# Inter-device spacing issues within wave and tidal energy converter arrays

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## Abstract

**Inter-device spacing within wave and tidal arrays will affect many aspects of array performance including power production, installation, maintenance and the effect upon the wider flow field. It follows that inter-device spacing within an array will vary based upon a number of factor including (but not limited to) characteristics of the incoming resource, water depth, device type and installation/maintenance methods. Therefore it is clear that the issues surrounding interaction effects within arrays are complex with a high degree of linkage between certain aspects of design. Despite the low level of understanding of many issues surrounding wave and tidal energy arrays there are a number of areas where guidance can be given to developers in order to assist in array design. One such area is the classification of arrays by size and complexity. Other more generic advice can be given to advise upon potential interaction effects whilst guiding early array design to encompass knowledge gathering to inform subsequent arrays that are greater in size and complexity.**

**Keywords:** Array, Interaction effects, Tidal, Wave

## 1. Introduction

In the short to medium term wave and tidal energy devices will be installed in multiple numbers at a given site. Such installations are commonly known as farms or arrays. As with many other technologies it is expected that the scale of arrays will increase in time from a few MW initially to perhaps many hundreds of MW. A key driver for installation of an array of devices is to increase the production of energy whilst maintaining or decreasing the unit cost of energy when compared to a series of isolated devices. This is achieved with general economy of scale, the sharing of systems (such as electrical connections) and reduced installation/maintenance costs per device.

As arrays become larger in size (in terms of number of devices and energy extracted) interaction effects between devices are expected to increase in magnitude and complexity. With limited research work having been completed to date regarding array performance and interaction effects the need for guidance is clear.

At the end of 2009 developers were at the preliminary stages of installing and operating devices within an array structure. Verdant Power tested six 35kW tidal turbines in the East river, New York, US. The project delivered power to the grid with the turbines operating on both ebb and flood tides. Pelamis Wave Power also saw devices installed within an array. Three 750kW floating devices were installed at Aguçadoura, Portugal and grid connected. In South Korea a 1MW installation of vertical axis tidal turbines was installed in the Uldolmok strait in 2009. Plans to expand the rated capacity at this and other potential tidal stream sites within the country are being pursued. In the short term (2010 onwards) there are a large number of developers that have plans to install arrays of wave and tidal energy devices.

Equimar is a project funded by the 7th European framework protocol to develop protocols and standards that will deliver a suite of protocols for the equitable evaluation of marine energy converters (based on either tidal or wave energy). These protocols will harmonise testing and evaluation procedures across the wide variety of devices presently available. The work described in the paper is part of a work package dedicated to the issues surrounding the design and performance of wave and tidal energy arrays.

## 2. Array classification

A useful concept that has arisen from this aspect of Equimar is the definition of the size of an array. At present wave and tidal energy devices have a wide range of rated powers and physical sizes. Therefore attempting to quantify array size by the number of devices or rated power will not be inclusive of all available technologies. A key driver for nearly all types of wave and tidal device will be the minimisation of negative interaction effects between devices whereby structural loading is increased and/or power production is reduced. This will arise for devices operating in the wake flow of another device upstream or upwave. The wake of a marine energy converter is caused by energy extraction. For a tidal turbine this takes the form of a gradually expanding field of fluid that travels downstream and has a lower velocity and higher turbulence intensity than the ambient flow. For wave energy devices a wave field is radiated form the device again in a predominantly down-wave direction. Interaction effects arising from a device operating in the wake generated from another device is most likely to negatively influence the structural loading and power performance of a wave/tidal device.

Early arrays will most certainly be composed of a single row of devices aligned perpendicular to the incoming wave or tidal resource (where the resource has a low degree of directionality). This will minimise any interaction effects between devices. Arrays can be expanded by including a second row where downstream or down wave devices are positioned in the spaces left between devices in the upstream/up wave row. This is the limit of what we will refer to as 1st-generation arrays. This configuration has the following benefits.

