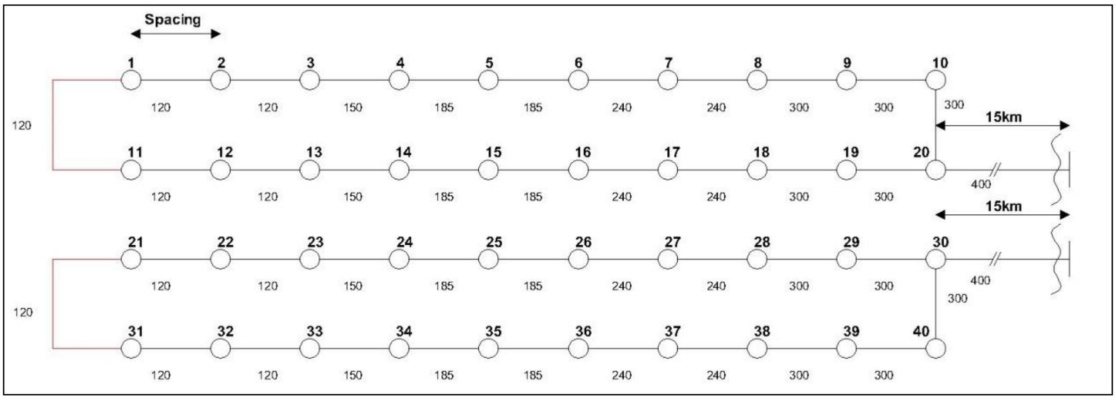



FIGURE 4.16 DOUBLE SIDED RING CONFIGURATION (NUMBERS BELOW INTER-WEC CABLES DENOTE CSA)

As shown in Figure 4.16 this configuration gives an alternative circuit, through the adjacent radial, for each radial, in the case of a fault within the array circuit or the removal of a WEC.  Thus all generators can keep generating once the circuit is reconfigured.  Each radial in this case would need to be rated to carry the power of two radials in one direction and its own power in both directions.  The radial cables' capacity would need to be increased to allow for the bi-directionality and increased capacity of this circuit.

**Double Sided Ring Configuration (D)**

| Criteria | | |
|---|---|---|
| Economic | Cost | 1.69 x (A) |
| Functional | Installation | No more difficult than (A) but will require additional time for redundant circuits. |
| | Operation | Allows for continued generation in the case of a faulty array cable or WEC removal. |
| | Maintenance | Allows for WEC off-station maintenance with no loss of generation. |
| | Protection | All protection functions possible.  No submarine switchgear. |

The double sided ring overcomes the disadvantage of the radial configuration for the least additional cost.  The double sided ring still costs 169% of the radial configuration.

### 4.5.5 Star Cluster (E)

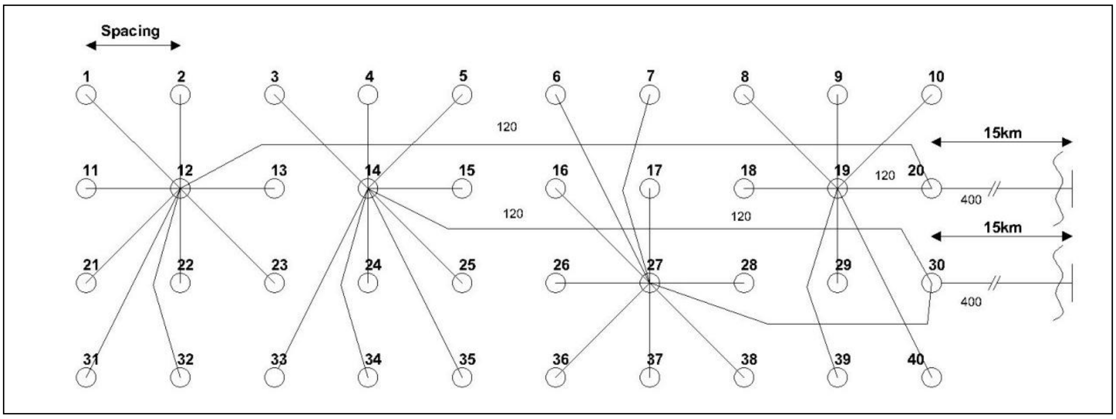



**FIGURE 4.17 STAR CLUSTER CONFIGURATION (NUMBERS BELOW INTER-WEC CABLES DENOTE CSA)**

As shown in Figure 4.17 this configuration gives a separate circuit for almost all WECs. The exception is the ‘hub’ WECs which could be WECs or simply submarine or floating hubs/substations. Thus all generators can keep generating if one of the cables to a WECs fails once there is protection and isolation equipment in the ‘hub’. This also means that these cables only need to be rated for a single WEC. However, if the same physical grid layout is maintained some array cables may be relatively long in comparison to radial network configurations.

| Star Cluster Configuration (E) | | |
|---|---|---|
| Criteria | | |
| Economic | Cost | 1.54 x (A)<br>1.06 x (A) when physically optimised – see below |
| Functional | Installation | Could be very difficult to connect multiple cables to a single WEC or even a single hub. Cable routes would be complex for vessels to complete. Cables may have to cross each other. |
| | Operation | Allows for continued generation in the case of a faulty WEC cable. However some cables in the network would still cause a disconnection of multiple WECs. |
| | Maintenance | Allows for WEC off-station maintenance with no loss of generation. However if WECs are used for hubs this may be difficult. |
| | Protection | All protection functions possible but hub may require large amount of switchgear which could create difficulties. Further issues with switchgear if submarine hub used. |

The star cluster is the least cost option after the radial network, and has a major benefit of only having a single cable connection to the majority of WECs. The major disadvantage of the star cluster arrangement is that multiple connections must be made to the star ‘hub’ which could be a WEC or a submarine/floating ‘hub’. Both of these options could be difficult to achieve and crucially the system still has a higher cost than a radial configuration at 154% relative cost.

If the star cluster network is optimised to reduce the length of the connection to the star ‘hub’ this breaks the physical grid layout of the array but reduce the overall cost of the star cluster network. With nine (9) connections to four hubs (also WECs) and maintaining the 400m device separation, an optimised star cluster would be almost comparable to a radial configuration at 106% relative cost. This is illustrated in Figure 4.18.

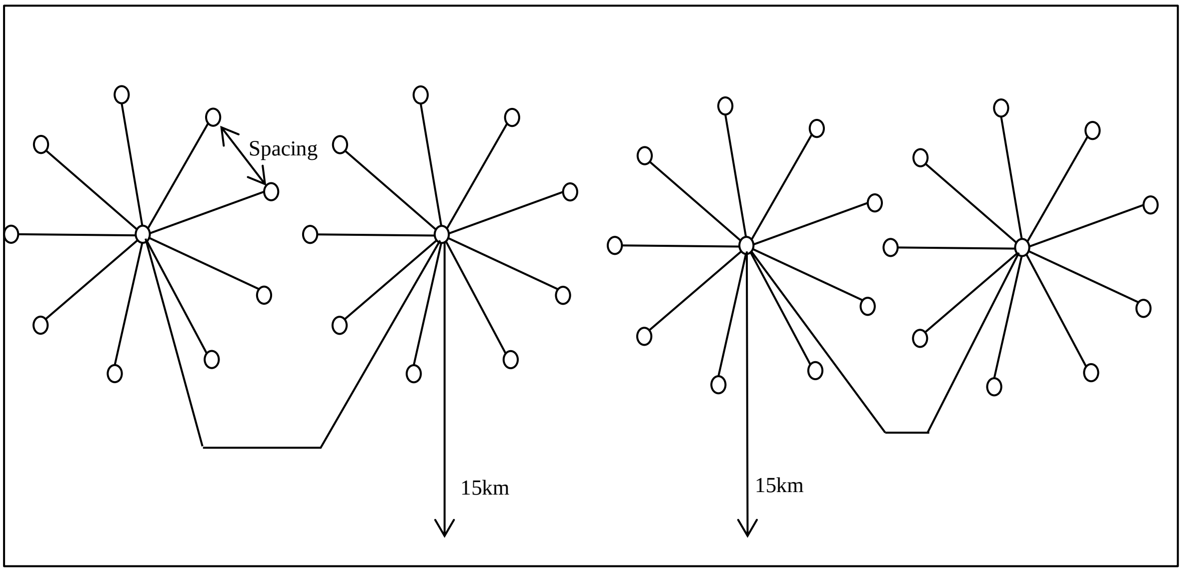



**FIGURE 4.18 'OPTIMISED' STAR CLUSTER CONFIGURATION**

### 4.5.6 Overcoming Radial Limitations

Table 4.22 shows the relative cost of the array only, and the array and export cabling for the various alternative configurations detailed in Figure 4.12 and the previous sections. This shows that the radial network is the least cost solution from an array configuration perspective. This is primarily due to the additional cabling required for the proposed alternatives. Also to allow redundancy in the circuits the cross sectional area (CSA) of some of the cables must be increased, thereby also increasing cost.

**TABLE 4.22 COST OF ALTERNATIVE ARRAY NETWORK CONFIGURATIONS**

| Network Configuration | Relative Cost (Array Only) | Relative Cost (Array and Export) |
|---|---|---|
| **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 |
| **Star Cluster Network (E) with optimised layout** | 1.06 | 1.01 |

In conclusion, the simple radial network (A) is the most advantageous in terms of economic criteria. An optimised star cluster network (optimised E) is very similar in cost but requires a central 'hub' and breaks the physical grid layout of the array. The radial network is less suitable based on functional criteria. In particular the disadvantage for the radial network configuration is the lack of redundancy in the event of array cable failure or WEC removal, and also the requirement for two cable connections to most WECs. In reality, the cost of the electrical system would need to be kept as low as possible, therefore any functional considerations may not take precedence over economic ones. Thus, radial networks are selected here as the most suitable array network configuration for WEC array electrical networks.

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 WEC arrays there is an issue with removal of WECs in the circuit which needs to be resolved. This can be done with a number of options including:

1. 'Standby' or 'dummy' WECs to 'slot' into place upon removal of a WEC.
2. A system for temporarily bridging the gap left by the WEC in the electrical circuit.

3. Submarine switchgear allowing continued operation of the infield circuit (see Section 4.4.3).

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

For the disadvantage of having two cables connected to most WECs and three to some the additional cost of this must be more than the additional cost of the star cluster configuration plus any additional costs inherent in the 'hub' required for the star cluster network. It is possible, but unlikely, that the star cluster configuration would be more economically competitive than the radial given the higher cost of the network and the potential hub costs. There are also some methods for overcoming the requirement for two cables to each WEC such including:

1. The use of submarine switchgear or a passive 'T' junction box allowing a single cable from a radial circuit to the WEC (see Section 4.4.3).
2. The bundling of the two dynamic cables to a single hull penetration into the device.
3. The bundling of two three-phase cables into a single six core (2 x three phase) cable through submarine switchgear or a passive 'T' junction box.

## 4.6 Techno-Economic Optimisation

It has been shown in Section 4.5 that a radial array network configuration is the least cost option for WEC arrays, with the star cluster configuration comparable if the electrical network design can dictate the physical array layout. The radial configuration, however, lacks redundancy in the network to cater for WEC removal and a possible requirement for two cables connected to most WECs. However, solutions are proposed for this in Section 4.5.6. The optimisation of WEC array electrical networks therefore comes through the selection and design of appropriate interfaces between the WEC and the radial electrical network. These interfaces must balance cost and functionality.

### 4.6.1 Least Cost Solution

The least cost solution should involve minimising the use of any potentially expensive components in the system such as submarine hubs or submarine connectors. Although detailed costs are not available for all components, the least cost solution is based on the indicative relative costs outlined in Section 4.4.

**TABLE 4.23 LEAST COST SOLUTION PROPOSED OPTIONS**

| Interface | Option | Relative Cost | Description |
|---|---|---|---|
| Dynamic Cable – WEC | 4.4.1 (1) | 1.0 | Downtube |
| Dynamic Cable – Static Cable | 4.4.2 (1) | 1.0 | Submarine 'non mate-able' connector |
| WEC MV Switchgear | 4.4.3 (2) | 1.0 | WEC MV Switchgear and Two Dynamic Cables |

This would minimise cost due to having no requirement for mate-able submarine connectors or submarine switchgear/hub. However, this would require two dynamic cables from the WEC and could potentially require a time-consuming and complicated installation process. This solution would lack some functionality as the disconnection of a WEC could also be a long process. With this solution, therefore, we are sacrificing functionality for cost.

### 4.6.2 Maximum Functionality Solution

The maximum functionality solution would involve increasing the availability of the overall WEC array and reducing the time required to undertake installation and maintenance activities. The maximum functionality solution is proposed to comprise of the following options outlined in Section 4.4.

TABLE 4.24 MAXIMUM FUNCTIONALITY SOLUTION PROPOSED OPTIONS

| Interface | Option | Relative Cost | Description |
|---|---|---|---|
| Dynamic Cable – WEC | 4.4.1 (3) | 2.5 | Hull Penetration / Connector Combination |
| Dynamic Cable – Static Cable | 4.4.2 (1) | 1.0 | Submarine 'non mate-able' connector |
| WEC MV Switchgear | 4.4.3 (1) | 3-5 | Submarine MV Switchgear 'hub' |

This solution would allow for easy isolation and removal of the WEC for maintenance activities while keeping the electrical circuit integrity for upstream devices to continue generating. Although detailed costs are not available for components, this solution would be expected to be at least three times the cost of the least cost solution from Section 4.6.1.

### 4.6.3 Optimised Solution

The optimised solution seeks to maximise functionality at the lowest relative cost. It is proposed here that circuit continuity (i.e. redundancy) is achieved with a system such as that proposed in Section 4.5.6. Therefore the only functionality required is to disconnect the WEC quickly and at the lowest possible cost. The optimised solution is proposed to comprise of the following options outlined in Section 4.4.

TABLE 4.25 OPTIMISED SOLUTION PROPOSED OPTIONS

| Interface | Option | Relative Cost | Description |
|---|---|---|---|
| Dynamic Cable – WEC | 4.4.1 (2) | 1.5 | Submarine Hull Penetration |
| Dynamic Cable – Static Cable | 4.4.2 (3) | 1.3-2.5 | Floating dry-mate connector |
| WEC MV Switchgear | 4.4.3 (2) | 1.0 | WEC MV Switchgear and Two Dynamic Cables |

This solution gives the required functionality for the WEC electrical system with only ~25% increase (assuming the lower end of the dynamic to static cable interface cost) over the least cost option given in Section 4.6.1. This system would allow for quick and cost-effective disconnection of the WEC. The electrical system could be safely isolated for these activities. The key interfaces selected for this optimised solution are shown in Figure 4.19.

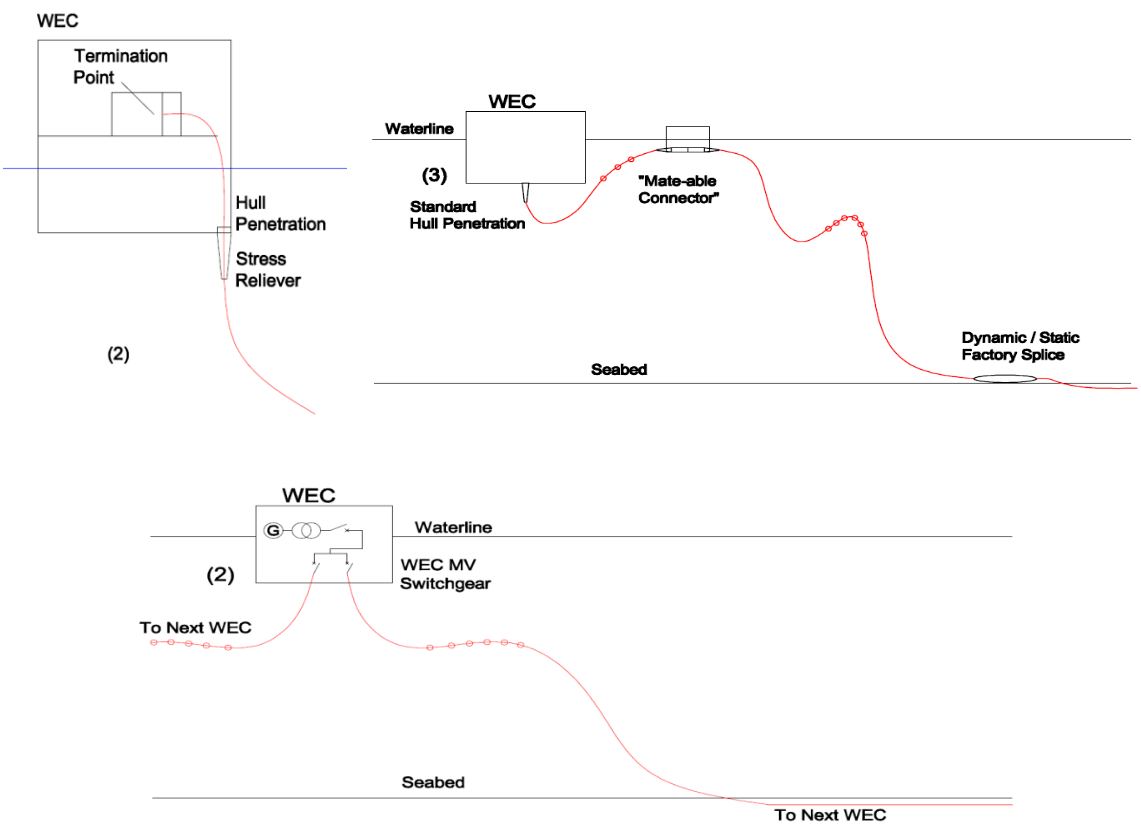



FIGURE 4.19 TECHNO-ECONOMIC OPTIMISED KEY INTERFACES

## 4.7 Array Voltage and Efficiency Analysis

In this section the candidate WEC arrays (1, 2 and 3) are analysed in order to look at the optimum voltage levels and efficiency.

From Section 4.3.13 the WEC arrays to be assessed are:

**WEC Array 1** - Small scale array (pre-commercial demonstrator)

| | |
|---|---|
| **Capacity:** | 10MW |
| **Distance from shore:** | 12km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 1 |

**WEC Array 2** - Medium scale array (commercial)

| | |
|---|---|
| **Capacity:** | 40MW |
| **Distance from shore:** | 15km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 2+ |

**WEC Array 3** - Large scale array (commercial)

| | |
|---|---|
| **Capacity:** | 150MW |
| **Distance from shore:** | 20km |
| **Transmission voltage:** | HVAC |
| **Number of transmission connections:** | 1 |

As shown in Section 4.5 a radial configuration is considered the most cost effective solution but requires some optimisation at the key interfaces, to ensure low cost but acceptable functionality of the electrical network. For the purposes of efficiency and voltage level analysis, a radial type electrical configuration is assumed for the WEC arrays.

### 4.7.1 WEC Array 1

| | |
|---|---|
| **Capacity:** | 10MW |
| **Distance from shore:** | 12km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 1 |

The deployment of a 10MW WEC array would most likely be a pre-commercial demonstrator or early commercial type project in order to prove the deployment of multiple devices on an array scale. The business case to be made for such a project may be slightly different to a commercial project due to grant funding and/or a favourable energy tariff. There would be other aspects of the project where economies of scale would be lost such as vessel mobilisation and dockside costs. The requirement for high efficiency may not be of highest priority for this scale of project. High availability may be a more important consideration.

The electrical configuration in this case is a single radial of ten (10) 1MW WECs. Figure 4.20 shows the configuration of the 10 devices. If the site configuration permitted, the main transmission cable could enter the array in the centre (e.g. WEC 6), thus allowing a tapering of the cable CSA to both sides from this point which would reduce the overall cost of the cable used within the array.

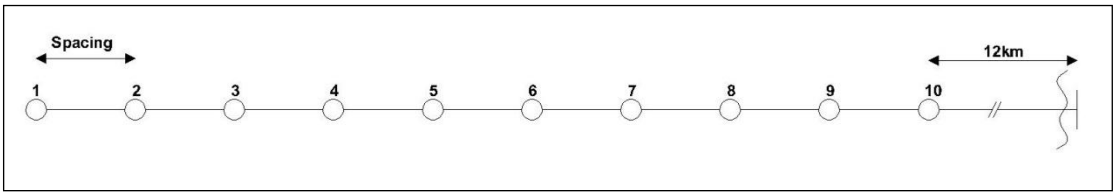



**FIGURE 4.20 WEC ARRAY 1 ELECTRICAL CONFIGURATION**

**<u>Methodology:</u>**

The WEC array electrical network is arranged in radial circuits. For larger arrays a ‘forked’ radial is utilised as this further reduces cable CSA in the radials. The methodology is as follows:

- Cables (array and export) are sized based on maximum continuous current at 10kV, 20kV & 33kV and, for WEC array 3, 132kV. Practical limitations are observed (see below).
- For a given circuit, active power losses are calculated for the range of 0-100% (at intervals of 10%) wave farm output power for each voltage level using Equation 4.1 and Equation 4.2 given in Section 4.3.9. For clarity these equations calculate

conductor and dielectric losses. This gives the efficiency of the circuit at different WEC array outputs.

- Using the Wavebob WEC energy distribution information given in Section 4.3 (see Figure 4.6), the average annual network efficiency (referred to as network efficiency for the rest of this section) for the WEC array is obtained. This is simply calculated as the network efficiency for the WEC array output multiplied by the percentage of time annually which the WEC array generated this output for. Note that this assumes all WECs in the array generate the same power simultaneously. This assumption may not be true over very short time intervals (minutes) but is likely to be true over longer intervals (hours).
- If a average annual network efficiency of 96% is not achieved initially then an iterative approach is taken by increasing the cable's CSA, and recalculating, to achieve this target.

For practical limitations a minimum cable CSA of $35mm^2$ for 10kV & 20kV and $50mm^2$ for 33kV are assumed. A maximum cable CSA of $500mm^2$ is assumed. 10-15 WECs are connected in each radial depending on the voltage and the total installed capacity.

Theoretically any amount of power could be transmitted at any voltage (given a large enough cable), but in reality there are practical limitations on the amount of power that would be transmitted at MVAC and HVAC. ABB present the practical limitations for transmission at various voltages in [112], which are replicated in Figure 4.21. These do not account for maximum distances, which are of practical importance when considering very long lines (i.e. >50km). Cables >50km are not considered here.

| Submarine and land XLPE cables for 3-phase AC | | | | | | |
|---|---|---|---|---|---|---|
| **Cable type** | **10kV** | **20kV** | **30kV** | **66kV** | **132kV** | **220kV** |
| 1 x 3-core | 15MW | 30MW | 50MW | 100MW | 200MW | 285MW |
| 3 x 1-core | 25MW | 50MW | 80MW | 150MW | 300MW | 460MW |

**FIGURE 4.21 RECOMMENDED MAXIMUM TRANSMISSION CAPACITIES GIVEN IN [112]**

Higher voltage cables have a higher cost, but the higher voltage results in smaller cable CSA, given the same power transmission requirement. For initial WEC arrays the voltage may initially be limited by certain components, notably submarine connectors. Given the demand, these components would become available at higher voltages; however, it must be established how cost effective they are.

The cables are sized as outlined in Section 4.3.10 in order to give the optimum solution for a given voltage level. In this instance 10kV and 20kV are assessed, as the rated power of the array is considered too low for a 33kV connection. Table 4.26 shows the detailed cable sizing and loss calculation for the 10MW array, for 200, 300 and 400m device separation.

Although the device separation is assumed to be 200, 300 and 400m, the cables lengths examined are 400, 500 and 600m. This is due to the requirement for additional cable from the seabed into the device. In 100m water depth, an additional 100m at both ends is assumed.

**TABLE 4.26 CALCULATION OF LOSSES FOR WEC ARRAY 1 (100% OUTPUT) – 200, 300 & 400M SPACING**

| Wavefarm 1 (200m Spacing) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Link | 1-2 | 2-3 | 2-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | Transmission | | |
| | | Cable Length (m) | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 12000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 2.99 | 3.98 | 4.96 | 5.94 | 6.92 | 7.90 | 8.88 | 9.85 | | |
| | | Current (A) | 58 | 115 | 173 | 230 | 286 | 343 | 399 | 456 | 513 | 569 | | |
| | | CSA (mm2) | 35 | 35 | 70 | 95 | 120 | 185 | 240 | 300 | 300 | 400 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 166 | 166 | 240 | 288 | 327 | 405 | 464 | 564 | 564 | 627 | Infield | Transmission |
| 10kV | | R (Ω/km) | 0.67 | 0.67 | 0.34 | 0.25 | 0.2 | 0.16 | 0.1 | 0.079 | 0.079 | 0.064 | 28.53% | 71.47% |
| | | C (μF/km) | 0.23 | 0.23 | 0.39 | 0.32 | 0.35 | 0.38 | 0.47 | 0.56 | 0.56 | 0.62 | | |
| | | L (mH/km) | 0.41 | 0.41 | 0.37 | 0.37 | 0.35 | 0.34 | 0.32 | 0.27 | 0.27 | 0.26 | TOTALS | |
| | | Loss (%) | 0.10% | 0.54% | 0.41% | 0.40% | 0.40% | 0.38% | 0.28% | 0.25% | 0.28% | 7.60% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.75 | 0.89 | 91.05% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 3.99 | 4.98 | 5.97 | 6.95 | 7.93 | 8.92 | 9.90 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 144 | 172 | 201 | 229 | 257 | 286 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 50 | 50 | 70 | 95 | 95 | 185 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 199 | 199 | 243 | 292 | 292 | 412 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.49 | 0.34 | 0.25 | 0.25 | 0.13 | 32.62% | 67.38% |
| | | C (μF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.18 | 0.22 | 0.22 | 0.22 | 0.28 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.43 | 0.38 | 0.4 | 0.4 | 0.34 | TOTALS | |
| | | Loss (%) | 0.08% | 0.14% | 0.20% | 0.27% | 0.25% | 0.29% | 0.24% | 0.20% | 0.22% | 3.91% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.39 | 0.49 | 95.10% |

| Wavefarm 1 (300m Spacing) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Link | 1-2 | 2-3 | 2-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | Transmission | | |
| | | Cable Length (m) | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 12000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 2.99 | 3.97 | 4.95 | 5.93 | 6.90 | 7.87 | 8.85 | 9.82 | | |
| | | Current (A) | 58 | 115 | 172 | 229 | 286 | 342 | 398 | 455 | 511 | 567 | | |
| | | CSA (mm2) | 35 | 35 | 70 | 95 | 120 | 185 | 240 | 300 | 300 | 400 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 166 | 166 | 240 | 288 | 327 | 405 | 464 | 564 | 564 | 627 | Infield | Transmission |
| 10kV | | R (Ω/km) | 0.67 | 0.67 | 0.34 | 0.25 | 0.2 | 0.16 | 0.1 | 0.079 | 0.079 | 0.064 | 33.33% | 66.67% |
| | | C (μF/km) | 0.23 | 0.23 | 0.39 | 0.32 | 0.35 | 0.38 | 0.47 | 0.56 | 0.56 | 0.62 | | |
| | | L (mH/km) | 0.41 | 0.41 | 0.37 | 0.37 | 0.35 | 0.34 | 0.32 | 0.27 | 0.27 | 0.26 | TOTALS | |
| | | Loss (%) | 0.12% | 0.67% | 0.51% | 0.50% | 0.50% | 0.48% | 0.35% | 0.31% | 0.35% | 7.57% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.74 | 0.93 | 90.75% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 3.99 | 4.97 | 5.96 | 6.94 | 7.92 | 8.90 | 9.87 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 144 | 172 | 200 | 229 | 257 | 285 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 50 | 50 | 70 | 95 | 95 | 185 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 199 | 199 | 243 | 292 | 292 | 412 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.49 | 0.34 | 0.25 | 0.25 | 0.13 | 37.73% | 62.27% |
| | | C (μF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.18 | 0.22 | 0.22 | 0.22 | 0.28 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.43 | 0.38 | 0.4 | 0.4 | 0.34 | TOTALS | |
| | | Loss (%) | 0.10% | 0.17% | 0.26% | 0.34% | 0.31% | 0.37% | 0.30% | 0.25% | 0.28% | 3.90% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.39 | 0.51 | 94.87% |

| Wavefarm 1 (400m Spacing) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Link | 1-2 | 2-3 | 2-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | Transmission | | |
| | | Cable Length (m) | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 12000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 2.98 | 3.96 | 4.94 | 5.91 | 6.88 | 7.85 | 8.82 | 9.78 | | |
| | | Current (A) | 58 | 115 | 172 | 229 | 285 | 341 | 397 | 453 | 509 | 565 | | |
| | | CSA (mm2) | 35 | 35 | 70 | 95 | 120 | 185 | 240 | 300 | 300 | 400 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 166 | 166 | 240 | 288 | 327 | 405 | 464 | 564 | 564 | 627 | Infield | Transmission |
| 10kV | | R (Ω/km) | 0.67 | 0.67 | 0.34 | 0.25 | 0.2 | 0.16 | 0.1 | 0.079 | 0.079 | 0.064 | 37.54% | 62.46% |
| | | C (μF/km) | 0.23 | 0.23 | 0.39 | 0.32 | 0.35 | 0.38 | 0.47 | 0.56 | 0.56 | 0.62 | | |
| | | L (mH/km) | 0.41 | 0.41 | 0.37 | 0.37 | 0.35 | 0.34 | 0.32 | 0.27 | 0.27 | 0.26 | TOTALS | |
| | | Loss (%) | 0.15% | 0.81% | 0.61% | 0.60% | 0.59% | 0.57% | 0.41% | 0.37% | 0.42% | 7.54% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.74 | 0.96 | 90.45% |
| | | Power (MVA) | 1.00 | 2.00 | 2.99 | 3.99 | 4.97 | 5.95 | 6.92 | 7.90 | 8.88 | 9.85 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 143 | 172 | 200 | 228 | 256 | 284 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 50 | 50 | 70 | 95 | 95 | 185 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 199 | 199 | 243 | 292 | 292 | 412 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.49 | 0.34 | 0.25 | 0.25 | 0.13 | 42.13% | 57.87% |
| | | C (μF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.18 | 0.22 | 0.22 | 0.22 | 0.28 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.43 | 0.38 | 0.4 | 0.4 | 0.34 | TOTALS | |
| | | Loss (%) | 0.12% | 0.21% | 0.31% | 0.40% | 0.37% | 0.44% | 0.36% | 0.30% | 0.34% | 3.89% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.38 | 0.54 | 94.64% |

The overall network efficiencies for full rated output of the WEC array are given in Table 4.27.

**TABLE 4.27 SUMMARY OF NETWORK EFFICIENCIES FOR FULL RATED OUTPUT**

| Spacing | 200m | | 300m | | 400m | |
|---|---|---|---|---|---|---|
| Voltage | 10kV | 20kV | 10kV | 20kV | 10kV | 20kV |
| Efficiency | 91.05% | 95.10% | 90.75% | 94.87% | 90.45% | 94.64% |

The network efficiency is dependent on the output of the WEC array and will be higher for lower output power. The network efficiency over the full range of output power is shown in Figure 4.22 for the 10MW array. It can be seen that the network efficiency of the 10kV network falls rapidly (due to $I^2R$ losses) as the WEC array output increases when compared to the 20kV network.

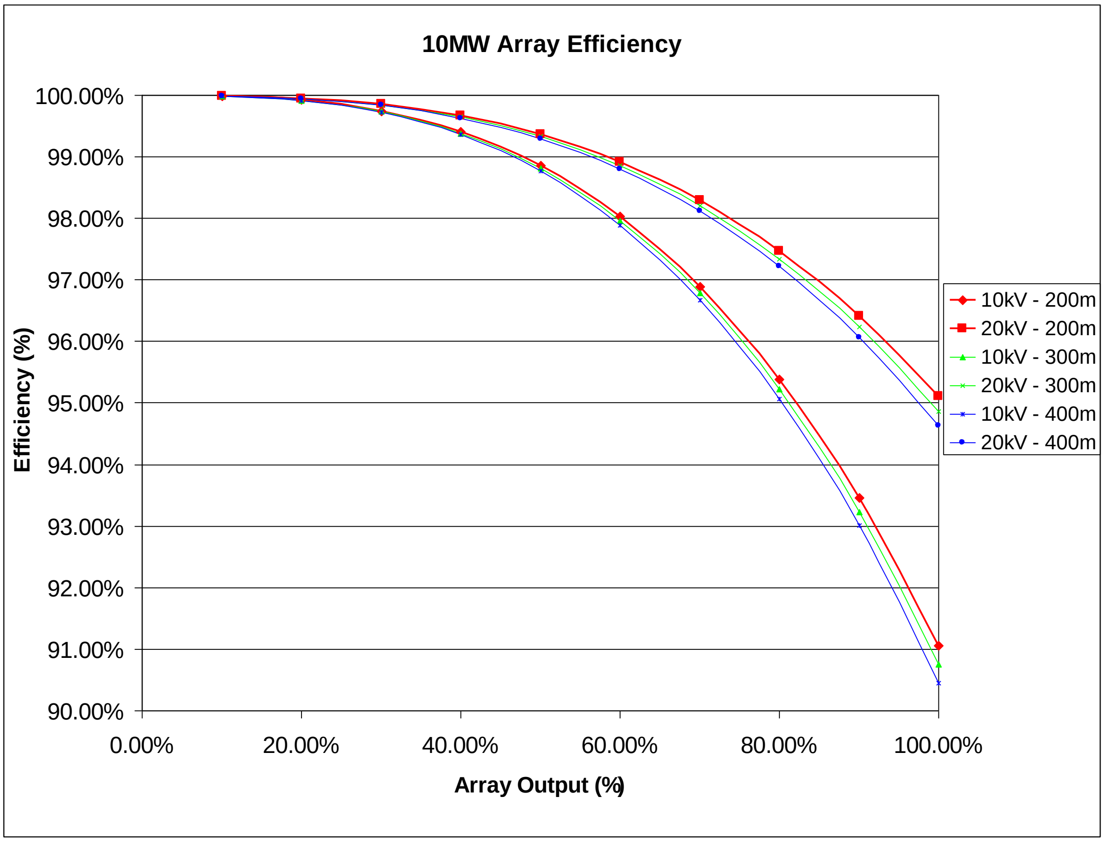



**FIGURE 4.22 EFFICIENCY OF WEC ARRAY 1 VERSUS OVERALL WEC ARRAY OUTPUT**

The energy yield distribution of the Wavebob device at the Belmullet site was determined in Section 4.3.3. Using this, the network efficiency can be calculated.

