COMMISSION OF THE
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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Deliverable D5.3

Protocols & guidance for device specification and quantification of performance

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Protocols & guidance for device specification and quantification of performance

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Summary

Arrays of wave and tidal energy devices will require a precise set of performance metrics with which can be used for absolute and comparative purposes. Many of the device specifications have been addressed previously within the device classification template report as part of this work. This document deals with more general definitions that quantify the performance of an array as a whole.

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1. INTRODUCTION

Arrays of wave and tidal energy devices will require a precise set of performance metrics with which can be used for absolute and comparative purposes. Many of the device specifications have been addressed within the device classification template report as part of this work. This document deals with more general definitions that quantify the performance of a device or array as a whole.

It is likely that arrays will evolve in size and complexity as the technology develops. A useful concept that has arisen from this aspect of the Equimar protocols is the definition of the size of an array. 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. It follows that it may be possible to experience positive interaction effects whereby power production is increased and/or structural loading is decreased; discussion on this issue will follow later. 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). 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 (see Figure 1). 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

Second generation arrays would be for multiple rows of devices (greater than 2) where interaction effects do occur. The 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. Figure 1 illustrates this issue as 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.

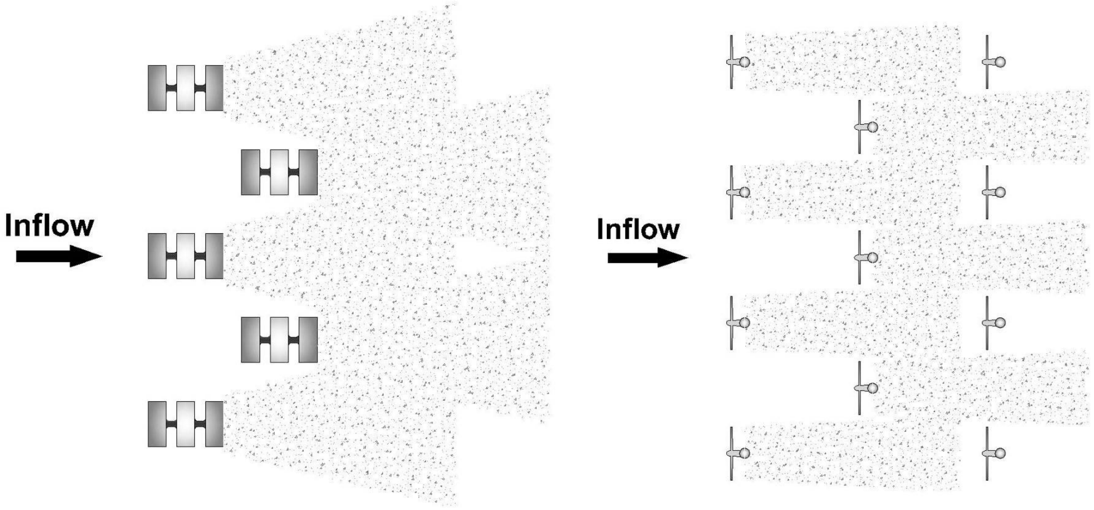

Figure 1: 2-Row wave energy array (left) and 3-row tidal array (right)

The definition given above means that the rated power of an array is independent of this classification. Instead it is driven by the operational complexity of the array.

The classification of arrays in this manner is important as many of the device and performance metrics applied to arrays become more subjective for 2nd-generation arrays. Definition and comparisons between several 1st-generation arrays should, in theory, be easier.

2. QUANTIFICATION OF THE INFLOW TO AN ARRAY

As arrays develop and grow in size it is likely that the inflow to the array might vary spatially such that one end of the array is exposed to a different set of environmental conditions to the other end.