1. It will minimise device interaction
2. Maintenance and access to devices is not restricted as both rows can be approached from outside the array
3. Arrays can potentially become quite large with this configuration depending upon location

Wave energy sites could have rated power outputs of tens of MW in a single or double offset-row arrangement as many wave sites are not physically constricted. Deep water devices certainly could employ wide rows in order to increase array size and reduce interaction effects. 1st-generation tidal arrays might be constrained by the width of a channel and the need to limit lateral blockage but the high power density could also allow early arrays to generated tens of MW of power with minimal device interaction.

Second generation arrays would be for multiple rows of devices (greater than 2) where interaction effects do occur. Here it will be difficult for the most downstream/down wave devices to avoid operating in the wake or radiated flow field of device upstream/up wave. However it will likely transpire that benefits of a large number of devices at the same site outweigh the potential for increased device loading and/or reduced performance and access issues to some devices within the array in much the same way that modern offshore wind farms are now composed of multiple rows of turbines. Figure 1 illustrates this issue with a 2nd-generation tidal array composed of 3-rows of devices with the wakes hatched for the first 2 rows. The furthest row downstream is most likely to encounter some form of negative interactive effects from the upstream rows whilst access to the middle row could be more difficult due to the bounding effect of the two adjacent rows.

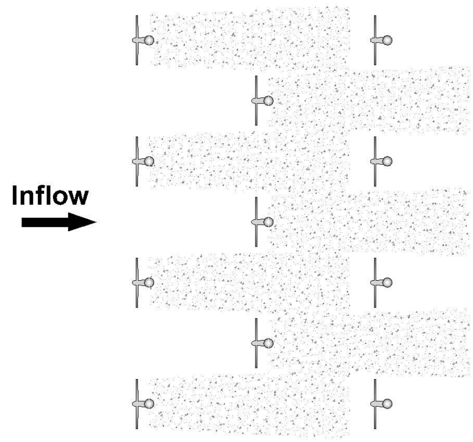


**Figure 1:** 3-row, 2nd generation tidal array.

This method of classifying arrays means that the rated power or number of devices within an array is independent of this taxonomy. Instead it is driven by the operational complexity of the array. This will facilitate more targeted guidance for the industry as arrays begin to be installed.

## 3. Existing information regarding interaction effects

It is apparent that for wave and tidal technologies nearly all of this work has been conducted either at small-scale or using numerical simulation tools that have been validated (or not) using experimental studies. There are clear deficiencies in the work completed to date; the most common experimental parameters are scale effects and the inability to accurately replicate full-scale met-ocean conditions. Numerical modelling suffers from a lack of experimental validation at all scales. Measurements from wind farms show a significant reduction in power associated with interaction effects between adjacent turbines.

### 3.1 wind farm interaction effects

Wind turbines have good similarity with tidal energy with the common features of extraction of kinetic energy from a moving fluid. Tidal differs most significantly with the constrained nature of the flow field and turbulence structures in water and air are also quite different. However, whilst quantitative results from wind turbine trials cannot be used for tidal energy the methods and approaches used can serve as a platform for understanding.

Early work was conducted to quantify the intensity of wind turbine wakes with respect to down wind distance. Many smaller-scale experiments were conducted in large wind tunnels whilst full-scale measurements were gathered at sites such as Goodnoe Hills in the U.S.A [1]. Kite anemometry measurements at 9 rotor diameters downstream yielded flow speed reductions of between 10 and 15% depending upon ambient turbulence intensity. Work has been published regarding the power losses at the Middlegrund offshore wind farm [2]. At the latter site average power of the farm is approximately 90% of rated power. Peak power is as low as 40% although this is for a narrow and infrequent wind direction and owes much to the single line of closely spaced devices which is not a typical wind farm configuration.