**TABLE 4.28 SUMMARY OF ANNUAL NETWORK EFFICIENCY**

| Spacing | 200m | | 300m | | 400m | |
|---|---|---|---|---|---|---|
| Voltage | 10kV | 20kV | 10kV | 20kV | 10kV | 20kV |
| Network Efficiency | 96.21% | 97.92% | 96.08% | 97.82% | 95.95% | 97.72% |

This means that, although on initial inspection there would appear to be a 4% difference in efficiency between a 10kV and 20kV system efficiency, the 'real' effect of this is around 2% difference in annual average network efficiency. This illustrates the importance of understanding the characteristics of the WEC to establish the true network efficiency.

It also means that, although both 10kV and 20kV initially appear not to have achieved the 96% efficiency target set out in Section 4.3.7, once the energy distribution of the site and WEC system is taken into account, the network efficiency is approximately 96% for the 10kV system and over 97.5% for the 20kV system.

From Figure 4.22 it appears that the spacing has minimal impact on the network efficiency. In fact, from 200 to 400m spacing the difference in network efficiency is 0.26% for 10kV and 0.2% for 20kV. Spacing would appear not to be critical in the network efficiency calculation.

Therefore 96% network efficiency can be achieved using the circuit in Figure 4.23 and the cable sizes in Table 4.29.

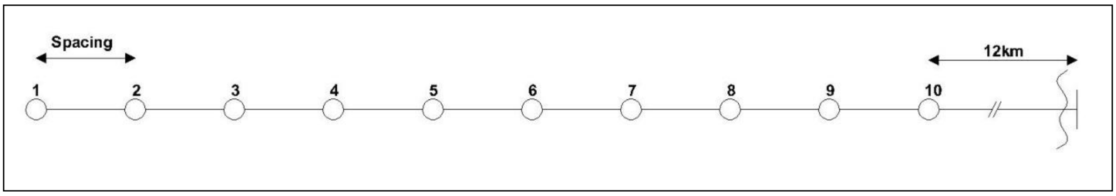



**FIGURE 4.23 WEC ARRAY 1**

**TABLE 4.29 CABLE CSA ($MM^2$) REQUIRED TO ACHIEVE NETWORK EFFICIENCY OF 96%.**

| | Circuit Section | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Voltage** | **1-2** | **2-3** | **3-4** | **4-5** | **5-6** | **6-7** | **7-8** | **8-9** | **9-10** | **10-Shore** |
| **10kV** | 35 | 35 | 70 | 95 | 120 | 185 | 240 | 300 | 300 | 400 |
| **20kV** | 35 | 35 | 35 | 35 | 50 | 50 | 70 | 95 | 95 | 185 |

As would be expected the 20kV network requires significantly smaller CSA cables and this also results in approximately 1.5-2% improvement in energy efficiency over the 10kV system. Using the normalised cable cost model from Section 4.3.12, the relative cost difference between the 10kV and 20kV network is calculated. In this case, the 20kV system has a relative cost which is 79% of the 10kV system. Therefore, although the same CSA cable would be more expensive for 20kV than 10kV, the 20kV network is less costly in this instance as the CSA required for the array and export network is smaller. In this case then the more efficient operating voltage (20kV) results in a lower relative cost. This does not consider other component costs such as transformers, switchgear or submarine connectors which may be more expensive given a 20kV system.

### 4.7.2 WEC Array 2

| | |
|---|---|
| **Capacity:** | 40MW |
| **Distance from shore:** | 15km |
| **Transmission voltage:** | MVAC |
| **Number of transmission connections:** | 2+ |

The deployment of a 40MW WEC array would be a commercial project using proven WECs on an array scale. The business case to be made for such a project may be helped due to a favourable, but sustainable, energy tariff. At this size of array, economies of scale would be possible on common costs. The requirement for high efficiency would be critical at this point for a viable business case.

The electrical configuration in this case would be four (4) radials of ten (10) 1MVA WECs. The radials would be connected together at the nearest WEC to shore, and then two cables would connect the array to the grid. Figure 4.24 shows the configuration of the 40 devices.

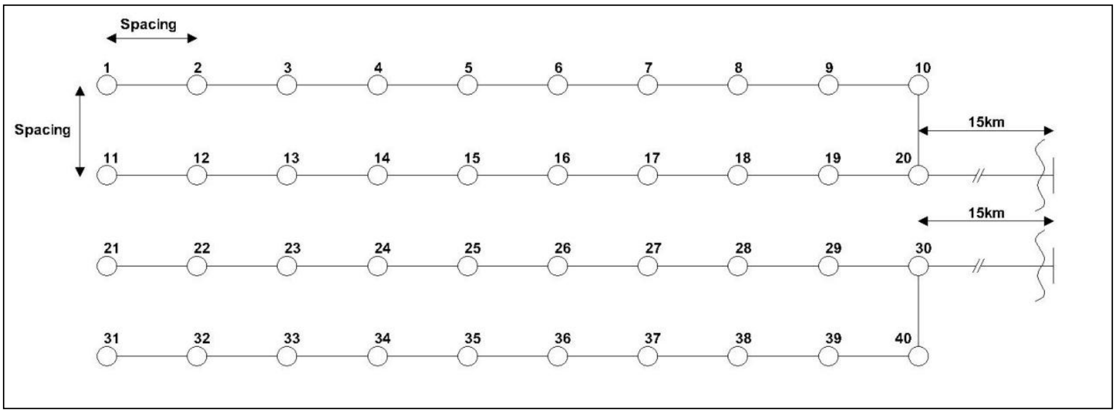



**FIGURE 4.24 WEC ARRAY 2 ELECTRICAL CONFIGURATION**

The cables are sized as outlined in Section 4.3.10 in order to give the optimum solution for a given voltage level. In this instance 20kV and 33kV are assessed, as the rated power of the array is considered too high for a practical 10kV network, particularly for transmission to shore. Table 4.30 shows the detailed cable sizing and loss calculation for the 40MW array, for 200, 300 and 400m device separation. Only one half of the array is assessed (WECs 1-20) but since the other half of the array is a mirror the overall network efficiency is identical.

**TABLE 4.30 CALCULATION OF LOSSES FOR WEC ARRAY 2 (100% OUTPUT) – 200, 300 & 400M SPACING**

| Wavefarm 2 (200m Spacing) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Link | 1-2 (11-12) | 2-3 (12-13) | 3-4 (13-14) | 4-5 914-15) | 5-6 (15-16) | 6-7 (16-17) | 7-8 (17-18) | 8-9 (18-19) | 9-10 (19-20) | 10-20 | Transmission | | |
| | | Cable Length (m) | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 15000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 3.00 | 3.99 | 4.98 | 5.96 | 6.95 | 7.93 | 8.91 | 9.89 | 19.75 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 144 | 172 | 200 | 229 | 257 | 285 | 570 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 95 | 400 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 168 | 199 | 243 | 243 | 292 | 292 | 627 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.34 | 0.34 | 0.25 | 0.25 | 0.063 | 32.82% | 67.18% |
| | | C (µF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.22 | 0.22 | 0.22 | 0.22 | 0.41 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.38 | 0.38 | 0.4 | 0.4 | 0.29 | TOTALS | |
| | | Loss (%) | 0.08% | 0.14% | 0.20% | 0.27% | 0.34% | 0.29% | 0.24% | 0.27% | 0.22% | 0.25% | 4.71% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.93 | 1.07 | 94.66% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 4.00 | 4.99 | 5.99 | 6.98 | 7.97 | 8.96 | 9.95 | 19.88 | | |
| | | Current (A) | 17 | 35 | 52 | 70 | 87 | 105 | 122 | 139 | 157 | 174 | 348 | | |
| | | CSA (mm2) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 150 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 368 | Infield | Transmission |
| 33kV | | R (Ω/km) | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.16 | 19.19% | 80.81% |
| | | C (µF/km) | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.19 | | |
| | | L (mH/km) | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.38 | TOTALS | |
| | | Loss (%) | 0.04% | 0.05% | 0.06% | 0.08% | 0.09% | 0.11% | 0.13% | 0.15% | 0.16% | 0.18% | 4.44% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.88 | 0.95 | 95.23% |

| Wavefarm 2 (300m Spacing) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Link | 1-2 (11-12) | 2-3 (12-13) | 3-4 (13-14) | 4-5 914-15) | 5-6 (15-16) | 6-7 (16-17) | 7-8 (17-18) | 8-9 (18-19) | 9-10 (19-20) | 10-20 | Transmission | | |
| | | Cable Length (m) | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 15000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 3.00 | 3.99 | 4.97 | 5.95 | 6.93 | 7.91 | 8.88 | 9.86 | 19.69 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 144 | 172 | 200 | 228 | 256 | 285 | 568 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 95 | 400 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 168 | 199 | 243 | 243 | 292 | 292 | 627 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.34 | 0.34 | 0.25 | 0.25 | 0.063 | 37.95% | 62.05% |
| | | C (µF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.22 | 0.22 | 0.22 | 0.22 | 0.41 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.38 | 0.38 | 0.4 | 0.4 | 0.29 | TOTALS | |
| | | Loss (%) | 0.10% | 0.17% | 0.26% | 0.34% | 0.42% | 0.37% | 0.30% | 0.34% | 0.28% | 0.31% | 4.70% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.93 | 1.10 | 94.52% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 4.00 | 4.99 | 5.99 | 6.98 | 7.97 | 8.95 | 9.93 | 19.84 | | |
| | | Current (A) | 17 | 35 | 52 | 70 | 87 | 105 | 122 | 139 | 157 | 174 | 347 | | |
| | | CSA (mm2) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 150 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 368 | Infield | Transmission |
| 33kV | | R (Ω/km) | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.16 | 22.91% | 77.09% |
| | | C (µF/km) | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.19 | | |
| | | L (mH/km) | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.38 | TOTALS | |
| | | Loss (%) | 0.05% | 0.06% | 0.08% | 0.10% | 0.12% | 0.14% | 0.16% | 0.18% | 0.20% | 0.23% | 4.43% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.88 | 0.97 | 95.16% |

| Wavefarm 2 (400m Spacing) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Link | 1-2 (11-12) | 2-3 (12-13) | 3-4 (13-14) | 4-5 914-15) | 5-6 (15-16) | 6-7 (16-17) | 7-8 (17-18) | 8-9 (18-19) | 9-10 (19-20) | 10-20 | Transmission | | |
| | | Cable Length (m) | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 15000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 2.99 | 3.99 | 4.97 | 5.94 | 6.92 | 7.89 | 8.86 | 9.83 | 19.63 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 143 | 172 | 200 | 228 | 256 | 284 | 567 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 95 | 400 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 168 | 199 | 243 | 243 | 292 | 292 | 627 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.34 | 0.34 | 0.25 | 0.25 | 0.063 | 42.37% | 57.63% |
| | | C (µF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.22 | 0.22 | 0.22 | 0.22 | 0.41 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.38 | 0.38 | 0.4 | 0.4 | 0.29 | TOTALS | |
| | | Loss (%) | 0.12% | 0.21% | 0.31% | 0.40% | 0.50% | 0.44% | 0.36% | 0.41% | 0.33% | 0.37% | 4.68% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 | 0.04 | 0.92 | 1.12 | 94.38% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 4.00 | 4.99 | 5.98 | 6.97 | 7.96 | 8.94 | 9.92 | 19.81 | | |
| | | Current (A) | 17 | 35 | 52 | 70 | 87 | 105 | 122 | 139 | 156 | 174 | 347 | | |
| | | CSA (mm2) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 150 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 368 | Infield | Transmission |
| 33kV | | R (Ω/km) | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.16 | 26.30% | 73.70% |
| | | C (µF/km) | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.19 | | |
| | | L (mH/km) | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.38 | TOTALS | |
| | | Loss (%) | 0.06% | 0.07% | 0.09% | 0.12% | 0.14% | 0.17% | 0.19% | 0.22% | 0.25% | 0.27% | 4.43% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.88 | 0.98 | 95.08% |

The overall network efficiencies for full rated output of the WEC array are given in Table 4.31.

TABLE 4.31 SUMMARY OF NETWORK EFFICIENCIES FOR FULL RATED OUTPUT

| Spacing | 200m | | 300m | | 400m | |
|---|---|---|---|---|---|---|
| Voltage | 20kV | 33kV | 20kV | 33kV | 20kV | 33kV |
| Efficiency | 94.66% | 95.23% | 94.52% | 95.16% | 94.38% | 95.08% |

The network efficiency is dependent on the output of the WEC array and will be higher for lower output power. The network efficiency over the full range of output power is shown in Figure 4.25 for the 40MW array. It can be seen that the network efficiency of the 20kV network is very similar to the 33kV array.

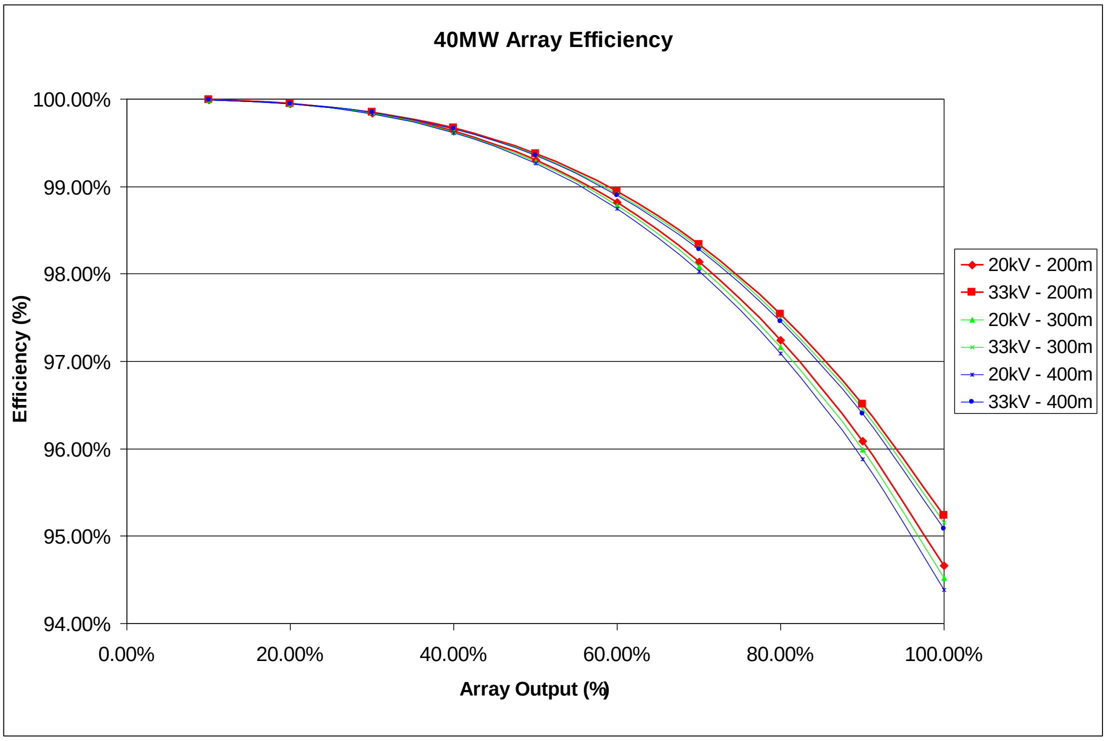



FIGURE 4.25 EFFICIENCY OF WEC ARRAY 2 VERSUS OVERALL WEC ARRAY OUTPUT

The energy yield distribution of the Wavebob device at the Belmullet site was determined in Section 4.3.3. Using this, the network efficiency can be calculated.

TABLE 4.32 SUMMARY OF NETWORK EFFICIENCY.

| Spacing | 200m | | 300m | | 400m | |
|---|---|---|---|---|---|---|
| Voltage | 20kV | 33kV | 20kV | 33kV | 20kV | 33kV |
| Network Efficiency | 97.73% | 97.97% | 97.67% | 97.94% | 97.61% | 97.91% |

This means that, although on initial inspection there would appear to a 0.7% difference in network efficiency between a 20kV and 33kV system efficiency, the real effect of this difference on annual average network efficiency is practically negligible. This illustrates the importance of understanding the characteristics of the WEC in question to establish the true network efficiency.

It also means that although both 20kV and 33kV networks initially appear not to have achieved the 96% network efficiency target set out at the beginning, once the energy distribution of the site and WEC system is taken into account, the network efficiency is approximately 97.6 – 98% for both 20kV and 33kV.

From Figure 4.25 it appears that the spacing has negligible impact on the network efficiency. In fact, from 200 to 400m spacing the difference in network efficiency is 0.12% for 20kV and 0.06% for 33kV. Spacing would appear not to be critical in the network efficiency calculation.

Therefore a network efficiency of >97% can be achieved using the circuit in Figure 4.24 and the cable sizes in Table 4.33.

**TABLE 4.33 CABLE CSA (MM$^2$) REQUIRED TO ACHIEVE NETWORK EFFICIENCY OF >97%.**

| | **Circuit Section** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Voltage** | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | 10-20 | **20-Shore** |
| **20kV** | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 95 | **400** |
| **33kV** | **50** | **50** | **50** | **50** | **50** | **50** | **50** | **50** | **50** | **50** | **150** |

Using the normalised cable cost model from Section 4.3.12, the relative cost difference between the 20kV and 33kV network is calculated. In this case the 33kV system has a relative cost which is 69% of the 20kV system. Therefore, although the same CSA cable would be more expensive for 33kV than 20kV, the 33kV network is less costly in this instance as the CSA required for the array and export network is smaller. In this case then the more efficient operating voltage (33kV) results in a lower relative cost. This does not consider other component costs such as transformer, switchgear or submarine connectors, which may be more expensive given a 33kV system.

### 4.7.3 WEC Array 3

| | |
|---|---|
| **Capacity:** | 150MW |
| **Distance from shore:** | 20km |
| **Transmission voltage:** | HVAC |
| **Number of transmission connections:** | 1 |

The deployment of a 150MW array would be a major commercial project using proven WECs on an array scale. The business case to be made for such a project may be helped due to a sustainable energy tariff. At this size of array economies of scale would be possible on common costs. The requirement for high efficiency would be critical at this point for a viable business case.

The electrical configuration in this case would be ten (10) radials of fifteen (15) 1MVA devices. The radials would be connected together in pairs at the nearest device to shore and then five (5) cables would connect the array an offshore substation. As discussed previously the breakeven point for the use of an offshore substation (versus multiple MV export connections) in the offshore wind industry is around 100MW. It is expected that this breakeven point would be higher for WEC arrays but this is dependent on the design of offshore substations for deep water. 150MW is assumed here to be the point where a deep-water offshore substation would be economically viable, however it is possible that this would be higher. The offshore substation aggregates the collected power from all the radials and steps the voltage up to HVAC for export. Figure 4.26 shows the configuration of the 150 devices. The distance from the offshore substation to the outlying radials is assumed to be 4 times the spacing distance, 2 times the spacing for the next closest radials, and 1 times for the closest radial.

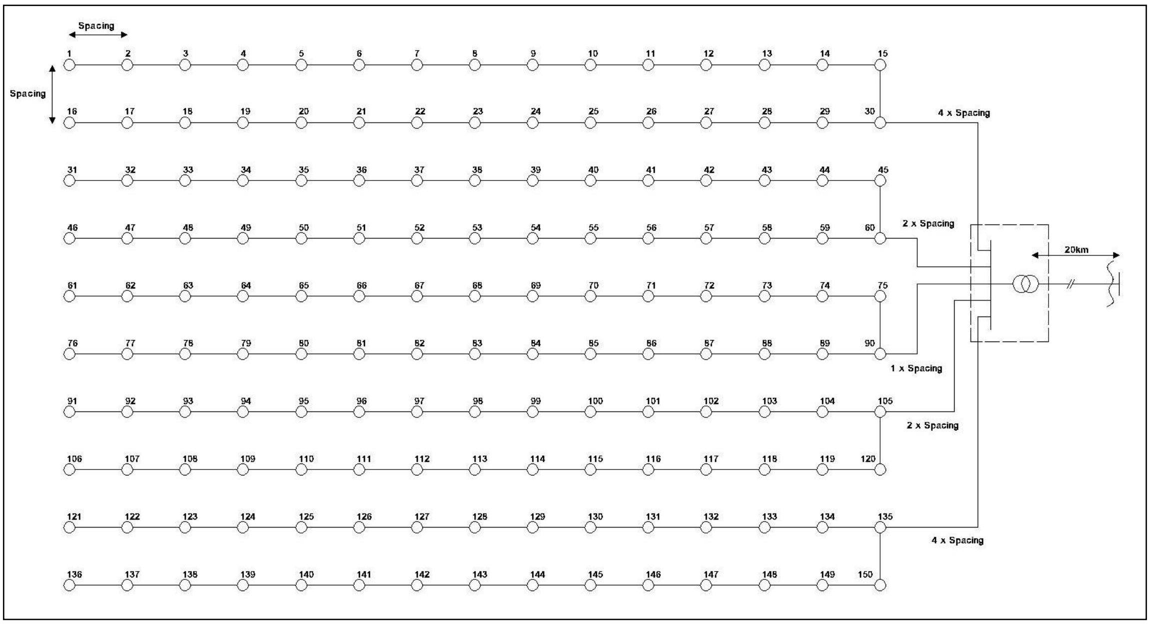



**FIGURE 4.26 WEC ARRAY 3 ELECTRICAL CONFIGURATION**

The cables are sized as outlined in Section 4.3.10 in order to give the optimum solution for a given voltage level. In this instance 20kV and 33kV are assessed for the array circuits, as the rated power of the circuits is considered too high for a practical 10kV network. The voltage for the transmission to shore is assessed as 132kV, being a typical transmission voltage used in offshore wind farms. Table 4.34 shows the detailed cable sizing and loss calculation for the 150MW array, for 200, 300 and 400m device separation.

## TABLE 4.34 CALCULATION OF LOSSES FOR WEC ARRAY 3 (100% OUTPUT) – 200, 300 & 400M SPACING

**Wavefarm 3 (200m Spacing)**

| | | Link | 1-2 (16-17) | 2-3 (17-18) | 3-4 (18-19) | 4-5 (19-20) | 5-6 (20-21) | 6-7 (21-22) | 7-8 (22-23) | 8-9 (23-24) | 9-10 (24-25) | 10-11 (25-26 | 11-12 (26-27 | 12-13 (27-28) | 13-14 (28-29) | 14-15 (29-30) | 15-30 | 30- OSS | 60-OSS | 90-OSS | Transformer | Transmission | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 400 | Cable Length (m) | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 1000 | 600 | 400 | | 20000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 3.00 | 3.99 | 4.98 | 5.96 | 6.95 | 7.93 | 8.91 | 9.89 | 10.87 | 11.84 | 12.82 | 13.80 | 14.77 | 29.53 | 29.53 | 29.53 | 147.24 | 145.48 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 144 | 172 | 200 | 229 | 257 | 285 | 314 | 342 | 370 | 398 | 427 | 852 | 852 | 852 | | 644 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 120 | 120 | 150 | 185 | 185 | 240 | 2 x 240 | 2 x 240 | 2 x 240 | | 500 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 168 | 199 | 243 | 243 | 292 | 329 | 329 | 368 | 412 | 412 | 472 | 944 | 944 | 944 | | 655 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.34 | 0.34 | 0.25 | 0.2 | 0.2 | 0.16 | 0.13 | 0.13 | 0.1 | 0.05 | 0.05 | 0.05 | | 0.05 | 63.70% | 36.30% |
| | | C (μF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.22 | 0.22 | 0.22 | 0.34 | 0.34 | 0.26 | 0.28 | 0.28 | 0.31 | 0.28 | 0.28 | 0.28 | | 0.2 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.38 | 0.38 | 0.4 | 0.37 | 0.37 | 0.35 | 0.34 | 0.34 | 0.33 | 0.34 | 0.34 | 0.34 | | 0.38 | TOTALS | |
| | | Loss (%) | 0.08% | 0.14% | 0.20% | 0.27% | 0.34% | 0.29% | 0.24% | 0.27% | 0.22% | 0.20% | 0.22% | 0.19% | 0.17% | 0.18% | 0.15% | 0.37% | 0.22% | 0.15% | 1.20% | 1.02% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.11 | 0.07 | 0.04 | 1.77 | 1.51 | 3.74 | 97.51% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 4.00 | 4.99 | 5.99 | 6.98 | 7.97 | 8.96 | 9.95 | 10.93 | 11.91 | 12.89 | 13.87 | 14.85 | 29.68 | 29.68 | 29.68 | 148.17 | 146.39 | | |
| | | Current (A) | 17 | 35 | 52 | 70 | 87 | 105 | 122 | 139 | 157 | 174 | 191 | 208 | 226 | 243 | 260 | 519 | 519 | 519 | | 648 | | |
| | | CSA (mm2) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 70 | 70 | 95 | 95 | 300 | 300 | 300 | | 500 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 245 | 245 | 292 | 292 | 564 | 564 | 564 | | 655 | Infield | Transmission |
| 33kV | | R (Ω/km) | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.34 | 0.34 | 0.25 | 0.25 | 0.079 | 0.079 | 0.079 | | 0.05 | 50.42% | 49.58% |
| | | C (μF/km) | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.15 | 0.15 | 0.17 | 0.17 | 0.25 | 0.25 | 0.25 | | 0.2 | | |
| | | L (mH/km) | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.43 | 0.43 | 0.41 | 0.41 | 0.35 | 0.35 | 0.35 | | 0.38 | TOTALS | |
| | | Loss (%) | 0.04% | 0.05% | 0.06% | 0.08% | 0.09% | 0.11% | 0.13% | 0.15% | 0.16% | 0.18% | 0.20% | 0.15% | 0.16% | 0.13% | 0.14% | 0.22% | 0.13% | 0.09% | 1.20% | 1.03% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.06 | 0.04 | 0.03 | 1.78 | 1.52 | 3.60 | 97.60% |

**Wavefarm 3 (300m Spacing)**

| | | Link | 1-2 (16-17) | 2-3 (17-18) | 3-4 (18-19) | 4-5 (19-20) | 5-6 (20-21) | 6-7 (21-22) | 7-8 (22-23) | 8-9 (23-24) | 9-10 (24-25) | 10-11 (25-26 | 11-12 (26-27 | 12-13 (27-28) | 13-14 (28-29) | 14-15 (29-30) | 15-30 | 30- OSS | 60-OSS | 90-OSS | Transformer | Transmission | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 500 | Cable Length (m) | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 1400 | 800 | 500 | | 20000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 3.00 | 3.99 | 4.97 | 5.95 | 6.93 | 7.91 | 8.88 | 9.86 | 10.84 | 11.81 | 12.78 | 13.75 | 14.72 | 29.41 | 29.41 | 29.41 | 146.53 | 144.77 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 144 | 172 | 200 | 228 | 256 | 285 | 313 | 341 | 369 | 397 | 425 | 849 | 849 | 849 | | 641 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 120 | 120 | 150 | 185 | 185 | 240 | 2 x 240 | 2 x 240 | 2 x 240 | | 500 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 168 | 199 | 243 | 243 | 292 | 329 | 329 | 368 | 412 | 412 | 472 | 944 | 944 | 944 | | 655 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.34 | 0.34 | 0.25 | 0.2 | 0.2 | 0.16 | 0.13 | 0.13 | 0.1 | 0.05 | 0.05 | 0.05 | | 0.05 | 68.99% | 31.01% |
| | | C (μF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.22 | 0.22 | 0.22 | 0.34 | 0.34 | 0.26 | 0.28 | 0.28 | 0.31 | 0.28 | 0.28 | 0.28 | | 0.2 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.38 | 0.38 | 0.4 | 0.37 | 0.37 | 0.35 | 0.34 | 0.34 | 0.33 | 0.34 | 0.34 | 0.34 | | 0.38 | TOTALS | |
| | | Loss (%) | 0.10% | 0.17% | 0.26% | 0.34% | 0.42% | 0.37% | 0.30% | 0.34% | 0.28% | 0.25% | 0.27% | 0.24% | 0.21% | 0.22% | 0.19% | 0.52% | 0.30% | 0.18% | 1.20% | 1.02% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.15 | 0.09 | 0.05 | 1.76 | 1.49 | 3.85 | 97.43% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 4.00 | 4.99 | 5.99 | 6.98 | 7.97 | 8.95 | 9.93 | 10.91 | 11.88 | 12.86 | 13.84 | 14.81 | 29.60 | 29.60 | 29.60 | 147.69 | 145.92 | | |
| | | Current (A) | 17 | 35 | 52 | 70 | 87 | 105 | 122 | 139 | 157 | 174 | 191 | 208 | 225 | 242 | 259 | 518 | 518 | 518 | | 646 | | |
| | | CSA (mm2) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 70 | 70 | 95 | 95 | 300 | 300 | 300 | | 500 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 245 | 245 | 292 | 292 | 564 | 564 | 564 | | 655 | Infield | Transmission |
| 33kV | | R (Ω/km) | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.34 | 0.34 | 0.25 | 0.25 | 0.079 | 0.079 | 0.079 | | 0.05 | 56.32% | 43.68% |
| | | C (μF/km) | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.15 | 0.15 | 0.17 | 0.17 | 0.25 | 0.25 | 0.25 | | 0.2 | | |
| | | L (mH/km) | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.43 | 0.43 | 0.41 | 0.41 | 0.35 | 0.35 | 0.35 | | 0.38 | TOTALS | |
| | | Loss (%) | 0.05% | 0.06% | 0.08% | 0.10% | 0.12% | 0.14% | 0.16% | 0.18% | 0.20% | 0.23% | 0.25% | 0.19% | 0.20% | 0.16% | 0.17% | 0.30% | 0.17% | 0.11% | 1.20% | 1.03% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 | 0.09 | 0.05 | 0.03 | 1.77 | 1.51 | 3.67 | 97.55% |

**Wavefarm 3 (400m Spacing)**

| | | Link | 1-2 (16-17) | 2-3 (17-18) | 3-4 (18-19) | 4-5 (19-20) | 5-6 (20-21) | 6-7 (21-22) | 7-8 (22-23) | 8-9 (23-24) | 9-10 (24-25) | 10-11 (25-26 | 11-12 (26-27 | 12-13 (27-28) | 13-14 (28-29) | 14-15 (29-30) | 15-30 | 30- OSS | 60-OSS | 90-OSS | Transformer | Transmission | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 600 | Cable Length (m) | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 1800 | 1000 | 600 | | 20000 | | |
| | 100% | Power (MVA) | 1.00 | 2.00 | 2.99 | 3.99 | 4.97 | 5.94 | 6.92 | 7.89 | 8.86 | 9.83 | 10.80 | 11.77 | 12.73 | 13.70 | 14.67 | 29.30 | 29.30 | 29.30 | 145.82 | 144.07 | | |
| | | Current (A) | 29 | 58 | 86 | 115 | 143 | 172 | 200 | 228 | 256 | 284 | 312 | 340 | 368 | 396 | 423 | 846 | 846 | 846 | | 638 | | |
| | | CSA (mm2) | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 | 120 | 120 | 150 | 185 | 185 | 240 | 2 x 240 | 2 x 240 | 2 x 240 | | 500 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 168 | 168 | 168 | 168 | 168 | 199 | 243 | 243 | 292 | 329 | 329 | 368 | 412 | 412 | 472 | 944 | 944 | 944 | | 655 | Infield | Transmission |
| 20kV | | R (Ω/km) | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.49 | 0.34 | 0.34 | 0.25 | 0.2 | 0.2 | 0.16 | 0.13 | 0.13 | 0.1 | 0.05 | 0.05 | 0.05 | | 0.05 | 72.93% | 27.07% |
| | | C (μF/km) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.22 | 0.22 | 0.22 | 0.34 | 0.34 | 0.26 | 0.28 | 0.28 | 0.31 | 0.28 | 0.28 | 0.28 | | 0.2 | | |
| | | L (mH/km) | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.43 | 0.38 | 0.38 | 0.4 | 0.37 | 0.37 | 0.35 | 0.34 | 0.34 | 0.33 | 0.34 | 0.34 | 0.34 | | 0.38 | TOTALS | |
| | | Loss (%) | 0.12% | 0.21% | 0.31% | 0.40% | 0.50% | 0.44% | 0.36% | 0.41% | 0.33% | 0.30% | 0.33% | 0.28% | 0.25% | 0.27% | 0.22% | 0.66% | 0.37% | 0.22% | 1.20% | 1.02% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 | 0.19 | 0.11 | 0.06 | 1.75 | 1.48 | 3.97 | 97.36% |
| | | Power (MVA) | 1.00 | 2.00 | 3.00 | 4.00 | 4.99 | 5.98 | 6.97 | 7.96 | 8.94 | 9.92 | 10.89 | 11.86 | 12.83 | 13.80 | 14.78 | 29.52 | 29.52 | 29.52 | 147.22 | 145.46 | | |
| | | Current (A) | 17 | 35 | 52 | 70 | 87 | 105 | 122 | 139 | 156 | 174 | 191 | 208 | 225 | 241 | 259 | 517 | 517 | 517 | | 644 | | |
| | | CSA (mm2) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 70 | 70 | 95 | 95 | 300 | 300 | 300 | | 500 | LOSSES DISTRIBUTION | |
| | | CCC (A) | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 245 | 245 | 292 | 292 | 564 | 564 | 564 | | 655 | Infield | Transmission |
| 33kV | | R (Ω/km) | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.34 | 0.34 | 0.25 | 0.25 | 0.079 | 0.079 | 0.079 | | 0.05 | 60.97% | 39.03% |
| | | C (μF/km) | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.15 | 0.15 | 0.17 | 0.17 | 0.25 | 0.25 | 0.25 | | 0.2 | | |
| | | L (mH/km) | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.43 | 0.43 | 0.41 | 0.41 | 0.35 | 0.35 | 0.35 | | 0.38 | TOTALS | |
| | | Loss (%) | 0.06% | 0.07% | 0.09% | 0.12% | 0.14% | 0.17% | 0.19% | 0.22% | 0.25% | 0.27% | 0.30% | 0.23% | 0.24% | 0.19% | 0.21% | 0.39% | 0.21% | 0.13% | 1.20% | 1.02% | Lost MVA | Efficiency |
| | | Lost power (MVA) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.11 | 0.06 | 0.04 | 1.77 | 1.51 | 3.74 | 97.51% |

The overall network efficiencies for full rated output of the WEC array are given in Table 4.35.

