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

Grant agreement number: 213380

Deliverable D4.2

Data Analysis & Presentation
To *Quantify Uncertainty*

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Data Analysis & Presentation To *Quantify Uncertainty*

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Content

Nomenclature

CI	Confidence interval
CL	Confidence level
$\bar{\bar{\bar{E}}}$	Environmental matrix
H_{mo}	Significant wave height derived from spectral moments, $4\sqrt{m_0}$
LOI	Location of interest
n	Amount of data points
P	Converted Power
Prob	Probability of occurrence
P_{avail}	Power available from the resource
$P_{average}$	Yearly average converted power
P_{wave}	Wave power
s	Sample standard deviation
t^*	Statistical parameter representing the confidence level of the confidence interval
T_e	Energy Period (m_{-1}/m_0)
v	Water speed
$\bar{x}$	Sample mean
η	Non-dimensional performance

1 Introduction

1.1 Rationale

The Sea Trial Manual (D4.1) describes the type of operations required to advance an ocean energy conversion device (wave and tide) from an intermediate scaled sub-systems proving machine (circa 1:4) to a full size solo prototype pre-production unit and on towards a pre-commercial device ready for economic evaluation in a small array deployment. This progression covers development Stages 3 to 4 in the 5 Stage development programme on which the EquiMar technical protocols are based.

The process spans a large range of engineering development and introduces heavy offshore operations, device certification, health and safety considerations, environmental issues, regulatory and permit requirements and improved economic predictions. An important factor that strongly influences these two Stages is that they are conducted at outdoor test sites were conditions occur by nature so they must be accepted rather than controlled or produced on demand. This applies equally to wave and tidal technologies: although tidal conditions are considered predictable, local conditions experienced by a device are strongly influenced by Spring-Neap cycles and weakly or non-deterministic, locally correlated events such as depth varying turbulent structures, wind-wave-current interaction etc. Sea trial programmes must, therefore, be robust enough to accommodate this loss of predictability so requires the careful selection of a test site(s) and extended deployment durations.

Unfortunately, time equates to escalating costs for the device development companies undertaking the sea trials with the inevitable reality that it is probable fully completed programmes will be rarely achieved. A standard methodology to specify the degree of completion of the test programmes is required and by which to express the level of confidence, or degree of uncertainty that dictates the risk assessment for continuing forward.

There are three approaches that can be adopted to, firstly, improve the confidence limit and secondly, quantify (or qualify) the risk. These are:

- Conduct analysis of the sea states occurring at the test site to calculate the probability of survival, or extreme, events occurring within specified deployment durations
- Conduct analysis of the sea states occurring at the open water test site to evaluate the scatter of metocean conditions from the station average and the deviation of the average from a classical form, such as Bretschneider for wave fields or predicted conditions based on surface measurements or numerical results in the case of tidal velocity. These factors will influence the range of device performance characteristics.
- Based on the above and the number of device settings to be investigated, plan the sea trial programme to ensure all important events are experienced and captured.

Ideally, the programme would require several performance observations to be made in each element of a site's metocean conditions (e.g. a bi-variate H_{m0}-T_e sea state scatter diagram for wave energy or a velocity-direction-depth scatter diagram for tidal) to confidently produce an empirical time averaged power matrix for the machine. The length of deployment this would require will depend on the variability of the conditions at the site and the number of device configurations under investigation, such as control strategies and survival mode verification.

In practice achieving a 100% completion of this specification in a constrained time frame would be extremely difficult. The first two criteria are dealt with in the EquiMar Resource Protocol. The third is covered in this document which describes a very important statistical approach to evaluating the confidence limits that can be applied to the sea trial data when the ideal full data acquisition schedule has not been achieved.

1.2 Scope

This report aims at providing a methodology for the analysis and presentation of data obtained from sea trials of marine energy converters, according to Annex 1 – Description of Work of the EquiMar project, where task 4.2 is defined. Some slight modifications have been made to the original structure due to re-adjustments in accordance with the on-going research.

Before defining the methodology for analysing and presenting the results of the performed sea trials, the objectives, or the questions for which answers are sought, are presented. In other words - What 'high level' information is ideally the outcome of the sea trials?

These are:

- An estimation of the uncertainty of the performance figures device characteristics involved.
- Overall device power conversion performance (possibly at different power conversion stages) at the site of the performed sea trials, with the local sea conditions.
- Power production estimates based on the sea trials, but at other sites and possibly at other scales of the device. This will in some cases only be possible through use of numerical or analytical models of the device, typically developed through laboratory testing of the device. These models will initially have to be verified / calibrated against the sea trial data.

Thus, the goal of this deliverable is to provide a methodology which addresses the above, and in particular the first point.

1.3 Introduction to the procedure

The basic sea trial parameters (as defined in D4.1) are used as input for the methodology, i.e. characteristic sea parameters, device power parameters at various stages in the conversion line (e.g. from tide/wave-to-wire), hydrodynamic loadings and other relevant criteria, are used.

In the formulation of the methodology, the following challenges have to be met and tackled:

- The environment in which the sea trials are performed is, although predictable to a degree, by nature uncontrollable.
- Some test data will be from conditions under which the control settings, or configuration, of the device have not been optimal. The methodology should allow inclusion of these data in the presentation without this punishing the reported device performance.
- The methodology should be a 'black box' approach – it should be as generically applicable as possible. Especially in the field of wave energy converters the variety of device types presents a challenge to formulate the methodology in a way so it is universally applicable.
- The methodology should encourage and reward increasing amounts of relevant data - data which demonstrate the power production capabilities of the device in many varied conditions and increase confidence.
- The level of uncertainty in the measured performance data should be quantifiable.

The principle of the methodology presented in the remaining part of this report is based on following basic steps:

- Definition/selection of the parameters defining the environment in which the device is operating and the size of bins / discretization hereof.

  - For wave energy converters, this will in the general case lay out an n-dimensional matrix, which can be simplified into the wave climate scatter diagram (e.g. given in terms of H_{m0} and T_e, n=2) or even simpler, e.g. a list of wave states (n=1). More complex cases will include parameters such as spectral shape of waves, water current speed and direction etc.

  - In the most basic case for tidal devices this will be conducted via discretization of tidal velocities (n=1), velocities and direction (n=2) and/or velocity – depth (n=2 or n=3). In more complex cases parameters such as metrics describing waves/current interaction, turbulence, etc. might have to be included.

  The larger the number of parameters and finer discretization to be considered, the longer the sea trial needs to be in order to provide the device performance to a defined level of certainty so the more exact the understanding and predicable will be the device performance.

- In order to focus the effort in the sea trials on the important parts of the n-dimensional matrix describing the environment, a ‘zoning’ thereof can be performed. Within a ‘zone’ of the matrix the performance of the device will be characterized by a single performance value, non-dimensionalized as function of the applied environmental data, e.g. mechanical power absorbed by the machine divided by the incident hydrodynamic power. This usefully removes the variability and uncertainty due to environmental change within the zone; hereafter in this document unless stated otherwise, the term ‘performance’ implies ‘non-dimensionalized performance’. In the definition of the zones the significance of each of the zones should be balanced. Thus, in the less significant parts of the matrix the zones can be larger, and vice-versa (this can be evaluated through the contribution of each zone to the overall average of the resource available to the device).