From the above work numerical models were developed [3]. Barthelmie et al [4] compared 5 numerical models to predict losses at the horns Rev and Nysted offshore wind farms. Normalised power for turbines downwind of the first row averaged approximately 0.8. As perhaps expected it was stated that existing models coped well with small wind farms but under-predicted losses due to wake interaction for larger multi-row wind farms. A further paper suggested that power decay in downstream rows or turbines was greater and could reduce overall power output in the range of 60% to 80% depending upon wind direction [5]. From the work referenced above the following is clear:

1. Power losses due to interaction effects are large in multiple row wind farms
2. Numerical and analytical models increasingly under-predict power losses as the number of rows increase
3. These serious issues are more relevant to 2nd-generation wave and tidal arrays. 1st-generation arrays should not suffer due to the lack of device interaction.

### 3.2 Experimental studies

Almost all wave and tidal energy experimental work regarding interaction effects has been performed at small scale. No doubt some wave and tidal energy device developers have conducted scale trials to measure wake and radiated wave fields but with the emphasis upon testing of single devices to demonstrate commercial viability and the need to protect intellectual property much of this information (if it exists) is not in the public domain. There has been some scale studies performed for tidal energy devices investigating wake effects and interaction [6-8]. Laboratory studies offer controlled conditions albeit with a different ambient turbulence structure to that of a full-scale tidal site.

Wave energy studies have focused upon point-absorbing devices due to the discovery that close inter-device spacing can enhance energy capture due to resonant effects caused by the radiated wave fields [9]. However, it should be noticed that positive constructive interference of the diffracted and radiated wave fields (which might enhance power absorption) occur only at determined frequencies whereas it can even turn into negative destructive effects at some other frequency ranges.

### 3.3 Numerical and analytical studies

There have been a number of analytical studies that have aimed to ascertain the percentage of the kinetic energy can be efficiently extracted from a tidal channel [10-12]. All find absolute limits or define acceptable levels of energy extraction. It should be noted that the answers tend to vary considerably.

As wave energy converter extract a relatively small percentage of the available energy efforts have tended to focus upon the effects far down wave of the extraction point such as work conducted for the Wavehub in the southwest of the UK [13].

Other numerical studies, rather theoretical and based on linear wave theory, have focused on the interactions within a small number of heaving point-absorbers with the aim of defining optimal configuration for power absorption. In some cases ([14]) it has been shown that it is possible to obtain a large increase of power absorption with a specified configuration at determined frequencies. However, a similar approach applied to irregular random waves ([15]) did not seem to indicate optimal configurations because of the canceling effect between destructive and constructive interference at different frequencies.

Device-specific numerical studies are now being published for both wave [16] and tidal energy [17] studying effects of wake flow fields and device interaction. Future works in the wave energy field will probably aim at applying specific control strategies to improve positive interference effects but it is likely that first deployments will aim at keeping inter-device distances large enough to avoid any kind of interference.

## 4. Key drivers of interaction effects

### 4.1 Metocean parameters

Directionality of the resource will govern the degree of interaction between devices. Both wave and tidal energy benefit somewhat from relatively low directionality. Most wave sites tend to have a strong prevailing wave direction. Tidal sites often have a bi-directional resource that reverses close to 180˚ between flood and ebb tides. However, this is not always the case. Sites such as Portland Bill [18] on the south coast of the UK exhibit a degree of ‘swing’ as the water flows around the headland. Flow detachment causes a reverse in flow direction such that it is far from bi-directional. In this case the downstream region disturbed by a device will be wider than normal. Small fluctuations in inflow direction during a tidal cycle will also lead to a wider wake. This was termed ‘wake meandering’ in the wind industry. Figure 2 illustrates the extended wake field. Device spacing might need to be increased to account for such effects if strong device interaction is to be avoided.

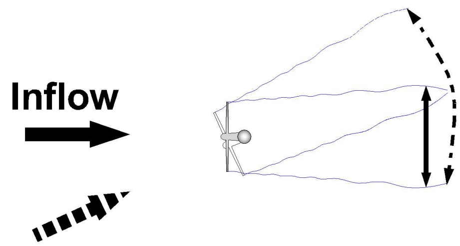


**Figure 2:** Wider wake flow for increased resource directionality.

Bathymetry may affect array device interaction within an array. A lack of continuity of depth within and surrounding the array area may lead to changes in direction of waves/tidal currents that could affect the magnitude of device interaction. It is most likely that for a wave energy array such a site would be avoided due to strong wave refraction. Similarly for tidal energy strong vortices in the horizontal plane would probably preclude a site but for the reason of increased and unsteady structural loading upon devices.