**TABLE 4.35 SUMMARY OF NETWORK EFFICIENCIES FOR FULL RATED OUTPUT**

| Spacing | 200m | | 300m | | 400m | |
|---|---|---|---|---|---|---|
| Voltage | 20kV | 33kV | 20kV | 33kV | 20kV | 33kV |
| Efficiency | 97.51% | 97.60% | 97.43% | 97.55% | 97.36% | 95.51% |

The network efficiency is dependent on the output of the WEC array and will be higher for lower output power. The network efficiency over the full range of output power for the 150MW array is shown in Figure 4.27. It can be seen that the network efficiency of the 20kV network is almost identical to the 33kV array, given that the transmission section at 132kV is also identical.

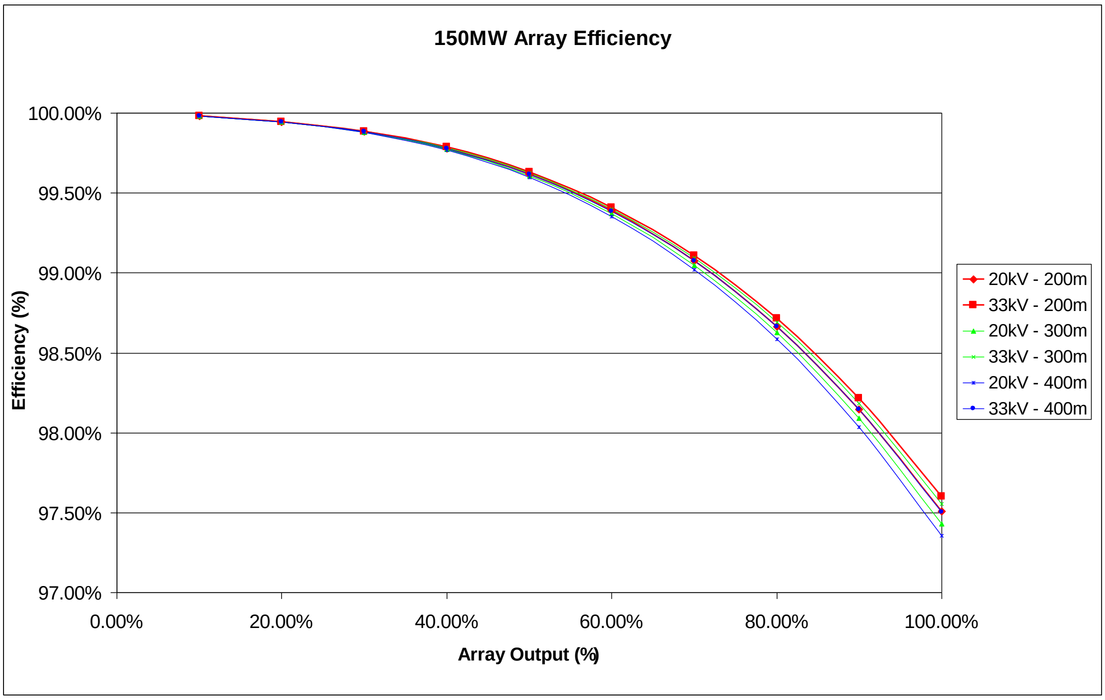



**FIGURE 4.27 EFFICIENCY OF WEC ARRAY 3 VERSUS OVERALL WEC ARRAY OUTPUT**

The energy yield distribution of the Wavebob device at the Belmullet site was determined in Section 4.3.3. Using this, the network efficiency can be calculated.

TABLE 4.36 SUMMARY OF NETWORK EFFICIENCY.

| Spacing | 200m | | 300m | | 400m | |
|---|---|---|---|---|---|---|
| Voltage | 20kV | 33kV | 20kV | 33kV | 20kV | 33kV |
| Network Efficiency | 98.91% | 98.95% | 98.87% | 98.93% | 98.84% | 98.91% |

This shows that once the energy distribution of the site and WEC system is taken into account the network efficiency is approximately 98.81 – 98.95% for both 20kV and 33kV array network and the 132kV transmission network.

From Figure 4.27 it appears that the spacing has negligible impact on the network efficiency. In fact, from 200 to 400m spacing the difference in network efficiency is 0.11% for 20kV and 0.04% for 33kV. Spacing would appear not to be critical in the network efficiency calculation.

Therefore network efficiency of >98.8% can be achieved using the circuit in Figure 4.26 and the cable sizes in Table 4.37.

TABLE 4.37 CABLE CSA (MM$^2$) REQUIRED TO ACHIEVE NETWORK EFFICIENCY OF >98.8% (* 132KV CABLE FOR TRANSMISSION)

| | Circuit Section | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Voltage | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 |
| **20kV** | 35 | 35 | 35 | 35 | 35 | 50 | 70 | 70 | 95 |
| **33kV** | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | Circuit Section | | | | | | | | |
| Voltage | 10-11 | 11-12 | 12-13 | 13-14 | 14-15 | 15-30 | 30-OSS | OSS-Shore* | |
| **20kV** | 120 | 120 | 150 | 185 | 185 | 240 | 2 x 240 | 500 | |
| **33kV** | 50 | 50 | 70 | 70 | 95 | 95 | 300 | 500 | |

Using the normalised cable cost model from Section 4.3.12, the relative cost difference between the 20kV and 33kV network is calculated. In this case the 33kV system has a relative cost which is 95% of the 20kV system. Therefore, although the same CSA cable would be more expensive for 33kV than 20kV, the 33kV network is less costly in this instance as the CSA required for the array and export network is smaller. In this case then, the marginally more efficient operating voltage (33kV) results in a lower relative cost. This does not consider other component costs such as transformers, switchgear or submarine connectors which may be more expensive given a 33kV system.

### 4.7.4 Summary

The results are summarised in Figure 4.28 showing the achievable network efficiency for the candidate WEC arrays 1, 2 and 3 presented in this section. It is important to note that these network efficiencies are achievable for the generation characteristic introduced in Section 4.3.3. However, it is also important to note that the real network efficiency for an electrical network cannot be calculated without an understanding of the generation characteristic of the WEC devices.

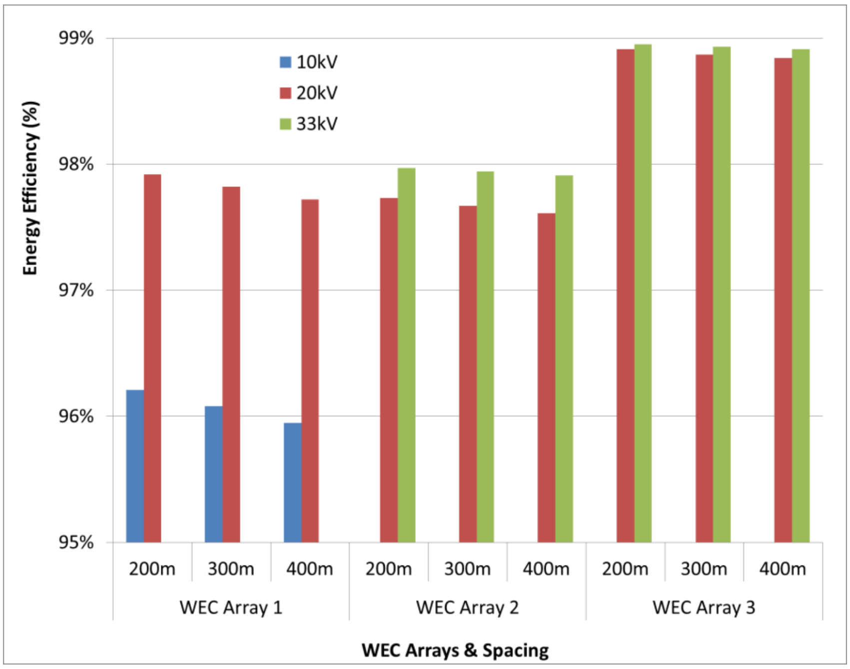



**FIGURE 4.28 ACHIEVABLE NETWORK EFFICIENCY FOR WEC ARRAYS 1-3**

Also of note from Figure 4.28 is that array spacing has negligible impact on the network efficiency of the WEC array electrical network. However, as shown in Figure 4.29, increased array spacing increases the length of cable required within the array and this has an impact on the economics of the WEC array electrical network. This is explored further in Chapter 5.

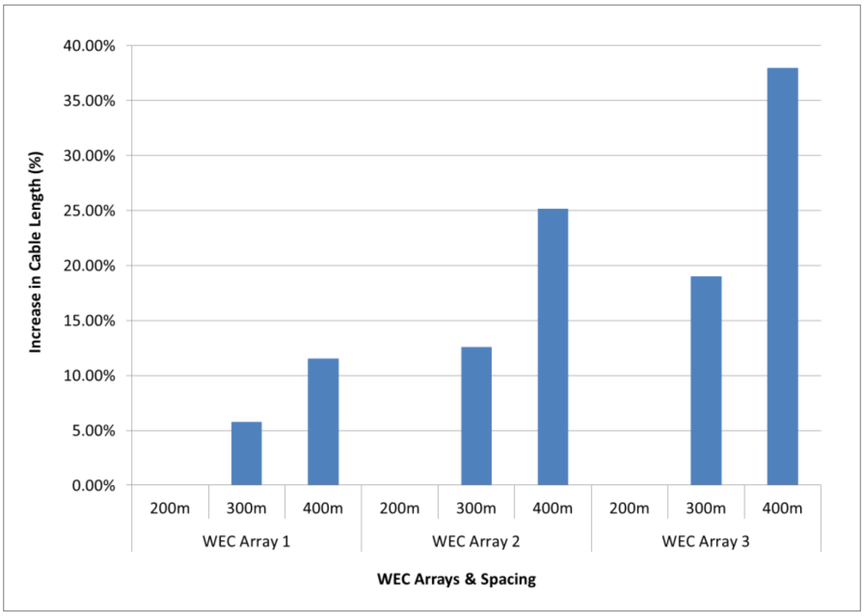



**FIGURE 4.29 INCREASE IN ARRAY CABLE LENGTH FROM INCREASED SPACING.**

## 4.8 Achieving CAPEX Targets

In this chapter, a techno-economic optimisation exercise has been carried out in order to assess the best technical solution that can be achieved within the target costs of €1m/MW as introduced in Section 4.2. However, normalised (or relative) and indicative costs have been used. This acknowledges that actual costs are difficult to quantify in a generic sense and are also volatile over time. The following costs are assumed for the cable and key interface components in WEC array 2, the 40MW array.

- Base case cable cost (10kV, 95mm$^2$) of €350/m installed
- Base case cost for key interfaces:
    1. Dynamic Cable to WEC: €100k
    2. Dynamic Cable to Static Cable: €40k
    3. WEC MV Switchgear: €0k (included in WEC cost)
    4. Offshore Substation: N/A

Using the above estimated base cost, the total cost for WEC array 2 electrical network is shown in Table 4.24. Note that 400m array spacing and 33kV voltage are assumed.

TABLE 4.38 ESTIMATED COST FOR TECHNO-ECONOMIC OPTIMISED WEC ARRAY 2

| Item | Cost |
|---|---|
| **Array Cabling** | €7,022,400 |
| **Export Cabling** | €13,125,000 |
| **Dynamic Cable to WEC Interface (x 2 for 38 WECs, x 3 for 2 WECs)** | €12,300,000 |
| **Dynamic Cable to Static Cable (x 2 for 38 WECs, x 3 for 2 WECs)** | €8,200,000 |
| **WEC MV Switchgear** | €0 (part of WEC CAPEX) |
| **TOTAL** | €40,647,400 |
| **TOTAL (per MW)** | €1,016,185 / MW |

Therefore, it can be shown that the techno-economic optimisation has presented estimated WEC electrical network costs of €1.02m/MW, marginally above the target costs outlined in Section 4.2. With further optimisation and cost reduction through purchasing efficiencies it is expected that this cost can be lowered further.

This shows however, the challenge of achieving the target CAPEX even with an optimised solution. There are many upward pressures on this CAPEX but some possible strategies to reduce it also. These challenges and mitigating strategies are explored in Chapter 5.

## 4.9 Conclusion

In this chapter the design considerations, constraints and assumptions have been introduced to allow for the design and optimisation of WEC array electrical networks. It has been shown here and in Chapter 3 that there are many aspects to be considered when designing a WEC array electrical network. Array physical layout and spacing is a critical design consideration for WEC array electrical networks. Electrical network design economics is just one consideration for the physical layout and spacing, and any implications on criteria such as interference, moorings or vessel access must be considered.

From the analysis in Chapter 3 the key differences between offshore wind electrical networks and WEC array electrical networks have been identified. In particular the key interfaces of the WEC array electrical network have been introduced and analysed. These key interfaces are critical to the functionality of a WEC array electrical network but may be high cost items. Several alternative designs have been proposed for these key interfaces and have been assessed for functionality and relative cost.

The array network configuration alternatives have also been assessed from an economic and functional perspective. It is concluded that the radial network would be the optimum network as it is likely to be the lowest cost. There are deficiencies with a radial network for a WEC array, and these have been addressed with some solutions proposed to overcome these deficiencies.

Star cluster networks overcome these limitations at a comparable cost. There is, however, a requirement for a collector 'hub' within star cluster networks. These hubs have been proposed involving complex power equipment located in submarine hubs on the seafloor. This is feasible, but presents economic, technical, and safety concerns. Radial networks may be easier to implement in a more cost effective and safe manner in the medium-term.

For a radial network a techno-economic optimisation has been undertaken which defines the least cost key interfaces while maintaining the necessary functionality in the WEC array electrical network. This optimised solution allows the WEC array electrical network to be achieved at costs which are within the target envelope for commercial WEC arrays.

Some candidate WEC arrays from 10MW – 150MW have been evaluated to understand the achievable annual average network efficiency of the WEC array electrical network. This shows that network efficiencies of >96% and up to 99% can be achieved for the presented WEC array electrical network designs. Higher voltage ratings increase network efficiency and result in lower cable cost but this may be negated by higher cost transformers, switchgear and submarine connectors. Increased spacing has negligible effects on network efficiency but has an economic penalty as will be discussed in Chapter 5.

The optimised electrical network has been shown to be achievable within the presented target costs for the electrical networks for commercial WEC arrays, i.e. €1m/MW

# Chapter 5

# Economic Challenges and Cost Reduction Strategies for WEC Array Electrical Networks

## 5.1 Introduction

In this chapter economic challenges, unique to wave energy electrical network design, are introduced. These challenges are analysed to quantify the impact of design decisions on the techno-economic performance of WEC array electrical networks. The optimised array network which is outlined in Chapter 4 is used as a candidate in analysis.

There are also potential strategies to improve the economics of the WEC array electrical network. The strategies for maximising the value of the WEC array electrical network are introduced and evaluated for the optimised candidate network.

## 5.2 Economic Challenges for WEC Array Electrical Networks

As there is likely to be significant pressure on the overall business case for early stage WEC arrays, it is necessary to reduce the costs of major capital expenditure such as the electrical network. However, designers must be wary not to compromise critical safety and functionality in order to meet this downward cost pressure.

The 'medium' size, 40MW, WEC array is taken from Section 4.7.2 as a candidate array. This is shown in Figure 5.1. This candidate array has the following assumptions for analysis in this chapter:

- Each WEC (node) is rated at 1MW with unity power factor
- Each WEC has a 30% capacity factor

- The inter-WEC spacing is 400m (array cables are 400m + twice the depth)
- The water depth is 100m
- The export distance is 15km
- Operating voltage is 20kV unless otherwise stated

This is used in conjunction with the normalised cable cost model given in Section 4.3.12 in order for an economic analysis to be undertaken.

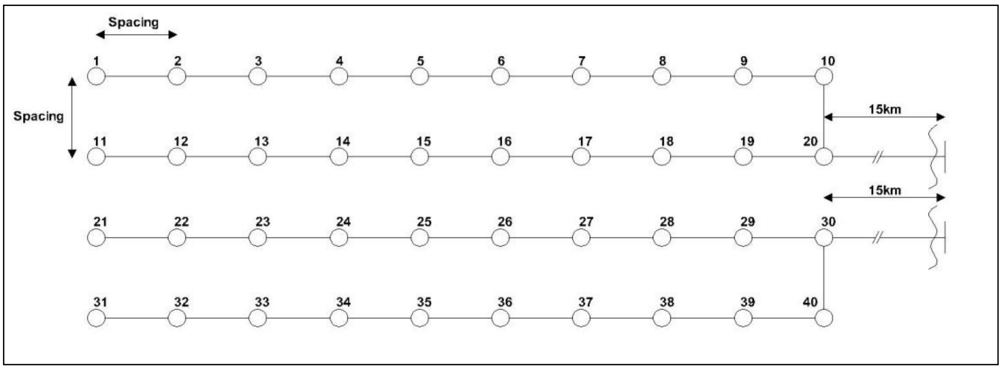



**FIGURE 5.1 CANDIDATE, 40MW WEC ARRAY 2**

### 5.2.1 Redundancy and Star Cluster Networks

**AS OUTLINED IN SECTION 4.5, RADIAL NETWORKS RESULT IN THE LOWEST COST BUT LACK REDUNDANCY. REDUNDANCY. REDUNDANCY CAN BE ADDED TO THE NETWORK CONFIGURATION BUT AT A COST. IN SECTION 4.5 THIS COST IS QUANTIFIED FOR VARIOUS NETWORK CONFIGURATIONS WITH THE RELATIVE COSTS GIVEN IN**

Table 4.22.

Star cluster networks may be attractive, as when they are physically optimised, they can have costs similar to radial networks. There are additional challenges associated with the necessary ‘hubs’ in star cluster configurations. These challenges may increase costs of the array electrical network substantially. This is detailed in Section 4.4.5. Ultimately, WEC array electrical network designs which utilise star cluster networks with submarine ‘hubs’ may not achieve target costs.

### 5.2.2 WEC Array Spacing

In Section 4.7.4 the potential additional cost of increasing WEC spacing from 200m to 400m is introduced. This shows that, for certain arrays, doubling the spacing from 200m to 400m could increase the circuit length (and hence costs) by up to 37% (see Figure 4.29).

There is a balance between optimizing the array spacing for hydrodynamic interference and also reducing the electrical system costs. The increased cost associated with increasing array spacing must be offset by the resultant potential increased yield or lower losses though interference.

### 5.2.3 Individual WEC ratings

At the current stage of the industry's maturity there is a trend, both in the wave and tidal sectors, towards devices with ratings of 1MW. Individual WEC ratings of 1MW are therefore used as the base case in any analysis done in this thesis. There are, however, a number of exceptions to this trend. Offshore wind turbines are mostly rated around 3-4MW with a trend towards higher power turbines (5MW and larger). These smaller device ratings present a challenge to the economics of WEC array electrical systems as each device in an array requires dynamic cables (floating WEC), submarine connectors, and a cable connection to the next device in the array. More devices in the array means additional cost for the array, certainly on a per MW level.

The costs of the dynamic and static submarine cables only is evaluated here, as the export cable cost would not change given the same array rating. The relative cost of the array electrical network (versus the base case) is established for a 40MW WEC array with 250kW, 500kW, 1MW (base case), 2MW, and 4MW individual WEC ratings. The overall rating of the array remains at 40MW in all cases, i.e. the quantity of WECs changes depending on the WEC rating. Therefore, for 250kW WECs there are 160 WECs in the array, for 500kW there are 80 WECs, for 2MW there are 20 WECs, for 3MW there are 13 WECs, and for 4MW there are 10 WECs. The array and export voltage is also 20kV in all cases.

As lower rated WECs are likely to require less spacing between devices, the array spacing is adjusted using a scaling factor (approximate Froude scaling). Therefore, for 250kW WEC spacing is 268m, for 500kW spacing is 328m, for 2MW spacing is 480m, for 3MW spacing is 544m, and for 4MW spacing is 592m.

The relative cost as a multiple of the base case is calculated by re-assessing the cable CSA requirements for the array network in each case, and calculating the relative cost using the normalised submarine cable cost model (Section 4.3.12). The results are shown in Figure 5.2. The relative cost is shown for the array electrical network only and the full electrical system (i.e. array and 15km export cable). This shows that the relative cost of the array electrical network is higher given smaller WECs in the network and lower given larger WECs. 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 significantly for larger individual WECs, with decreases to as low as 0.4 times possible for the array cable costs.

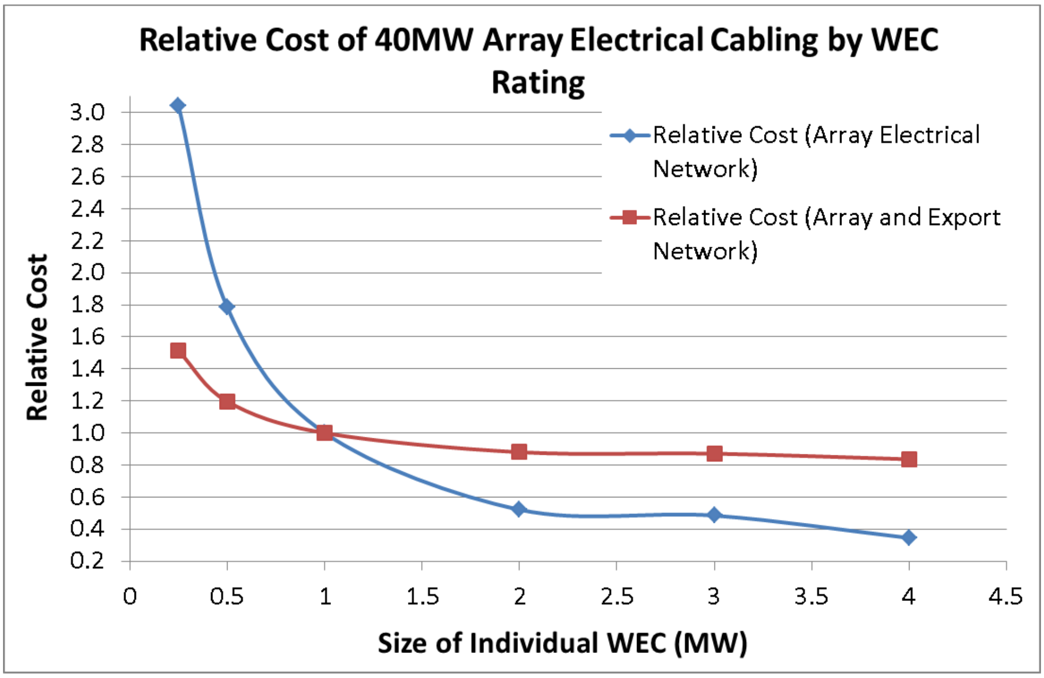



FIGURE 5.2 RELATIVE COST OF 40MW ARRAY ELECTRICAL CABLING BASED ON DEVICE RATING

The focus here is on the electrical network cables only. However, it is worth noting that lower WEC ratings increase other elements of CAPEX such as installation and moorings.

### 5.2.4 Device Capacity Factor

The capacity factor of offshore wind turbines is typically in the region of 30-40% [71] depending on turbine type, location, and yearly wind speed. Given the variety of WEC concepts available, it is unclear what capacity factors these WECs will have. For 'direct drive' WECs, the capacity factor could be very low; <20%, due to the need for a high peak power rating (relative to the average) to absorb wave energy.

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%. In order to allow a comparative analysis, the annual energy from the array remains constant. Therefore, the 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. E.g. an array with 10% capacity factor has a peak output of 120MW but an average output of 12MW.

The relative cost as a multiple of the base case is calculated by re-assessing the cable CSA requirements for the array network in each case, and calculating the relative cost using the normalised submarine cable cost mode (Section 4.3.12). The results are shown in Figure 5.3. The relative cost is shown for the full electrical network only (i.e. array and 15km export cable). This is because capacity factor affects the cost of both array and export systems. The relative cost is assessed at two voltage levels (20kV and 33kV). This shows that the relative cost of the electrical network is higher for WECs with lower capacity factor, and lower for WECs 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%.

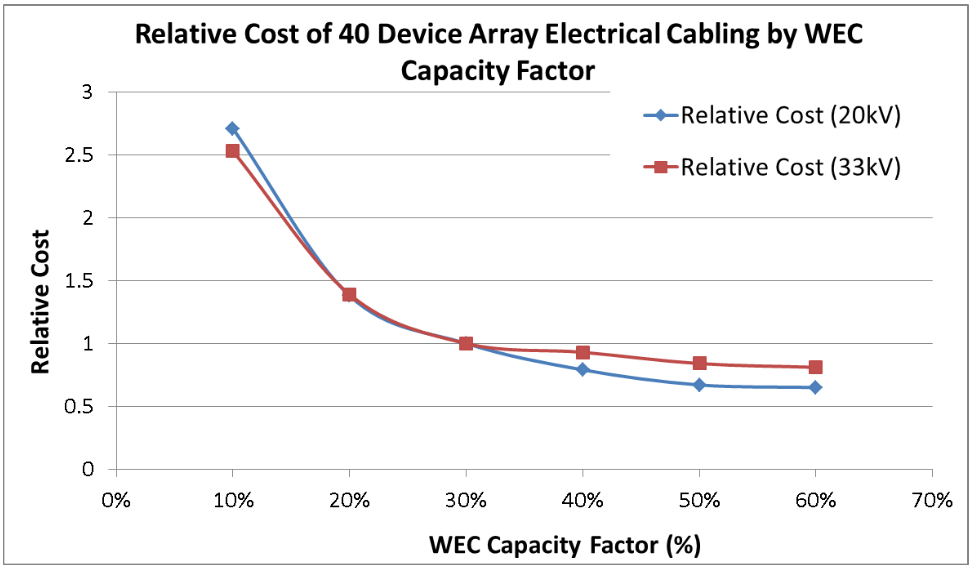



**FIGURE 5.3 RELATIVE COST OF 40 DEVICE ARRAY ELECTRICAL CABLING BASED ON DEVICE CAPACITY FACTOR**

### 5.2.5 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 WEC 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 Section 4.5. For floating WECs, there is a connection required between the dynamic cable and the static cable. In some cases there is 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 Sections 3.3 and 4.4.

However, as these connectors are a requirement for WEC array electrical networks, which does not exist in offshore wind, they add to the overall cost of the electrical network. In some cases, where a radial circuit is used, there is a requirement for two connectors per device. As mentioned in Section 4.2, the electrical network has a target cost of €1m/MW. Also. Section 4.4.2 shows that electrical connectors could cost anywhere from €30-€300k per installed connector. To avoid exceeding the threshold of €1m/MW two €250k connectors may not be feasible, i.e. €0.5m/WEC on connectors alone. If the individual WECs are larger than 1MW this may help to reduce the 'per MW' cost of the submarine connectors.

Although wet-mate connectors may increase the functionality of the device, they may be unfeasible in the medium-term due to cost. Ultimately, submarine connectors are required and it is simply a matter of trying to balance the cost with the functionality of the connector. This has been discussed in Section 4.6.

### 5.2.6 Array and Export Voltage

The voltage of the array and export system is an important design factor when considering the cost of the electrical network. The array voltage can be dictated by the WEC design or the availability of key interface components such as submarine connectors. It is desirable for the array and export system voltage to be as high as possible, but this is constrained by economic considerations and component availability.

Typical offshore wind farm array systems operate at 33kV [64], with a move towards array systems at up to 66kV. Typically the array system is connected in multiple radials to a fixed offshore substation where the voltage is stepped up to high voltage (132kV+) for export to shore. For WEC arrays it is likely that lower voltages will be used initially due to the rating of individual WECs and limited array sizes. Eventually, voltages of up to at least 33kV will be required for WEC arrays although array voltages may need to be higher to avoid the complications of offshore substations in deeper water as outlined in Section 3.3.4.

It is difficult to quantify a generic cost difference for various array and export voltages, as each WEC array will have different considerations depending on a variety of factors including number of WECs, WEC ratings, array spacing, distance to shore, and grid connection voltage. Although increasing the voltage rating of a particular cable increases the cost of that cable (if the cross sectional area (CSA) remains the same), an increased voltage rating allows a lower current rating and hence a smaller CSA. Therefore, in certain circumstances, and notably for larger arrays, an increase in voltage can ultimately decrease the electrical network costs, particularly for the cable element of this cost. Increase in voltage of the network, however, causes an increase in cost of other equipment like switchgear and transformers.

As an example, the information presented in Figure 5.3 (which shows relative figures only) is reproduced in Figure 5.4, illustrating the absolute difference in cost between 20kV and 33kV array and export cable systems for a variety of WEC capacity factors. The cost difference can be up to 33% for low capacity factors (where high CSA is required at lower voltages); however, this can reduce to almost 0% difference for 40% capacity factors. For clarity, this means that the 33kV system can be up to 33% less costly than a 20kV system at lower capacity factors and is not more costly for our candidate array.

In conclusion, selecting the optimum system voltage can have an impact on the economics of the electrical system but each array must be evaluated separately.

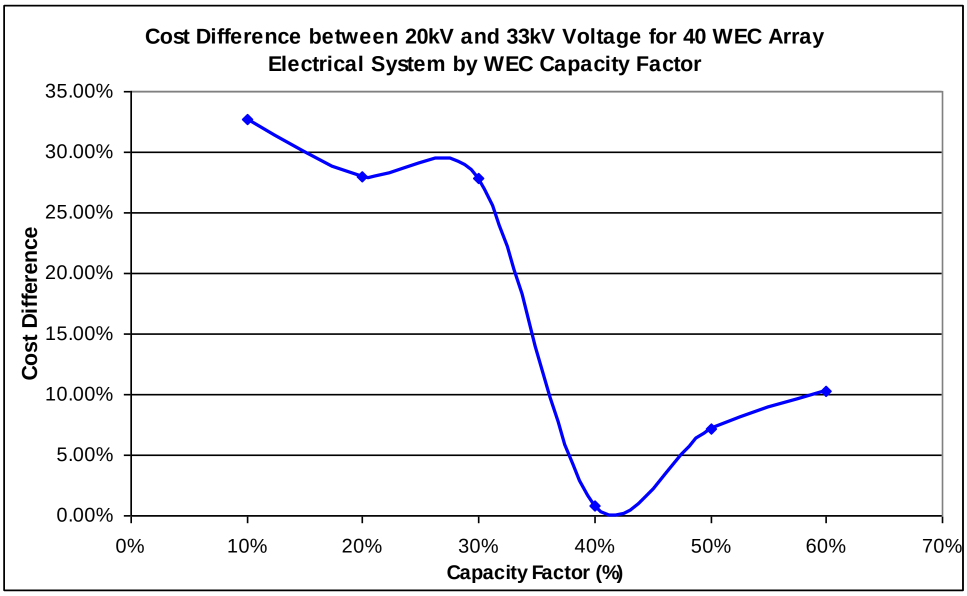



**FIGURE 5.4 COST DIFFERENCE BETWEEN 20KV AND 33KV VOLTAGE FOR 40 DEVICE FARM ELECTRICAL CABLING BY WEC CAPACITY FACTOR**

It is also worth noting that increasing the system voltage may have impacts on the key interfaces such as the submarine connector discussed in Section 5.2.5.