- The performance of the device within each zone of the matrix is then reported as an average and a parameter indicating the uncertainty (e.g. by confidence interval or standard deviation). The average and uncertainty can be based on a subset of all the measurements within the zone. A minimum number of data points are required, however the basic idea is that it is tolerable to use only a few points (in the case that not more of them are available), however this will cause the associated level of uncertainty to be high. It also implies that it will not necessarily be advantageous to base the average on only the very highest data points within the zone, since these might produce a larger uncertainty than slightly more conservative ones.

- In the case where the sea trial data are used directly for estimation of performance at a different target location, analysis should in principle be carried out as above, but using the environmental parameter matrix corresponding to the new target location. In this situation scaling of structure, results and environmental parameters can be applied.

- When the acquired data is used for a different target location, it is possible that the available data from the sea trials does not fit the environmental conditions of the new target location very well. This will become apparent if there are zones of the target location matrix which will not be populated by sea trial data points. This raises the need for the use of analytic/numerical models for inter/extrapolation of measured data. Typically, these will be semi-empirical models that have been developed in collaboration with device physical testing based on laboratory investigations or desktop analyses etc. The acquired sea trials data can then further verify and/or calibrate such models, and subsequently they can be used for extending the application range of the sea trials.

- The outcome of the analysis of the sea trial will be a table of environmental conditions corresponding to the defined zones with corresponding values of the performances (in terms of averages and uncertainties). Based on this, the power matrix, yearly power production etc. can be calculated, along with the corresponding level of uncertainty.

At the intermediate scale and in the early stages of the full size device sea trials, the above outlined methodology can (and probably should) be applied at the various steps of the conversion of the power from energy resource (e.g. tide/wave) to wire to fully evaluate the sub-systems and power chain efficiencies. Once established the device performance can be concentrated on the production of electricity and supply quality.

Figure 1 presents a schematic overview of the whole procedure. As explained in more details in this document, the model can be fine-tuned by adapting the zoning, including more environmental parameters in the development of the procedure and by applying it to various steps in the power conversion chain.

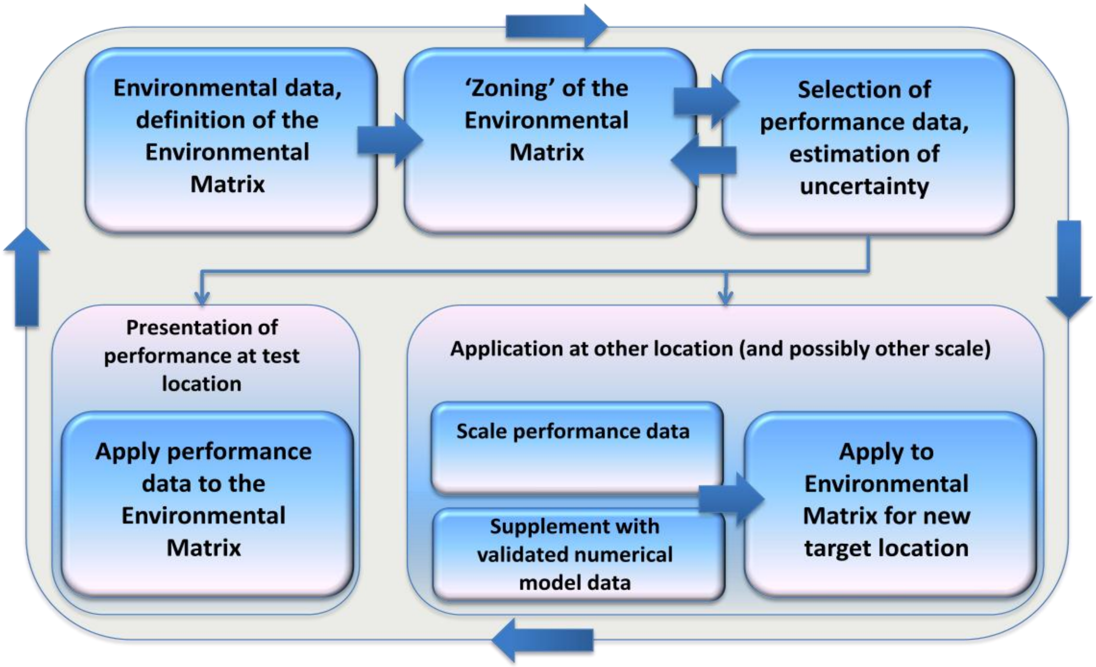

Figure 1: Schematic overview of the procedure.

2 Performance assessment at test location

2.1 Environmental matrix

The environmental conditions that can have an effect on the performance of marine energy extracting devices are numerous. Some of these are:

- Wave effects: wave height, wavelength, wave spectrum, directional spreading of the waves;
- Current/tidal effects: water current speed, directions, velocity profile effects, descriptions of turbulence, depth, water level;
- Wind effects: speed, direction and turbulence;
- Physical properties of the test location: Topography, bathymetry, and physical oceanography.

All these parameters and conditions describing the environment are defined by the n-dimensional matrix named the Environmental matrix, $\bar{\bar{E}}$.

$\bar{\bar{E}}$ can be established at any location of interest. It is based on time series of data covering long enough time spans to capture the overall variability of the environment, e.g. between 1 and 3 months for tidal – longer if seasonal variations are to be captured, and in the order of 10 years[1] or more for waves. The procedure can be simplified by selecting a defined amount of the dominant parameters e.g. the two main parameters characterizing the waves, the wave height and wave period (e.g. H_{m0} and T_e), or the speed of the tidal flow at hub height. In Table 1 the distribution of the occurrence of a tidal velocity is shown in a one-dimensional diagram and the wave conditions at a certain location are summarized in Table 2 showing a two dimensional scatter diagram, based on H_{m0} and T_e.

The tidal diagram presents the yearly average occurrence of every tidal velocity, based on 5-10 minutes records. The values in the scatter diagram refer to the yearly occurrence of a particular sea condition. Each sea condition in the wave scatter diagram is characterized by the two corresponding wave parameters and each value corresponds to measurements made over a defined period of time, generally 20 or 30 minutes. The size of the cells, delimited by the increments on the axes (=bins), can be defined as considered relevant for the concept, but as a guide a cell size of 0.1 – 0.2 m/s for velocity or 1 s and 0.5 m for wave period and wave height appears reasonable.

Note that it might not be physically possible to measure or predict the available hydrodynamic power at the exact location of the device (especially for devices installed close-to-shore or on-shore). In most cases, the available hydrodynamic power will be measured at some distance from the device. In this case, it is important that the reference point is positioned similarly when the performance is measured at an alternative location.