2.1 DRIVERS AND METHODS OF QUANTIFYING THE INFLOW TO AN ARRAY

For this aspect of the protocols the reader is referred to I.A where single point measurements of the wave and tidal energy resource are given. II.B (sea trials) also gives a good insight into applicable device specification and data acquisition requirements for wave and tidal devices. This advice is applicable to all stages and sizes of arrays where the inflow is judged to vary appreciably across the extent of the array. This is generally driven by site and environmental variables.

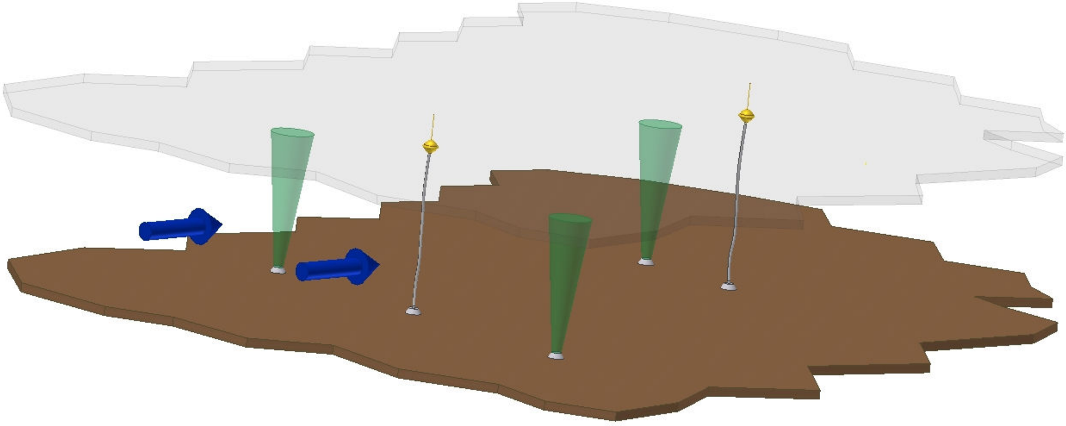

Figure 2: Array resource measurments might require increased spatial coverage

The need for accurate quantification of inflow conditions is important at the planning, installation and operational stage of the array. With the device thrust force and power proportional to the square and cube of the velocity respectively the need for a high level of accuracy is clear.

2.2 QUANTIFYING THE INFLOW TO A TIDAL ENERGY ARRAY

If the water depth remains constant across an area including the array and outside its spatial footprint it is reasonable to assume that the inflow is constant with lateral distance (perpendicular to the principle direction of flow). As it the case with wind turbines that extract kinetic energy from a moving fluid inflow velocity measurements should be made upstream at a point in the flow that is not influenced by the operating devices. This distance is generally taken to be 5-characteristc lengths of the hydrodynamic subsystem e.g. 5 horizontal axis rotor diameters (or equivalent characteristic length).

For tidal devices within an array the principle driver for varying inflow across an array will be changes in water depth. A good example is the Race of Alderney which flows between the UK channel Island of Alderney and Cap de la Hague on mainland France. The Eastern part of the race has a typical spring peak flow approaching 5m/s whereas the deeper more tranquil Western part of the race has a spring peak flow of 3m/s. An array covering a large part of the race would then require distinct inflow measurements dependant upon the degree of inflow variability as illustrated in Figure 3.