### 5.2.7 Cable Installation and Export Distance

Seabed characteristics have a significant impact on the cost of submarine cable installations with the ideal conditions for cable laying and protection being soft mud, sand or clay where the cable can be ploughed into the sand and buried to a depth where it is protected (typically 2 metres). Conveniently, this would also be an ideal condition for drag embedment anchors for WEC mooring. However, not all sites have these conditions, particularly high energy (wave and tidal) sites that may have little or no sediment cover or mobile sediment [113]. Cable installations might be required in sites that have swept rock, cobble, reefs, boulder fields, glacial till, or other characteristics. In some cases the cable route may cross several distinctly different seabed conditions.

The impact this can have on the economics of the electrical system cannot be underestimated. Trenching methods requiring rock saws radically increase installation costs. Post-installation protection using rock dumping or concrete mattresses could cost more than the installed cable itself and therefore could potentially double the costs [57]. These costs are not quantified here but the economics of the cable installation and protection forms an integral part of the site selection process. Sites which allow lower cost cable installations will ultimately be more competitive. A 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)

Careful selection of sites with sediment is one way of avoiding expensive cable installation methods. This could 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 requires numerous additional components such as bend restrictors, stress relievers, floatation module and scour protection. Again, this adds to the cost of the electrical system. Nevertheless, this increase is expected to be relatively modest.

Export distance also has a very understandable impact on the cost of the electrical system. This does not need to be quantified and it should be obvious that longer export systems, which should be noted to include the offshore distance from the WEC array to the shore landing as well as the onshore distance to the grid connection point, increases costs. This should also form an integral part of the site selection process and some sites will benefit from short export distances and grid connection points close to the cable landing point.

Finally, offshore substations may be cost-prohibitive to install at deep-water WEC array sites and require expensive foundation solutions such as jacket structures, or alternatively, semi-submersible, spar or submarine installation. These requirements increase the cost of an offshore substation dramatically and very large arrays may be required before such an expense can be justified.

### 5.2.8 WEC Dynamic Response

As with the site characteristics, the effect of the WEC dynamic response on the economics can be difficult to quantify as there are many factors which must be considered in the design of a dynamic cable. The response amplitude operator (RAO) of the device describes the behaviour of the device in real sea-states. There is no doubt that WECs with a lower dynamic response cause less stress, acceleration and fatigue loading on the cable, which in turn enable the construction cost of the cable to be lower.

Fatigue lifetime of materials is an important design consideration of dynamic cables [85] and there are considerations to be made at pinch points of the cable. For example, the connection to the WEC where a stress reliever is required and the cable accessories including buoyancy module, vortex induced vibration strakes, and scour protection. All of these elements add to the cost of the dynamic cable and consequently to the overall electrical system cost.

It is anticipated that the impact of this on the overall electrical network cost is relatively limited, although certainly not insignificant.

## 5.3 Maximising Value from WEC Array Electrical Networks

In this section strategies to reduce the CAPEX of the electrical network of WEC arrays are introduced, i.e. strategies to maximise the value of the electrical network asset with particular emphasis on the cabling system. This in turn reduces the overall CAPEX of WEC arrays and help allow cost competitive wave energy to be realised.

There are a number of strategies explored here in order to achieve this increase in value from the WEC array electrical network. In some cases, comparison is made to offshore wind to provide context. However, it should be noted that WEC devices have very different characteristics than offshore wind turbines.

### 5.3.1 Strategies for Maximising Value of WEC Array Electrical Networks

#### *5.3.1.1 Addressing Economic Challenges*

There are numerous challenges to the economics of WEC array electrical networks introduced throughout Chapter 4 and in Section 5.2. It is noted that through careful design of WEC devices and WEC arrays these challenges can be addressed. Optimum design of WEC devices in terms of device rating, capacity factor, and device response characteristics reduce the costs for WEC array electrical networks. Costs can also be reduced through optimum design of WEC arrays in terms of array spacing, electrical network configuration, key interfaces, and site characteristics.

Some of these cost reduction opportunities are outlined in Chapter 4 and in Section 5.2. The sections below describe additional strategies that may allow some reduction in the costs of WEC array electrical networks.

#### *5.3.1.2 Less Than 100% Rating Based on Statistical Data*

It is expected that a WEC Array would reach 100% output for only a small proportion of its annual operation. This leads to the hypothesis that the electrical export system could be rated at less than 100% of the 'nameplate' rating of the WEC array. In this case the rating means that the export cable is under-rated when the WECs do reach maximum output simultaneously, leading to either output curtailment or a combination of one of the techniques described in Section 5.3.1.3 and 5.3.1.4. However any potential loss in generated energy revenue may be offset by the savings gained from using a lower rated cable.

The UK National Grid & Crown Estate established the optimum economic case for electrical export systems for offshore wind farms in [114]. This concluded that the optimum wind farm capacity is 112% of the export cable capacity, i.e. the optimum export cable capacity is 89.3% of the wind farm capacity. This finding is based on the optimum MWh/£GB CAPEX, taking into account availability and overall lifetime economics of the wind farm. The report acknowledged that curtailment of generation would be necessary at certain times. The same conclusions may not be true for WEC arrays with different generation characteristics but this demonstrates the viability of exploring the concept for wave energy.

By simulating a small WEC array, the effect that <100% rating of the cabling has on the proportion of time that the cable limits are exceeded can be evaluated. From this, 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. This analysis is presented in Section 5.3.2.1.

#### *5.3.1.3 Dynamic Rating Based on Environmental Data*

The current carrying capacity, or ampacity, of power cables is calculated according to IEC60287 [98]. 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 but can be lower. 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 such as [84] 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 similarly varies over time and across the route.

#### *5.3.1.4 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 and humidity) and/or measure/model the temperature of the conductors themselves so as 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 [79].

To date this has been utilised successfully, with varying levels of sophistication, on transmission systems in a number of countries. It has also been utilised for offshore wind farm export cables [82].

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 methodology in Section 5.3.1.3, this would give greater accuracy and confidence regarding the actual maximum current rating at any given time.

#### *5.3.1.5 Other Methods*

Other methods which could potentially be employed include gas or liquid cooling, and burial methods (such as backfilling with low thermal resistivity aggregate), but these are considered outside the scope of this study as they are expected to be cost prohibitive.

Also of note is the study in [104] which looks at the 'sharing' of an export cable between an offshore wind farm and a WEC array.  This is a novel idea and is shown to be advantageous in [104]; however it is not explored further here.

### 5.3.2 Detailed Analysis and Results

Below is the detailed analysis performed for the strategies presented above.  The method used is outlined in each section and the analysis is performed on the candidate WEC array, Figure 5.1, with the exception of 5.3.2.1 which uses a 5 device array to reduce the complexity of the calculations.

#### *5.3.2.1 Less Than 100% Rating Based on Statistical Data*

A small WEC array 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 this is a much simplified, idealised model of the system which is intended to demonstrate the principle only.  It is noted that each WEC has a different characteristic and the potential for this solution must be evaluated on a case by case basis.

Unlike the candidate WEC array (Figure 5.1), the physical spatial arrangement of the devices is considered here (Figure 5.6).  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 analysis.

Since interference is not considered, if all 5 WECs were in a row parallel to the approaching wavefront, they would all react identically and simultaneously. If each individual WEC is generating 100% output, then the WEC array is also generating 100% output.

A JONSWAP wave spectrum is used to generate an irregular wave elevation time series. This is fed into the a WEC time domain model, derived from the time domain model in [115], which in turn gives a captured mechanical power time series for each WEC. In order to convert this captured mechanical power to an output electrical power, a simple power-take-off (PTO) is modelled; first introducing a storage element by continuously averaging the captured mechanical power over half a wave period (i.e. $T_P/2$), and then allowing an assumed (conservative) 70% conversion efficiency. The output is then limited to a maximum of 1MVA per device. This model is shown graphically in Figure 5.5. Note again that this simplified model is used to demonstrate the principle only and is not representative of any particular WEC device.

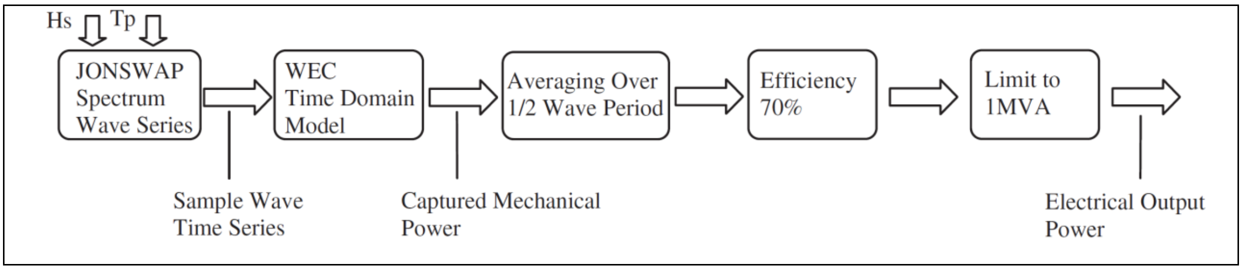



**FIGURE 5.5 REPRESENTATION OF WEC AND PTO MODEL FOR ANALYSIS OF ARRAY OUTPUT**

For simplicity, a two dimensional long crested irregular wave is considered to be incident on the array. In order to avoid simultaneous operation, the array layout is staggered so that some devices are 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. In a real sea-state, short-crested waves would provide additional smoothing, so the case considered here may provide slightly more instantaneous peaks than in a more realistic sea-state. This array is shown in Figure 5.6.

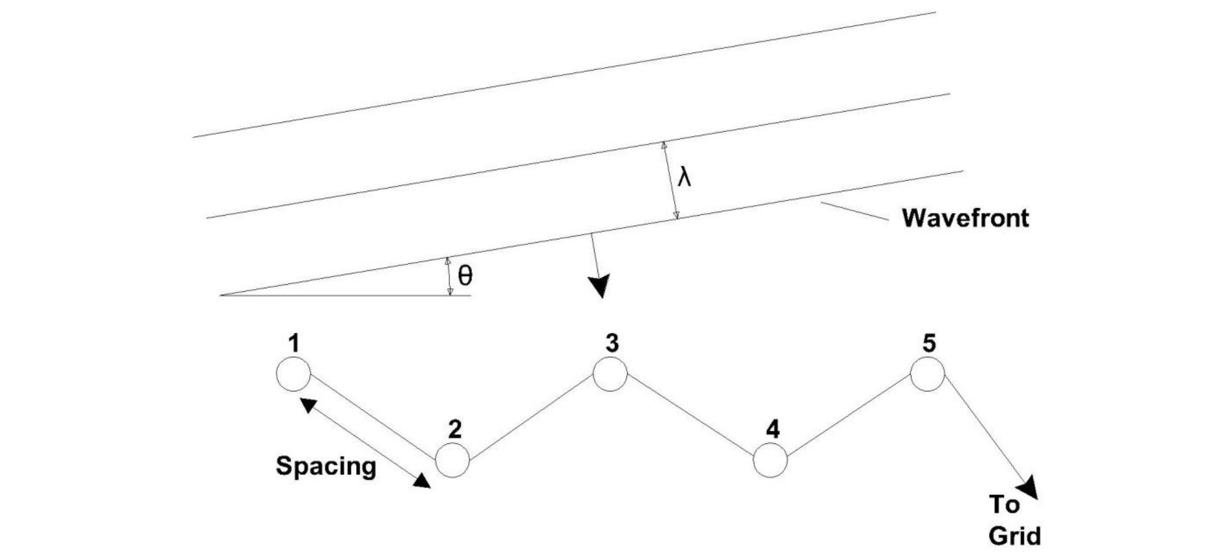


FIGURE 5.6 CONCEPT OF ARRAY FOR ANALYSIS (Θ = ANGLE OF INCIDENCE, Λ = WAVELENGTH)

The base case is established by sizing the cables in the array based on nameplate (100%) output current. This assumes each WEC having a 1MVA rating. The electrical network voltage is 10kV in this case, as a higher voltage would not be necessary due to this array capacity. The cable cross sectional areas (CSA) required are shown in Table 5.1.

TABLE 5.1 CABLE CSA FOR ARRAY BASED ON MAXIMUM CONTINUOUS CURRENT

| Cable Link | Required Capacity | Rated Capacity | CSA |
|---|---|---|---|
| 1-2 (400m) | 1MVA | 2.9MVA | $35mm^2$ |
| 2-3 (400m) | 2MVA | 2.9MVA | $35mm^2$ |
| 3-4 (400m) | 3MVA | 3.4MVA | $50mm^2$ |
| 4-5 (400m) | 4MVA | 4.15MVA | $70mm^2$ |
| 5-Grid (10km) | 5MVA | 5MVA | $95mm^2$ |

It should be noted that this configuration gives large active power losses at 100% output, which would normally be unacceptable. However, losses are ignored here as they do not dictate the cable CSA selection in larger arrays at higher voltage.

For the export cable only (i.e. WEC 5-Grid), reducing the cable CSA from $95mm^2$ to $70mm^2$ would reduce the export capacity from 5MVA to 4.15MVA, or 83% of the rated array output. From the normalised cost model in Section 4.3.12, this gives a saving of 15% for the export cable. The time series output from the five device array is assessed to calculate the energy generated when the array output exceeds 4.15MVA. This allows a cost benefit analysis to be carried out to see if the potential savings outweigh the possible loss of energy from the array.

A model of the array, which incorporates the power conversion shown in Figure 5.5 for each WEC, was built in MatLab®. The angle of incidence of the approaching wavefront can be varied to give the total output of the five devices for any sea state and any angle of incidence. This MatLab model, and associated code, is shown in Figure 5.7 and Figure 5.8. Spacing is 400m between WECs. The combined output of all of the devices in the array gives the output power across the export cable (WEC 5-Grid). As mentioned previously, cables losses are not considered here. It should be noted however, that cable losses would be higher for the same power export, given a reduced CSA cable.

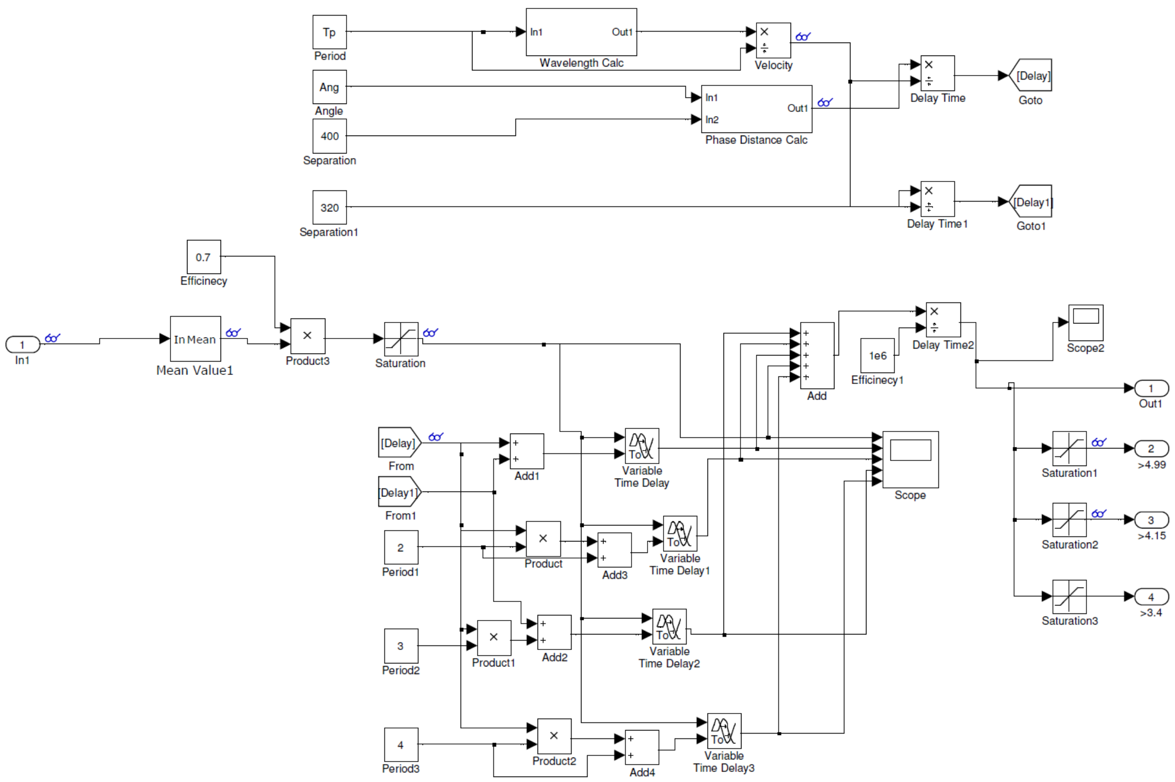



**FIGURE 5.7 MATLAB SIMULINK MODEL FOR ANALYSIS**

```
% Script for looking at power output from 5 device array
profile on
fields=fieldnames(Power);
A=[];
B=[];
C=[];
D=[];
E=[];
for ff=1:length(fields)

    name          = fields{ff};
    t             = Time.(name);
    Pwrpu         = Power.(name);
    [token remain]  = strtok(name,'Hs');
    [token remain]  = strtok(token,'Tp');
    Hs            = str2double(token)/100;
    [token remain]  = strtok(remain,'Tp');
    Tp            = str2double(token)/100;
    clear token remain
    Ang           = 0;
    sim PhaseShifting3;
    index         = find(yout(1:13091,1)>4.149);
    index1        = find(yout(1:13091,1)>4.99);
    index2        = find(yout(1:13091,1)>3.39);
    a             = length(index1)/length(yout(1:13091,1)); % Percentage of time maximum output of array
    b             = length(index)/length(yout(1:13091,1)); % Percentage of time >83% (>4.15MW) output of array
    c             = length(index2)/length(yout(1:13091,1)); % Percentage of time >67% (>3.4MW) output of array
    d             = (mean(yout(1:13091,1))); %mean output power of array from each cell
    %e            = ((mean(yout(1:13091,3))-4.149)/(5-4.149))/(mean(yout(1:13091,1))); % of energy >4.15MW
    e             = ((mean(yout(1:13091,1)))-(mean(yout(1:13091,4))))/(mean(yout(1:13091,1))); % of energy from >83% output of the array
    A             = [A,a];
    B             = [B,b];
    C             = [C,c];
    D             = [D,d];
    E             = [E,e];
    disp(['Hs= ',num2str(Hs),'     Tp= ',num2str(Tp)])
end
profile off
profile viewer
```

**FIGURE 5.8 MATLAB CODE FOR CALCULATION OF WEC ARRAY OUTPUT**

The angle of incidence is 0° when the wavefront is parallel to the line dissecting WECs 1, 3 and 5. Therefore, the wavefront meets these three WECs simultaneously and also WECs 2 and 4 simultaneously, though out of phase with WECs 1, 3 and 5. This would be considered the worst case scenario, and this was confirmed by analysing the output of the array between 0° and 90° angle of incidence. In all cases the worst case output, i.e. the output with the highest occurrence of array peak power, was given at 0°.

The percentage of time (over a finite time series) that the array generates maximum output (5MVA), and the percentage of time the array generated more than 83% output (>4.15MVA) were evaluated for all sea-states (i.e. all combinations of $H_s$ and $T_p$ in the scatter diagram). These percentages were multiplied by the percentage occurrence of these cells from the Belmullet (West Mayo, Ireland) scatter diagram, as shown in Figure 5.9, to give the annual percentage for each value. The percentage of energy generated during the period where the array output was greater than 4.15MW was also calculated. These values were all taken at 0° angle of incidence. Results are shown in Table 5.2. The total energy generated at 100% output cannot be calculated, but the total energy generated when the array is producing more that 83% output can.

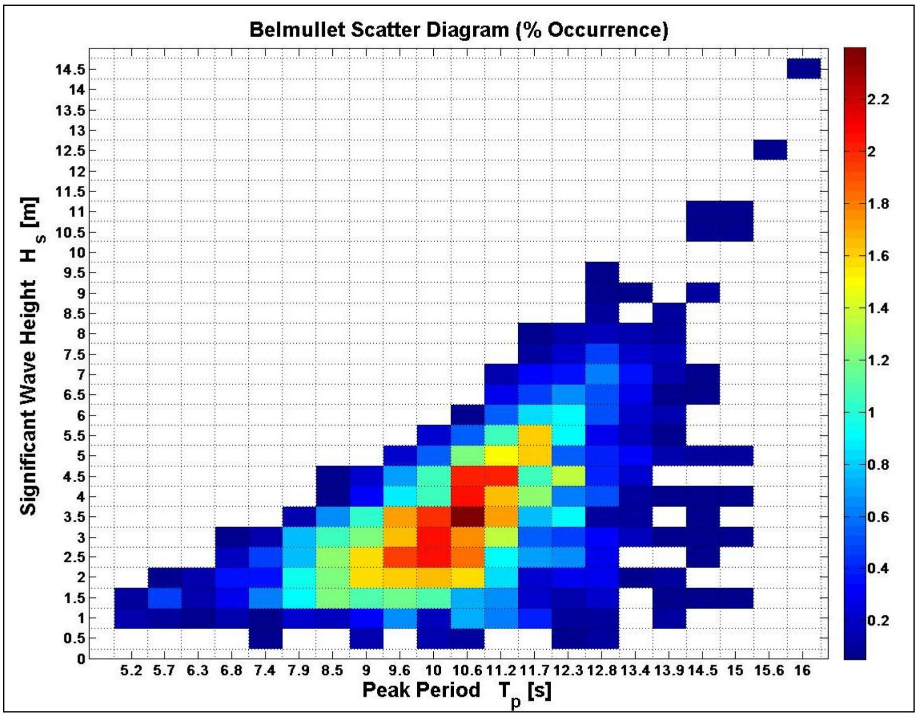



FIGURE 5.9 BELMULLET SCATTER DIAGRAM [94]

TABLE 5.2 ANNUAL OUTPUT OCCURRENCE AND ANNUAL ENERGY OUTPUT PROPORTION FOR ANALYSED DATA

| | 100% Output (5MVA) | >83% Output (>4.15MVA) |
|---|---|---|
| Total Annual Output (% of year) | 3.20% | 6.20% |
| Total Annual Energy Generated (MWh) | N/A | 2.98% |

It is evident that in the course of a year the output power of the full array is 100% (5MVA) for 3.2% of the year, and greater than 83% (>4.15MVA) for 6.2% of the year.

However, the energy generated in the time that the array output is >83% (>4.15MVA) is only 2.98% of the total annual energy output. This means, that if the cable was 70mm$^2$ instead of 95mm$^2$, less than 3% of the overall energy (MWh) would need to be curtailed, i.e. would be lost.

To analyse the financial implications of this, the exact costs of the cable, the revenue expected, and the cost of capital would be required. For the purpose of demonstration it is assumed that a 95mm$^2$ cable costs €350/m installed and that the revenue for energy is €200/MWh. Also a 10% cost of capital is assumed. The 'discounted years to break even' is defined as the time in which the CAPEX saved by reducing the export cable CSA, plus the potential interest on this saved CAPEX, is offset by lost revenue due to curtailment from the reduction in CSA. This is a simple 'present value' annuity calculation solved for the number of payments (i.e. number of years) as shown in Equation 5.1 and can be repeated with the =NPER() function in MS Excel. Table 5.3 shows the relevant calculated results.

**TABLE 5.3 HYPOTHETICAL 'BREAK-EVEN' CALCULATION**

| | |
|---|---|
| Annual energy (with 30% capacity factor): | 13,140MWh |
| Annual revenue no curtailment | €2.628m |
| Annual revenue with curtailment of 2.98%: | €2.550m |
| Lost revenue per annum with curtailment | €78,314.40 (D) |
| CAPEX for 10km of 95mm$^2$ cable | €3.5m |
| CAPEX for 10km of 70mm$^2$ cable (-15%) | €2.975m |
| Savings from CSA reduction | €525k (A) |
| Cost of Capital | 10% (B) |
| **Discounted years to break even** | **~10 years (C)** |

$$A \times \left( (1+B)^C + D(1+B) \times \left( \frac{(1+B)^C - 1}{B} \right) \right) = 0$$

**EQUATION 5.1 - SOLVED FOR C**

This calculation shows that the initial savings in CAPEX gained from utilising a smaller CSA for the export cable is offset within 10 years by the lost revenue. Over a typical 25 year project this would not make financial sense.

This calculation assumes 100% availability, and high revenue which may fall over time, and neglects active power losses. Because of these factors revenue will be lower. Also the figures established above are based on 0° angle of incidence, which is the worst case scenario and uses idealised wave conditions. In reality any given site will have a prevailing wave direction, and also a spread of angles for the incoming wave. To reduce the likelihood of devices reacting simultaneously to an oncoming wave, the WEC array could be orientated away from the prevailing wave direction. Therefore, the percentage annual energy generated when the array output is >4.15MVA could be lowered. These factors would make the financial case for reducing the export cable CSA more favourable, making this approach a viable option.

Other techniques, such as detuning individual WECs to change their response characteristic and further staggering of the array to increase the phase shifting between devices, could also allow for further reductions in potential energy curtailment. As an example the row of WECs 1, 3 and 5 were taken out of phase by putting a constant time delay of 2 seconds between WECs 1 and 3, and 4 seconds between WECs 1 & 5. In this case, the energy curtailed for a 70mm$^2$ cable drops from 2.98% to 1.96%. This leads to a 28 year 'discounted years to break even' when the calculation shown in Table 5.3 is repeated with this lower curtailment percentage. Therefore, by staggering the array further, the amount of energy to be curtailed can be reduced and the economics will become more favourable.

Using simplified models and a number of assumptions, the principle of this strategy for cable system cost reduction shows promise. However, the conclusions here are only based on the simplified PTO model given in Figure 5.5 and the simplified array given in Figure 5.6. With more reliable device and array modelling including interference, detailed cost benefit analysis based on expected revenues, availability data, confirmed cable costs and calculated cable losses, a business case could be made to employ this methodology to the WEC array electrical system.

Note that the ampacity ratings are taken from IEC 60287, which is based on 100% load factor. Additional short term ampacity would be available in the cable by employing methods from IEC 60853, which looks at cyclic loading and emergency current ratings [116]. This may allow the cable to be utilised above its ampacity rating for short periods, thus reducing potential curtailment further still.

This strategy could also be combined with one of the strategies below, thus reducing the amount of potential curtailment to a negligible level.

#### 5.3.2.2 *Dynamic Rating Based on Environmental Data*

As mentioned previously, the ampacity of a cable is a function of its ability to dissipate heat. This is based on a number of factors, some of which vary both over time, and across the route of the cable as it passes from one zone to another. These factors are based on environmental data such as sea-water and air temperature, and route conditions such as burial depth and seabed/soil conditions. These conditions can be accurately established from historical data and site investigation, allowing the setting of seasonal ratings and the calculation of accurate ampacity.

By focussing on the candidate WEC array (Figure 5.1), and in particular the export cables which are 400mm$^2$ for 20kV and 150mm$^2$ for 33kV, the effect of lowering the cable CSA is evaluated. Table 5.4 shows the ampacity of these cables (and the next smallest CSA) at the assumed values (see Section 5.3.1.3).

**TABLE 5.4 AMPACITY OF RATED AND NEXT CSA DOWN FOR WEC ARRAY**

| Voltage | Required Ampacity | Cable CSA | Ampacity (assumed environmental conditions) |
|---|---|---|---|
| 20kV | 567 A | 400mm$^2$ | 627A |
| | | 300mm$^2$ (next smallest CSA) | 564 A |
| 33kV | 347 A | 150mm$^2$ | 368 A |
| | | 120mm$^2$ (next smallest CSA) | 330 A |

Focussing on the west coast of Ireland, Figure 5.10 shows that the sea-water temperature varies seasonally from approximately 6-15°C. The air temperature for the land-based portion of the cable is also important (shown in Figure 5.11) and varies seasonally from approximately 3-17°C, although with some extremes. This implies that the cable ampacity varies throughout the year due to ambient temperatures.

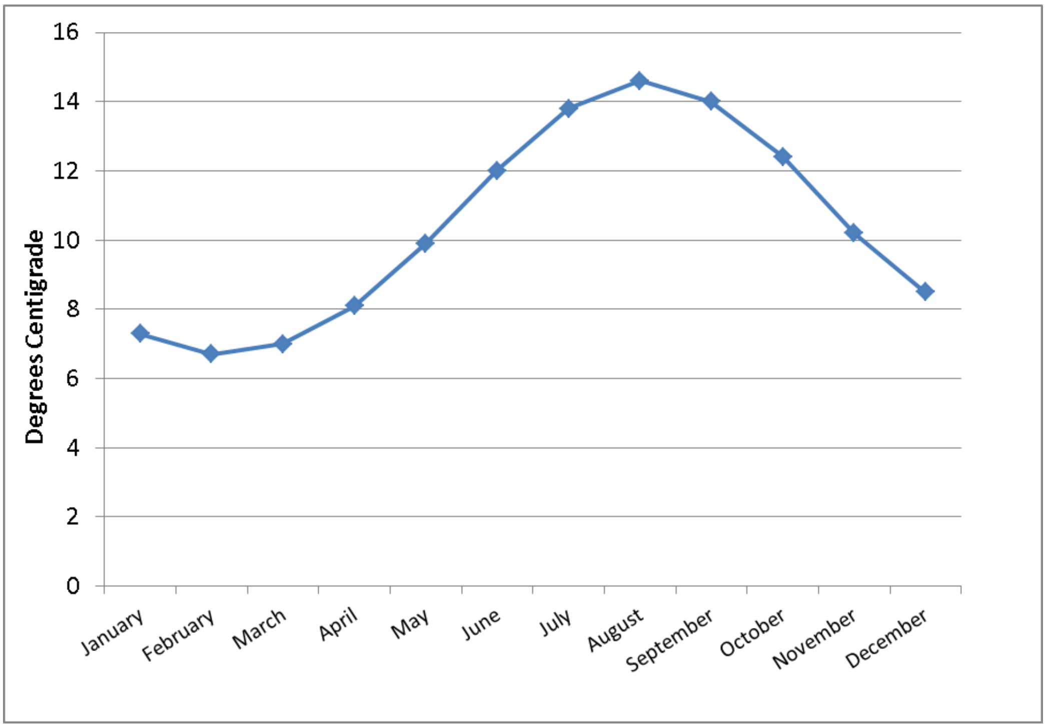



**FIGURE 5.10 AVERAGE MONTHLY SEAWATER TEMPERATURE AT MALIN HEAD 1961-1990 (SOURCE: MET EIREANN)**

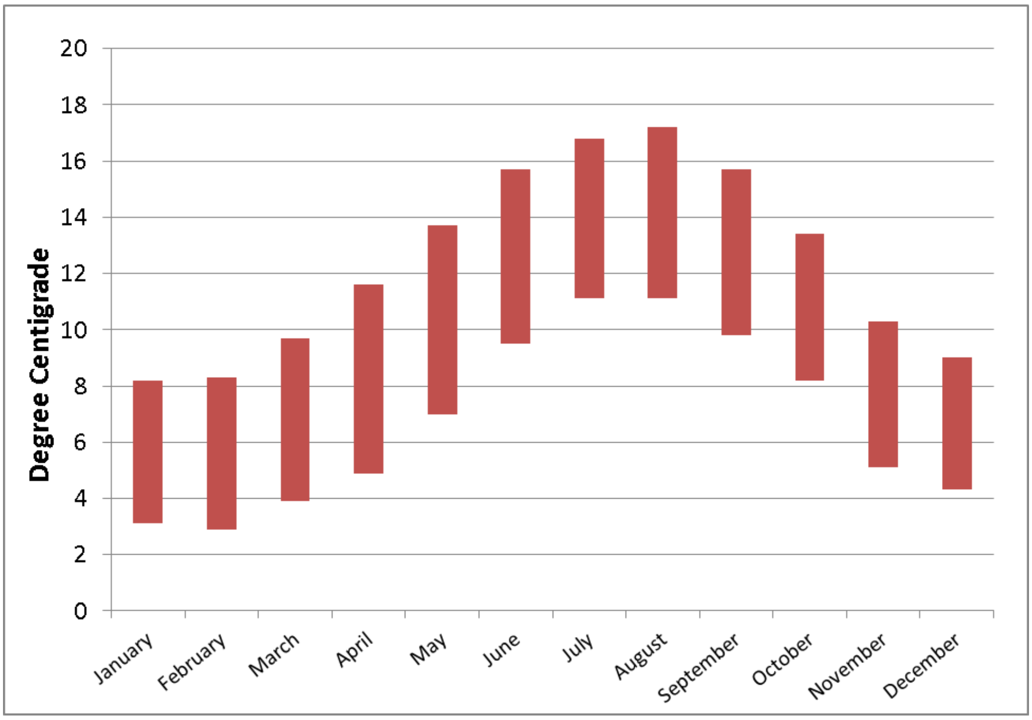



**FIGURE 5.11 AVERAGE MONTHLY AIR TEMPERATURE RANGE AT BELMULLET 1961-1990 (SOURCE: MET EIREANN)**

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, the available and required ampacity across the year for the selected cable and the next smallest CSA cable are evaluated.