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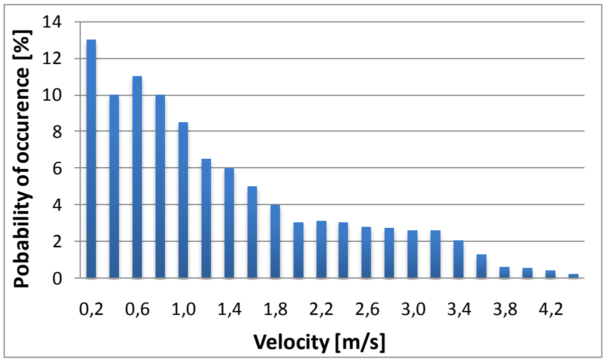
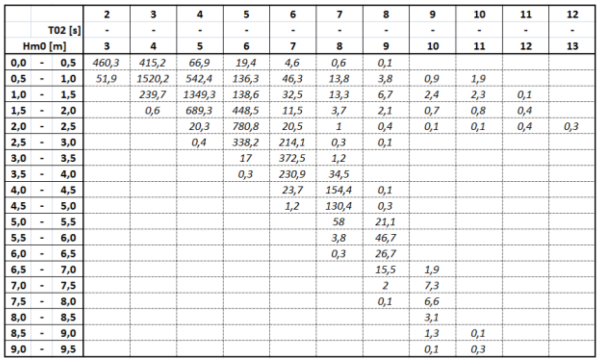
[1] Obtaining 10 years of verified measured wave data from a particular site of interest could prove to be a barrier to progress. To maintain the minimal environmental uncertainty it is common to resort to model predicted data proving the computer program output is validated for an appropriate grid node over a short duration. More information can be found in WP 2.

Table 1 & 2: Illustrations of environmental matrices; a 1-dimensional diagram representing the variability of the water speed and a 2-dimensional scatter diagram as used in wave energy ($\bar{\bar{E}}$).





	2	3	4	5	6	7	8	9	10	11	12
T02 [s]	-	-	-	-	-	-	-	-	-	-	-
Hm0 [m]	3	4	5	6	7	8	9	10	11	12	13
0,0 - 0,5	460,3	415,2	66,9	19,4	4,6	0,6	0,1				
0,5 - 1,0	51,9	1520,2	542,4	136,3	46,3	13,8	3,8	0,9	1,9		
1,0 - 1,5		239,7	1349,3	138,6	32,5	13,3	6,7	2,4	2,3	0,1	
1,5 - 2,0		0,6	689,3	448,5	11,5	3,7	2,1	0,7	0,8	0,4	
2,0 - 2,5			20,3	780,8	20,5	1	0,4	0,1	0,1	0,4	0,3
2,5 - 3,0			0,4	338,2	214,1	0,3	0,1				
3,0 - 3,5				17	372,5	1,2					
3,5 - 4,0				0,3	230,9	34,5					
4,0 - 4,5					23,7	154,4	0,1				
4,5 - 5,0					1,2	130,4	0,3				
5,0 - 5,5						58	21,1				
5,5 - 6,0						3,8	46,7				
6,0 - 6,5						0,3	26,7				
6,5 - 7,0							15,5	1,9			
7,0 - 7,5							2	7,3			
7,5 - 8,0							0,1	6,6			
8,0 - 8,5								3,1			
8,5 - 9,0								1,3	0,1		
9,0 - 9,5								0,1	0,3		

2.2 Zoning

A further acceptable simplification of the $\bar{\bar{E}}$ process can be done by combining several environmental conditions into a larger zone, e.g. a range of tidal velocities or different cells of the wave scatter diagram. These zones should be chosen carefully as only one performance value will be stated per zone together with a confidence interval. The zones are unique for every location and can be adjusted over time when more experience is gained. (More details will follow concerning the adjustments of the zones in section 2.6.) On a first approach, the zones should be chosen in order to segment as well as possible the yearly average available energy, e.g. calculated by multiplying the available power by its probability of occurrence. In general, a zone should represent at maximum 20% of the yearly average available energy. However, the zones should also include a minimum amount of data points; therefore their selection should also consider the available data points and in an early stage maybe also their related performance. Theoretically, once the amount of data points is abundant all the zones should tend to be as small as the size of one cell of the environmental matrix.

The characterizing parameters of every zone (water current velocity for tidal devices or H_{m0} and T_e for wave energy converters, symbolised by X in equation 1) are the average of the environmental parameters of the bins or cells weighted by the probability of power availability of the different bins or cells that are include in that zone:

$$X_{zone\ j} = \frac{\sum_{i=1}^{n} X_i \cdot (P_{avail})_i \cdot Prob_i}{\sum_{i=1}^{n} (P_{avail})_i \cdot Prob_i} \tag{1}$$

2.3 Selection of the performance data

The choice of the device performance data within each scatter diagram element affects mainly the stated performance and its related confidence interval. It is possible that the amount of data that is found in a zone is limited, since during the measurement period some sea conditions may not occur frequently or sensors may not be operative. In these zones, the performance results can be found to be randomly distributed and inconsistent, since the device might not always perform in the same way. The performance can fluctuate due to device related causes, such as inconsistent control of the device, or due to some variation of other environmental parameters that are not taken into account in the simplified representation of the environmental matrix, e.g. influence of tides, direction of the wave or currents, etc.

For every zone, the average of the performance of the selected data points will be stated with the corresponding confidence interval that reflects the accuracy of the stated performance. The confidence interval improves when the standard deviation of the selected data points decreases and/or when the amount of selected data points increases. (The confidence interval will be discussed more in detail in the section 2.4). The performance stated in a zone should be based on a minimum amount of data points, which can be adjusted to the variability of the control parameters for that zone. It is recommended to include an as large as practically possible amount of data points in order to prove that the device is capable of operating repeatedly to the stated performance. The statement that a minimum of 5 data points have to be considered in every zone is meant to be indicative as its significance is directly linked to the size of the zone.

Figure 2 illustrates why selecting the data points with the highest performance might not always be the best choice. A Student's t-distribution is used in the example; however performance data does not necessarily follow this trend. In the left figure, a limited amount of data points including the highest performances are selected. This results in a high average performance but also in a high standard deviation and therefore a large confidence interval. In the second figure, a same amount of data points is considered not including the few with the highest performances. This results in a slightly lower performance but smaller standard deviation and consequently a better confidence interval.

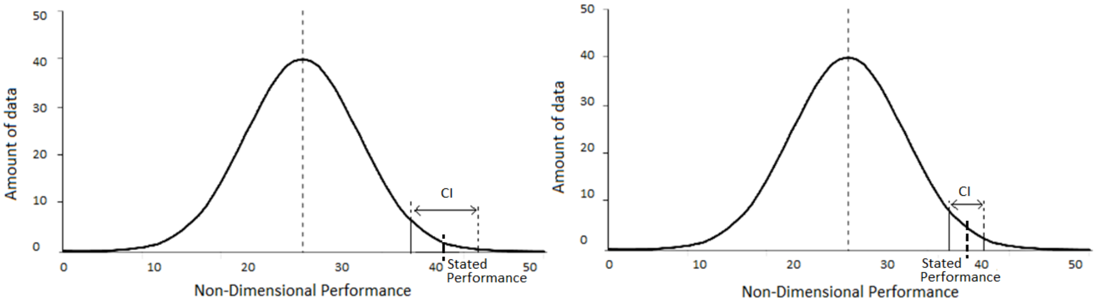


Figure 2: Influence of the selection of the data points

2.4 Statistical evaluation of data points in indicated zones

A confidence interval (CI) gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data. It indicates the reliability of the calculated performance as the confidence level (CL) can be determined, which specifies how likely the interval will contain the parameter. In other words, between the bounds of the CI is where the true value of measured parameters is expected to fall CL% of the time. Note that all these different parameters should be calculated based on the non-dimensional performance of the data points.