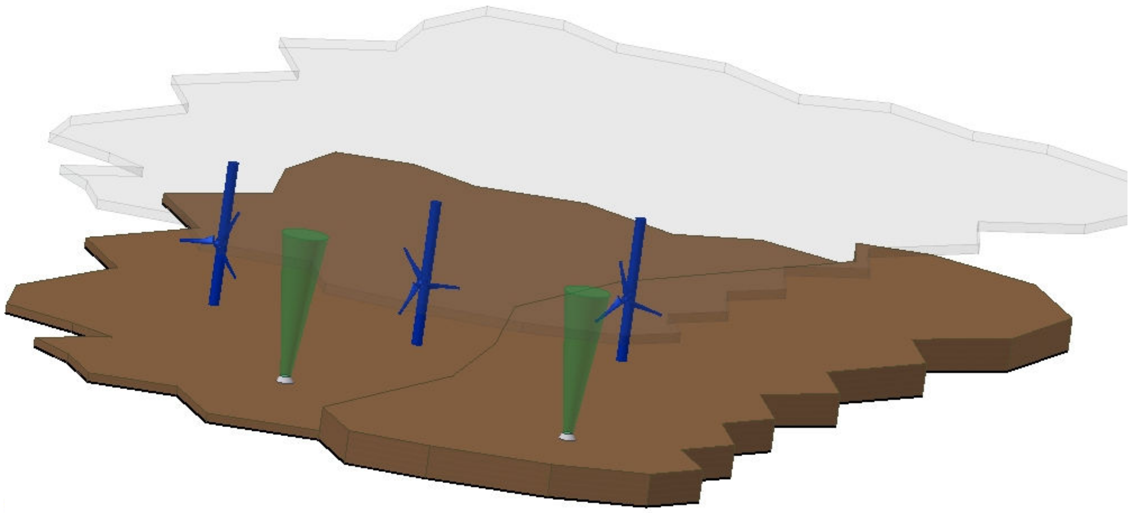

Figure 3: Array installation over varying depth will require increased measurment to accurately define inflow conditions.

Whilst varying depth can affect the flow speed varying bed conditions can affect the amount of free stream turbulence in the flow that will in turn influence device loading and control. Step changes in bathymetry upstream can shed turbulent structures far downstream so appropriate mapping well upstream of the array is recommended even if at lower resolution than that employed close to the array footprint. Shipping charts and a range of different resolution bathymetric surveys are often available for most areas close to shore and should be used appropriately to assess whether any change in inflow across a tidal array might exist.

It is recommended that if inflow conditions are thought to vary that site resource assessment for an array consists of several locations of measurement. These can be conducted incrementally if the array is to be constructed in a modular fashion.

2.3 QUANTIFYING THE INFLOW TO A WAVE ENERGY ARRAY

In the open ocean in deep water wave energy varies only slowly over distances of tens or hundreds of kilometres, as can be ascertained from satellite mapping and buoy data. However, within the area dedicated to a wave energy converter (WEC) array, just a few kilometres on a side, the power variation may be substantial, possibly tens of percent depending on the size of the area and the sea-bed bathymetry. Physical processes in the nearshore can significantly change the wave conditions. As waves enter shallower water they lose energy by shoaling and other processes, so for sites where the water depth changes are large, there may be large associated power changes. Waves are also refracted towards the maximum fall line of the sea-bed slope, so seabeds that have complex 2D bathymetry will result in focusing and defocusing of waves, giving rise to power ‘hot-spots’ and ‘cool-spots’. Another factor that can substantially affect the wave energy over the array is the degree of sheltering due to the local coastline, which will vary with the wave direction. Generally the designers of the array will attempt to minimise the sheltering, but the numerous constraints on array siting may mean that sheltering remains significant.

The wave energy inflow is best quantified by a directional wave-buoy (or equivalent instrumentation) ahead of the array by a distance sufficient for it not to be substantially affected by the WECs in the array, e.g. of the order of one to a few hundred metres depending on the size of the WECs. In an area of deep water (i.e. greater than half the wavelength of the waves being absorbed) this single measurement may suffice as inflow characterisation. However, in shallower water, perhaps with complex bathymetry and perhaps with local sheltering characteristics, predicting the wavepower at points within the array may need, in addition, the use of a nearshore wave transform program that models the bathymetry and local coastline and is driven by the incoming directional wave field data.