The seasonally adjusted ampacity is calculated according to IEC60287 using the equations and constants outlined below. Some assumptions, detailed below, were made about the cable configuration and dimensions to undertake this calculation. The air temperature (Figure 5.11) is used in 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.

**Calculation of Ampacity (IEC 60287)**

From IEC60287-1-1 the permissible current rating (ampacity) of a power cable is given as:

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}} \qquad \textbf{EQUATION 5.2}$$

where

$I$ is the current flowing in one conductor (A);

$\Delta\theta$ is the conductor temperature rise above the ambient temperature (K);

NOTE The ambient temperature is the temperature of the surrounding medium under normal conditions, at a situation in which cables are installed, or are to be installed, including the effect of any local source of heat, but not the increase of temperature in the immediate neighbourhood of the cables due to heat arising therefrom.

$R$ is the alternating current resistance per unit length of the conductor at maximum operating temperature (Ω/m);

$W_d$ is the dielectric loss per unit length for the insulation surrounding the conductor (W/m);

$T_1$ is the thermal resistance per unit length between one conductor and the sheath (K.m/W);

$T_2$ is the thermal resistance per unit length of the bedding between sheath and armour (K.m/W);

$T_3$ is the thermal resistance per unit length of the external serving of the cable (K.m/W);

$T_4$ is the thermal resistance per unit length between the cable surface and the surrounding medium, as derived from 2.2 of Part 2 (K.m/W);

$n$ is the number of load-carrying conductors in the cable (conductors of equal size and carrying the same load);

$\lambda_1$ is the ratio of losses in the metal sheath to total losses in all conductors in that cable;

$\lambda_2$ is the ratio of losses in the armouring to total losses in all conductors in that cable.

The above figures must be calculated for each cable CSA by firstly developing a physical cross sectional model of the cable to ensure that all dimensions can be calculated. Secondly $T_1$ to $T_4$ are calculated according to the equations and graphs in IEC 60287-2-1. Thirdly $\lambda_1$ and $\lambda_2$ are calculated according to IEC 60287-1-1. Finally, the ampacity of the cable can be calculated by adjusting Δθ for a variety of ambient temperatures as per Figure 5.11.

Figure 5.12 shows the results of the seasonal adjustment for a 20kV system. Based on the adjustment of the seasonal temperatures alone, it is shown that a 300mm$^2$ 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 has decreased versus the CSA required using the assumed values.

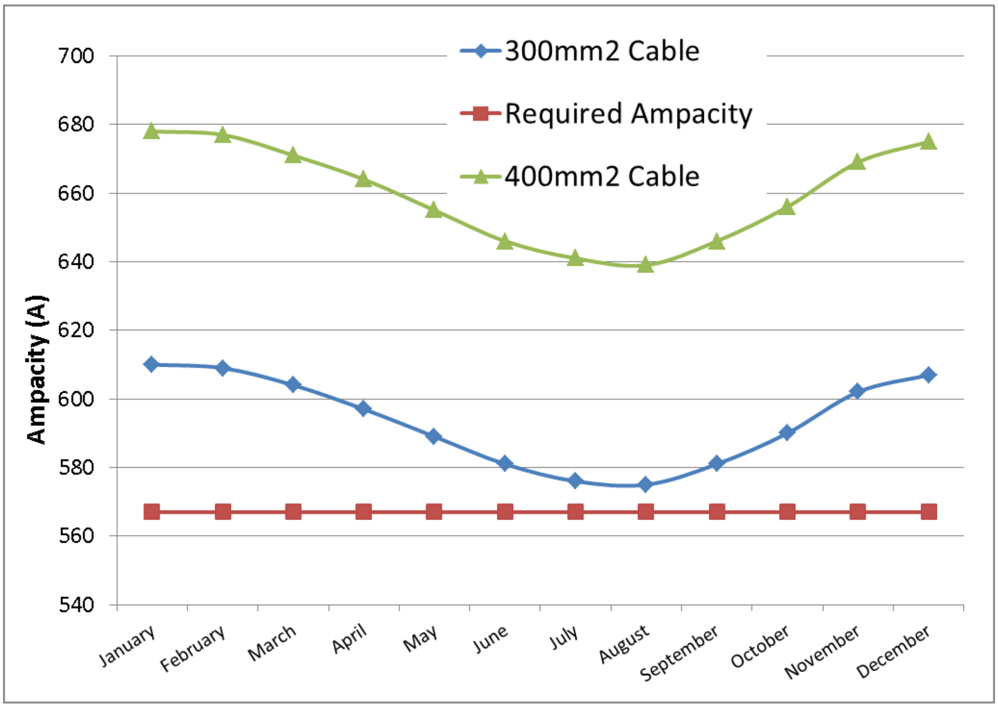



**FIGURE 5.12 SEASONAL AMPACITY OF 20KV CABLES**

Figure 5.13 shows the results of the seasonal adjustment for a 33kV system. Based on the adjustment of the seasonal temperatures alone, it is shown that a 120mm$^2$ cable is not suitable for this application. The output of the array exceeds the ampacity limit of the 120mm$^2$ cable from May through October. However, this is only when the output of the array is greater than 95%. Thus, from this analysis, a 150mm$^2$ cable is more suitable. However, one of the other methods, such as that outlined in Section 5.3.2.1, may be applied to allow the use of a 120mm$^2$ cable.

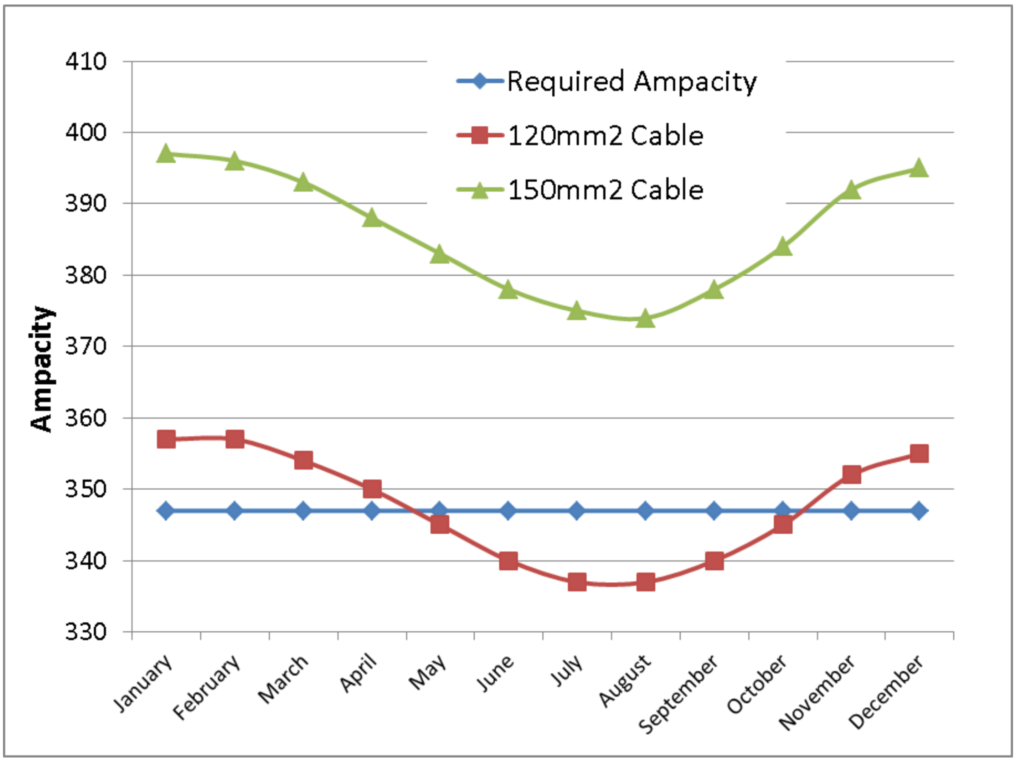



**FIGURE 5.13 SEASONAL AMPACITY OF 33KV CABLES**

For the 20kV array, the reduction in cost of the export cable by reducing the cable from 400mm$^2$ to 300mm$^2$ would be approximately 10%. For the 33kV array, the cost savings from reducing the export cable from 150mm$^2$ to 120mm$^2$ would be approximately 6%. These savings only consider the export cables. Further savings on the overall network system costs could be made by reducing the array cables' CSA, particularly those nearest the export side, using the same methodology.

#### *5.3.2.3 Dynamic Rating Based on Real Time Measurement*

The methodology in Section 5.3.2.2 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 in order 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, allows 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 [82], [117]. 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 improves 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 chapter, with full confidence that the power cable asset is maintained within safe limits. It also means that any output curtailment is kept to an absolute minimum. Such a system increases the costs of the installation, but this would be expected to be a marginal increase, potentially offset by savings through the reduction of cable CSAs.

## 5.4 Conclusion

In this chapter, the major economic challenges and potential strategies for improving WEC electrical network economics have been introduced and evaluated. It is clear that design decisions can be made, both for the WEC and the WEC array, which ultimately could increase WEC array electrical network costs by several multiples. WEC technologies can be developed and design decisions made which, ultimately, lead to the design of a WEC array electrical system which is unfeasible at a competitive cost.

Design issues such as WEC device rating, WEC capacity factor, array spacing, and site conditions, all influence the economics of the WEC array electrical network. Design choices may be made to reduce cost, or otherwise improve WEC device or WEC array performance with no regard for the impact this may have on WEC array electrical system cost.

Importantly, design decisions can also be made to radically reduce electrical system costs and assist in making wave energy competitive with other forms of offshore renewables.

If wave energy converters with a capacity factor of approximately 30% are installed in an array, the utilisation factor of the electrical network, and in particular the export cable, would also be 30%. A number of strategies are proposed to increase the utilisation of the power cables for a WEC array, which would mean a reduction in cost for the electrical network.

Increasing the capacity factor of the individual WECs would increase the utilisation factor and thus reduce the cost of the electrical network. Savings of up to 40% of the cost of the cable network could be achieved. Conversely, if the WECs have a capacity factor of less than 20%, the costs could be expected to rise significantly. The design of the WEC device itself dictates the capacity factor, but device developers should note the economic penalties of a low capacity factor device within an array.

Modelling and simulation of an array of WECs can assist in providing statistical data of the WEC array power output. This permits the assessment of the utilisation of the electrical infrastructure, and reduction in export cable capacity by 10-20%, to allow reduction in costs of the electrical network. This may require some curtailment of the array output power, but this should be a very small percentage of annual energy from the WEC array. Strategic spacing of the WECs within the array may be required to achieve this effect, but could be further optimised to reduce energy curtailment. This strategy, coupled with other methods described here, could potentially lead to no loss of energy whatsoever within the array, while reducing CAPEX.

The use of detailed environmental data from the site location could allow the ampacity of a cable to be modelled annually. This would allow the maximum utilisation of the cable at all times of the year and curtailment at times when the cable design limits may exceeded. Through this, a reduction in export cable capacity by 10-20% may also be achieved, thus further reducing CAPEX.

Real time distributed temperature sensing (DTS) provides a constantly updating profile of temperature across the entire length of the cable. This allows accurate and reliable dynamic ampacity of the cable to be calculated, thus allowing the full utilisation of the cable at all times. It also serves to identify hotspots along the cable route and protect the cable over the long term.

These strategies have been shown to allow for cost reductions and increased utilisation of the power cables. The choice of strategy depends on the overall economics of the project and the information available to the designer while specifying the electrical network. It should be noted that the strategies listed, although demonstrated on power cables, would also have applications in other power system components in the WEC array electrical network, such as power transformers, power converters and switchgear.

# Chapter 6

# Resource Induced Flicker Assessment for Wave Energy Converters

## 6.1 Introduction

For wave energy converters the input resource, in the form of ocean waves, has a typical period range of 5-20 seconds. This varies depending on the site location and dominant sea-states. Wave energy converters, which drive power take off systems from oscillating motions, absorb mechanical power twice per wave cycle and therefore, depending on the energy storage or smoothing available, the electrical power output has half the period of the input resource. This is particularly the case in ‘direct drive’ wave energy converters that have no inherent storage capability.

Voltage flicker is a power quality problem caused by regular changes in active and reactive power either to a load or from a generator. The regular power changes induce a voltage change at the point of connection (POC) which is proportional to the amplitude of the power change and at the same frequency. The impedance of the grid (grid strength) at the POC is a factor in the amplitude of the voltage change.

The frequency of interest for flicker assessment is between 1mHz and 20Hz, and is most severe at 8.8Hz [118]. The frequency of the primary resource for wave energy converters lies within this range. Therefore, the coupling of the input resource to the output power of a wave energy converter will cause voltage flicker at the point of connection, which may exceed the permitted limits under specific conditions.

In this chapter, the nature of the flicker issue from wave energy converters is established. Some practical tools for the evaluation of flicker from a device are introduced. These tools are suitable for early stage flicker assessment to assist in the design process of WECs. They are not meant as substitutes for existing codes and standards outlined in this chapter. Some potential strategies for overcoming resource induced flicker from WECs are presented also.

### 6.1.1 Power Quality and Flicker

#### *6.1.1.1 Flicker*

Voltage flicker, or just flicker, refers to the subjective impression that is experienced by humans to changes occurring to the illumination intensity of light sources [118]. These changes are caused by rapid, regular changes to the voltage level of the electrical supply to the light source in question, typically an incandescent light bulb. It is the human element of flicker that makes it difficult to evaluate. Flicker may induce discomfort in the form of nausea, headaches, annoyance and distraction. In extreme cases, flicker may even induce epileptic fits.

The rapid voltage variations are caused by devices connected to the electrical system. These are mainly loads but can also be caused by generators, particularly renewable generators with fast changing input resources. The voltage variations are caused by a fluctuation in the power consumed or generated by a load or generator respectively, more severely for reactive power fluctuations. Therefore, for a generator; the rapid, regular changes of the output power have the potential to manifest itself as a flicker problem.

Flicker is measured in flicker severity (unitless) and is normally given in short-term flicker, $P_{st}$, and long term flicker, $P_{lt}$. The weighted average flicker severity over 10 minutes is $P_{st}$, and the cube root of the cubed average over 120 minutes is $P_{lt}$ [119].

#### *6.1.1.2 Grid Code Requirements*

As the issue of flicker affects all users of the power system, including power generators and consumers, all electrical power system operators have flicker limits within their respective grid codes. The limits are broadly similar across jurisdictions. The limits for flicker from the Irish and UK grid codes are given in Table 6.1 and Table 6.2 along with those recommended in IEC 61000-3-7. They are separated into distribution connected (MV) and transmission connected (HV). Note that a limit of flicker severity of 1.0 means that it is at the level of perception (Note: not everyone perceives flicker at this level. but 50% of subjects in controlled studies). There is some disparity between the distribution connected limits, with Irish limits being relatively low and hence more restrictive. The transmission connected limits are identical.

TABLE 6.1 FLICKER SEVERITY LIMITS FOR DISTRIBUTION (MV) CONNECTIONS

| | Ireland [120] | UK [121] | IEC [122] |
|---|---|---|---|
| $P_{st}$ | 0.35 | 1.0 | 0.9 |
| $P_{lt}$ | 0.35 | 0.8 | 0.7 |

TABLE 6.2 FLICKER SEVERITY LIMITS FOR TRANSMISSION (HV) CONNECTIONS

| | Ireland [120] | UK [121] | IEC [122] |
|---|---|---|---|
| $P_{st}$ | 0.8 | 0.8 | **0.8** |
| $P_{lt}$ | **0.6** | **0.6** | **0.6** |

#### *6.1.1.3 Voltage Fluctuation Calculation*

The fluctuation in voltage across the electrical power system is caused by power flows (both active and reactive) within the system. In reality, as reactance is normally much larger than resistance within the power system, reactive power flows create much greater fluctuation in voltage than active power flows. However, this is not strictly true at 'weaker' parts of the network where the network may be more resistive. For a generator connected to the grid the amplitude of voltage fluctuation at its POC is caused by several factors [63] namely:

1. The amount of active and reactive power ($S = P + jQ$) to/from the generator

2. The impedance ($Z = R + jX$) of the grid (sometimes given as a fault level or fault current) at the POC

3. The impedance phase angle, $\psi_k$ (the ratio of the resistance (R) to reactance (X) within the grid impedance, i.e. $\tan^{-1}(X/R)$). This is also referred to as the X/R Ratio

This is illustrated in Figure 6.1.

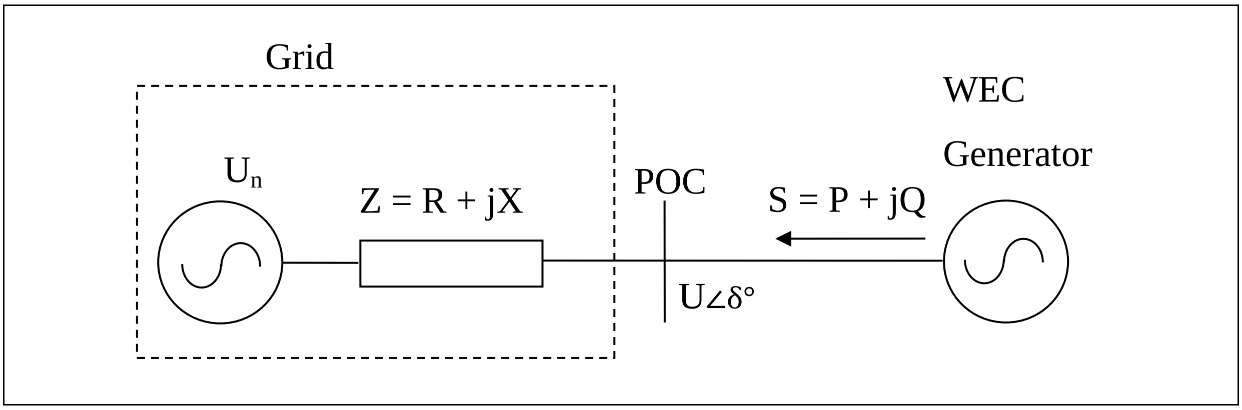



FIGURE 6.1 SIMPLE REPRESENTATION OF GENERATOR CONNECTED TO THE GRID.

There are a variety of possible methods for calculating voltage change at a node caused by a load or generator into that node. Voltage fluctuation (ΔU) calculations in this chapter have been carried out according to Equation 6.1. This equation is a simplified voltage fluctuation equation using an infinite bus circuit but is shown in [123] to closely model a full load flow equation with minimal error. Therefore, it is sufficiently accurate for this analysis.

$$a = \frac{U_n^{\ 2}}{2} - (RP + XQ)$$
$$b = (P^2 + Q^2) \times Z^2$$
$$U = \sqrt{a + \sqrt{a^2 - b}}$$

Equation 6.1

### 6.1.2 IEC Existing and Emerging Power Quality Standards

Within the International Electrotechnical Commission (IEC) there is a Technical Committee (TC) preparing international standards for marine energy conversion systems. TC114 will develop IEC standards under IEC 62600. One of these standards is IEC 62600-

30, “Marine Energy - Wave, tidal and other water current converters - Part 30: Electrical power quality requirements for wave, tidal and other water current energy converters” [124].

IEC 62600-30 is currently preparing the first draft of the standard. This standard will provide guidance on the power quality requirements, including voltage flicker, and how to measure same. In general, this standard will provide the same guidance as the equivalent existing wind power quality standard, IEC 61400-21 [125]

Ultimately, any WEC is required to comply with relevant industrial standards and norms. Therefore, it is expected that commercial scale WECs will comply with IEC 62600-30 once published.

However, resource induced flicker is a unique issue for WECs and the likelihood is that relevant standards are not applied until after the WEC is designed and prototype tested. Flicker is also difficult to quantify at an early stage as it is site specific. As such, there is a requirement for an earlier stage design tool that allows WEC designers to assess flicker implications at an earlier stage in technology development.

### 6.1.3 Rationale for Flicker Assessment Tool

Ultimately, as stated, the use of international standards and norms are the fundamental method for assessing and characterising flicker from a commercial WEC. These standards should be adopted by any WEC developer before commercial devices are offered to the market.

However, there is a need for an initial assessment tool for early stage characterisation of flicker during the design and testing of WEC devices. This tool is described in detail in Section 6.3.2. The flicker assessment tool can be considered a ‘pre-commercial’ tool and should not be substituted for compliance with relevant existing and emerging standards and norms.

## 6.2 Wave Energy Resource Induced Flicker

### 6.2.1 Flicker Curve

The flicker emission is unity (i.e. 1.0) when it is at the threshold of perception, i.e. greater or equal than 1.0 means the flicker can be perceived (by 50% of subjects in controlled tests). The flicker emission unity threshold is shown in Figure 6.2 at the 230V level (for rectangular voltage changes). This illustrates the allowable percentage voltage fluctuation (ΔU/U) at various frequencies. It is evident in Figure 6.2 that at 8.8Hz the flicker unity threshold is very low at ~0.3% (ΔU/U); however, it is over 1% for frequencies below 100mHz and above approx. 20Hz. The flicker curve given in Figure 6.2 is taken from [126]. Similar curves are also available from [121], [122] & [127]

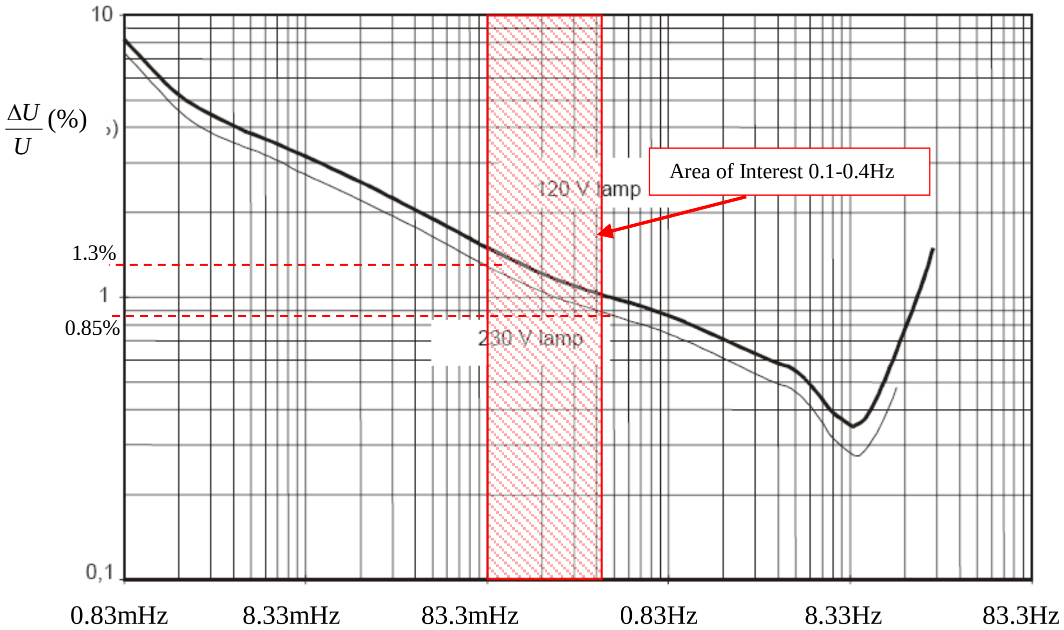



**FIGURE 6.2 VOLTAGE FLUCTUATION CORRESPONDING TO FLICKER EMISSION UNITY THRESHOLD FOR 120V AND 230V LAMP.**

### 6.2.2 Voltage Flicker Emission from Wave Energy Converters

The area of particular interest in the flicker curve for wave energy is at the frequency of the primary resource, typically 0.05-0.2Hz (i.e. $T_p$ = 5-20 seconds. In actual fact, as the power output is only positive, the WEC effectively 'half-wave rectifies' the resource and so the frequency of the output power is twice that of the primary resource. Therefore, the area of interest is 0.1-0.4Hz**.** This range is highlighted in Figure 6.2 and, as can be seen, the limit of voltage fluctuation (ΔU/U) to give unity flicker emission in this range is ~0.85-1.3%.

Other sources of flicker are also possible such as from potential switching operations (generators connecting and disconnecting) and control system effects but this chapter is primarily focused on the 'resource induced' flicker concerns for WECs.

## 6.3 Flicker Assessment

### 6.3.1 Basic Flicker Assessment

In [121] a simple, first pass, assessment of potential flicker is given. This shows that the percentage voltage change for balanced 3-phase systems can be defined as shown in Equation 6.2.

$$\Delta U(\%) = \frac{100 \times S_n}{S_k}\% \qquad \text{Equation 6.2}$$

Equation 6.2 gives the generator nominal power, $S_n$ (in MVA), as a percentage of the grid fault level, $S_k$ (in MVA). This is useful for an initial assessment and as illustrated in the previous section if this value is greater than 0.85-1.3% then it is obvious that the generator in question may exceed flicker limits. However, this simplified measure makes a number of assumptions, in particular about the grid conditions, making it only useful as a first pass, high level calculation.

### 6.3.2 Flicker Assessment Tool

Flicker emission levels, given in $P_{st}$ and $P_{lt}$, can be relatively difficult to calculate and for the purposes of developing WEC devices it would be particularly beneficial to have a more accurate tool for first-pass analysis of the likely flicker issues associated with a particular technology.

As such, flicker assessment charts have been developed that allow a quick but relevant assessment to be conducted. The following assumptions have been made in the development of the charts:

1. The power output is assumed to be continuously oscillating, i.e. with a fixed amplitude and frequency. This would not necessarily be the case in reality as the amplitude and period of the wave resource would change over time but is considered a worst case scenario.

2. The power factor is assumed to be constant while the power output is oscillating. In reality, it may be difficult to maintain a constant power factor while active power is continuously oscillating.
3. The power oscillation is assumed to occur at the more flicker sensitive frequency in the area of interest (see Figure 6.2), i.e. 0.4Hz – giving unity flicker at 0.85% $\Delta U/U$. This would not be the case in reality and so can be considered a worst case scenario.
4. The power oscillation is assumed to be rectangular, which is the most severe, or worst, case. This would not be the case in reality and the fluctuating output power from a WEC would more likely be sinusoidal or triangular in shape. These correction factors are not applied here.

Therefore, the flicker assessment charts have some inherent safety factors built-in due to the use of worst case scenarios.

The charts are developed by calculating the maximum $\Delta S_n/S_k$ which, given the assumptions above, causes the maximum permissible $\Delta U/U$ for a range of X/R ratios and power factors. As mentioned above, a maximum 0.85% $\Delta U/U$ applies to a unity flicker, i.e. $P_{st}$ of 1.0, at 0.4Hz. Therefore, for a $P_{st}$ of 0.8, a $\Delta U/U$ of 0.68% (0.85% x 0.8) is the maximum permissible. For a $P_{st}$ of 0.35, a $\Delta U/U$ of 0.2975% (0.85% x 0.35) is the maximum permissible $\Delta U/U$.

The maximum $\Delta S_n/S_k$ is calculated using Equation 6.1 for a number of X/R ratios (1-25, in increments of 1) and at three power factors (unity (1.0), 0.95 lagging, and 0.95 leading). These ranges should cater for most scenarios WEC technology developers may consider.

For the avoidance of doubt note that 'lagging' power factor implies that the generator is exporting active power and reactive power. 'Leading' power factor implies that the generator is exporting active power but importing reactive power. This is the normal convention for generators.

The following information is ideally required to utilise the charts:

1. Grid fault level, $S_k$ – This can be derived from the grid impedance, Z, or short circuit current, $I_k$.
2. Grid X/R ratio, or impedance phase angle, $\psi_k$.
3. WEC max fluctuating power ($\Delta S_n$). Note that this may be a percentage of the WEC nominal power, $S_n$, and may even be greater than the $S_n$ (in the case of a PTO which absorbs power from the grid during the wave cycle, i.e. complex conjugate control).
4. WEC output power factor ($\cos\theta$).
5. Site resource scatter diagram (optional).
6. $P_{st}$ and $P_{lt}$ limits in the jurisdiction.

All of these items are not strictly necessary and some can be derived from guidance given in the IEC standards, as outlined in the following steps.

The following steps are required to utilise the charts:

1. If known, the $\Delta S_n \backslash S_k$ ratio is calculated, i.e. the ratio of the fluctuating generator power to the grid fault level. If the grid fault level is not known then it can be substituted for a 'typical' multiple of $S_n$ ( [119] recommends multiples in the range of 20-50).
2. The power factor ($\cos\theta$) is noted. If PF not known then it can be substituted for a typical case (0.95 lagging -1.0).
3. The $P_{st}$ and $P_{lt}$ applicable limits are noted. If not known then these can be substituted for a typical value (0.8 would be prudent in most cases).
4. The X/R ratio is noted. If not known then these can be substituted for a typical value (1-4 is prudent).
5. A suitable chart (given the $P_{st}$ and $P_{lt}$ limits) is chosen from Figure 6.3, Figure 6.4 and Figure 6.5 and the intersection of $\Delta S_n \backslash S_k$ & X/R is marked.
6. If that intersection lies above the applicable power factor line then there is a potential issue with flicker for the chosen configuration and a further, detailed, study is required. If that point lies below the line then there is no issue with flicker for the chosen configuration, even in the worst case scenario.