Based on the principle of "Confidence Intervals for Unknown Mean and Unknown Standard Deviation," the sample mean $\bar{x}$ and the corresponding CI can be calculated using the Student's t-distribution:

$$\bar{x} \mp CI = \frac{\sum_{i=1}^{n} x_i}{\mathrm{n}} \pm t^* \frac{s}{\sqrt{n}} \tag{2}$$

Where:

- x_i is the non-dimensional performance of an individual data point.
- $\bar{x}$ is the mean of the samples and corresponds to η, the stated non-dimensional performance of the zone.
- s is the sample standard deviation (as not the whole population is considered) of the non-dimensional performance data, calculated by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{3}$$

  Note that the coefficient of variation should remain equal when the standard deviation of the power is calculated based on these values.

- n is the number of samples considered.
- t^* is the statistical parameter representing the CL of the interval. It is based on the Student's t-distribution with n-1 degrees of freedom and a CL of 95% is proposed to be used.

Comment: In order to propose a general and common approach the Student's t-distribution has been selected as it is considered to be the most appropriate. However, the distribution of the performance of the data might not follow the Student's t-distribution and moreover it is possible that the shape of the distribution would vary over time, when more performance data becomes available and is included. In this case, more sophisticated treatment may be required, e.g. non-symmetric distribution.

In the summarizing performance table it is necessary to state an overall statistical appreciation of the average non-dimensional performance of the device. The combined standard deviation of different zones can be calculated as stated in equation 5 if the various zone-related standard deviations are of the same magnitude. If this can be assumed this pooled estimate, which takes the weighted average of the standard deviations of the different zones by taking the mean performance, probability of occurrence and the available hydrodynamic power of every zone into account, can be used else a Monte Carlo simulation should be applied. The Monte Carlo simulations seems also the most valid to calculate the overall Confidence Interval.

$$\eta_{\mathrm{overall}} = \frac{\sum_{\mathrm{zone=1}}^{\mathrm{n}} (\mathrm{P_{avail}})_{\mathrm{zone}} \cdot \mathrm{Prob_{zone}} \cdot \eta_{\mathrm{zone}}}{\sum_{\mathrm{zone=1}}^{\mathrm{n}} (\mathrm{P_{avail}})_{\mathrm{zone}} \cdot \mathrm{Prob_{zone}}} \tag{4}$$

$$s_{overall} = \sqrt{\left(\frac{\sum_{zone=1}^{n} (P_{avail})_{zone} \cdot Prob_{zone} \cdot (\eta_{zone}{}^2 + s_{zone}^2)}{\sum_{zone=1}^{n} (P_{avail})_{zone} \cdot Prob_{zone}}\right) - \eta_{overall}{}^2} \tag{5}$$

2.5 Presentation of the performance

The performance of the device can be summarized together with the characterizing wave parameters and the statistical appreciation in a table. In this table, the performance shall be presented in the form of a non-dimensional number and for one device operating at the location of interest. In the example of Table 3 the performance is given as the conversion from wave to useful power (e.g. mechanical, hydraulic or electric). However, the same table is applicable to any conversion step from wave-to-wire. It is therefore recommended to clearly state which performance is used and what the general specifications of the device and location are, e.g. capture width, rotor diameter or swept area, installed capacity, scale of the device, open seas or benign site, etc.

Table 3 and 4: Example of the performance table of a wave and tidal energy converter (based on illustrative values).

Performance from the sea trials performed at *Point 3 in Danish North Sea*													
Environmental parameters						Non-dimensional parameters				Performance parameters			
Zone	H_{mo}	T_e	P_{wave}	Prob	$P_{wave.}$Prob	η	s	n	CI	P	s	CI	P.Prob
	[m]	[s]	[kW]	[-]	[kW]	[-]	[-]	[-]	[-]	[kW]	[kW]	[kW]	[kW]
1	1	5,6	118	0,468	55	0,195	0,041	80	0,009	23	4,8	1,1	11
2	2	7,0	591	0,226	133	0,284	0,062	67	0,015	168	36,6	8,9	38
3	3	8,4	1595	0,108	172	0,152	0,044	48	0,013	242	70,2	20,4	26
4	4	9,5	3207	0,051	164	0,098	0,029	13	0,017	314	93,0	55,7	16
5	5	11,2	5907	0,024	142	0,063	0,015	27	0,006	372	88,6	35,0	9
6	6	13,0	9873	0,012	118	0,038	0,017	5	0,020	375	167,8	193,0	5
Weighted average			785			0,133	0,090		0,090	104	71,0	70,9	
Total				0,889	785								104
Yearly Production [MWh/y]										915			
Load factor [-] (400kW installed capacity)										0,26			

Performance from simulated sea trials of a tidal turbine (based on [ref. Bahaj et al 2007] scaled to R = 10m, RPM = 60)												
Environmental parameters					Non-dimensional parameters				Performance parameters			
Zone	U	P_{avail}	Prob	P_{avail}xProb	η	s	n	CI	P	s	CI	P.Prob
	[m/s]	[kW]	[-]	[kW]	[-]	[-]	[-]	[-]	[kW]	[kW]	[kW]	[kW]
1	1	161	0,206	33	0,323	0,223	21641	0,003	52	35,9	0,5	10,7
2	1,5	544	0,157	85	0,435	0,133	16465	0,002	237	72,5	1,1	37,1
3	2	1291	0,107	138	0,419	0,080	11238	0,001	541	103,5	1,9	57,8
4	2,5	2521	0,068	173	0,365	0,045	7204	0,001	919	114,6	2,6	63,0
5	3	4356	0,041	177	0,295	0,022	4284	0,001	1286	95,0	2,8	52,4
6	3,5	6917	0,017	117	0,225	0,009	1776	0,000	1554	63,9	3,0	26,2
Weighted Average		723			0,342	0,106	6	0,106	247	76,7	76,6	
Total			0,595	723								247,1
Yearly Production [MWh/y]									2.166			
Load factor [-] (2,2MW installed capacity)									0,11			

Note that the turbine used in Table 4 has a cut-in and out speed range of 0.75-3.75 m/s.