2.4 MODULAR INSTALLATION OF ARRAYS

Further to the definition of 1st and 2nd generation arrays device developers are encouraged to deploy addition resource measurement equipment at 1st generation sites for the following reasons:

1. To gather down stream/wave measurements for array expansion at that site
2. To provide understanding of down stream/wave that can be used to inform array design at other locations

Figure 4 illustrates this concept using targeted measurements around a 1st-generation single row tidal array. Inflow is measured upstream of the array. Measurements to quantify the available resource to a second row of devices are staggered allowing 2 different locations to be evaluated. It would be prudent to deploy measurement equipment in such locations simultaneously to reduce costs. The flow measurement points for the 3rd-row are also staggered in a similar manner; it is assumed that the energy capture of the devices in the single row array will be equal thus justifying this approach. In the case of tidal energy these measurements can also be used to quantify the inflow to the array when the tide turns. For wave energy this is not required as the predominant wave direction is generally strong.

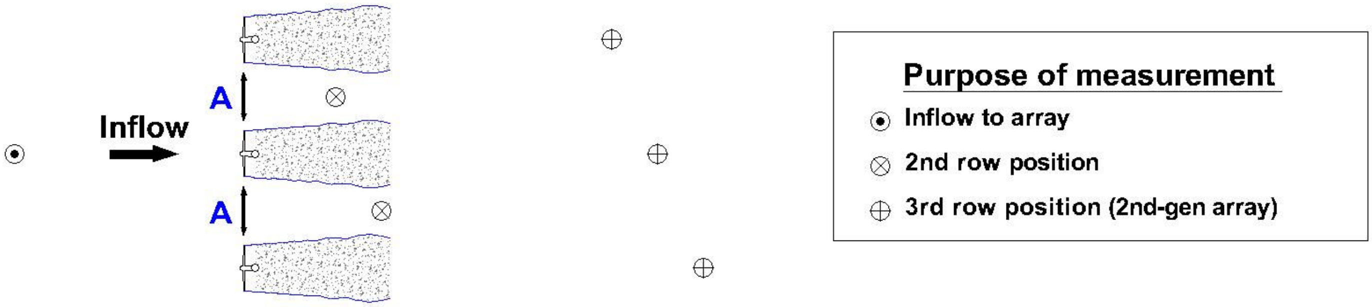

Figure 4 informing array design through additional resource measurements

3. DEVICE VARIABILITY WITHIN AN ARRAY

This aspect of arrays is expected to only become significant for 2nd-generation installations where inflow conditions to devices will vary throughout the array. It follows this section more forward-looking in nature than other aspects of array design and performance. The concept of device variability in terms of rated power performance and physical design is in contrast to the most similar technology which is offshore wind where large installations of several rows of turbines are now installed offshore. All devices are identical in terms of power performance despite interaction effects existing to reduce the overall performance of the array compared to the same number of isolated devices.

3.1 TIDAL ENERGY DEVICE VARIABILITY

The issue of device variability within a tidal energy array could be applicable due to the predictable nature of the resource in terms of flow speed and direction. Reduced resource in the centre of a 2nd-generation multi-row array will hold true for marine current devices exposed to alternating direction of flow. Whether it is appropriate to design devices with different power take off systems or to just reduce the rated power output of devices with a reduced inflow resource will no doubt governed by the cost/benefit analysis performed by developers.

Changes in bathymetry and water depth might also require different physical sizes of device within an array. Once again a choice can be made to effectively have two arrays in close proximity and aggregate power output or to treat them as a single entity. It may also transpire that sites with very uneven bed conditions might not be suitable for array installation due to the device variability required.

As the technology matures to reach 2nd-generation arrays developers will have a number of tidal energy device variants that will facilitate the issues addressed above. At this time more in-depth discussion of device variability are not deemed to be productive until the industry is more informed about tidal devices operating in smaller (1st-generation) arrays.

