2013-9

Impacts on the Electrical System Economics from Critical Design Factors of Wave Energy Converters and Arrays

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Recommended Citation

Sharkey, S., Conlon, M. and Gaughan, K. Impacts on the Electrical System Economics from Critical Design Factors of Wave Energy Converters and Arrays. Paper presented at EWTEC Technical visit, 6th. Sept. 2013.

Impacts on the Electrical System Economics from Critical Design Factors of Wave Energy Converters and Arrays

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***Abstract*— It is expected that ultimately, like offshore wind farms, electrical systems will make up to a quarter of the overall Capex of wave farms. This is a significant element of cost and consideration must be taken in the design of both individual wave energy converters (WECs) and arrays of WECs to ensure that these costs can be minimised. In a worst case scenario design decisions could increase the cost of the electrical system by several orders and ultimately make the technology uncompetitive.**

This paper outlines the impacts on the cost of the electrical system arising from design factors of WECs and WEC arrays or wave farms. The paper uses a cost model to examine the impact to the cost of WEC array electrical systems caused by changing of key design factors. The design factors examined include WEC unit rating, capacity factor, interface to the electrical network, array spacing, export voltage, array design, site selection, export distance, and WEC dynamic response. All of these design factors have an impact on the economics of the electrical system and hence the economics of the wave farm as a whole.

The paper concludes that there are some critical design choices which should be avoided if a cost-effective wave farm is to be established. It is also concluded that some design choices could ultimately reduce the overall Capex of WEC arrays enhancing their competiveness.

***Keywords*— Wave Energy, Electrical Networks, Capacity Factor, Submarine Cables, Economics**

I. INTRODUCTION

The cost of electrical systems for Wave Energy Converter (WEC) arrays will be affected by design factors of WECs themselves and also the designs of the WEC arrays. These design factors are often decided at prototype stage when the long term impacts of these factors are not clearly understood. Ultimately this can affect the competitiveness of the technology. Of course many design factors will affect the competitiveness of a given technology but this paper focuses on the effects on the impacts on the electrical system only.

This paper outlines the WEC and WEC array design factors which will affect the cost of WEC array electrical system. Factors such as WEC unit rating, capacity factor, key interfaces with the electrical network, array spacing, export voltage, array configuration, site selection, export distance and WEC dynamic response are all introduced. The impacts these design factors will have on the electrical system costs are quantified where possible.

A ‘medium’ size, 40MW, see Figure, WEC array is taken from [1] as a candidate array. The candidate array has the following assumptions:

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

This will be used in conjunction with the unitised cable cost model previously presented by the authors [2] in order for an economic analysis to be undertaken.

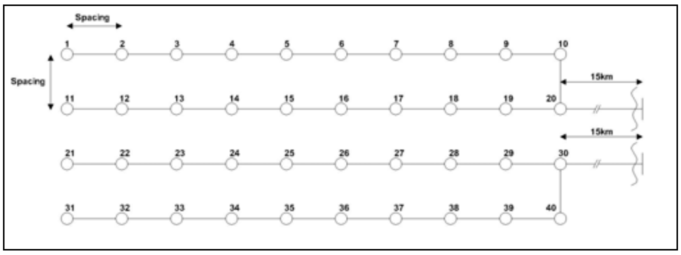

Fig. 1 Candidate, 40MW, Array

II. TARGET COST FOR WAVE ENERGY ELECTRICAL SYSTEMS

Offshore wind energy is considered a suitable benchmark for large scale wave energy to target [3] and it is unlikely that wave energy can be competitive if it does not match or exceed the cost competitiveness of offshore wind. Current capital costs of offshore wind are approximately €3.8m/MW [4]. The electrical system including cabling, offshore substation, onshore grid and installation make up approximately 20-25% of this overall cost for wind energy and the same is expected to be true for wave energy also [5], [6].

Therefore if wave energy is to be competitive with offshore wind the electrical system costs will need to be of the same magnitude as offshore wind, i.e. approximately €0.75-0.95m/MW assuming that other parts of the farm are the same proportional costs as offshore wind. This is a huge challenge for wave energy considering the additional requirements over wind such as submarine connectors, dynamic cables and potentially large transmission distances. This target cost level must be a key driver in designing the electrical systems for wave farms.