Table 3 and 4 state the environmental parameters, the non-dimensional performance and the performance parameters of one device at the location of interest. It states the values independently for every zone and the weighted average or total value over the several zones. In addition the yearly converted or produced energy and the load factor for one device is given. These are defined and calculated as such:

- The 'Non-Dimensional Performance' η is the ratio between the converted power at the stage of consideration, e.g. power supplied to the grid, and the available power resource P_{avail}, e.g. P_{wave}, for the given power capture width or area. This is given individually for every zone and a weighted average should be calculated in order to give a overall value for the whole year:

$$\eta_{zone} = \frac{P_{zone}}{(P_{avail})_{zone}} \tag{6}$$

$$\eta_{Overall} = \frac{\sum_{zone=1}^{n} (P_{avail})_{zone} \cdot Prob_{zone} \cdot \eta_{zone}}{\sum_{zone=1}^{n} (P_{avail})_{zone} \cdot Prob_{zone}} \tag{7}$$

- The 'Converted Power' P is the average converted power when the particular environmental parameters describing of a zone occurs, e.g. the tidal velocity or characterizing wave height and wave period. It corresponds to multiplying the non-dimensional performance of the device by the average available power resource in that particular zone, e.g. P_{wave} for a zone,:

$$P_{zone} = (P_{avail})_{zone} \cdot \eta_{zone} \tag{8}$$

- The yearly average converted power is the sum of the yearly average converted power of every zone. From this yearly average converted power, the yearly total converted energy or energy production can be calculated by multiplying it with the amount of hours in a year.

$$P_{yearly\ average} = \sum_{Zone=1}^{n} P_{zone} \,.\, Prob_{zone} \tag{9}$$

$$Yearly\ converted\ energy = \mathrm{P}_{\text{yearly average}} \cdot \frac{8766}{1000} \tag{10}$$

- The 'Load Factor' represents the yearly average usage of the installed capacity.

$$Load\ factor = \frac{P_{yearly\ average}}{P_{installed}} \tag{11}$$

2.6 Fine-tune the model

2.6.1 Adjusting the zoning

As some zones might be short of data points or when more data becomes available, the selected zones might have to be adapted in order to include more or less data points. A lack of data points in certain zones might require to enlarge the zones while abundance might enable the reduction in size of them, making the performance statement more specific.

Developers are free to choose the amount and size of the zones as long as the confines are respected – a zone should not represent more than 20% of the yearly average power resource and it should include a number of points appropriate to the assessed variability of the occurring sea-states. However, as they are directly linked to the accuracy and confidence interval of the performance statement, they should be chosen carefully.

2.6.2 Introduction of new data

The performance of the device observed in the sea trials will often be investigated as soon as an acceptable amount of data is available. However, the sea trials can proceed for a longer period resulting in new performance data. This data might overlap or complement the initial data by having similar or different sea-state parameters and performances. Together with this new available data, the selection of the performance data and setup of the zones should be repeated.

This should result in the reduction in size of the zones and/or of the confidence intervals.

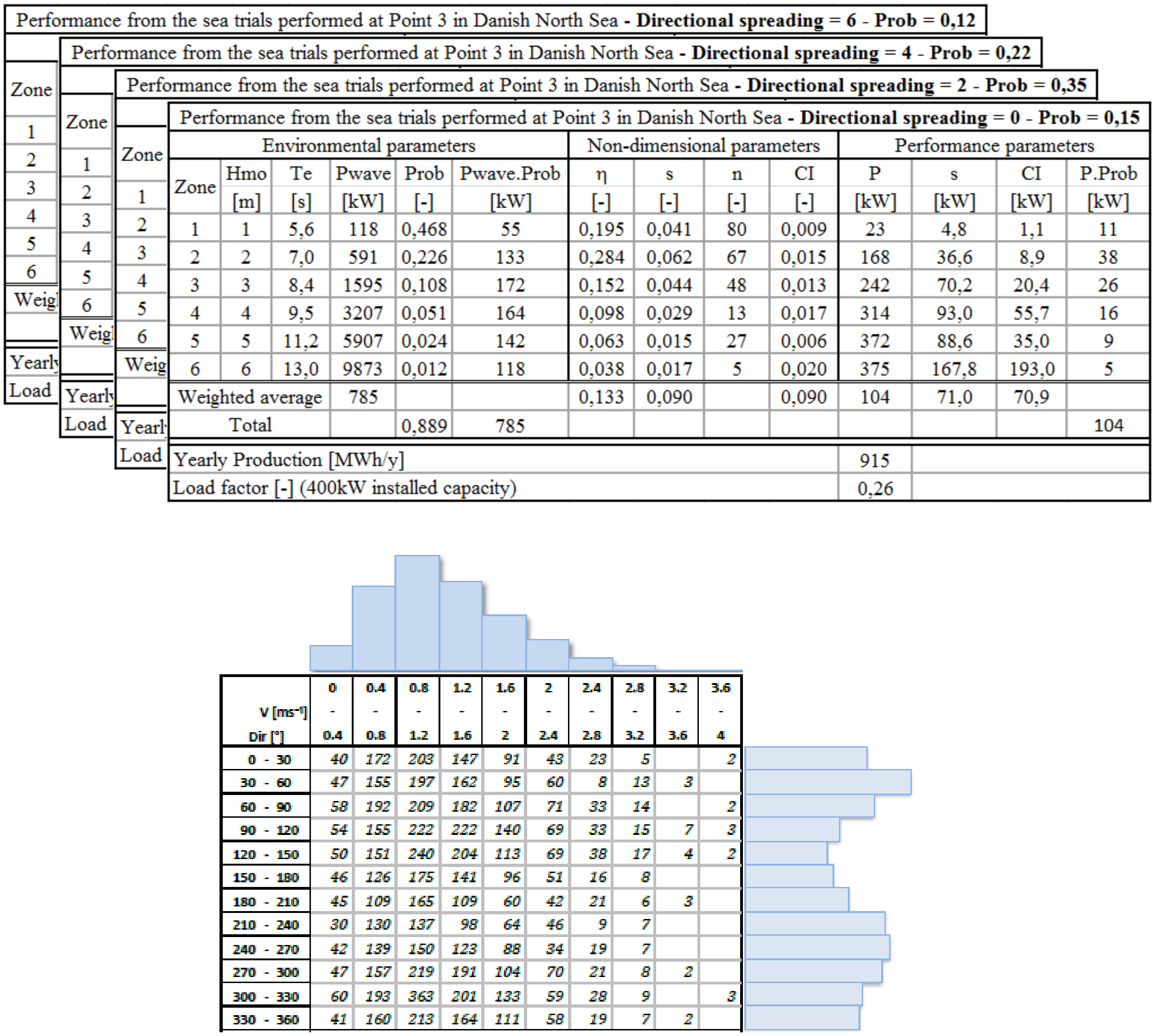
2.6.3 Application of the procedure for different conversion steps

Besides presenting the performance in terms of electricity production it can be useful to present the performance of one or more intermediate conversion steps. An intermediate conversion step might be more representative, especially in the case of a pre-prototype scale device where the Power Take-Off subsystem does not exactly reflect the full-scale situation, and it might be a helpful tool to investigate the power conversion efficiency throughout the process. Significant differences in behaviour between the different conversion steps might reveal interesting features of the device and indicate areas requiring improvement.

2.6.4 Include more environmental parameters

The inclusion of more parameters in the performance table will make it more specific and could characterize the dependency of the device towards additional variables. This can especially be useful to state advantages of a certain device or to emphasize more specifically the performance under more detailed sea-state parameters at a location of interest. Numerical work would be recommended to determine the sensitivity of the device performance to the parameter in question, in advance of proving trials.

It is suggested to maintain the same reference parameters, e.g. tidal velocity or characterizing wave height and wave period, and to add a new constraint to the data. It would be comparable to 3-dimenisionalising the scatter diagram by taking a new parameter into account. For every value or range of values of this parameter, a new basic scatter diagram arises with complimentary data points, resulting in multiple performance tables, each being dependent on the new considered parameter. The fine-tuning of the zones of each diagram can be done independently and so finally the performance of the device can be given more accurately, together with the dependence on each individual variable.