3.2 WAVE ENERGY DEVICE VARIABILITY

At most wave energy site the prevailing wave direction is generally strong with low directional variability. When the direction does change it is often slow such that devices can be reoriented for optimal power capture. Therefore device variability is unlikely to occur for wave devices in a wave energy array. 2nd-genreation arrays (as defined here) are also less likely for wave energy as arrays can be made wider than tidal energy arrays as wave energy sites often have lower spatial constraints. Thus 2-row arrays can have high rated power outputs negating the need to expand with a 3rd row. Clearly this will be site-dependent but generally it is believed that limiting arrays to 2 rows will be adhered to in order to maximise array power output and minimise negative interaction effects in the short term. It should be considered that electrical connection costs will increase with array width and thus for 1st-generation wave energy arrays a limiting array width is likely to exist (for a specific site and device type). In closing it should be considered that spatial constraints such as adjacent shipping lanes, fishing, geophysical concerns (e.g. seabed conditions) have the potential to drive array design over and above the variables already mentioned.

Once again this does not apply to point-absorbing devices where radiated wave fields may increase the power output of devices in the centre of a square array. However, the issue of device variability will depend upon whether the increase in absorbed power occurs over a wide range of wave conditions. If this is not the case then it might be more prudent to keep the rated power of all devices equal noting that some devices in the centre of the array will have higher generation load factors than those at the edge of the array.

4. QUANTIFICATION OF ARRAY PERFORMANCE PARAMETERS

Definitions are presently in draft format with the IEC document IEC/TC 114/PT 62600-1 regarding Marine Energy Terminology. Equimar will use the definitions contained within the IEC report where stated. There are identified herein by *italic text*.

4.1 GENERAL PARAMETERS

Rated Power

Rated power is not really fixed – even for a given hardware configuration. The rated power of a device generally defined as the manufacturer’s nameplate power on the machine and is nearly always the maximum electrical output of the generator. There are several reasons:

From the device developers point of view, the rated power is the maximum power that the machine can economically generate – there are diminishing returns and the manufacturer will not install extra capacity, in generator size and all other components upstream and downstream in the powertrain plus the structure to support it, if the additional energy (MWh/year) doesn’t justify it; profit must continue at the margin. The narrower the distribution of generated power is the better – and the higher the capacity factor (defined below).

The second set of reasons relates to the rewards and costs of ownership. The owner of a machine earns revenue from the MWh sold plus any tariff, but faces costs that comprise expenditure on capital minus capital grants (capex) and on operations and maintenance (opex). Opex includes a cost for the connection to the grid related to its power capacity. So again there is a marginal cost/benefit constraint: the owner will not pay for extra connection capacity if insufficient energy is generated to pay for it. Consequently the owner may downrate the machines, i.e. not operate at the highest power, again to narrow the power distribution. The owner may also downrate the machines in order to avoid excessive wear and tear that might increase opex. The machines may also be operated closer to shore, in a milder wave climate, because that also reduces opex and reduces transmission losses and cable costs. Capex sets a lower limit to downrating: the owner will not buy a large machine only to downrate it if a smaller, cheaper one would do. The owner’s rated power is likely to be quite close to the manufacturers but with differences that take account of the differing constraints.

In conclusion: for arrays the simple, practical definition of rated power is the grid connection capacity (defined by the sum of the nameplate rated power) divided by the number of machines. For 1st-generation arrays the issue of variable rated devices (see section 3) is unlikely to occur thus the definition of array rated power is simplified.

Availability

IEC/TC 114/PT 62600-1 defines availability as:

3.7 Availability (power production)
Ratio of the total number of hours during a certain period, excluding the number of hours that the marine energy converter could not be operated due to maintenance or fault situations, to the total number of hours in the period, expressed as a percentage