III. Design Factors Which Influence Electrical System Costs

As discussed above there are design factors which will impact on the cost of the electrical system for WEC arrays. These design factors may be dictated by a variety of requirements such as physical limitations of the device or components parts of the device, installation requirements, manufacturing requirements, power take off (PTO) characteristics etc. It is important that WEC designers have a clear understanding of the impact which design decision will make and this will be elaborated in the next sections.

Design factors which are to be analysed in this paper are outlined below.

A. Individual WEC Rating

The current trend in wave energy is for devices around 1MW capacity although there are some exceptions with larger and smaller individual ratings. The current trend in offshore wind is now approx 4MW per turbine with many manufacturers developing turbines from 5-8MW. The trend towards 1MW WEC devices may be more an indication of the early stage of the wave energy industry and physical limitations of construction facilities, sites and installation equipment.

However, higher rated individual WECs will take advantage of economies of scale in a number of areas such as installation, manufacturing, and electrical infrastructure. The affect this has on WEC array electrical system cost is outlined in Section IV-A below

B. WEC Capacity Factor

The capacity factor of offshore wind turbines is typically in the region of 30-40% [7] depending on turbine type, location, average wind speed etc. So if a wind turbine has a rating of 1MW, then the average annual output for the turbine would be in the region of 300-400kW. If the same turbine had the same average annual output, but a capacity factor of 10%, then the turbine would have a peak rating of 3-4MW. This would obviously have an impact on the electrical network as the cables would need to be rated for the peak power. Higher rated, more expensive cables would be required even though the annual delivered energy (MWhrs) would not change. The opposite is also true in that a higher capacity factor would allow for lower rated cables to be installed, reducing the electrical system costs.

Therefore, designing a WEC with a high capacity factor will lend to a more cost effective WEC array electrical network. The affect this has on WEC array electrical system cost is outlined in Section IV-B below

It is worth noting that low capacity factor also suggests, although does not guarantee, a highly variable power output. This may have effects on power quality and grid compliance but is not the topic of study here.

C. Key Interfaces with the Electrical Network

If we take away the array and export cabling, and the onshore grid, which account for ~80% of the electrical system cost, out of the total costs presented in Section II we are left with ~€0.2m / MW for the interfaces between the electrical network and the WECs in the array. This is a simplified calculation but shows the constraint on the cost for the electrical system to be in line with that of offshore wind and hence the drive for a low cost solution.

The authors explored the economics of the ‘key interfaces’ between the WEC and the electrical system in [8]. Key interfaces such as the Dynamic Cable to WEC, Dynamic Cable to Static Cable and WEC MV Switchgear interfaces are critical to the functionality of the overall WEC array electrical system.

These interfaces can be realised in a variety of manners and the cost of the electrical system will be affected by how the key interfaces are realised. The affect this has on WEC array electrical system cost is outlined in Section IV-C below

D. Array and Export Voltage

The voltage of the array and export system is an important design factor when considering the cost of the overall system. The array voltage can be dictated by the WEC design or the availability of key interface components such as submarine connectors. It is in general, however, desirable for the array and export system voltage to be as high as possible but this will be naturally constrained by economics.

Typical offshore wind farm array systems operate at 33kV [9] with a move towards array systems at up to 66kV. Typically the array system is connected in multiple radials back 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. The affect this has on WEC array electrical system cost is outlined in Section IV-D below

E. Array Electrical Configuration and Array Spacing

There are a number of configurations possible for the WEC array electrical system as shown below in Figure 2. Alternative A, simple radial networks, is the configuration of choice for offshore wind as it has proved the most cost effective. Other configurations will bring additional benefits and have been promoted as solutions for WEC arrays particularly Alternative E, star cluster. These benefits may bring additional costs however.

Device separation for arrays will affect the cost of the array electrical system as obviously a larger separation between devices will require longer cables. Array spacing may ultimately be dictated by the requirement to reduce interference between WECs or even to allow for constructive interference.

This is detailed further in Section IV-E below.