Performance from the sea trials performed at Point 3 in Danish North Sea - **Directional spreading = 6 - Prob = 0,12**

Performance from the sea trials performed at Point 3 in Danish North Sea - **Directional spreading = 4 - Prob = 0,22**

Performance from the sea trials performed at Point 3 in Danish North Sea - **Directional spreading = 2 - Prob = 0,35**

Performance from the sea trials performed at Point 3 in Danish North Sea - **Directional spreading = 0 - Prob = 0,15**

Environmental parameters						Non-dimensional parameters				Performance parameters			
Zone	Hmo [m]	Te [s]	Pwave [kW]	Prob [-]	Pwave.Prob [kW]	η [-]	s [-]	n [-]	CI [-]	P [kW]	s [kW]	CI [kW]	P.Prob [kW]
1	1	5,6	118	0,468	55	0,195	0,041	80	0,009	23	4,8	1,1	11
2	2	7,0	591	0,226	133	0,284	0,062	67	0,015	168	36,6	8,9	38
3	3	8,4	1595	0,108	172	0,152	0,044	48	0,013	242	70,2	20,4	26
4	4	9,5	3207	0,051	164	0,098	0,029	13	0,017	314	93,0	55,7	16
5	5	11,2	5907	0,024	142	0,063	0,015	27	0,006	372	88,6	35,0	9
6	6	13,0	9873	0,012	118	0,038	0,017	5	0,020	375	167,8	193,0	5
Weighted average			785			0,133	0,090		0,090	104	71,0	70,9	
Total				0,889	785								104
Yearly Production [MWh/y]										915			
Load factor [-] (400kW installed capacity)										0,26			

V [ms^{-1}] Dir [°]	0 - 0.4	0.4 - 0.8	0.8 - 1.2	1.2 - 1.6	1.6 - 2	2 - 2.4	2.4 - 2.8	2.8 - 3.2	3.2 - 3.6	3.6 - 4
0 - 30	40	172	203	147	91	43	23	5		2
30 - 60	47	155	197	162	95	60	8	13	3	
60 - 90	58	192	209	182	107	71	33	14		2
90 - 120	54	155	222	222	140	69	33	15	7	3
120 - 150	50	151	240	204	113	69	38	17	4	2
150 - 180	46	126	175	141	96	51	16	8		
180 - 210	45	109	165	109	60	42	21	6	3	
210 - 240	30	130	137	98	64	46	9	7		
240 - 270	42	139	150	123	88	34	19	7		
270 - 300	47	157	219	191	104	70	21	8	2	
300 - 330	60	193	363	201	133	59	28	9		3
330 - 360	41	160	213	164	111	58	19	7	2	

Figure 3: Illustration of taking another environmental parameter into account, resulting in several performance tables each dependant on a different value of a third parameter (top) or a 2D environmental matrix for tidal velocities and bearings (down).

These different tables can then be summarized in an overall table taking the probability of occurrence of this third environmental parameter into account. Possibilities for this additional environmental parameter, which can have an influence on the marine energy conversion device, could be:

- Water current speed and direction
- Water depth
- Wave spectral shape (sea-state frequency mix)
- Wave directionality (angle of attack of the incoming wave)
- Directional spreading of the waves
- Wind speed and direction
- Hub depth for tidal devices

More device related parameters could also be introduced in order to investigate their effect on the performance, e.g. physical modifications of the device or the use of different control strategies.

3 Performance at another target location

3.1 Applying the new Environmental Matrix

When moving to a different location, the following procedures must be followed if it is intended to use data from other sea trials in the estimation and presentation of the performance:

- Report the other sea trial data (η) related to the specific zones on the new scatter diagram. The representative environmental parameters should be scaled to the same factor that the geometrical dimensions of the device would be scaled for that new location.
- Define a new zoning of the scatter diagram based on the new power-probability (P_{avail}.Prob) and data points at location, maintaining the requirements stated in section 2.
- Estimate which of the zones does not comply with the requirement of minimum number of data points necessary to have a reliable estimation of the performance (section 2.2): highlighting the "blank" zones.

Note that the scaling of the environmental parameters and of the device do not relate on the same way for tidal and wave energy converters. For wave energy converters, the scaling of the geometrical dimensions of the device and of the environmental parameters follows the Froudes Model Law. For tidal devices this is more complicated as different laws might be relevant, e.g. for near to full scale prototypes, Reynolds scaling is required in order to adequately scale the hydrodynamics forces and Froudes law scaling may be required to scale structural and free surface effects.

In order to cover "blank" zones, the use of numerical models should be considered.

The following Figure 4 illustrates the scaling of data and the selection of zones. Although the example is for a wave device, the process is identical for tidal devices. In the top left figure, the original performance data that was collected at an intermediate scale benign site is superposed on the underlying scatter diagram, which presents the location of interest for the deployment of the full-scale device. The acquired data can be up-scaled, in this case 4.5:1, according to the planned device full scale size (which generally should fit the scatter diagram at this location), as can be seen in the top right figure. Based on this up-scaled values and the scatter diagram of the location of interest a new zones can be done selected, following the requirements (Figure 4 bottom left). It can be observed that the scaled data points do not cover entirely the new scatter diagram, resulting in uncovered areas. The performance of these "blank" areas, which are marked with rounds on the bottom right Figure 4, could not be identified by the sea trials but a validated numerical tool could be considered here.