Significant changes in bed roughness characteristics will alter the ambient turbulence intensity. For tidal energy this will affect the length of the wake with a more turbulent flow leading to reduced wake length [8].

High levels of bed roughness are less of an issue for many wave energy devices in water depths greater than 0.5 wavelengths.

The percentage energy capture of a wave or tidal device will influence the intensity of any wake formed downstream/down wave. It follows that if more energy is extracted from a tidal or wave climate then the downstream flow field will be more heavily suppressed. For tidal turbines increased energy capture is not likely to influence the wake far enough downstream at distances where downstream rows might be located [19]. Wave energy devices extract a much smaller percentage of the available resource so increasing capture efficiency might also have a relatively small influence upon device interaction.

Installation and maintenance issues may be prevalent for 2nd-generation arrays. Access to rows of devices in the centre of an array may be driven not by the need to minimise device interaction but possibly to allow sufficient space for craft required during the installation and maintenance phases.

## 5. Informing array design

Despite the lack of knowledge of how wave and tidal devices might interact it is possible to make qualitative assessments of many situations. Figure 3 shows the evolution of a 1st- generation array. On the left is single row array of wave energy line-absorbers. The radiated wave field is shown approximately diverging at a 30˚ angle down wave.

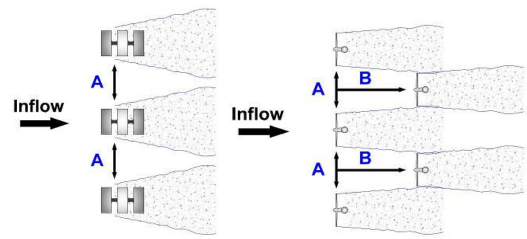


**Figure 3:** Principal device spacing for a 1st-generation marine energy array; single row (left), 2 row (right).

It is intuitive that if distance *A* is large then the wave or tidal field moving through the gap between 2 devices will remain relatively unchanged towards the centre of the gap. As distance *A* is reduced the amount of undisturbed wave /tidal flow will also reduce. At some small value of *A* adjacent devices will affect each other and this is likely to be a negative interaction. It also now follows that there must be an optimal value of A where adjacent device spacing is acceptably small but also where enough of the wave/tidal resource can pass through the gap. Now we have the ideal scenario for an expanded 1st-generation array with 2 rows. Distance B will be optimised where the downstream/wave row is operating in flow conditions similar to that of the first row. As the tidal device wake and the wave device radiated field will tend to diverge this further supports the theory that there is an optimal value of B depending upon device type, operation and met-ocean conditions. Whilst we cannot give definitive values for A and B we can inform device developers in a generic manner to empower the industry to acquire data to optimise inter-device spacing.

The statements above do not apply in the same manner to point-absorbing wave energy converters as shown in figure 4. Here, positive interaction effects can occur which have been the focus of many experimental and theoretical studies too numerous to mention. Efforts have been made to utilise the radiated wave field from devices to increase the power generated from the array to a value greater than an equivalent number of isolated devices. It remains to be seen if the first arrays of point absorbers do perform in a manner similar to that predicted in previous work.

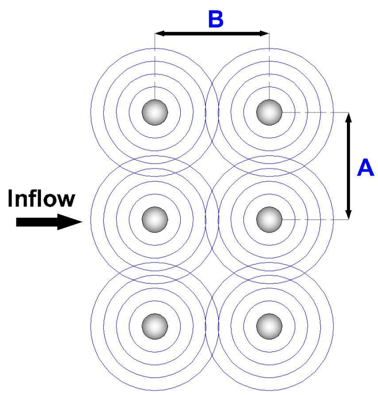


**Figure 4:** Point-absorber wave energy array showing radiated wave fields.

The issues surrounding 2nd-generation arrays can be simplified by the diagram depicted in figure 5. Here a tidal device is operating in the wake flow of an upstream device (the same scenario exists for many wave energy converters).