3.8 Availability (resource)
Ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided

Given that the resource is intermittent, and in the northern hemisphere, highly seasonal, the cost-efficient response is to schedule routine and preventative maintenance for the periods of reduced resource, e.g. in summer in the northern hemisphere. This strategy keeps availability at a maximum when the resource is high. Unforeseen failure must be attended to as soon as possible, so that machines don’t lose generated MWh, but is subject to the constraint of repair crew and equipment availability and economies of scale – e.g. waiting until a given percentage of machines are down, then attending to all at once. Also important is the nature of the damage. For some devices, availability is binary: either the device is fully operational or stopped. Wind turbine operation is often of this nature. Some devices might employ ‘graceful degradation’ when a fault in encountered. Here performance is reduced but the device still operates at reduced power. This is a cost-effective alternative to binary availability – and an alternative to the 'fraction of time' definition given at the start of this section. It is particularly appropriate for marine devices where access for maintenance may be severely constrained due to cost (e.g. vessels or divers) or weather. Availability is a difficult to fix because it is subject to uncertainty of failure occurrence, type and the costs of remediation. This uncertainty is mitigated by experience.

For arrays the availability should be aggregated over all devices. Therefore if 10% of devices are not in operation over 50% of the year the array availability will be 95%. It is then more difficult to account for 'graceful degradation' within an array as unless declared (or detected). Instead it will manifest as a reduction in power output that can be expressed in terms of a reduced capacity factor (defined below).

Capacity factor

IEC/TC 114/PT 62600-1 defines capacity factor as:

3.10 Capacity factor (energy)

Ratio of the energy that an electric generating system actually produces which would have been produced had the ***rated capacity*** *been utilized for the given period*

Once again for an array the rated capacity is defined for the array as a whole.

Conversion efficiency

IEC/TC 114/PT 62600-1 defines conversion efficiency as:

3.16Conversion efficiency

Electrical power output compared to the captured power

This definition as it stands is slightly ambiguous in terms of where the power is quantified. Captured power could be measured at the hydrodynamic subsystem or within the power take-off subsystem. Similarly electrical power output could be measured at the exit of an individual device or at the onshore grid connection point.

For arrays it is most useful to define captured power at the rear of the device and the electrical power output at the grid delivery point.

4.2 WAVE ENERGY-SPECIFIC PARAMETERS

Capture width

A useful quantity widely used in the wave energy industry is the 'capture width' of a machine. This is the mechanical power developed by the machine, in watts, divided by the mechanical power in the waves, in watts per metre of wave front. The result is termed 'capture width' and is equivalent to the width of wavefront in metres over which all energy is captured. For example a machine might have a capture width of 30 metres: this does not mean, of course, that a width of 30m spanning the machine is reduced to total calm; it means that behind the machine there is an area of reduced wave height, considerably wider than the capture width, and tapering away downwave of the machine as the free field re-energizes the wake, much as for wind turbines.

The capture width can be specified as a frequency-dependent quantity when it is measured in single-frequency waves, or as an aggregate Figure in a given, specified irregular sea. The frequency-dependent curves of capture width are useful for the development – designers can rapidly assess the effects of design changes, aiming in general to increase and broaden the curves so as to increase overall power in the irregular seas encountered in the real world.

The capture width depends on the size of the machine and, to compare machines fairly, allowance should be made for this. One can produce a non-dimensionalized number by dividing the capture width by some length characteristic of the machine. One proposal [Retzler et al, 2003] for the characteristic length is 'displacement width', namely, the cube root of displaced volume. The resulting non-dimensionalized capture width is then correctly scale-independent and, moreover, shape-independent. The differences between different machines of this non-dimensionalized capture width will then be due to operating principle, technology etc. not on size or shape.

Spacing number

A second non-dimensionalized number would be useful in the case of arrays, namely a spacing number, being the average spacing between machines divided by the capture width. In general developers will be concerned, for economic reasons, to keep the spacing number low because this offers potential savings in electrical cabling, mooring emplacement and other infrastructure, but within the constraints of keeping negative hydrodynamic interaction between devices low and, of course, ensuring there is no risk of unwanted mechanical interference.

Retzler CH, Pizer DJ, Henderson R, Ahlqvist J, Cowieson F, Shaw M, 2003, "Pelamis: Advances in the numerical and experimental programme" Proc. 5th European Wave Energy Conference University College Cork, Cork, Ireland September 17-20, 2003