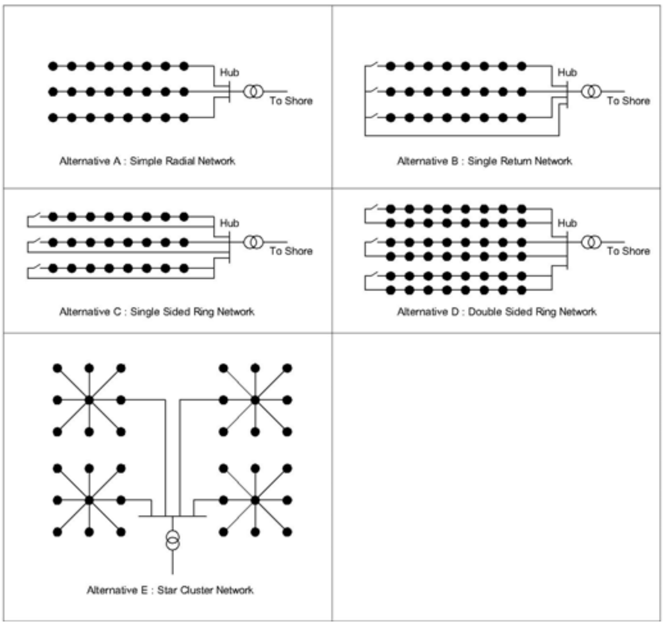

Fig. 2 - Alternative Array Network Configurations

F. Site Characteristics and Export Distance

One design factor which can have significant influence on the cost of a WEC array electrical system is the characteristics of the site itself. There are significant challenges presented from the site which will increase cost of WEC array electrical system. Three of the more dominant site characteristics in this regard are

- Seabed conditions at the site: This will dictate the cost of the cable installation which can vary hugely with various installation and cable protection requirements
- Transmission distance: Deepwater WEC arrays will require water depths of 100m or deeper for mooring integrity and this forces the arrays further from the shore meaning a longer transmission distance. What should also be considered is the distance to the grid connection onshore once the cable has landed.
- Water depth: As mooring integrity may force the array into deeper water there are challenges for the installation of offshore substations which conventionally have been installed in <50m water depth.

This is detailed further in Section IV-F below.

G. WEC Dynamic Response

An important system component for deepwater WEC arrays is the dynamic power cable, or umbilical, between the WEC and the submarine electrical system. The requirement for dynamic cables is one of the key differences between offshore wind and WEC array electrical systems.

Dynamic cables are required to connect to WECs which have a huge range of movement in heave, pitch and surge along with other movements caused by tidal flows, tidal ranges and wind. Dynamic cables will undergo cyclic loading every few seconds which, depending on the sea conditions, will mean millions of cycles per annum [10]. This cyclic loading is the major design challenge in dynamic cables and the WEC dynamic response is a design criterion for the cable.

Different WECs can have various dynamic response requirements and some WECs have several components with different dynamic responses. WEC dynamic response is referred to as a response amplitude operator (RAO). Some devices are inherently designed to have a lower RAO such as some floating OWCs or floating Overtopping devices. With lower RAOs the design demands on the dynamic cables will be lower and this will result in a lower cost of a significant component. This is detailed further in Section IV-G below.

IV. Quantifying the Economic Impact of Design Factors

In the above section a variety of design factors of both WECs and WEC arrays are introduced and their potential impacts on the economics of the electrical system are outlined. In this section these impacts are discussed further and quantified if possible to act as a design guide for WEC developers. The purpose is to allow developers to understand and quantify the impact of various WEC design decisions on the electrical system economics.

A. Individual WEC Rating

Just the cost of the dynamic and static submarine cables will be evaluated here. The relative cost of the array (versus the base case) is established for the candidate 40MW array (Figure 1) 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. The array and export voltage is 20kV in all cases. Inter-WEC spacing is adjusted depending on individual WEC rating but remains the same multiple of device width, based on typical point absorber widths.

The relative cost as a percentage of the base case is shown in Figure 3 below. The relative cost is shown for the array only and the full electrical system (i.e. array and 15km export cable). This shows that as expected the relative cost is higher for smaller devices and lower for larger devices. The difference can be as much as 3 times for the array cable costs. It should be noted that the costs do not decrease as much for larger individual devices with decreases to as low as 0.4 times possible for the array cable costs.