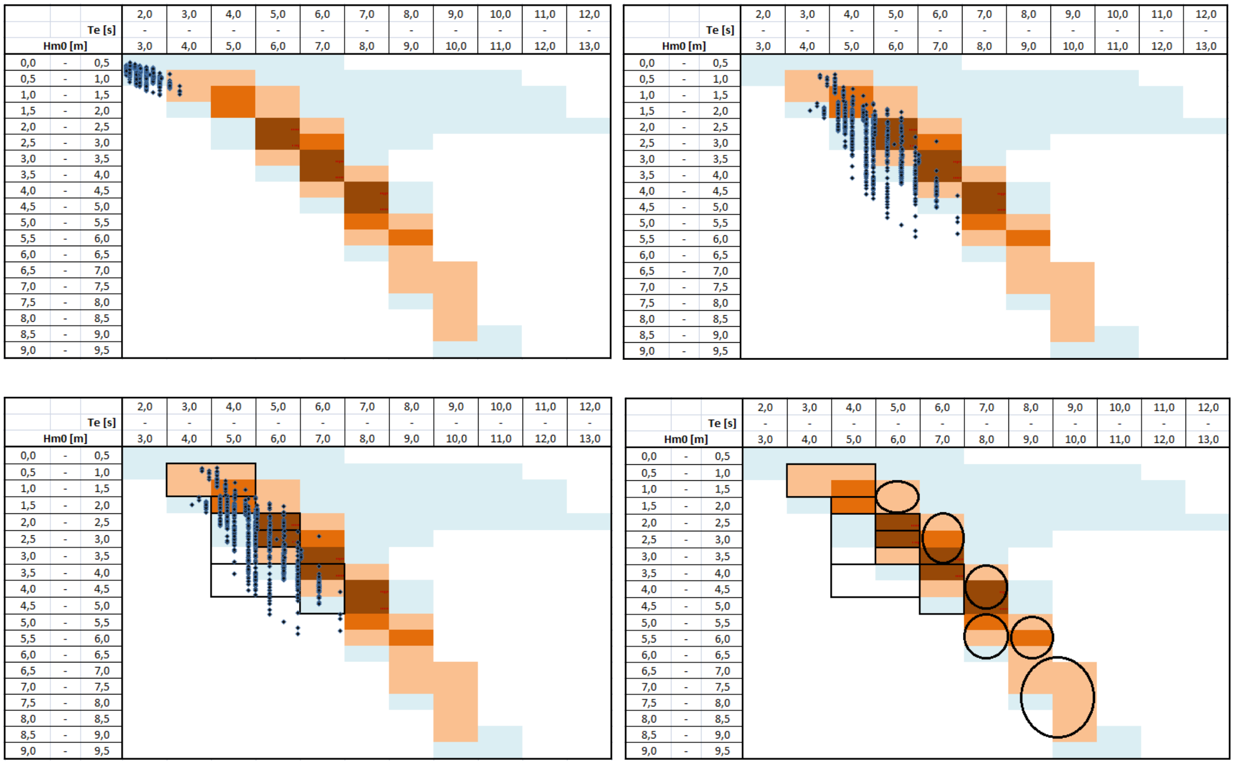


Figure 4: The wave parameters from the original sea trial site are scaled up (4.5:1) to fit the environmental climate of the LOI, and a new zoning and the identification of blank zones is performed. The intensity of the background colour illustrates the approximate average yearly contribution in wave power (P_{wave} . Prob) of the corresponding wave parameters. (This example is based on illustrative values)

3.2 Complementing the sea trial data

Numerical models might be used in connection to sea trials in case the data from the sea trials is not sufficient to cover all zones of interest of the scatter diagram. This can occur due to one of the following conditions:

1. After a sea trial with missing/not-occurring sea state parameters.
2. After sea trials where one or more sensors are not functional.
3. When changing location and/or scale.
4. When passing from lower to higher discretization of the scatter diagram.

Validated numerical model predictions or empirical tank testing results can be used to extend the cover of the power matrix.

The blank zones can be treated either with a simple extrapolation of results from previous measurements in a different location and therefore with an associated confidence interval related to the specific zone, or with numerical models.

In the second case, the numerical model must be calibrated around the single real sea measurements (best results) and the accuracy of the model after implementation over the entire population of available data must be stated.

Nevertheless the accuracy of the numerical models is hard to track. It would be useful to specify in which areas of the scatter diagram the calibration of the model has been performed: indication as to whether it is spread all over the diagram or regards only some specific zones (likely in the case of scaling).

Table 5: Performance table complemented with numerical model data (Based on illustrative values)

Performance from the sea trials performed at *Point 3 in Danish North Sea*														
Environmental parameters						Non-dimensional parameters					Performance parameters			
Zone	H_{mo}	T_e	P_{wave}	Prob	$P_{wave.}$Prob	η	s	n	CI	ηnum.*	P	s	CI	P.Prob
	[m]	[s]	[kW]	[-]	[kW]	[-]	[-]	[-]	[-]		[kW]	[kW]	[kW]	[kW]
1	1	5,6	140	0,34	48	0,195	0,025	27	0,010		27	3,5	1,3	9
2	2,2	7,2	871	0,25	221	0,268	0,041	80	0,009		233	35,7	7,9	59
3	3,1	8,4	2018	0,12	234	0,192	0,042	67	0,010		387	84,8	20,6	45
4	3,8	9,1	3285	0,08	256	0,152	0,031	13	0,019		499	101,8	56,2	39
5	4,5	10,2	5164	0,06	315	0,121	0,033	48	0,010		625	170,4	48,9	38
6	5,5	11,5	8697	0,03	270	0,052	0,021	3	0,039	0,065	565*	-	-	18*
7	6,5	14,2	14999	0,02	225	0,010	-	1	-	0,021	315*	-	-	5*
Weighted average			1569			0,136					213*	-	-	
Total				0,90	1569									213*
Yearly Production [MWh/y]										1820*				
Load factor [-] (650kW installed capacity)										0,33*				

* Values derived from numerical calculations should be marked and specifications regarding how they have been obtained have to be provided.

Table 5 illustrates how the data obtained at one specific location can be used to estimate the performance at another location of interest. In this example the new location of interest is slightly more energetic; therefore a small up-scaling is required for the device, e.g. 1:1,10. As the higher wave conditions did not occur in the reference location, insufficient data is available for the zones representing the greater wave conditions. The non-dimensional performance of the zones not respecting the limit of minimum required data points are marked in red. Their performance values are in this case substituted by the numerically calculated values, marked in green.

4 Marine energy resource and power output uncertainty

4.1 Marine energy resource and conversion characteristics

Contrary to the main conventional large hydro, thermal or nuclear energy sources, tidal and wave energy will produce a variable power output due to the nature of their energy source. This is the same as for the other main renewable sources, wind and solar energy. However, although these renewable energy sources are caused directly or indirectly by the sun or the moon, their variability and predictability is very different.

4.1.1 Tidal energy

Tidal current velocities vary normally from a minimum to a maximum and back two or four times a day, depending if the site experiences a diurnal or semi-diurnal cycle, or even a combination of the two. The absolute maximum and minimum velocity values depend on the location and tidal cycle, if it is Spring or Neap tide. The tidal velocities are predictable and they are also notionally bi-directional, although not necessarily parallel. The output of tidal power systems can be predicted accurately years in advance, allowing future electricity output to be known and seasonal variations are extremely low. At a monthly level, variability is similarly limited by the averaging of output across two Spring-Neap tide cycles. A full lunar cycle (28 days) is often a minimum requirement for validation and extrapolation of the tidal resource using harmonic analysis.

Whilst the use of harmonic tidal constituents can often give extremely accurate predictions of tidal velocities there are a number of factors that can lead to variability between measured and harmonic (predicted) data. These include:

- Local bathymetry effects - changes in speed and direction
- Exposed nature of site – increasing likelihood of significant wave motion
- Seasonal metocean conditions – storm surges etc.

For this reason sea trials should aim to operate over the more aggressive winter months in order to acquire this valuable device performance data.

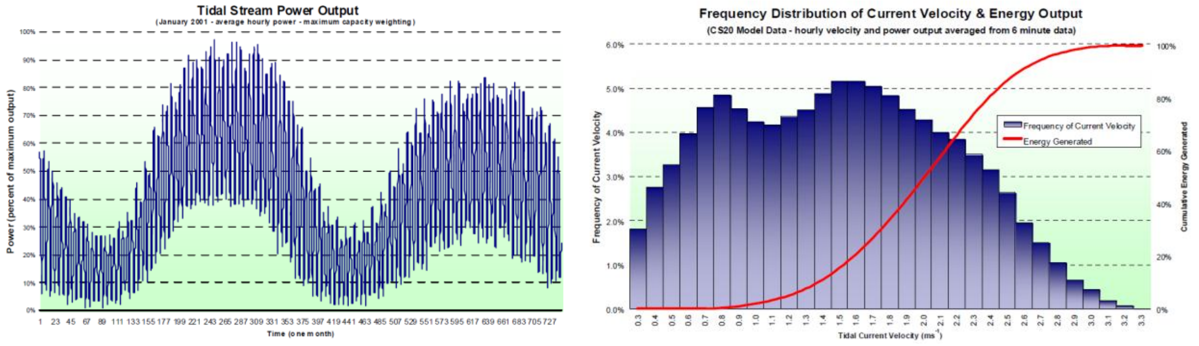


Figure 5 & 6: Illustration of a possible tidal stream power output and its frequency distribution in matters of velocity and power (Based on Sinden G.,2005).