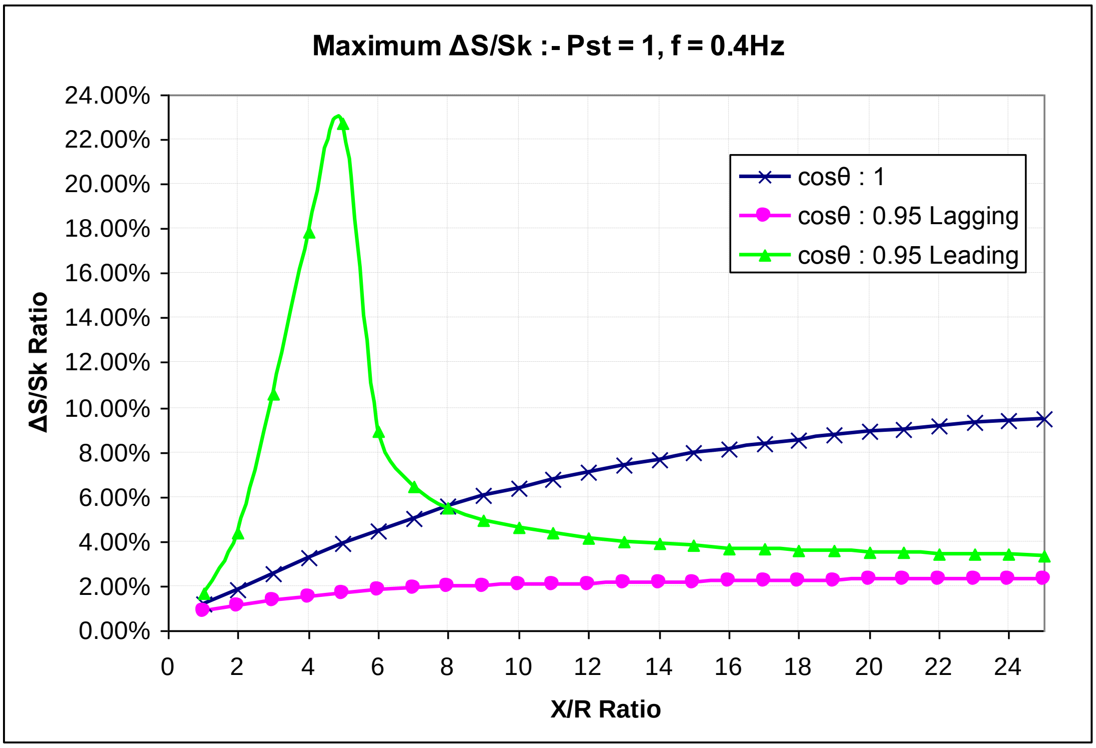



FIGURE 6.3 MAXIMUM PERMISSIBLE ΔSN/SK FOR $P_{ST}$ = 1.0

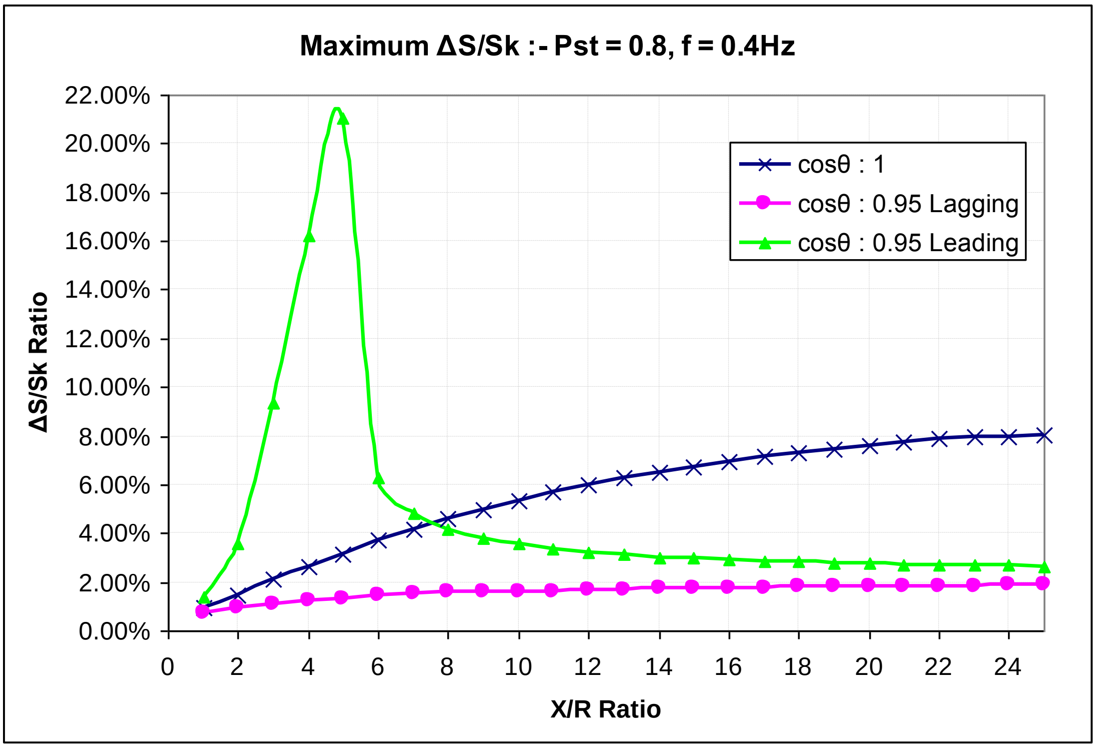



FIGURE 6.4 MAXIMUM PERMISSIBLE ΔSN/SK FOR $P_{ST}$ = 0.8

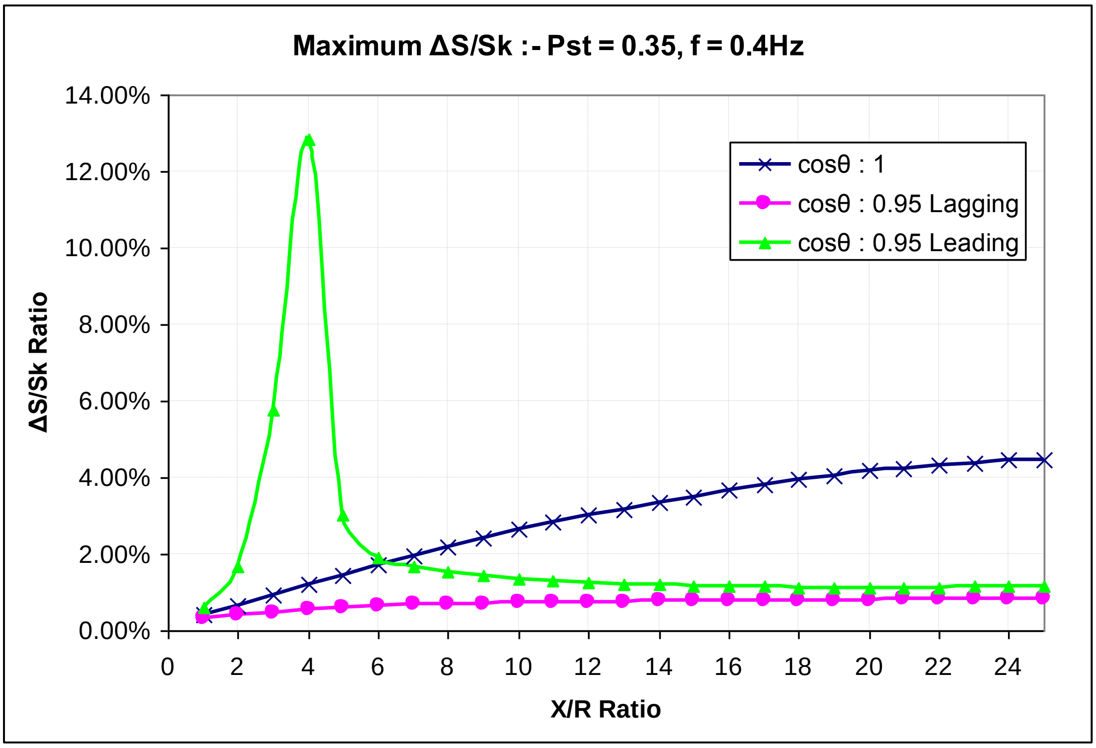



**FIGURE 6.5 MAXIMUM PERMISSIBLE ΔSN/SK FOR $P_{ST}$ = 0.35**

Two observations are apparent from Figure 6.3, Figure 6.4 and Figure 6.5.

Firstly, the 0.95 lagging power factor curve allows much lower power fluctuation ($\Delta S_n/S_k$) than that for unity power factor. This is due to the fact that the reactive current flows from generator to grid in this case and contributes to the voltage variation amplitude.

Secondly, there is a large peak around the X/R ratio of 4 for the 0.95 leading power factor curve. This allows much higher power fluctuation ($\Delta S_n/S_k$) than that for unity power factor. This peak only occurs at low X/R ratios and from X/R=6 onwards the 0.95 leading power factor allows lower power fluctuation than for unity power factor. This is due to the fact that the reactive current flows from grid to generator in this case. For low X/R ratios this has the effect of cancelling out the voltage variation from the active power flow (from generator to grid). When the X/R ratio becomes larger, the reactive current causes the voltage to drop more than the active current causes it to rise.  This means that the voltage dips to the point that it exceeds the flicker emission limit.

### 6.3.3 Examples of Flicker Assessment Chart Use

Two theoretical examples using Figure 6.3 are given in Table 6.3 and illustrated in Figure 6.6.

**TABLE 6.3 THEORETICAL EXAMPLES USING FLICKER GUIDANCE CURVES.**

| | **Example 1** | **Example 2** |
|---|---|---|
| **Grid Fault Level ($S_k$)** | 40 MVA | 30 MVA |
| **WEC Max Fluctuating Power ($\Delta S_n$)** | 1 MVA | 1 MVA |
| **$\Delta S_n/S_k$** | 2.5 % | 3.3 % |
| **$P_{st}$ and $P_{lt}$ limits in the jurisdiction** | 1.0 | 1.0 |
| **Grid X/R Ratio** | 2 | 5 |
| **WEC Power Factor (cosθ)** | 1 | 1 |
| **Site Scatter Diagram** | $T_p$ min: 5 s | $T_p$ min: 5 s |
| **Potential Flicker Issue** | Yes. Detailed Study Required | No. No Flicker Study Required |

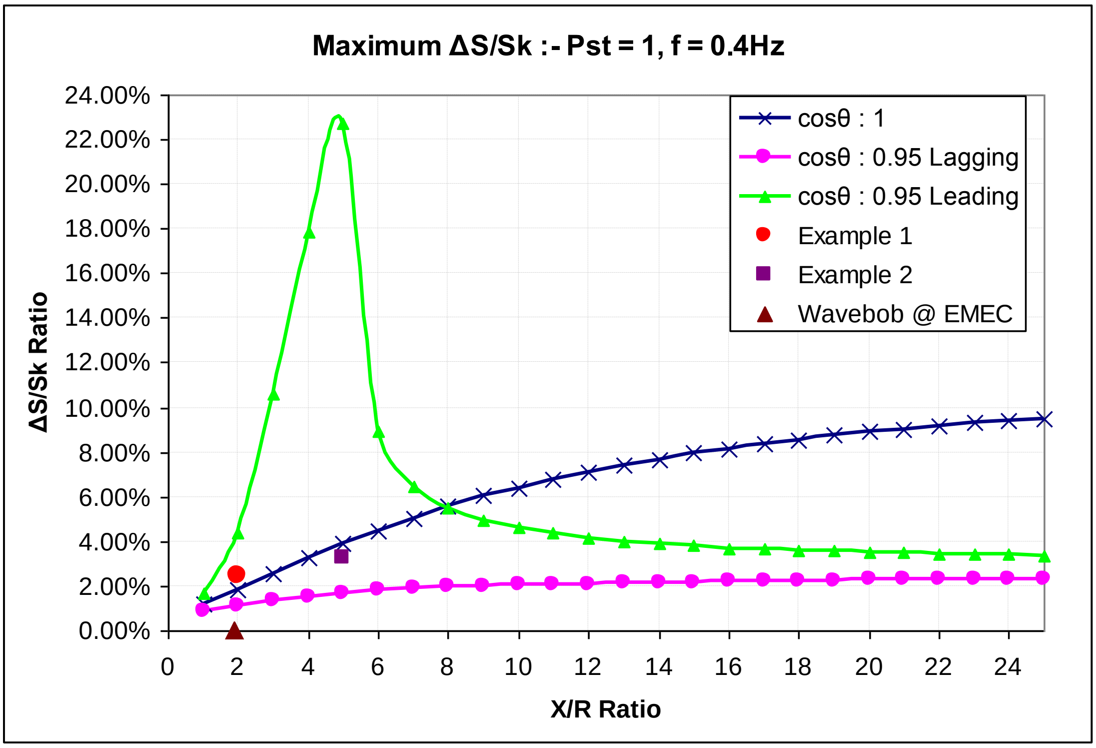



**FIGURE 6.6 EXAMPLE USE OF CHART WITH POINTS FOR EXAMPLE 1 & 2 SHOWN (WAVEBOB CASE STUDY ALSO SHOWN – SEE SECTION 6.4.2)**

The examples shown in Table 6.3 and Figure 6.6 illustrate that even though the WEC in Example 2 is connected to a weaker grid, i.e. one with a lower fault level, because it has a higher X/R ratio, the same WEC fluctuating power, $\Delta S_n$, can be connected to it without exceeding a $P_{st}$ limit of 1.0. This is shown as the Example 1 point (red circle) which is above the "cosθ : 1" line. Example 2 (purple square) is shown below this line. The Wavebob Case Study is also shown in Figure 6.6 (brown triangle) and is explained in Section 6.4.2.

### 6.3.4 Flicker Measurement Standards

Flicker is a known issue associated with a number of renewable generators. Industry standards exist for the assessment of flicker as outlined in Section 6.1.2. Notable power quality standards are IEC 61400-21 for wind energy [125] and IEC 62600-30 [124], which are being developed by the IEC Technical Committee TC114 for wave and tidal devices.

It is not the intention to replace these standards. The tools given in this chapter are meant to be practical, user-friendly tools that can be used at the design stage. The application of these tools assists with compliance with relevant standards such as IEC. The compliance with approved industry standards, like the IEC standards, is a requirement of any device connecting to the network.

The methods in 6.3.1 and 6.3.2 can be seen as a preliminary, ‘go / no-go’, assessment. If these indicate that further analysis is required then a full flicker assessment must be carried out in line with industry standards.

The method of measurement of flicker for wind turbines is given in [125] and the design specification for a flickermeter is given in [119]. A flickermeter essentially filters the voltage magnitude profile to separate the frequency components that cause flicker. The flicker level is then quantified by means of a model of the human ‘lamp-eye-brain’ response. A block diagram of a flickermeter is shown in Figure 6.7.

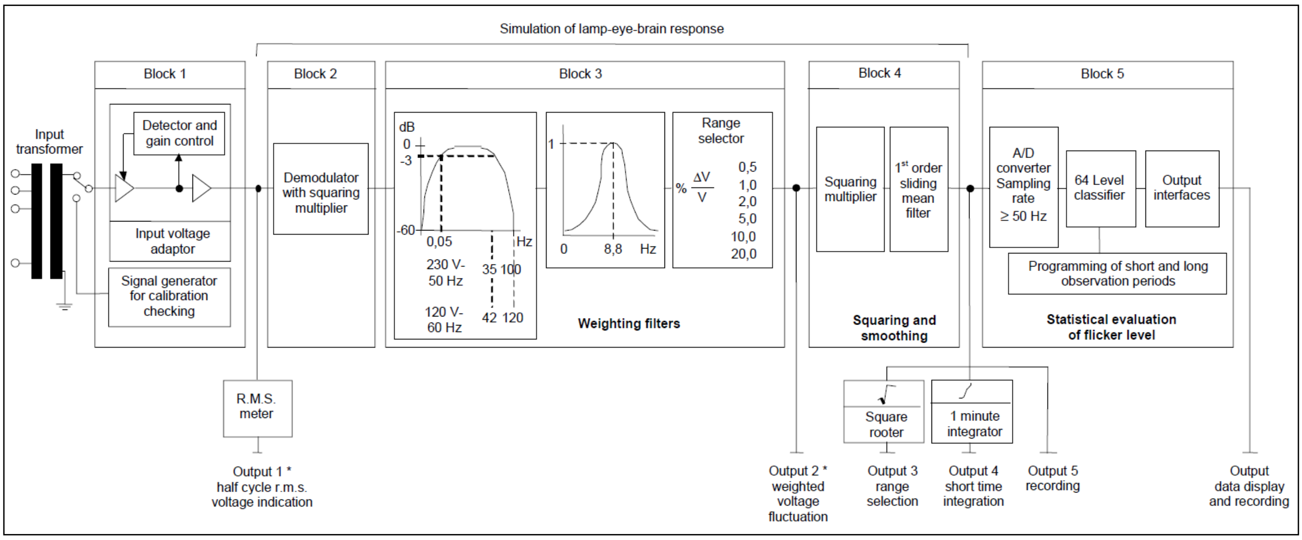



**FIGURE 6.7 BLOCK DIAGRAM OF FLICKERMETER FROM [119]**

The full flicker assessment method involves either measuring or simulating the power output from the WEC and calculating the resultant change in voltage at the point of connection. Once this is done, the voltage profile is fed through a flicker meter to give $P_{st}$ and $P_{lt}$ values.

## 6.4 Case Study: Wavebob

A case study is undertaken here to show the use of the flicker assessment tools discussed in Section 6.3 and also to assess, for an actual grid connected wave energy converter, the severity of the flicker for the entire scatter diagram. This illustrates the sea-states that induce the largest flicker emission levels.

The case study considers the Wavebob WEC at the European Marine Energy Centre (EMEC) test site. The characteristics for the case study are given in Table 6.4. These values are derived from information provided by Wavebob and EMEC.

**TABLE 6.4 PARAMETERS FOR CASE STUDY**

| Wavebob @ EMEC | |
|---|---|
| $\Delta S_n/S_k$ | 0.00164 % |
| $P_{st}$ and $P_{lt}$ limits in the jurisdiction | 1.0 |
| Grid X/R Ratio | 1.87 |
| WEC Power Factor (cosθ) | 1 |

### 6.4.1 Basic Flicker Assessment

Using Equation 6.2, the potential voltage variation ΔU/U is calculated as 0.164%. This is below the level of any issue with flicker, 0.85%. Therefore, this basic assessment shows that the case study WEC does not present any issue with flicker. There are, however, issues with this basic assessment method that make it unsuitable and the flicker assessment charts should be used.

### 6.4.2 Flicker Assessment Charts

The relevant flicker assessment chart is given in Figure 6.3 where the $P_{st}$ limit is 1.0 and is reproduced with the result in Figure 6.6 in Section 6.3.3. The $\Delta S_n/S_k$ percentage in this case is 0.00164% and the X/R ratio is 1.87. This means that the intersection point for these values is below the line for 'cosθ = 1'. Therefore, from the flicker assessment charts it is apparent that the case study WEC does not present any issue with flicker. This is expected as the ratio of $S_n/S_k$ is very small in this case study. Normally, this would indicate that no further assessment is required.

### 6.4.3 Full Flicker Assessment

No further assessment would normally be required for this case study due to the large $S_k/S_n$ ratio and hence no flicker issue.

Nevertheless, in order to investigate the flicker emissions from the WEC further, a full assessment was carried out with the grid fault level/WEC rated power ratio ($S_k/S_n$) set to 1.0 and the X/R ratio set to 1.2 ($\psi_k$ = 50°). This gives the 'flicker coefficient', c ($\Psi_k$), for all the sea-states at the site. The X/R ratio chosen is one of several recommended X/R ratios given in [125].

The 'flicker coefficient', c($\Psi_k$) , is a non site specific (i.e. generic) value and can be divided by the actual $S_k/S_n$ ratio for any site to give the actual $P_{st}$ values, at the same impedance phase angle ($\Psi_k$), for that site.

The assessment was carried out using time domain simulations of the Wavebob WEC (un-tuned) at the EMEC test site. The original scatter from [128] is adapted to use custom intervals for $H_s$ and $T_p$ values, suitable for the Wavebob in-house simulations tools and is shown in Figure 6.8. This shows that the highest occurring sea-states are at lower period ($T_p$ : 5.5-8.5 seconds)

| | | Annual Occurrence % (Total = 100%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hs [m] | *5.75* | | | | | 0.01 | 0.03 | 0.19 | 0.36 | 0.50 | 0.25 | 0.12 | 0.08 |
| | *5.25* | | | | 0.00 | 0.01 | 0.03 | 0.42 | 0.37 | 0.10 | 0.04 | 0.01 | 0.01 |
| | *4.75* | | | | 0.01 | 0.10 | 0.32 | 0.55 | 0.41 | 0.08 | 0.03 | 0.01 | 0.02 |
| | *4.25* | | | 0.01 | 0.01 | 0.40 | 1.29 | 0.66 | 0.26 | 0.06 | 0.04 | 0.02 | 0.02 |
| | *3.75* | | | 0.01 | 0.31 | 0.96 | 2.03 | 0.80 | 0.21 | 0.06 | 0.02 | 0.01 | 0.01 |
| | *3.25* | | 0.02 | 0.09 | 1.44 | 2.22 | 1.64 | 0.60 | 0.14 | 0.07 | 0.03 | 0.02 | 0.02 |
| | *2.75* | | 0.14 | 0.73 | 2.53 | 2.95 | 0.85 | 0.37 | 0.14 | 0.09 | 0.05 | 0.02 | 0.02 |
| | *2.25* | 0.06 | 0.76 | 3.49 | 3.37 | 2.28 | 0.81 | 0.40 | 0.20 | 0.12 | 0.06 | 0.02 | 0.02 |
| | *1.75* | 0.71 | 2.12 | 5.12 | 3.65 | 1.73 | 0.77 | 0.41 | 0.19 | 0.09 | 0.03 | 0.01 | 0.02 |
| | *1.25* | 2.27 | 4.89 | 5.16 | 3.49 | 1.81 | 0.84 | 0.42 | 0.17 | 0.07 | 0.04 | 0.01 | 0.02 |
| | *0.75* | 6.26 | 9.13 | 6.34 | 3.69 | 1.75 | 0.81 | 0.46 | 0.26 | 0.15 | 0.07 | 0.02 | 0.01 |
| | | *5.50* | *6.50* | *7.50* | *8.50* | *9.50* | *10.50* | *11.50* | *12.50* | *13.50* | *14.50* | *15.50* | *16.50* |
| | | Tp [s] | | | | | | | | | | | |

FIGURE 6.8 SCATTER DIAGRAM FROM EMEC ADAPTED FROM [128]

A 10 minute simulated power output time series from the device was evaluated and the $c(\Psi_k)$ calculated for each of the cells in the scatter diagram, i.e. each sea-state. The voltage variation was calculated using the same formula from [123] presented Section 6.1.1.3 and the $P_{st}$ value was calculated using a third party IEC flicker assessment software program [129], [130]. This software program calculates the $P_{st}$ value in line with the relevant IEC standard.

The flicker coefficient for the scatter diagram is presented in Figure 6.9 with the characteristics shown in Table 6.5.

**TABLE 6.5 PARAMETERS FOR $C_F$ CALCULATION**

| Wavebob @ EMEC | |
|---|---|
| $\Delta S_n/S_k$ | 100% (make $\Delta S_n = S_k$ for $c(\Psi_k)$ calculation) |
| Grid X/R Ratio | 1.2 ($\psi_k$ = 50°) |
| WEC Power Factor (cosθ) | 0.98 lagging |

| | Flicker Coefficient, c(ψk) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hs (m) | 5.75 | | | | | 31.86 | 29.78 | 23.4 | 19.31 | 14.85 | 13.02 | 8.58 | 7.17 |
| | 5.25 | | | | 33.34 | 30.56 | 25.03 | 21 | 16.46 | 12.78 | 9.84 | 8.49 | 6.72 |
| | 4.75 | | | | 30.98 | 26.17 | 20.88 | 18.79 | 15.08 | 10.46 | 8.96 | 7.25 | 5.93 |
| | 4.25 | | | 29.96 | 27.07 | 22.45 | 21.23 | 15.62 | 11.69 | 8.54 | 7.21 | 5.32 | 4.17 |
| | 3.75 | | | 26.63 | 24.41 | 18.72 | 15.29 | 13.11 | 8.82 | 8.8 | 5.89 | 4.83 | 3.42 |
| | 3.25 | | 28.19 | 23.27 | 19.13 | 15.55 | 13.25 | 8.87 | 6.89 | 5.4 | 4.01 | 2.96 | 2.6 |
| | 2.75 | | 20.82 | 18.48 | 16.48 | 10.71 | 8.74 | 7.35 | 5.14 | 3.94 | 3.31 | 2.65 | 1.74 |
| | 2.25 | 14.55 | 15.79 | 15.1 | 11.28 | 9.17 | 5.04 | 4.58 | 3.72 | 2.63 | 2.26 | 1.83 | 1.48 |
| | 1.75 | 10.7 | 12 | 8.29 | 6.58 | 4.87 | 3.43 | 2.95 | 2.12 | 1.77 | 1.29 | 0.92 | 0.87 |
| | 1.25 | 6.28 | 6.66 | 5.44 | 3.96 | 2.6 | 2.17 | 1.7 | 1.06 | 1 | 0.65 | 0.64 | 0.45 |
| | 0.75 | 2.73 | 2.22 | 2.03 | 1.43 | 1.06 | 0.97 | 0.48 | 0.4 | 0.34 | 0.26 | 0.25 | 0.23 |
| | | 5.50 | 6.50 | 7.50 | 8.50 | 9.50 | 10.50 | 11.50 | 12.50 | 13.50 | 14.50 | 15.50 | 16.50 |
| | | Tp (s) | | | | | | | | | | | |

**FIGURE 6.9 $C(\Psi_K)$ FOR WAVEBOB, ($\Psi_K$ = 50°)**

What is evident in Figure 6.9 is that the more severe flicker occurs at the lower period (higher frequency) sea-states (<10 seconds). This is expected as the flicker limits are lower for higher frequencies in the area of interest shown in Figure 6.2. As the significant wave height, $H_s$, becomes larger and therefore the sea-state contains more energy, the flicker becomes more severe at higher period (low frequency) sea-states. However, this is only to a point as the highest period (lowest frequency) sea states exhibit a drop off in flicker severity, even for large Hs values.

In Figure 6.9 the highest flicker coefficient is 33.34 ($H_s$ = 5.25, $T_p$ = 8.5). For a $P_{st}$ limit of 1.0, what can be inferred is that the Wavebob device exceeds the flicker limits for any Grid Fault Level/WEC Rated Power Ratio ($S_k/S_n$) of less than 33.34, given an X/R ratio of 1.2 ($\psi_k$ = 50°) and power factor of 0.98 lagging. Using this $c(\Psi_k)$ value for the EMEC case study shown in Table 6.4 it is clear that the maximum flicker emission, $P_{st}$ , at EMEC for the Wavebob device would be 0.0546 ($c(\Psi_k)$ / $(S_k/S_n)$ = 33.36/610), for $\Psi_k$ of 50°, which is well below the limit of 1.0. This verifies our initial assessments in 6.4.1 and 6.4.2

It should be noted that this simulation is a ‘un-tuned’ Wavebob WEC. The Wavebob WEC can be tuned with the opening, partial opening and closing of its submerged tank. When tuned, the response of the WEC could be reduced for higher energy sea-states meaning a potential reduction in the maximum flicker coefficient witnessed.

For this worst case cell ($H_s$ = 5.25, $T_p$ = 8.5) other X/R ratios and power factors are evaluated. As per [125] a range of typical X/R Ratios are evaluated, namely 0.57 ($\psi_k$ = 30°), 1.2 ($\psi_k$ = 50°), 2.7 ($\psi_k$ = 70°), and 11.4 ($\psi_k$ = 85°). Also a range of power factors are evaluated between 0.95 lagging and 0.95 leading. The results are plotted in Figure 6.10.

Figure 6.10 shows that the flicker coefficient becomes smaller as the X/R ratio becomes larger and also, that as the power factor changes from lagging to leading the flicker coefficient becomes smaller.  This coincides with the results shown in the flicker assessment charts in Figure 6.3, Figure 6.4 and Figure 6.5.

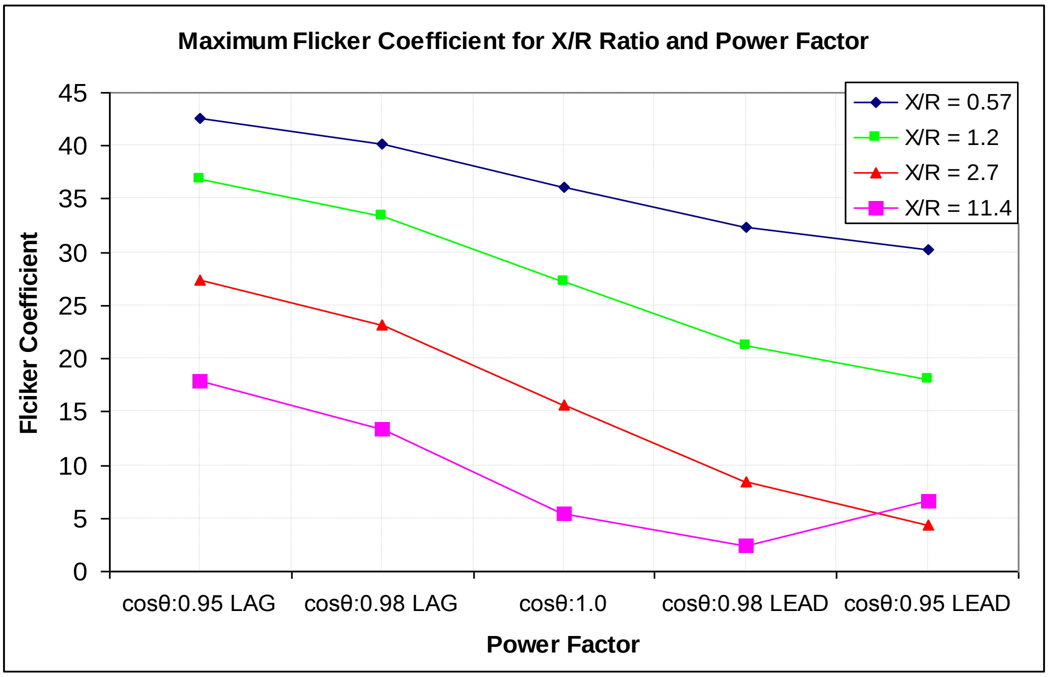



**FIGURE 6.10 WAVEBOB C($\Psi_K$) FOR VARIOUS X/R RATIOS AND POWER FACTORS**

## 6.5 Array Cancellation Effect

It has been demonstrated in this chapter that WECs have the potential to cause 'resource induced' flicker. This raises the obvious question of whether there will be a cancellation effect in an array of WECs that mitigates this flicker emission.

This issue is well understood in wind farms [63] with an array cancellation factor generally in the order of $n^{-1/2}$ where n is the number of wind turbines in the array. This means that a wind farm with 10 turbines would have an equivalent flicker emission of 3.16 ($10^{-1/2}$) individual turbines and not 10, i.e. there is a cancellation factor of 31.6%. As larger wind farms require connection to stronger grid nodes with higher fault levels, this has the effect of lowering the flicker emissions from the array.

Interference and interaction of WECs in arrays is less well understood than for wind turbine arrays. Some work has been carried out on the potential of flicker cancellation from WEC arrays [43] but the interference effects were simplified. Therefore, it is difficult to currently predict what smoothing may occur. Some smoothing is expected to occur but, depending on the layout of the array and the sea-state, there may be occasions where the fluctuating power of the WECs occur simultaneously which reduces the cancellation factor.

It is likely that the cancellation factor for WEC arrays is somewhere between $n^{-1/2}$ and 1 (i.e. no smoothing), depending on numerous factors in the configuration of the array.

## 6.6 Flicker Mitigation

If the resource induced flicker from a WEC exceeds the local emission limits then there are several possibilities for overcoming this. Some of these have been discussed previously in [131].

### 6.6.1 Energy Storage/Smoothing:

An energy storage system could be installed either on the WEC device itself or at the point of connection (POC) to smooth the power fluctuations and hence reduce flicker if necessary. There are several options available for energy storage. Mechanical storage solutions are available such as flywheels or hydraulic accumulators. Electrical and electrochemical storage solutions are also possible such as capacitors or battery energy storage. Each storage solution has characteristics which dictate its suitability, or unsuitability, for overcoming flicker from a WEC. The suitability of a storage solution for operation in the marine environment shall also be an important factor if the storage system is to be installed within the WEC.

The storage system has to be fast acting and rated for the amplitude of the power fluctuation. It is also subjected to multiple cycles during its lifetime. The addition of storage inevitably means additional cost and an efficiency reduction in the overall system which needs to be factored into any techno-economic analysis of the overall WEC system.

### 6.6.2 Spatial Configuration (Cancellation Effect)

As discussed in Section 6.5 when the cancellation effects in WEC arrays are better understood, it may be possible to reduce flicker by an appropriate spatial design of the array.

### 6.6.3 Control Strategy

A control strategy could be implemented in certain situations that not only reduces power fluctuation from individual devices [132] but also varies the characteristic responses of devices in a WEC array to avoid a statistical summing of power fluctuations and maximise the flicker cancellation factor.

In general, control systems may control a WEC for maximum energy absorption and conversion or could control a WEC for continuous power output (i.e. minimise fluctuations). A storage system, or inherent storage (e.g. hydraulic accumulators), may be required to allow the control of the WEC for continuous power output. Controlling a WEC to minimise power fluctuations at the output could reduce overall energy production for a WEC at a given site. This should be factored into the overall techno-economic analysis of the WEC system.

### 6.6.4 Reactive Power Compensation

Another possibility to counter a power fluctuations problem is the addition of a controlled reactive power device such as a STATCOM at the POC [133], [134]. This can instantaneously control the import and export of reactive power (VARs) from/to the grid and hence control the voltage level to be sufficiently smooth at the POC. So as the active power from the WEC fluctuates the reactive power from the STATCOM also fluctuates proportionally. The net result would be that even though the active power from the WEC continues to fluctuate, the STATCOM negates the effect this has on voltage at the POC.

Like energy storage, this solution means additional costs and losses in the overall system. This must be factored into the overall techno-economic analysis of the WEC system.

### 6.6.5 Increasing Short Circuit Power

By reconfiguring the network at the POC or by the reinforcing the network up to the POC, the fault (short circuit) level can be increased meaning that the power fluctuations would not affect the voltage as severely. This would typically mean the installation of additional overhead lines and transformers to strengthen the connection to the WEC array.

Any costs for additional overhead lines, transformers or switchgear would typically be passed onto the project developer. Therefore, this solution is likely to be the most costly of those suggested in this section.

## 6.7 Conclusion

Flicker is a power quality issue that any renewable power generator needs to consider. Flicker is of particular interest in wave energy due to the fact that 'resource induced' flicker lies in the frequency range of the flicker curve.

As flicker assessment can be complicated and specialised a number of options for assessing flicker are presented. These range from a preliminary calculation, the use of bespoke flicker assessment charts, and a full flicker assessment. The simplicity of the flicker assessment charts should allow for any party to evaluate the potential flicker from a wave energy converter at a given site. This facilitates an understanding of flicker impacts at an early stage in the design process.

A case study was undertaken to show the use of these methods. However, the case study WEC was shown, with the flicker assessment graphs, to not have a flicker issue at the specified site. This is due to the very large $S_k/S_n$ ratio.

The flicker coefficient, $c(\Psi_k)$, was evaluated for the case study WEC according to IEC standards. The flicker coefficient can be used to evaluate flicker at different sites in the future. This flicker coefficient showed that the 'resource induced' flicker is higher at lower period waves and particularly at high energy (high $H_s$), low period (low $T_p$) waves.

There are several possibilities for mitigating these flicker issues and the cancellation of flicker within an array is not yet fully understood. However, most mitigation strategies would have a cost and efficiency penalty on the overall system.