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

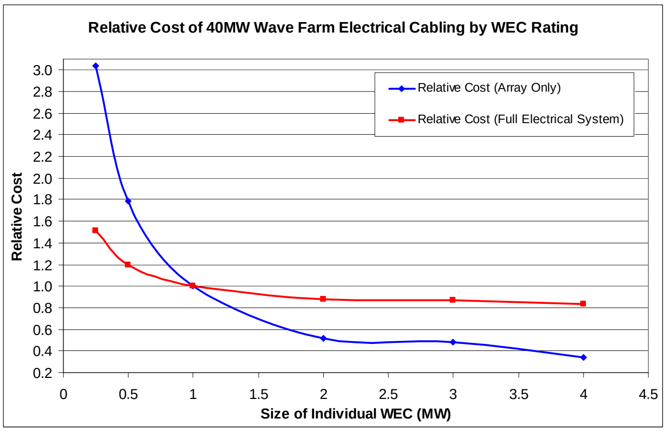

Fig. 3 – Relative Cost of 40MW array electrical cabling based on device rating

B. *WEC Capacity Factor*

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

The relative cost as a percentage of the base case is shown in Figure 4 below. The relative cost is shown for the full electrical system only (i.e. array and 15km export cable). This is because capacity factor effects both array and export systems. The relative cost is assessed at two voltage levels (20kV and 33kV). This shows that as expected the relative cost of the electrical network is higher for devices with lower capacity factor and lower for device with higher capacity factor. Halving the capacity factor from 30% to 15% would almost double the cost of the electrical network. Doubling the capacity factor form 30% to 60% would decrease the costs by up to 40%.

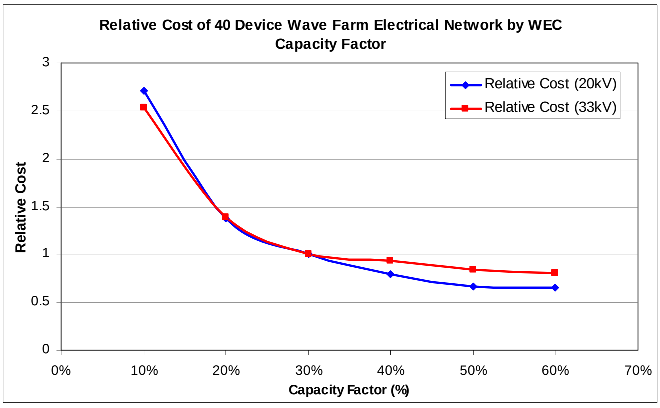

Fig. 4 – Relative Cost of 40 device array electrical cabling based on device capacity factor

C. *Key Interfaces with the Electrical Network*

In offshore wind farms the cables are routed, through J-tubes, straight into the turbine tower. This is not the case with ocean energy arrays as the devices are required to be removed for maintenance on a regular basis. This presents a number of issues, including redundancy in the electrical network.

As presented by the authors in [8] if the array network configuration is to be a radial network then the key interfaces between the WEC and the radial network need to be optimised. This means achieving a balance between the functionality of these interfaces and cost.

These key interfaces are categorised as;

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

There is certain functionality required at the key interfaces between the electrical system and the WECs. The required functionality includes the following;

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

The optimisation of the functionality and cost of these key interfaces is critical to providing a cost effective WEC array electrical network. As presented in [11] there are multiple manners in which the interfaces can be realised and the cost for these interfaces can change by a factor of three between the least cost and most cost solutions for these key interfaces.

Some WECs will lend themselves to lower cost key interfaces through integrated mate-able submarine connectors and onboard switchgear however WEC developers should avoid reliance on potentially expensive and unproven submarine electrical solutions such as submarine collector 'hubs' as ultimately these solutions will struggle to allow for cost competitive electrical systems.

D. *Array and Export Voltage*

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. However although increasing the voltage rating of a particular cable will increase the cost of that cable (if the cross sectional area (CSA) remains the same), in general an increased voltage rating allows a decreased current rating and hence a decreased CSA. Therefore an increase in voltage can ultimately decrease the system costs but this is not guaranteed.

As an example the information given in Figure 3 (which shows relative figures only) is reproduced in Figure 5 below showing the absolute difference in cost between 20kV and 33kV array and export cable system for a variety of WEC capacity factors. What can be seen is that 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 will not be more costly for our candidate array.

The conclusion here is that selecting the optimum system voltage can have an impact on the economics of the electrical system but each array must be evaluated separately.