A semi-diurnal pattern of tidal power occurs on approximately a 24hr 50min cycle (12hr 25min for an diurnal cycle), while the general pattern of demand variability occurs on an exact 24 hour cycle. This involves the relationship between hourly change in demand and tidal supply levels to change constantly.

Fast flowing tidal currents, although predictable, are notoriously turbulent. The velocity can temporarily reverse direction, increase to double its expected value or drop to zero, before fluctuating in the opposite direction moments later. Further complications arise due to unexpected flow phenomena such as flow direction variation within the water column and flow configurations influenced by the local bathymetry. A degree of filtering and time segmentation is anticipated in order to obtain the averages required for the construction of scatter diagrams

4.1.2 Wave Energy

Wave power is an intermittent energy source that shows variability at a number of different time scales, from the order of a couple of seconds (wave period) up to seasonal and inter-annular variations, and is dependent on the location. The location influences the different levels of availability and short distance differences (smaller than a wavelength) can cause a phase shift to the instantaneous available energy. A nearby located wave measuring buoy is required to predict the short term power variation. However its longer term predictability is decent but limited to maximum a couple of days in advance. The longer the forecast period the more uncertain the accuracy of the prediction is.

The wave power is primarily dependant on the wave height and secondarily the wave period. However, the wave spectrum, the directionality of the waves and other environmental parameters can have a significant impact on the performance of the device, especially resonant type WECs strongly influenced by the excitation force frequency.

The short-term variability of the output characteristic depends on the wave climate and on the working principle device, from wave-to-wire. The primary conversion step from wave to useful energy (potential energy, compressed hydraulics, etc.) can accentuate or smooth out the intermittent characteristic of the wave power. High peaks in the power output will have to be smoothened out as they could present difficulties for the integration of the device into the electricity networks. This can be done by incorporating an energy storage system directly into the device (e.g. electrical batteries, capacity filters, hydraulic accumulators, flywheels and others) and /or by relaying several devices, having alternating power peaks. As a rule of thumb, a good energy storage capacity would have a time spam of around 10 to 20 wave periods. For most intermittent renewable energy converters, the peak output of the device (i.e. the installed capacity) is generally around three times the long term average output.

At all sites the more energetic wave conditions have normally a relatively low probability of occurrence. Although still a vast amount of energy is available on a yearly average in these conditions, they are not the most suitable for energy production as their occurrence is low. However, the device requirements during these storm, or extremes, are extensive, particularly regarding the installed rated power and transmission lines since they are significantly larger than requirements based on the yearly average. It is in these periods that the device will produce the largest power peaks. Moreover, the survivability concerns might become predominant in these situations.

Wave power is subject to long term variation, as the annual and seasonal availability might differ significantly. In the UK, yearly variations up to 20% have been measured and the seasonal distribution can be in the order of seven between the output during winter months and that experienced during summer. This however can be beneficial from an electricity demand point of view, as general electricity consumption is larger in the winter.

Figure 7 & 8 show the level of uncertainty in the time history of the seaways at a location of interest, in these instances for the power flux and the approach directionality of the wave front.

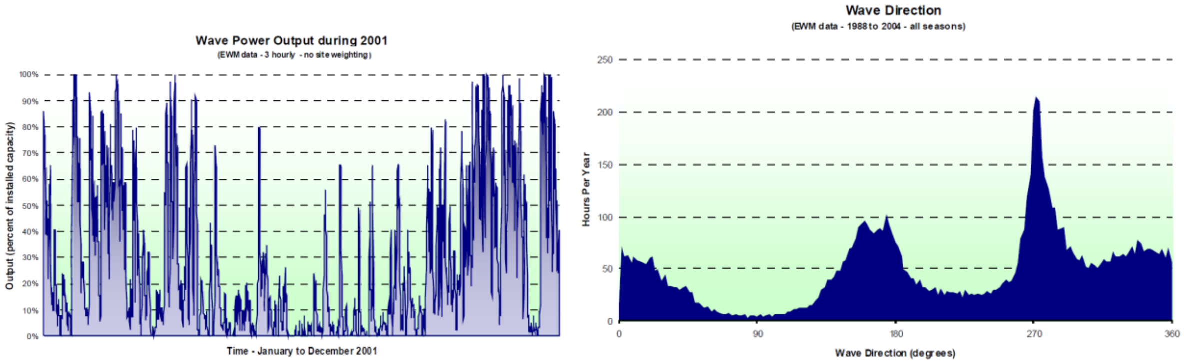


Figure 7 & 8: Illustration of the possible yearly distribution of wave power output and direction (Based on Sinden G., 2005).

4.2 Grid codes and power quality requirements

The rules governing the operation, maintenance and development of marine energy converters are stated in the Grid Code. They are normally specific for each technology or sector and region or country. They usually address issues concerning:

- Frequency / Power control
- Low/high frequency support
- Voltage support/reactive power compensation
- Power quality, flicker, harmonics
- Ramp rate
- Etc.

The electricity supplied by the device to the grid will have to comply with the Grid Code requirements.

5 Executive summary

This report has been written with the objective to describe a logical and widely-applicable method to analyze and present the data obtained from sea trials. It aims at presenting the obtained results from the sea trials on an uniform and clear form in order to indicate the uncertainty involved with the stated performance and to make the comparison between the performance of devices and the application of results to alternative locations possible.

As the sea trials will be performed in an uncontrollable environment and on devices that are undergoing development, it is expected that the obtained performances of the sea trials will exhibit large fluctuations. Moreover, all the possible environmental conditions might not occur during the period of the sea trials, as they are limited due to economical and/or technical restrictions. Therefore, it has to be expected that in most cases the sea trials will be incomplete or too short to state with high level of certainty the guaranteed performance of the device in all the possible environmental conditions.

The methodology described in this report, is applicable to a wide range of possible outcomes of the sea trials. It rewards cases where data is abundant and where the performance of the device for similar environmental conditions is consistent. However, it gives also the possibility for developers that did not obtain a lot of data or very consistent data, to state the results of their sea trials in an objective, documented and equitable way.

The obtained data from the sea trials is grouped into zones, depending on their abundance and their related environmental conditions. The average performance, together with associated standard deviation and confidence interval, is then calculated for every zone based on the performance of each data point that is included. The size of the zone is limited as it should not represent more than 20% of the available energy resource and it should include at least 5 data points. For more consistent performance results a lower standard deviation and confidence interval will be found, which can be further reduced by including more data points. Based on the performance in the individual zones, the yearly average performance, energy production and load factor can be calculated, together with their standard deviation and confidence interval.

The methodology can be applied at any of the intermediate transformation steps from the primary energy resource (e.g. wave or tidal) to power delivered to the grid.

6 References

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