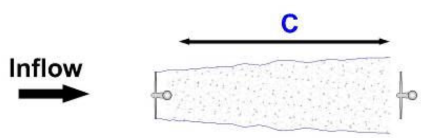


**Figure 5:** Tidal turbine operating in wake of upstream device.

The wake will be strongest for small values of *C* with the ambient wave/tidal conditions gradually infiltrating the wake as *C* becomes larger. Therefore we can say that the value of *C* will be optimised based upon balancing the negative interaction effects (structural loading and power generation) with the requirement to ensure arrays are relatively compact. The optimal value of C will vary with the parameters discussed in section 4.

## 6. Non-hydrodynamic issues

Apart from the considerations related to the hydrodynamic effects explained above, there are a number of technical requirements that might impose several constraints on the array configuration and on the inter-device distance.

Firstly, all marine energy converters will require station-keeping systems or foundations in order to maintain their position. Particularly, floating devices would probably adopt moorings with several anchors placed at a determined distance from the device and imposing a certain "footprint". If those devices were to be deployed and moored independently, the size of the "footprint" might impose an important constraint on the inter-device distance. A possible alternative would be constituted by a globally shared mooring arrangements for arrays in such a way that several converters might be moored and interconnected together. This would save infrastructures (in terms of anchors and chains) and might even prove to be beneficial for wave energy converters ([20]).

Another factor influencing the arrays configuration is represented by the electrical connection infrastructure. The rated power of the whole farm influences the choice of the connection and imposes requirements in terms of infrastructure and cabling ([21]). It is likely that future marine energy farms will host floating or submerged substations to allow elevation of the voltage for efficient transmission and their positioning will have to be defined accordingly to a feasible device configuration (figure 6).

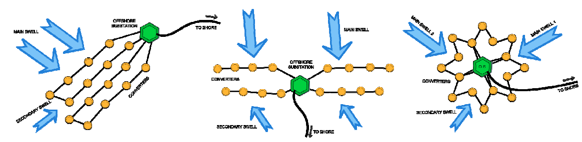

**Figure 6:** Possible alternatives for a wave energy converters array electrical connection configuration

Also, in some cases marine energy arrays will have to be electrically inter-connected before being linked to the general hub or substations. In such cases, the inter-device distance should be chosen according to the requirements defined by the umbilical cables design and the need to avoid extreme mechanical loads on one hand and excessive power losses on the other.

Finally, as mentioned before, another very important constraint on inter-device distance will arise from the need for vessels and their equipment to operate at ease on the single devices for maintenance and repairs. This requirement will be often device- and site-specific making it difficult to define guidelines to deal with it.

## 7. Conclusions

Wave and tidal energy arrays offer a means to harness and produce significant quantities of energy from the marine environment for human use. In the short to medium term it is most likely that arrays will be composed of up to 2 rows arranged perpendicular to the prevailing wave or tidal direction. For single row arrays lateral device spacing has the potential to be optimised but will depend upon a number of variables including device design and metocean parameters. It is recommended as part of Equimar that early arrays are used to inform later designs. This can be achieved by monitoring device performance parameters and acquiring additional metocean measurements such as downstream tidal or down wave climates.

Second generation arrays, as defined in this paper, may not appear for a number of years due both the level of understanding required to minimise negative interaction effects and also the reasonable installed capacity that 1st-generation arrays can achieve. It is clear that certain generic lessons can be learnt from the wind energy industry such as the levels of device interaction within a multi-row array and the deficiencies of numerical simulation tools in predicting wind farm power output. Whilst there is little quantitative guidance that can be given for wave and tidal arrays it is certain that efforts to study device interaction effects will soon accelerate. This paper highlights qualitative guidance that can be given in order to steer research towards the most salient issues surrounding array design.

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