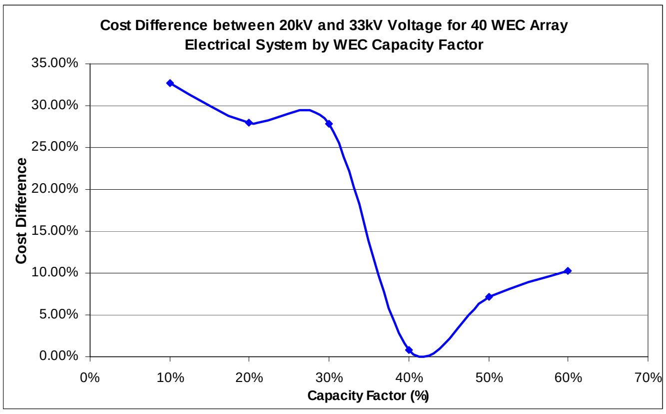

Fig. 5 – Cost Difference between 20kV and 33kV Voltage for 40 Device Farm Electrical Cabling by WEC Capacity Factor

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

E. Array Electrical Configuration and Array Spacing

We can evaluate the candidate wave farm using the alternative configurations as shown in Figure 2 under a number of criteria.

The following assumptions are made in addition to those shown in Section I.

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

Table I shows the relative cost of the array only, and the array and export cabling for the various alternative configurations detailed in Figure 2. This shows that the radial network (alternative A in Figure 2) is the least cost solution from an array configuration perspective. This is primarily due to 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 also increasing cost.

TABLE I - 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

Increasing the spacing between WECs within an array will naturally increase the array electrical system cost and this is not quantified as it is obvious that doubling the array spacing will essentially double the array electrical system cost.

It should be noted that there may also be a push to decrease spacing between devices. This could be to allow constructive interference, reduce WEC array footprint or take advantage of combined mooring systems. There will be a minimum distance which could be allowed which would consider dynamic cable configurations and cable installation vessel requirements. Therefore although decreasing array spacing will decrease electrical system costs this can only be realised to a physical limit depending on the site and WEC characteristics.

F. Site Characteristics and Export Distance

Seabed characteristics have a huge 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 deep enough depth that it will be protected (typically 2 metres). Conveniently this would also be an ideal condition for drag embedment anchors for WEC mooring. However not all sites will have these conditions, particularly high energy (wave and tidal) sites which may have little or no sediment cover or mobile sediment [11]. Cable installations may be required in sites which have swept rock, cobble, reefs, boulder fields, glacial spill, or any other type of characteristic. 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 must not be underestimated. Trenching methods requiring rock saws will radically increase installation costs. Post installation using rock dumping, concrete mattresses etc could cost more than the installed cable itself and therefore could more than double the costs [12]. These costs are not quantified here but the economics of the cable installation and protection must form an integral part of the site selection process and sites which allow lower cost cable installations will ultimately be more competitive.

Export distance will also have a very understandable impact on the cost of the electrical system. This does not need to be quantified and it is obvious that longer export systems, which should be noted to include the offshore distance from the WEC array to the shore landing and the onshore distance to the grid connection point, will increase 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 deepwater WEC array sites and will require expensive foundation solutions such as jacket structures or alternatively require semi-submersible, spar or submarine installation. These requirements will increase the cost of an offshore substation dramatically and very large arrays may be required before such expense could be justified.

G. WEC Dynamic Response

Like the site characteristics above 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 RAO of the device is one of these factors and there is no doubt that WECs with a lower dynamic response will cause less stress, acceleration and fatigue loading on the cable which in turn will allow the construction cost of the cable to be lower.

Fatigue lifetime of materials is an important design consideration of dynamic cables [10] and there are considerations to be made at pinch points of the cable such as the connection to the WEC where a stress reliever will be 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 hence to the overall electrical system.

That being said it if anticipated that in actual fact the impact of this on the overall electrical system cost will be relatively limited although it is certainly not insignificant.

V. Conclusions

At the current stage of the industry there are a large number of wave energy converters at various stages of development. In the majority of cases little consideration has been given to the final integration of the WECs into the electrical systems of WEC arrays. Design decisions can be made which ultimately could increase WEC array electrical system costs by several multiples. In this case technologies can be developed and design decisions made which ultimately will lead to a WEC array electrical system which is not possible at a competitive cost.

This paper aims to provide WEC and project developers with the knowledge to make informed design and site selection decisions. This knowledge will form part of a much larger design process with electrical systems being only one part.

It is clear that WEC developers can make design selections which will increase the electrical system costs but importantly decisions can also be made to radically reduce electrical system costs and ultimately assist in making wave energy competitive with other forms of offshore renewables.

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Acknowledgment

The authors would like to thank the continued support for this research by ESB Ocean Energy.

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