# Chapter 7

# The Domestic and Export Market for Irish Wave Energy

## 7.1 Introduction

There is an abundant wave energy resource surrounding Ireland and, given mature and cost effective technology, this could be accessed as renewable electrical energy. A concentrated effort is underway in the wave energy industry to develop reliable and efficient conversion technology and begin to develop early stage projects.

In Ireland, the renewable generation industry is dominated by onshore wind and this industry looks set to continue to grow even to a saturation point in terms of energy demand, and power system stability. The wind industry in Ireland is already looking to export markets for future growth.

Assuming that the right technology is available in the future to exploit the abundant wave energy resource in Ireland, this chapter examines where the market for this generated energy may be, and what technical, and economic, barriers exist to accessing this market.

## 7.2 Wave Energy Resource and Location in Ireland

The energy density of a given sea-state is calculated as a function of the wave height (in metres) and the wave period (in seconds). The annual average wave energy resource is expressed as kilowatts per metre (kW/m) and the resource off the west coast of Ireland is one of the highest energy resources in the world with a deep-water annual average resource of 70kW/m or higher off the west coast. This is shown in Figure 7.1.

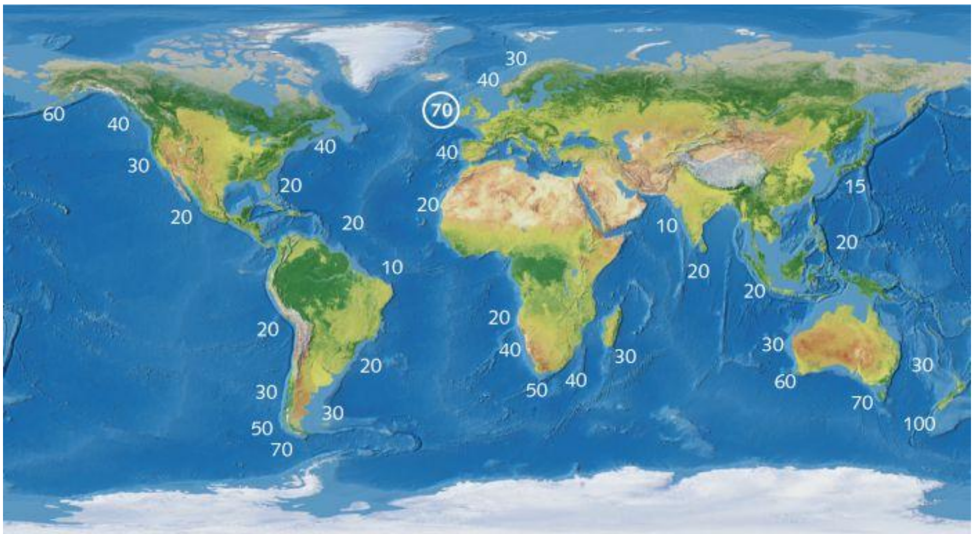



**FIGURE 7.1 GLOBAL ANNUAL WAVE ENERGY RESOURCE (KW/M) (SOURCE: OCEANENERGY.IE)**

It is important to differentiate between the theoretical resource and the practical or accessible resource. The theoretical resource is the energy that is available in the ocean waves and assumed unlimited deployment of wave energy converters (WECs) absorbing all available energy. The practical accessible resource is the energy that can be extracted and converted to electrical energy and is a small fraction of the theoretical resource. The practical resource is constrained by the WEC technology utilised and any local constraints such as shipping lanes, fishing zones, or areas of conservation.

A comprehensive study of the wave energy potential in Ireland was undertaken by ESB International [7] indicating that the theoretical annual wave energy resource in Ireland was 525TWh. This is within an electrical energy market with an annual demand of 34.5TWh in 2012 [135]. Thus, the available theoretical energy far exceeds the domestic Irish demand. However, from ESB International's report [7], the practical accessible resource is 21TWh. This represents 4% of the theoretical resource but over 60% of the total electrical energy demand of Ireland in 2012.

## 7.3 Hypothetical WEC Arrays for Analysis

The practical accessible resource of 21TWh corresponds to an annual average power output of around 2.4GW. Assuming a potential capacity factor of 40% for WEC arrays off the Irish west coast, this corresponds to a total practical installed capacity of 6GW. This represents the full exploitation of the practical resource in Ireland. It should be noted that the definition of practical resource may change based on market conditions, i.e. deeper water sites may become commercially viable or technology performance improves.

For the purposes of analysis this total capacity of 6GW is split into three candidate WEC arrays off the Irish west coast, each with a peak capacity of 2GW which, as explained in Section 7.6.1 is a viable transmission rating for HVDC transmission. The three areas for the WEC arrays were chosen to be roughly at the location of the Marine Institute data buoys M4 (NW Array), M1 (W Array) and M3 (SW Array). See Figure 7.2 for the location of these data buoys.

The Marine Institute data buoys are located in deeper water than would be expected for WEC arrays. The chosen locations of the three candidate WEC arrays can be seen in Figure 7.3 and are located around the 100m depth contour.

Although the candidate arrays are 2GW per array, it is expected that a 2GW array would not be installed as a first project in a single location. The scenario here is a hypothetical maximum utilisation of the practical accessible resource.

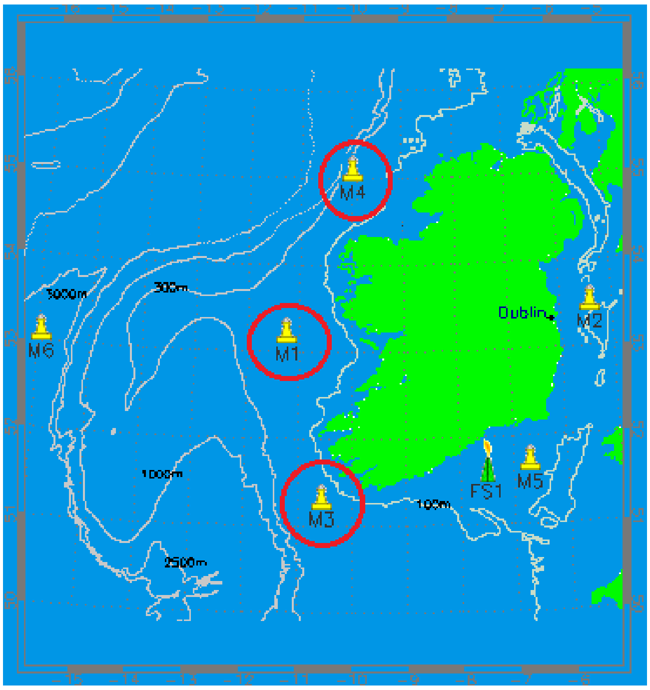



**FIGURE 7.2 LOCATIONS OF MARINE INSTITUTE DATA BUOYS (WWW.MARINE.IE)**

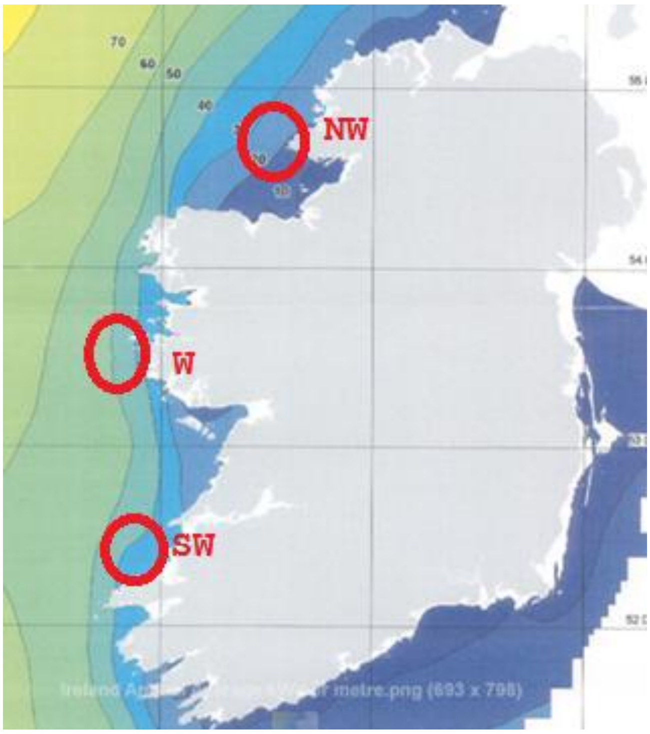



FIGURE 7.3 LOCATIONS OF THREE 2GW CANDIDATE WEC ARRAYS

## 7.4 2020 Targets and Wind Development in Ireland

In 2010, the gross final energy use from renewable sources in Ireland was 5.5% with the percentage of electrical generation capacity from renewables at 15% [136]. The 2020 target for gross final energy use under the EU Renewable Energy Directive 2009/28/EC is 16% for Ireland. In order to achieve this, 40% of electrical generation capacity must be from renewable sources by 2020. Based on the median demand forecast it is expected that 3.5-4GW of renewable energy will be required to meet this level of electrical generation from renewables.

In 2014, the EU began the process of defining the approach to emission reductions and renewable energy for 2030 [137]. The targets within the framework are not as clearly defined as the 2020 targets but call for an EU reduction in greenhouse gas emissions of 40% (over 1990 levels) by 2030, an increase in renewable energy to 27% of total energy usage, and an increase in energy efficiency by 30%. It remains to be seen how these EU wide targets will be translated into policy and renewable energy targets at a national level.

Ireland is on course to meet our 2020 target from onshore wind alone, and this has certainly been the focus of domestic energy policy. There is over 2GW of wind energy currently installed within the single electricity market (SEM). There is close to an additional

4GW planned within the group processing approach known as Gate 3 (3.2GW of onshore wind and 0.8GW of offshore wind) [138].

Beyond Gate 3 there is a further 12GW of planned onshore wind in the ‘queue’, sometimes referred to informally as Gate 4. Gate 4 projects will not be processed until Gate 3 has been completed.

On top of the projects in Gate 3 and Gate 4, there are additional projects planned that involve onshore wind in Ireland with direct export to the UK. Projects such as Greenwire [139], Energy Bridge [140], Marex [141] and Natural Hydro Energy [142] plan to offer wind energy to the UK market at a more competitive price than the UK would have to pay for offshore wind in its own territory. These projects have potential of up to 10GW beyond what is in Gate 3 and Gate 4. However, these projects are yet to receive clear approval from the Irish or UK government as of 2014.

It is clear then that Ireland has enough wind in planning to meet and far exceed its 2020 targets and not only provide enough renewable energy for the domestic market but potentially exploit this renewable energy for export. It is expected, however, that some of the proposed wind generation capacity in Gate 3, Gate 4 and the export projects will not be developed. The development of these projects depends on the market conditions, success in planning permission, and grid access among many other factors.

In order to facilitate the proposed volume of wind energy on the Irish electricity system, some important changes are currently taking place. Firstly, the transmission system needs to be upgraded to accommodate large volumes of wind in locations remote from demand centres. Secondly, the system needs to be designed to operate securely with large proportions of non-synchronous generation.

Eirgrid's Grid25 strategy [143] provides for the reinforcement of the transmission system in Ireland to assist in the exploitation of wind energy. Much of this reinforcement work is presently taking place to facilitate Gate 3 connections.

Another issue with high levels of wind on the system is the power system stability from high penetration of non-synchronous generation. High penetration of non-synchronous generation means a low system inertia that can cause system frequency stability issues during loss of generation or faults.

At present there is an imposed limit for non-synchronous generation. This requires that system non-synchronous penetration (SNSP) must not exceed 50% of the instantaneous system demand. This means that if non-synchronous generation capacity, predominantly wind, is more than 50% of instantaneous system demand, the instantaneous wind generation must be curtailed thus losing potential generation and revenue for wind farm owners. In 2012, 2.1% of all potential renewable energy generation in the SEM was curtailed [144].

Eirgrid [145] outlines a plan to enable this limit to be increased to 75%. However, even with this strategy some curtailment is still likely, and, as the capacity of wind generation grows, curtailment may increase and the revenue of wind plant would thus be reduced, perhaps to the point where investment in new renewable generation will suffer.

## 7.5 Wave Energy Opportunities in the Irish Market

In Section 7.4, the current market for wind in Ireland was outlined. There is currently around 16% wind energy as a proportion of total generation in Ireland and there are plans to increase this to 40%. At present, some curtailment of wind energy, due to system stability issues, is already in place and this may increase with further wind capacity. Wind farm developers are now looking to export markets for opportunities as the Irish market may provide limited opportunities beyond what is planned.

It is not certain, therefore, where wave energy fits into this market. Certainly it is expected that large scale WEC arrays are not be possible until after 2020 as WEC technology is still developing. The Irish domestic renewables market may be heavily saturated with wind energy when the time comes to begin large scale WEC arrays.

From this information it seems that the domestic market for wave energy may be limited, certainly over the next two decades. There may, however, be some opportunity for wave energy in the domestic Irish market as outlined in the scenarios below.

### 7.5.1 Non-Concurrence and Diversity

Waves are, like wind, an intermittent renewable source. Nevertheless, the physics of wave generation are different than wind energy and the intermittency may be non-concurrent with wind energy. So high and low outputs of WEC arrays may not occur with highs and lows of wind farms. This can be exploited in a number of ways:

- Firstly, the addition of diversity into the renewable energy mix is likely to reduce overall intermittency and the need for thermal backup [104], [146]. It should be noted that diversity of renewables, will not allow a higher SNSP, if all renewables remain non-synchronous.
- Secondly, expensive transmission infrastructure, for bringing remote output from wind farms to demand centres, can be shared with wave installations thus increasing the utilisation of the infrastructure [104].

There is likely to be several system wide benefits by adding wave energy to the domestic renewable energy mix. In the long term this could allow a more secure and cost effective electrical system.

### 7.5.2 Additional Interconnection and Storage in the System

Albeit, mostly focussed on market integration, the addition of more interconnection into the Irish system from neighbouring markets (UK and France) will certainly reduce the requirements for curtailment and allow greater penetration of renewables in the Irish domestic market [147]. HVDC interconnectors may also have the ability to provide 'synthetic' inertia, to increase the limits for non synchronous generation still further.

Large scale energy storage, such as pumped storage facilities, may allow the conversion of non-synchronous intermittent generation into dispatchable synchronous generation within the Irish market. Power-to-gas type schemes may also permit inter-seasonal storage. Large scale energy storage has the potential to dramatically change the market for renewables in Ireland and Europe, but the economic case to support this is not currently viable.

There are a number of ways a fully integrated system could develop with interconnection, storage and large penetration of renewables; however this is not the topic of this chapter.

### 7.5.3 Re-use of redundant infrastructure.

Some transmission infrastructure may become redundant as thermal plants on the west coast of Ireland are decommissioned. An example of this is the Moneypoint power station which was commissioned in the mid 1980s and has recently undergone a retrofit and installation of flue gas abatement systems. It is possible that the existing Moneypoint plant will be decommissioned in the mid-2020s, as it will be 40 years old by this point, and there are two dedicated 400kV lines from the plant (located on the west coast) to Dublin (the main load centre in Ireland) as shown in Figure 7.4.

The decommissioning of a station like Moneypoint may provide a ready asset for transmission; however the market and system issues will still apply.

**FIGURE 7.4 LOCATION OF MONEYPOINT AND ROUTE OF 400KV LINES TOWARDS DUBLIN**

### 7.5.4 Synchronous Wave Energy Converters

Wind turbines use non-synchronous generators and WECs are also expected to be non-synchronous generators based on current designs of prototypes. If WECs can be designed with synchronous generators then they would assist in system frequency support and may not be limited by curtailment. This may be possible for some hydraulic PTO type WECs as described in Section 3.2.1.3.

### 7.5.5 Irish Domestic Market for Ocean Energy Summary

As outlined in the above sections there is likely to be only a limited domestic market for wave energy in Ireland given the current market outlook. The addition of wave energy to the renewables mix may reduce intermittency, and could increase utilisation of exiting transmission infrastructure. If there is a limited domestic market for wave energy then an export market must be explored.

## 7.6 Export Market Opportunities

If the abundant wave energy resource off the west coast of Ireland cannot be exploited domestically, due to market and system issues, then an export solution must be explored. The UK is the geographically closest market to Ireland with France being the next closest.

2020 targets for gross energy from renewable sources are 15% in the UK and 23% in France. In the UK, this dictates a target of 30% of electricity generation from renewable sources by 2020. In France, this target is 27%. As of 2010, the UK reached 6.7% (towards a target of 30%) and France reached 14.5% (towards a target of 27%) of electrical generation from renewables [148].

These 2020 targets may present a challenge for both the UK and France, and imports of renewable electricity generation from Ireland could help them meet their 2020 targets and beyond. This is an opportunity for export of renewable energy from Ireland that is already being considered by the wind export projects presented in Section 7.4. It is important to note however that the cost of importing these renewables to the importing nation will be a critical factor to the potential of an export market for Irish renewables.

If wave energy cannot access the domestic market in Ireland, for the reasons outlined in previous sections, then it may require access to these export markets.

### 7.6.1 HVDC Technology and Costs

There are two ways in which wave energy off the west coast of Ireland can access export markets. Firstly, through an integrated export network through the Irish system which would require multiple interconnections between the Irish and export markets. This is a likely scenario to develop over the longer term.

Secondly, through dedicated transmission infrastructure from the WEC array to the export market. As explained previously, a fully integrated system may evolve in a number of ways and is not the topic of this chapter. Dedicated transmission for WEC array export systems however will be evaluated further here.

Due to the large submarine distances and large power capacities required for the candidate WEC arrays, High Voltage Direct Current (HVDC) transmission would be the only potential transmission solution for connecting Irish WEC arrays directly to the UK and France. HVDC transmission systems allow the long distance overland or submarine transfer of bulk electrical power. Over long distances they are more efficient and cost effective than High Voltage Alternating Current (HVAC) systems. HVDC transmission involves converting electrical power from AC to DC for transmission, then back to AC for connection to the grid at the other end. Figure 7.5 shows a representative HVDC transmission system,

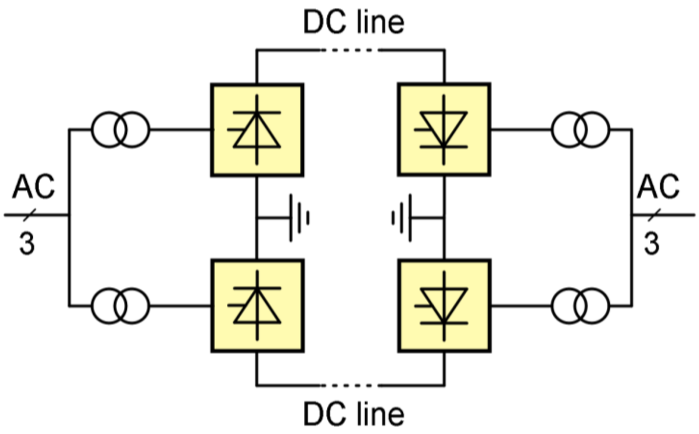



**FIGURE 7.5 TYPICAL HVDC TRANSMISSION SYSTEM (COURTESY WIKIPEDIA)**

HVDC cabled transmission systems are possible up to around 2.5GW per system [149], which is at the upper limit of the converter and cable technology. This was part of the rationale for splitting the 6GW of potential wave energy capacity into three 2GW WEC arrays for analysis.

The cost elements of HVDC systems to transmit power from WEC array projects with export to the UK would fall into the following categories:

- HVDC Converter Stations

- Offshore Platform – At WEC array end only
- Offshore cables
- Onshore cables

From [149], [150], [151], [152] & [153] reference costs were established for these components and are presented in Table 7.1. All reference costs are for 2GW systems only. Note that component costs are for reference only and there can be large variations across projects depending on market conditions, route characteristics, vessel requirements among many other aspects. Note also that a cost of €20m is estimated for an offshore platform for HVDC converter, i.e. the platform structure only.

**TABLE 7.1 COST REFERENCES FOR HVDC TRANSMISSION**

| Component | Reference Cost | Unit |
|---|---|---|
| HVDC Converter Stations | 0.15 | m€/MW |
| Offshore Platform | 20 | m€/platform |
| Offshore HVDC Cables | 2.0 | m€/km |
| Onshore HVDC Cables | 2.2 | m€/km |

There would also be a large cost for the WEC array electrical network that would involve the connection of the WECs in circuits to a central offshore substation and connection from that substation to the HVDC export transmission system. The cost of this array's electrical system is not considered here as this would also be required for a typical WEC array connected to the local grid and therefore is not an additional cost.

## 7.7 Case Study: Wave Array Export Transmission to UK and France

The previous sections demonstrated that a limited domestic market in Ireland may lead to exploring export markets and HVDC transmission would be an enabling technology for this. This section outlines the projected costs of such transmission systems for accessing export markets.

In Figure 7.6 the three proposed 2GW WEC arrays are shown ('NW', 'W' and 'SW' WEC Arrays from Figure 7.3) and five export access zones are shown (Z1-5). These access zones are chosen as the closest location to the WEC arrays that have access to Extra High Voltage (EHV – 380kV or higher) grids. As illustrated in Figure 7.6 seven routes were evaluated between the WEC arrays and the various zones.

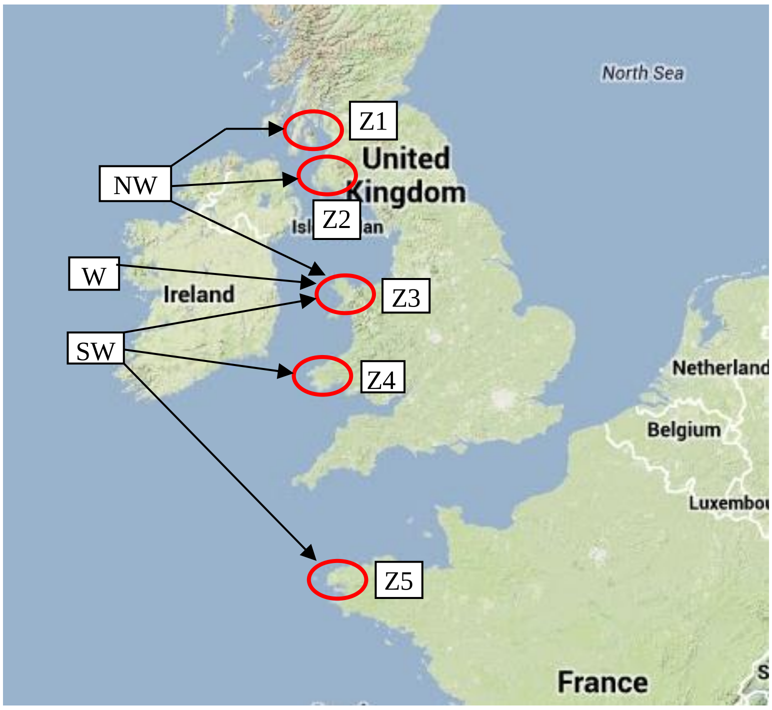



**FIGURE 7.6 LOCATIONS OF CANDIDATE WEC ARRAYS AND POTENTIAL CONNECTIONS TO EXPORT MARKETS**

The distance between the WEC Arrays and the relevant access zones was calculated using an online mapping tool. Straight line distances were calculated but these are increased by 20% to allow for expected route length increase over point to point distances. Within each zone there may be several connection nodes to the EHV grid and the range of costs given are for the closest node and the furthest node within the zone.

Table 7.2 shows the calculated capital costs for the seven export routes depicted in Figure 7.6. This presents the total cost of the offshore platform (€20m) at the WEC array, the offshore HVDC converter, the total cable route length (including onshore and offshore), and the onshore HVDC converter at the access zones. The costs presented in Table 7.1 are used to establish these capital costs.

**TABLE 7.2 CAPITAL COSTS FOR HVDC TRANSMISSION SYSTEM FOR WEC ARRAY EXPORT**

| From WEC Array | To Zone | Capital Cost Total | Capital Cost per MW (2GW system) |
|---|---|---|---|
| NW | Z1 | €1.3 – 1.47bn | €0.65 – 0.74m |
| NW | Z2 | €1.22bn | €0.61m |
| NW | Z3 | €1.55 – 1.58bn | €0.77 – 0.79m |
| W | Z3 | €1.55bn | €0.77m |
| SW | Z3 | €1.68bn | €0.84m |
| SW | Z4 | €1.55 – 1.91bn | €0.78 – 0.96m |
| SW | Z5 | €2.19bn | €1.1m |

Note that the per-MW figures are based on a 2GW system. It is expected that these costs do not scale linearly so would not be valid for a 500MW system, for example. This shows that for an export market to be exploited large scale WEC arrays are necessary to dilute the additional cost of the export system

## 7.8 Conclusion

It is well documented that Ireland has an abundant wave energy resource and with suitable and cost effective WEC technology this can be exploited for renewable electrical power generation.

Ireland has other abundant renewable resources, notably wind power. It is likely that onshore wind can meet Irish domestic demand for renewable electrical generation up to 2020. Domestic demand for renewables will be dictated by the growth in electrical demand and also by how much non-synchronous generation can be tolerated before power system stability becomes an issue.

The domestic market for wave energy may be limited in Ireland through saturation with onshore wind, system stability issues, or other causes. There is opportunity to export to neighbouring markets, namely the UK and France, to assist these countries increasing their penetration of renewable energy resources. Viable HVDC technology can connect the long distances and large power capacities to these neighbouring markets. However, there is an additional cost, for transmission systems, associated with accessing these export markets.

The cost of such systems could range from €1.2 – 2bn depending on the distance between the WEC array and the export market. This adds €0.6 – 1.1m / MW onto the capital cost of a WEC array project, which may be an unacceptable increase. This is based on a 2GW capacity and this scale of transmission is required to minimise the costs per MW which would increase for smaller capacities.

In order for wave energy from Ireland to be an attractive proposition for export markets, it is expected that it must be as commercially attractive as other forms of renewable energy. In this regard, offshore wind is a good benchmark. Current capital costs of offshore wind are approximately €4m / MW [151]. Therefore, in order to be commercially attractive for export, wave energy projects, including the cost of export transmission, must compete with these costs. The export system alone could comprise 25% or higher of the overall capital costs of potential projects. Thus, the challenge for cost effective WEC arrays may become more difficult given the additional 'export premium' cost.

Ireland has an enviable wave energy resource and there are many challenges in exploiting this, including developing cost effective WEC technology. A major challenge is in understanding where the long-term market lies for wave energy from Ireland. This chapter concludes that for large scale wave energy, the long-term market is an export one. This brings additional cost to any proposed large scale WEC array.

# Chapter 8

# Conclusions and Future Work

## 8.1 Discussion, Conclusion, and Contribution of Thesis

In this thesis, a comprehensive analysis has been undertaken of some key grid integration issues for WEC arrays. This thesis enhances the knowledge base in the subject area of WEC array electrical networks, WEC voltage flicker emission assessment, and the domestic and export market for wave energy in Ireland.

The objectives of this thesis are set out in Chapter 1 and in this Chapter it is assessed how these objectives have been met. The objectives are reproduced below.:

- Develop technically and economically acceptable electrical network designs for WEC arrays considering;
    - Economic constraints
    - Array technical requirements
    - Array functional requirements
    - Experience to date from both the offshore wind industry and the wave energy industry
    - Potential strategies for improving economics for WEC electrical networks
- Evaluate voltage flicker issues for WEC arrays and develop design tools to analyse same.
- Evaluate the market scale for wave energy in Ireland, considering electrical integration issues in both the domestic and export markets.

### 8.1.1 Techno-Economic Optimisation

**Objective:**

- *Develop technically and economically acceptable electrical network designs for WEC arrays considering;*
  - *Economic constraints*
  - *Array technical requirements*
  - *Array functional requirements*
  - *Experience to date from both the offshore wind industry and the wave energy industry*
  - *Potential strategies for improving economics for WEC electrical networks*

This objective has been achieved by firstly developing a comprehensive understanding of a wide range of considerations to be made when designing an optimum electrical network for WEC arrays. These are introduced in Chapter 3 and Chapter 4.

In Chapter 3, the state-of-the-art in WEC on-board systems and components, WEC array components, and WEC test sites and prototype electrical networks has been introduced and analysed. The state-of-the-art in offshore wind farm electrical networks has also been introduced and analysed. Although there are divergent concepts in the area of WEC electrical networks, there is much more convergence in electrical network design in the offshore wind industry and there is certainly cross-over possible, particularly the rationale behind design convergence, and with installation vessels and processes. The key differences between offshore wind farm and WEC array electrical networks have been shown to occur at 'key interfaces' which are critical in the techno-economic optimisation outlined in Chapter 4.

A techno-economic analysis of WEC array electrical network concepts has been detailed in Chapter 4. At the beginning of Chapter 4, the technical and economic considerations for the design and optimisation of WEC array electrical networks have been outlined. By introducing and analysing potential options for both the key interfaces and the WEC array electrical network configurations, a techno-economic optimisation has been carried out.

It has been concluded that radial network configurations are the optimum configuration for WEC arrays. However, some deficiencies with this configuration must be addressed, notably the lack of redundancy. Strategies for addressing these deficiencies have been introduced. Optimised key interfaces for a radial network have been presented that allow a WEC array electrical network to be realised within target costs while maintaining critical functionality.

The annual average network efficiency has been calculated for a number of candidate WEC arrays (10MW, 40MW and 150MW). This has demonstrated that network efficiency of up to 99% can be expected for the optimised WEC array electrical network. It has been noted that an understanding of the generation characteristic of the WECs within the array is critical to calculate network efficiency. Array spacing and operating voltage have negligible impact on efficiency, but affect the economics of the array.

The expected costs for the optimised array electrical network have been calculated and are shown to be on target for commercial WEC arrays, i.e. €1m/MW.

The economic challenges for WEC array electrical networks are introduced and some strategies to improve the economics analysed has been shown in Chapter 5. Design criteria such as WEC device rating, WEC capacity factor, array spacing, and site conditions have been shown to influence the economics of the WEC array electrical network. These design criteria can increase or decrease WEC array electrical network cost. Therefore, WEC and WEC array designers must balance the impact any design decisions have on the WEC array electrical network economics against any potential benefits.

Also in Chapter 5, some strategies for improving the economics of WEC array electrical networks have been introduced and evaluated. By understanding the characteristics of the WEC array, the electrical network can be under-rated to allow lower cost with minimal curtailment. Also, by applying dynamic ratings on the electrical network or using more sophisticated real time thermal rating systems, the electrical network can be utilised fully without risk of exceeding safe operating conditions. This may result in the reduction of electrical network ratings and hence a reduction in cost.

The objective to *Develop technically and economically acceptable electrical network designs for* has been achieved within Chapters 3-5 of this thesis.

### 8.1.2 Voltage Flicker Evaluation

**Objective:**

- *Evaluate voltage flicker issues for WEC arrays and develop design tools to analyse same.*

The issue of voltage flicker is prevalent for any renewable generator with a variable input resource. It has been demonstrated in Chapter 6 that for wave energy, there is a potential coupling of input resource, ocean waves, to output power. As the input resource lies within the frequency of interest for voltage flicker, it has been shown that it is highly likely that WEC devices will create flicker emissions.

The assessment and quantification of flicker emissions is a requirement for any renewable generator but the process is complicated. In order to allow early assessment of flicker emissions at design stage, a flicker assessment tool has been developed and its use is also outlined in Chapter 6. This tool is not a substitute for international standards but is a design tool.

A full flicker evaluation case study has also been undertaken in Chapter 6 to further understand the relationship between the resource and potential flicker emissions. It has been demonstrated that flicker emissions are higher at lower period (high frequency) input resource. In particular low period, high energy (i.e. high $H_s$) resource causes the highest levels of flicker emission. There are potential mitigation strategies for flicker but it has been shown that these may incur a cost or efficiency penalty.

The objective to *Evaluate voltage flicker issues for WEC arrays and develop design tools to analyse same* has been achieved within Chapter 6 of this thesis.

### 8.1.3 Irish Market Evaluation

**Objective:**

- *Evaluate the market scale for wave energy in Ireland, considering electrical integration issues in both the domestic and export markets.*

In Chapter 7, the potential domestic and export market for wave energy in Ireland has been assessed. In this chapter, the renewables market in Ireland is presented and it has been shown that onshore wind may saturate and limit the market for renewables in Ireland over the coming decades. Neighbouring markets such as the UK and France present an export opportunity for wave energy from Ireland.

Due to the distances to these export markets, HVDC transmission technology has been shown to be an enabling technology. This would enable access to export markets, but at a cost. It is concluded that these transmission systems would costs €0.6-1.1m/MW depending on transmission distance. Large WEC arrays would be required to dilute the cost of this transmission infrastructure.

The objective to *Evaluate the market scale for wave energy in Ireland, considering electrical integration issues in both the domestic and export markets* has been achieved within Chapter 7 of this thesis.

### 8.1.4 Summary and Key Conclusions

The major important conclusions of this thesis are presented in Table 8.1. This summarises the most important outcomes of the research in this thesis.

TABLE 8.1KEY CONCLUSIONS FROM THIS RESEARCH

| Key Conclusions |
|---|
| Radial networks are the optimal network configuration for offshore WEC array electrical networks |
| Electrical networks for WEC arrays can be achieved with high efficiency and at a cost to allow a competitive wave energy industry |
| This competitiveness can be improved further by applying strategies to reduce the WEC array electrical network capex. |
| Voltage flicker is demonstrated to be inherent and potentially severe for WEC output |
| Practical tools for assessing voltage flicker emissions from WECs have been presented |
| Voltage flicker is shown to be particularly severe for lower period sea states with large significant wave height |
| While Ireland has an enviable wave resource, integrating this into the Irish electricity system is challenging |
| Export markets are technically accessible but the cost of transmission is a barrier to competitiveness |

All of the above conclusions can be considered novel academic contributions and provide solutions to important questions being asked by the wave energy industry. This thesis provides guidance to WEC designers and WEC array designers and developers. This achieves the objectives set out in Chapter 1 of this thesis and assures that this work adds significantly to the knowledge base of the industry.

The thesis concludes that there are great challenges for wave energy in the area of grid integration. Through careful design, optimisation and analysis, it is evident that cost effective and technically suitable WEC arrays can be achieved.

## 8.2 Future Work

This thesis is practically focussed and therefore needs practical demonstration of the research conclusions. This is not possible to do within the confines of this thesis as the costs of demonstrating the suggested solutions would be excessive. As the wave energy industry moves from the current prototyping focus towards commercial array deployment, there will be an opportunity to review the findings of this research against practical applications. At that time, a clearer understanding of some of the issues in this work will be possible.

It is apparent that the targeted sites for WEC array installation of the western seaboard of Europe are exposed to extreme wave conditions. While this means that there is a large wave energy resource to be exploited, it also presents challenges to the installation of submarine electrical networks. A suggested follow-on research topic would be to analyse the wave energy at a proposed site in order to understand the weather risk to cable installation. This would involve exploring the requirements of cable installation vessels and undertaking a persistence analysis on the site wave resource. Weather risk is likely to be a large challenge and contractual issue for commercial arrays and a deeper understanding of this would be valuable to the industry.

Another major challenge for large scale WEC arrays will be the realisation and cost of offshore substations in deep water locations, which has been briefly assessed in this thesis. It is suggested that the technical solutions and economics of offshore substations for WEC arrays in 100m water depth should be explored as a detailed research topic. This is critical to understand the competitiveness of wave energy in the longer term.

Radial networks are proposed in this work as the optimal solution for WEC array electrical network configurations. There are deficiencies of radial networks in the areas of redundancy and requirements for multiple connections to devices. Some strategies to overcoming these deficiencies are presented in this research. A suggested follow on piece of research would be to undertake a techno-economic evaluation of these, and other potential, strategies to further understand the impact of this on the WEC array electrical system economics and performance. Some practical demonstration of these solutions should form part of this research.

It is clear from this work that the design of cost effective electrical networks will be challenging. The sharing of this expensive offshore electrical infrastructure with either offshore wind, solar, or tidal energy may ultimately improve the economics for wave energy.

A suggested follow-on piece of research would be to analyse the wind, wave, tidal and solar energy potential at a number of sites to assess the viability of a ‘shared’ electrical network approach.

From this research, it is also clear that Ireland’s renewable energy mix is heavily dependant on onshore wind energy and this has begun to influence system stability. The introduction of wave energy to the Irish renewables mix may assist in reducing intermittency within the power system and help with system stability. It has also been documented that wave energy is a more predictable renewable resource. A suggested follow-on piece of research would be to assess the value of adding a range or proportions of wave energy to the Irish renewable energy mix.

# Bibliography


[1] International Energy Agency - Ocean Energy Systems, "Ocean Energy Systems Annual Report 2012," IEA-OES, 2012.

[2] R. Green and N. Vasilakos, "The Economics of Offshore Wind," *Energy Policy,* vol. 39, pp. 496-502, 2010.

[3] RenewableUK, "Channelling the Energy - A Way Forward for the UK Wave & Tidal Industry Towards 2020," 2010.

[4] W. Dick, "Wave Energy Converter". U.S.A. Patent 6857266, 2005.

[5] A. Clement and et al, "Wave energy in Europe: current status and perspectives," *Renewable and Sustainable Energy Reviews,* vol. 6, no. 5, pp. 405-431, 2002.

[6] The Crown Estate, "Wave and Tidal Energy in the Pentland Firth and Orkney Waters: How the Projects Could be Built," The Crown Estate, 2011.

[7] ESBI, "Accessible Wave Energy Resource Atlas: Ireland: 2005," 2005.

[8] Carbon Trust, "UK Wave Energy Resource," 2012.

[9] V. deLaleu, Électricité de France, 2009. [Online]. Available: http://www.inter-mines.org/docs/0904140804PR_090319_DeLaleu.pdf. [Accessed November 2013].

[10] Elfosk, "Wave Power - Surveilance Study of the Development," 2011.

[11] RenewableUK, "Wind Energy in the UK. State of the Industry Report," 2012.

[12] RenewableUK, "Offshore Wind Forecasts of future costs and benefits," 2011.

[13] T. W. Thorpe, "An Overview of Wave Energy Technologies: Status, Performance and Costs," in *IMECHE Seminar - Wave Power - Moving Towards Commercial Viability,* 1999.

[14] National Oceanic and Atmospheric Administration, "Ocean Service Education,"

[Online]. Available: http://oceanservice.noaa.gov/education/kits/currents/media/supp_cur03a.html. [Accessed July 2014].

[15] European Commission, “Wave Energy Brochure,” [Online]. Available: http://ec.europa.eu/energy/res/sectors/doc/ocean/wave_energy_brochure.pdf. [Accessed July 2014].

[16] J. Falnes, Ocean Waves and Oscillating Systems, Cambridge University Press, 2002.

[17] R. Alcorn and D. O Sullivan, Electrical Design for Ocean Wave and Tidal Energy Systems, Institute of Engineering and Technology, 2013.

[18] R. Speirs, D. Wilson and H. Whittingtom, “Electrical Generation Systems Suitable for Use in Wave Power Schemes,” in *Edinburgh Wave Power Project*, 1977.

[19] D. O'Sullivan and G. Dalton, “Challenges in the Grid Connection of Wave Energy Devices,” in *8th European Wave and Tidal Energy Conference (EWTEC)*, 2009.

[20] D. O'Sullivan and A. Lewis, “Generator Selection for Offshore Oscillating Water Column Wave Energy Converter,” in *13th Power and Motion Control Conference*, 2008.

[21] D. O'Sullivan and A. Lewis, “Electrical Machine Options in Offshore Floating Wave Energy Converter Turbo Generators,” in *World Renewable Energy Congress*, 2008.

[22] M. Mueller, H. Polinder and N. Baker, “Current and Novel Electrical Generator Technology for Wave Energy Converters,” in *IEEE International Electric Machines & Drives Conference*, 2007.

[23] M. A. Mueller, “Electrical Generator for Direct Drive Wave Energy Converters,” *Generation, Transmission and Distribution*, vol. 109, no. 4, pp. 446-456, 2002.

[24] J. Shek, D. Macpherson, M. Mueller and J. Xiang, “Reaction force control of a linear electrical generator for direct drive wave energy conversion,” *IET Rewewable Power Generation*, vol. 1, no. 1, pp. 17-24, 2007.

[25] J. Fletcher, T. Judendorfer, M. Mueller, N. Hassanain and M. Muhr, “Electrical issues associated with sea-water immersed windings in electrical generators for wave and tidal current-driven power generation,” *IET Renewable Power Generation,* vol. 3, no. 2, pp. 254-264, 2009.

[26] M. Leijon, O. Danielsson, M. Eriksson, K. Thorburn, H. Bernhoff, J. Isberg, J. Sundberg, I. Ivanova, E. Sjostedt, O. Agren, K. Karlsson and A. Wolfbrandt, “An electrical approach to wave energy conversion,” *Renewable Energy,* vol. 31, no. 9, pp. 1309-1319, 2006.

[27] M. Leijon, C. Bostrom, O. Danielsson, S. Gustafsson, K. Haikonen, O. Langhammer, E. Stromstedt, M. Stalberg, J. Sundberg, O. Svensson and R. W. S. Tyrberg, “Wave Energy from the North Sea: Experiences from the Lysekil Research Site,” *Surveys in Geophysics,* vol. 29, no. 3, pp. 221-240, 2008.

[28] O. Danielsson, M. Leijon and E. Sjostedt, “Detailed study of the magnetic circuit in a longitudinal flux permanent-magnet synchronous linear generator,” *IEEE Transactions on Magnetics,* vol. 41, no. 9, pp. 2940-2495, 2005.

[29] C. Bostrom, B. Ekergard, R. Waters, M. Eriksson and M. Leijon, “Linear Generator Connected to a Resonance-Rectifier Circuit,” *IEEE Journal of Oceanic Engineering,* vol. 38, no. 2, pp. 255-262, 2013.

[30] O. Danielsson, “Wave Energy Conversion - Linear Synchronous Permanent Magnet Generator - PhD Thesis,” Uppsala University, Stockholm, 2006.

[31] M. Eriksson, “Modelling and Experimental Verification of Direct Drive Wave Energy Conversion - Buoy-Generator Dynamics - PhD Thesis,” Uppsala University, Stockholm, Sweden, 2007.

[32] R. Waters, “Energy from the Ocean Waves - Full Scale Experimental Verification of a Wave Energy Converter - PhD Thesis,” Uppsala University, Stockholm, Sweden, 2008.

[33] M. Santos, D. B. Haim, F. Salcedo, J. Villate and Y. Torre-Enciso, “Grid Integration of Wave Energy Farms: Basque Country Study,” in *3rd International Conference on Ocean Energy,* Bilbao, Spain, 2010.

[34] T. Boehme, G. Harrison and A. Wallace, “Assessment of distribution network limits for non-firm cconnection of renewable generation,” *IET Renewable Power Generation,* vol. 4, no. 1, pp. 64-74, 2010.

[35] J. Khan, D. Leon, A. Moshref, S. Arabi and G. Bhuyan, “Electricity System Scenario Analysis to Determine Level of Wave Power that Can be Integrated: a Case Study,” in *3rd International Conference on Ocean Energy*, Bilbao, Spain, 2010.

[36] T. Ahmed, K. Nishida and M. Nakaoka, “The Potential for Grid Power Integration of Offshore Ocean Wave Energy in the UK,” in *International Power Electronics Conference*, 2010.

[37] A. Blavette, D. O'Sullivan, M. Egan and A. Lewis, “Grid Compliance of Ocean Energy Converters: Control Strategies and Reccomendations,” in *European Wave and Tidal Energy Conference*, 2011.

[38] A. Blavette, D. O'Sullivan, M. Egan, A. Lewis and R. Alcorn, “Wave Energy Grid Integration in Ireland – A Case Study,” in *3rd International Conference on Ocean Energy (ICOE)*, Bilbao, Spain, 2010.

[39] A. Nambiar, A. Kiprakis, D. Forehand and A. Wallace, “Effects of Array Configuration, Network Impacts and Mitigation of Arrays of Wave Energy Converters Connected to Weak, Rural Electricity Networks,” in *3rd International Conference on Ocean Energy (ICOE)*, Bilbao, Spain, 2010.

[40] A.Kiprakis, A. Nambiar, D. Forehand and A. Wallace, “Modelling Arrays of Wave Energy Convertes Connected to Weak Rural Electrical Networks,” in *International Conference on Sustainable Power Generation and Supply*, 2009.

[41] A. Nambiar, A. Kiprakis and A. Wallace, “Voltage quality control of a 1MW wave farm connected to weak, rural electricity networks,” in *45th International Universities Power Engineering Conference (UPEC)*, 2010.

[42] A. Nambiar, A. Kaprakis and A. Wallace, “Quantification of voltage fluctuations caused by a wave farm connected to weak, rural electrical networks,” in *14th International Conference on Harmonics and Power Quality*, 2010.

[43] A. Blavette, D. O'Sullivan, A. Lewis and M. Egan, “Impact of a Wave Farm on its Local Grid: Voltage Limits, Flicker Level and Power Fluctuations,” in *IEEE/MTS OCEANS Conference*, Yeosu, South Korea, 2012.

[44] A. Blavette, D. O'Sullivan, A. Lewis and M. Egan, “Grid Integration of Wave and Tidal Energy,” in *ASME 30th International Conference on Ocean, Offshore and Arctic Engineering*, Rotterdam, The Netherlands, 2011.

[45] D. Murray, M. Egan, J. Hayes and D. O'Sullivan, “Applications of Supercapacitor Energy Storage for a Wave Energy Converter System,” in *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009.

[46] S. Muthukumar, S. Kakumanu, S. Sriram and V. Jayashankar, “Energy Storage Considerations for a Standalone Wave Energy Plant,” in *IEEE International Conference on Electric Machines and Drives*, San Antonio, Texas, 2005.

[47] S. Muthukumar, S. Kakumanu, S. Sririam, R. Desai, A. Babar and V. Jayashankar, “On Minimizing the Fluctuations in the Power Generated from a Wave Energy Plant,” in *IEEE International Conference on Electric Machines and Drives*, San Antonio, TX, 2005.

[48] A. Blavette, D. O'Sullivan, A. Lewis and M. Egan, “Dimensioning the Equipment of a Wave Farm: Energy Storage and Cables,” in *8th International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, 2013.

[49] University of Edinburgh, “Wave Energy Report on the Electrical Aspects of the Edinburgh University Wave Energy Device,” Edinburgh Wave Power Project, 1979.

[50] A. Wallace, “Design Considerations of Submarine Power Links,” Edinburgh Wave Power Project, 1976.

[51] J. Lopez, P. Ricci, J. Villate, A. Bahaj, L. Myers, C. Retzler and J. Dhedin, “Preliminary economic assessment and analysis of grid connection schemes for ocean energy arrays,” in *3rd International Conference on Ocean Energy (ICOE)*, Bilbao, Spain, 2010.

[52] L. Myers, A. Bahaj, C. Retzler, P. Ricci and J. Dhedin, “Inter-device spacing

issues within wave and tidal energy converter arrays," in *3rd International Conference on Ocean Energy (ICOE)*, Bilbao, Spain, 2010.

[53] P. Ricci, B. Counago, A. Rico, J. Villante and Y. Torre-Enciso, "Alternatives for the Design of Grid Connection Infrastructures for Wave Energy," in *3rd International Conference on Ocean Energy (ICOE)*, Bilbao, Spain, 2010.

[54] L. Martinelli, A. Lamberti, P. Ruol, P. Ricci, P. Kirrane, C. Fenton and L. Johanning, "Power Umbilical for Ocean Renewable Energy Systems - Feasibility and Dynamic Response Analysis," in *3rd International Conference on Ocean Energy (ICOE)*, Bilbao, Spain, 2010.

[55] I. Lopez, J. Andreu, S. Ceballos, I. M. d. Alegria and I. Kortabarria, "Review of wave energy technologies and the necessary power-equipment," *Renewable and Sustainable Energy Reviews,* vol. 27, pp. 413-434, 2013.

[56] P. Igic, Z. Zhou, W. Knapp, J. MacEnri, H. Sorensen and E. Friis-Madsen, "Multi-megawatt offshore wave energy converters - electrical system configuration and generator control strategy," *IET Renewable Power Generation,* vol. 5, no. 1, pp. 10-17, 2011.

[57] M. Kenny, "Electrical Connection Issues for Wave Energy Arrays - Masters Thesis," University College Cork, 2010.

[58] K. Thorburn, H. Bernhoff and M. Leijon, "Wave energy transmission system concepts for linear generator arrays," *Ocean Engineering,* vol. 31, pp. 1339-1349, 2004.

[59] M. Rahm, C. Bostrom, O. Svensson, M. Grabbe, F. Bulow and M. Leijon, "Offshore underwater substation for wave energy converter arrays," *IET Renewable Power Generation,* vol. 4, no. 6, pp. 602-612, 2009.

[60] C. Bostrom, E. Lejerskog, M. Stalberg, K. Thorburn and M. Leijon, "Experimental results of rectification and filtration from an offshore wave energy system," *Renewable Energy,* vol. 34, pp. 1381-1387, 2008.

[61] Equimar, "Deliverable 5.1 - Guidance protocols on choosing of electrical connection configurations," 2009.

[62] Wavenet, “Deliverable F3 - Power transmission from Wave Power Plants,” 2003.

[63] T. Ackermann, Wind Power in Power Systems, John Wiley and Sons, 2005.

[64] J. Twidell and G. G, Offshore Wind Power, Multi-Science Publishing, 2007.

[65] B. Franken, H. Breder, M. Dahlgren and E. Nielsen, “Collection Grid Topologies for Offshore Windparks,” in *18th International Conference on Electricity Distribution*, 2005.

[66] I. M. d. Alegria, J. Martin, I. Kortabarria, J. Andreu and P. I. Ereno, “Transmission Alternatives for Offshore Electrical Power,” *Renewable and Sustainable Energy Reviews,* vol. 13, no. 5, pp. 1027-1038, 2009.

[67] J. Green, A. Bowen, L. Fingersh and Y. Wan, “Electrical Collection and Transmission Systems for Offshore Wind Power,” in *Offshore Technology Conference*, 2007.

[68] J. Yang, J. O'Reilly and J. Fletcher, “Redundancy Analysis of Offshore Wind Farm Collection and Transmission Systems,” in *International Conference on Sustainable Power Generation and Supply*, 2009.

[69] O. Holmestrom and N. Negra, “Survey of Reliability of Large Offshore Wind Farms,” in *European Wind Energy Conference*, Milan, Italy, 2007.

[70] N. Negra, J. Todorovic and T. Ackermann, “Loss Evaluation of HVAC and HVDC Transmission Solutions for Large Offshore Wind Farms,” *Electric Power Systems Research,* vol. 76, no. 11, pp. 916-927, 2006.

[71] N. Boccard, “Capacity Factor of Wind Power Realized Values versus Estimates,” *Energy Policy,* vol. 37, pp. 2679-2688, 1009.

[72] C. Fitzgerald and G. Thomas, “A Preliminary Study on the Optimal Performance of an Array of Wave Power Devices,” in *7th European Wave and Tidal Energy Conference (EWTEC),* Porto, Portugal, 2007.

[73] J. Fitzgerald, “Position Mooring of Wave Energy Converters - PhD Thesis,” Chalmers University, 2009.

[74] J. Fitzgerald and L. Bergdahl, “Considering Mooring Cables for Offshore Wave

Energy Converters," in *7th European Wave and Tidal Energy Conference (EWTEC)*, Porto, Portugal, 2007.

[75] B. Child and V. Venugopal, "Optimal Configuration of Wave Energy Device Arrays," *Journal of Ocean Engineering,* vol. 37, no. 16, pp. 1402-1417, 2010.

[76] P. Ricci, J. Saulnier and A. Falcao, "Point Absorber Arrays: A Configuration Study off the Portugese West Coast," in *7th European Wave and Tidal Energy Conference*, Porto, Portugal, 2007.

[77] J. Cruz, R. Sykes, P. Siddorn and R. Taylor, "Estimating the loads and Energy Yields of Arrays of Wave Energy Converters under Realistic Seas," *IET Renewable Power Generation,* vol. 4, no. 6, pp. 488-497, 2010.

[78] J. Westphalen, G. Bacelli, P. Balitsky and J. Ringwood, "Control Strategies for Arrays of Wave Energy Converters," in *European Wave and Tidal Energy Conference*, 2011.

[79] T. Seppa, "Increasing Transmission Capacity by Real Time Monitoring," in *IEEE Power Enegineering Society Winter Meeting*, 2002.

[80] S. Walldorf, A. Ernst and S. Pancholi, "A Cost Effective Solution for Increasing Ratings on Underground Transmission Cables - A Case Study," in *IEEE Transmission and Distribution Conference*, 1999.

[81] B. Grotenhuis, J. Jaspers, A. Kerstens, A. v. d. Wey and F. Wild, "Increasing the Capacity of Cable Systems Using Cable Asset Management Based on Thermal and Mechanical Properties," in *IEEE International Conference on Electrical Distribution*, 2001.

[82] J. Downes and H. Leung, "Distributed Temperature Sensing Worldwide Power Circuit Monitoring Applications," in *International Conference on Power Systems Technology*, 2004.

[83] "Artemis Intellegent Power," [Online]. Available: http://www.artemisip.com/. [Accessed August 2013].

[84] Nexans, "Submarine Power Cables Specifications," 2008.

[85] L. Stenberg, "Wave Power Cable Connection - Masters Thesis," Royal Institute of Technology, Sweden, 2009.

[86] RenewableUK, "Offshore Wind and Marine Energy Health and Safety Guidelines," 2013.

[87] "Guidelines for Grid Connection of Marine Energy Conversion Systems," European Marine Energy Centre, 2009.

[88] C. Bartzsch, H. Huang, T. Westerweller and M. Davies, "HVDC Plus and SVC Plus; Reliable and Cost-Effective Power Transmission Solutions with Modular Multilevel Converters," in *Cigre Study Committee B4 - HVDC and Power Electronics Colloquium 2011*, 2011.

[89] "Beatrice Offshore Wind Demonstrator," [Online]. Available: www.beatricewind.co.uk. [Accessed August 2013].

[90] S. Breto and G. Moe, "Status, Plans and Technologies for Offshore Wind Turbines in Europe and North America," *Renewable Energy,* vol. 34, pp. 646-654, 2009.

[91] H. Landsverk, O. Granhuag, P. Skrten and S. Ranfoss, "36kV Vacuum Circuit Breaker Panel - The Perfect Switchgear for Wind," in *20th International Conference on Electricity Distribution*, Prague, Czech Republic, 2009.

[92] Z. Li, M. Zhao and Z. Chen, "Efficiency Evaluation for Offshore Wind Farms," in *International Conference on Power System Technology*, 2006.

[93] H. Brakelmann, "Efficiency of HVAC Power Transmission from Offshore Windmills to the Grid," in *IEEE Power Tech Conference,* Bologna, Italy, 2003.

[94] D. Mollison, "Ireland's Wave Power Resource - A report to the National Board for Science and Technology and Electricity Supply Board," NBST, 1982.

[95] J. Keller and B. Kroposki, "Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources," National Renewable Energy Laboratory (NREL), 2010.

[96] G. J. Anders, Rating of Electric Power Cables - Ampacity Computations for Transmission, Distribution and Industrial Applications, McGraw Hill, 1997.

[97] C. Moore, BICC Electrical Cables Handbook - 3rd Edition, Blackwell, 1997.

[98] International Electrotechnical Commission, “IEC 60287. Electrical Cables – Calculation of the Current Rating”.

[99] ABB, “XLPE Submarine Cable Systems - Attachement to XLPE Land Cable Systems - User's Guide,” 2010.

[100] S. Lundberg, “Performance Comparison of Wind Park Configurations - PhD Thesis,” Chalmers University, 2003.

[101] The Centre for Sustainable Electricity and Distributed Generation, “Cost Benefit Methodology for Optimal Design of Offshore Transmission Systems,” 2008.

[102] Department of Trade and industry (UK), “Study of the Costs of Offshore Wind Generation,” 2007.

[103] M. Banzo and A. Ramos, “Stochiastic Optimisation Model for Electric Power System Planning for Offshore Wind Farms,” *IEEE Transactions on Power Systems,* vol. 26, no. 3, pp. 1338-1348, 2010.

[104] E. Stoutenburg and M. Jacobson, “Optimizing Offshore Transmission Links for Marine Renewable Energy Farms,” in *OCEANS*, 2010.

[105] ESB International, “Atlantic Marine Energy Centre Cable Options Report,” 2009.

[106] “Pelamis Installation System,” [Online]. Available: http://www.pelamiswave.com/our-technology/installation. [Accessed August 2013].

[107] “Siemens Subsea Power Grid,” [Online]. Available: http://www.energy.siemens.com/hq/en/industries-utilities/oil-gas/applications/subsea-power-grid.htm. [Accessed August 2013].

[108] “ABB – Controlled Subsea Electric Power Distribution with SEPSIS,” [Online]. Available: http://www05.abb.com/global/scot/scot271.nsf/veritydisplay/84915130ebc8aa87c1256ef50045878f/$File/36-42%20-%20M147.pdf. [Accessed August 2013].

[109] “GE Vetco Gray - Subsea Power Systems,” [Online]. Available: http://www.ge-

energy.com/products_and_services/products/subsea_power_and_processing_systems/index.jsp. [Accessed August 2013].

[110] "MacArtney Medium Voltage Hub," [Online]. Available: http://www.macartney.com/systems/infrastructure/terminations/medium-voltage-hub. [Accessed August 2013].

[111] "Ocean Power Technologies - Underwater Subsation Pod," [Online]. Available: http://www.oceanpowertechnologies.com/pod.html. [Accessed August 2013].

[112] ABB, "Cables for Offshore Wind Brochure".

[113] J. Beale, "Transmission Cable Protection and Stabilisation for the Wave and Tidal Energy Industries," in *10th European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK, 2011.

[114] National Grid (UK), "Round 3 Offshore Wind Farm Connection Study," 2010.

[115] J. Candido and J. Justino, "Frequency, stochastic and time domain models for an articulated wave power device," in *ASME 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE)*, 2008.

[116] International Electrotechnical Commission, "IEC 60853. Calculation of the Cyclic and Emergency Current Ratings of Cables".

[117] M. Luton, G. Anders, J. Braun, N. Fujimoto, S. Rizzetto and J. Downes, "Real Time Monitoring of Power Cables by Fibre Optic Technologies. Tests, Applications and Outlook," in *International Conference on Insulated Power Cables*, 2003.

[118] A. Baggini, Handbook of Power Quality, John Wiley & Sons, 2008.

[119] International Electrotechnical Commission, "IEC 41000-4-15. Electromagnetic compatibility (EMC) - Part 4: Testing and Measurement Techniques - Section 15: Flickermeter: Functional Design and Specification".

[120] ESB Networks, "Distribution Code - Version 2.0," 2007.

[121] The Electricity Council, "Engineering Recommendation P28 - Planning Limits for Voltage Fluctuations Caused by Industrial, Commercial and Domestic Equipment

in the United Kingdom," 1982.

[122] International Electrotechnical Commission, "IEC 61000-3-7. Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installation to MV, HV and EHV power systems," 2008.

[123] A. Larsson, "The Power Quality of Wind Turbines - PhD Thesis," Chalmers University, Gothenberg, Sweden, 2000.

[124] International Electrotechnical Commission, "PT 62600-30. Project Team for Marine energy - Wave, tidal and other water current converters - Part 30: Electrical power quality requirements for wave, tidal and other water current energy converters," Ongoing.

[125] International Electrotechnical Commission, "IEC 61400-21. Wind turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines," 2008.

[126] European Copper Institute, Power Quality Application Guide - Voltage Disturbance - Flicker Measurement, 2005.

[127] British Standards Institution, "BS-EN 50160. Voltage Characteristics of Electricity Supplied by Public Electricity Networks," 2010.

[128] Equimar, "Deliverable D4.3 - Test Site Catalogue," 2011.

[129] P. H. Ashmole, "Flicker Simulator Using UK Filter - Version 5.2," 2000.

[130] P. Ashmole, "Quality of Supply - Voltage Fluctuations," *Power Engineering Journal,* vol. 14, no. 3, pp. 113-119, 2000.

[131] M. Lafoz, M. Blanco and D. Ramirez, "Grid Connection for Wave Power Farms," in *2011*, Birmingham, UK, 14th European Conference on Power Electronics and Applications.

[132] M. Santos, E. Tedeschi, P. Ricci, M. Molinas and J. Martin, "Grid Connection Improvement by Control Strategy Selection for Wave Energy Converters," *Renewable Energy and Power Quality,* vol. 9, pp. 1-6, 2011.

[133] M. Barnes, R. El-Feres, S. Kromlides and A. Arulampalam, "Power Quality

Improvement for Wave Energy Converters using a D-STATCOM with Real Energy Storage," 1st European Conference on Power Electronic Systems and Applications, 2004.

[134] A. Wallace and A. Kiprakis, "Reduction of voltage violations from embedded generators connected to the distribution network by intelligent reactive power control," in *5th International Conference on Power System Management and Control*, London, 2002.

[135] Eirgrid plc, "Annual Report," 2012.

[136] Department of Communications, Energy and Natural Resources, "Strategy for Renewable Energy: 2012-2020".

[137] European Commission, "2030 Framework for Climate and Energy Policies," 2014. [Online]. Available: http://ec.europa.eu/clima/policies/2030/index_en.htm. [Accessed October 2014].

[138] Eirgrid plc, "Gate 3 ITC Programme Final Results Scheduled Firm Access Quantities".

[139] "Greenwire Project Website," [Online]. Available: www.greenwire.ie. [Accessed Auguse 2013].

[140] "Energy Bridge project website," [Online]. Available: www.energybridge.ie. [Accessed August 2013].

[141] "Marex project website," [Online]. Available: www.organicpower.ie. [Accessed August 2013].

[142] "Natural Hydro Energy project website," [Online]. Available: www.naturalhydroenergy.com. [Accessed August 2013].

[143] Eirgrid plc, "Grid25 - A Strategy for the Development of Ireland's Electricity Grid for a Sustainable and Competitive Future".

[144] Eirgrid plc, "2012 Curtailment Report," 2013.

[145] Eirgrid plc, "All Island TSO Facilitation of Renewables Study".

[146] F. Fusco, G. Nolan and J. Ringwood, “Variability reduction through optimal combination of wind/wave resources - an Irish case study,” *Energy*, vol. 35, pp. 314-325, 2010.

[147] Eirgrid plc, “Interconnection Economic Feasibility Report,” 2009.

[148] “European Renewable Energy Statistics,” [Online]. Available: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Renewable_energy_statistics . [Accessed August 2013].

[149] CIGRE, “Technical Brochure 492: Voltage Source Converter (VSC) HVDC for Power Transmission - Economic Aspects and Comparison with other AC and DC Technologies,” 2012.

[150] Irish-Scottish Links on Energy Study (ISLES), “Route Development and Cost Estimation Report”.

[151] The Crown Estate, “Guide to an Offshore Wind Farm,” 2011.

[152] Institute of Engineering and Technology (IET), “Electricity Transmission Costing Study,” 2012.

[153] National Grid UK, “Offshore Development Information Statement”.

# Appendices

# Appendix A – List of Publications

Below is a list of publications by the thesis author which relate to the research within this thesis. Links to an online copy of each publication is provided for reference.

Journal Papers:

1. F. Sharkey, J. MacEnri, E. Bannon, M. Conlon and K. Gaughan, "Resource-induced voltage flicker for wave energy converters – assessment tools," *IET Renewable Power Generation,"* vol. 7, no. 6, pp 623-630, 2013

   http://arrow.dit.ie/engscheleart2/74/

2. F. Sharkey, E. Bannon, M. Conlon and K. Gaughan, *"Maximising value of electrical networks for wave energy converter arrays,"* International Journal of Marine Energy, vol. 1, no. 1, pp 55-69, 2013

   http://arrow.dit.ie/engscheleart2/73/

Book Chapters:

1. F. Sharkey, *"Electrical Design of Ocean Wave and Tidal Energy Systems – Chapter 10.1,"* The Institute of Engineering and Technology, 2013

   http://arrow.dit.ie/engschelebk/13/

Conference Papers:

1. F. Sharkey, M. Conlon and K. Gaughan, "Investigation of Wavefarm Electrical Network Configurations," in *World Renewable Energy Congress,* Linkoping, Sweden, 2011

   http://arrow.dit.ie/engscheleart/161/

2. F. Sharkey, E. Bannon, M. Conlon and K. Gaughan, "Dynamic Electrical Ratings and the Economics of Capacity Factor for Wave Energy Converter Arrays," in *9th European Wave and Tidal Energy Conference*, Southampton, UK, 2011

http://arrow.dit.ie/engscheleart/167/

3. F. Sharkey, M. Conlon and K. Gaughan, "Practical Analysis of Key Electrical Interfaces for Wave Energy Converter Arrays," in *4th International Conference on Ocean Energy*, Dublin, Ireland, 2012

   http://arrow.dit.ie/engscheleart/189/

4. F. Sharkey, J. MacEnri, E. Bannon, M. Conlon and K. Gaughan, "Voltage Flicker Evaluation for Wave Energy Converters – Assessment Guidelines," in *4th International Conference on Ocean Energy*, Dublin, Ireland, 2012

   http://arrow.dit.ie/engscheleart/188/

5. F. Sharkey, M. Conlon and K. Gaughan, "Impacts on the Electrical System Economics from Critical Design Factors of Wave Energy Converters and Arrays," in *10th European Wave and Tidal Energy Conference*, Aalborg, Denmark, 2013

   http://arrow.dit.ie/engscheleart/206/

6. F. Sharkey, K. Honer, M. Conlon, K. Gaughan and E. Robinson, "The Domestic and Export Market of Large Scale Wave Energy in Ireland and the Economics of Export Transmission," in *48th Universities' Power Engineering Conference*, Dublin, Ireland, 2013

   http://arrow.dit.ie/engscheleart/207/