Standardising resource assessment for wave energy converters

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Abstract

As the wave energy industry grows and begins to attract significant commercial investment, it is important that the industry begins to use generally accepted methods and procedures in order to increase industry and investor confidence. In response, the International Electrotechnical Commission (IEC) set up a Technical Committee charged with developing standards for the marine renewable energy sector (IEC/TC114). Subsequently, as one of its initial steps, the Committee created a project to develop a Technical Specification for the assessment and characterisation of wave energy resources. A Project Team including international experts from industry and academia with experience covering oceanography, engineering and wave energy technologies has been working towards this goal for the past two years. Although it is expected that this Technical Specification (TS) will continue to evolve as understanding of the wave energy resource and its relationship with Wave Energy Converters (WECs) develops, this paper details the main elements of the proposed wave energy Resource Assessment TS and explains the reasoning behind the specified methods and procedures. In addition, this TS's relationship with another TS specifying methods for assessing the Power Performance of WECs is also explained and illustrated using an example.

Keywords: Wave energy resource, standards, IEC

1. Introduction

An appropriate and accurate assessment and characterisation of the wave energy resource is fundamental to the development of the wave energy industry. This was recognised by the Marine Renewable Energy Technical Committee (TC114) of the International Electrotechnical Commission (IEC) who created a Project Team (PT) to develop an appropriate Technical Specification (TS). The Project Team first met in December 2009 and has met a further five times over the last 2½ years to produce the current draft Technical Specification. The Project Team includes members from both academia and industry with a wide range of backgrounds and knowledge, to help to ensure that the Specification remains appropriate for all potential users. Although individual sections of the Specification have been initially drafted by individual Project Team members, all sections have been reviewed and discussed by the Project Team at length and revisions made where they are considered to improve the Specification.

The Specification is now considered by the Project Team to have reached a point where it can be shared with the wave energy community in general to obtain feedback for further improvement. It is important when reviewing the proposed Specification to recognise that the industry is still young and it is therefore difficult to provide definitive guidance appropriate for all possible situations. It should also be recognised that the Specification needs to define procedures that are not overly burdensome for producers and users of wave energy resource data, whilst at the same time ensuring an acceptable level of data quality. However, it is also recognised that a resource assessment may be used to justify projects costing many millions of Euros, and so a relatively in-depth and detailed resource assessment is generally required. As far as possible the Project Team has tried to specify procedures in functional terms to allow different tools and methods to be used. This also means that the Specification should remain appropriate even when the specific tools and/or technologies used for wave energy resource assessment change over time.

The Project Team recognise that a relatively large number of wave energy resource assessments have been completed for a range of locations around the world [see for example 1-6, 7, 8]. Whilst it is not intended to question the quality of these resource assessments because they have not used generally accepted standardised procedures, it is difficult to assess their validity. The development of the Specification by the Project Team has focused on providing the significant benefits that can arise from standardisation. The first benefit is that the use of a clearly specified standard method reduces the potential ambiguity that arises in the absence of clear specifications. This in turn provides a greater level of confidence in the quality of the resource assessment, because ad-hoc and un-proven methods are not used. In addition, it means that resource assessments can more easily be compared. A second benefit is that the resource assessment can be defined in a manner that satisfies the requirements for estimating the power performance of wave energy converters. A third benefit is that standardisation provides a framework from which improvements in wave energy resource assessment can be structured. This should mean that developments in this field are more targeted at the requirements of the industry and the associated research requirements more easily identified.

It was decided early in the process that the Specification would primarily define the wave energy resource using data generated by numerical models that are validated using measured data.

The sophistication and power of modern hydrodynamic modelling tools such as SWAN [9], Mike21SW [10], TOMAWAC [11], etc. means that they are well suited for wave resource modelling. These tools are able to model the most important hydrodynamic processes that govern the growth and propagation of waves, and produce information on the full directional spectrum at any location in the model domain. In addition, because of the inter-annual variability of the annual average wave power, which can be as high as 30% [12], relying solely on 1-3 years of measured wave data would produce estimates with a high level of uncertainty. In many locations, ten years of wave data are necessary to provide reasonably certain estimates of the long term wave energy resource. Moreover, many common measurement instruments do not supply a full directional spectrum, which is considered important for a comprehensive assessment of the wave energy resource because of the potential influence of directionality on wave energy converter performance [13, 14].

This paper describes the main elements of the proposed Technical Specification with a focus on the underlying principles that have been adopted. It was decided early on that the Specification should accommodate three stages of resource assessment: *reconnaissance*, *feasibility* and *design*; and specify minimum requirements appropriate for each stage. These stages are described further in Section 2. Section 3 describes the generation and validation of the wave resource data, including how this is related to the stage of project development. Section 4 details the analysis of the wave resource data and its characterisation using two-dimensional spectra, parameterised sea-states and aggregated statistics. Section 5 discusses the calculation of uncertainty in the wave energy resource assessment. Section 6 then describes how the resource data are to be reported and combined with the Power Performance Assessment Technical Specification to produce an estimate of the average annual energy production for a wave energy converter. A final section discusses the status of the Technical Specification and identifies further work that would help to improve it.

2. The stages of wave energy resource assessment

The identification and development of a site suitable for the deployment of wave energy converters is an essentially iterative process. At the start of the process a large area, for example the west coast of Scotland, may be assessed, and a relatively high level of uncertainty may be acceptable as the primary objective is to identify the most promising regions in this area for future wave energy exploitation. As the process progresses, the primary objective shifts to project feasibility assessment and then to project design, and the resource assessment generally focuses on a smaller area and strives to generate more reliable, less uncertain estimates . This process is reflected in the Specification by defining three stages of resource assessment as shown in Table 1 below.

Stage	Uncertainty of mean annual wave power estimation	Typical long-shore extent
Site Reconnaissance	High	> 300 km
Project Feasibility	Medium	20 to 500 km
Project Design	Low	< 25 km

Table 1 - Stages of resource assessment

Although the stages are described in terms of a project development and typical long-shore extent this is only indicative. The appropriate stage of resource assessment is fundamentally defined by the degree of uncertainty that is required by the user. It will be noted in Table 1 that uncertainty is only defined qualitatively. This is a reflection of the

Project Team's view that there is currently insufficient understanding to produce a quantitative prediction of uncertainty in the assessment of the wave energy resource for each stage, although this is clearly a long-term goal. However, the Project Team have defined minimum requirements and methods that are expected to reduce the uncertainty of the wave energy resource assessment and associated these with the different stages of resource assessment.

3. Production of wave energy resource data

The Specification primarily defines the raw wave energy resource data using a time-series (hourly or 3-hourly) of directional spectra. The directional spectrum, together with other local factors such as water depth and marine currents provides all the necessary information to define the hydrodynamic conditions from which the power performance of a wave energy converter can be calculated. In many cases it is possible that a parameterised version of the resource data would be sufficient; however, maintaining the full directional spectra ensures that the maximum utility of the resource data is maintained. The Specification also states that a minimum of 10 years of data should be produced, which is considered the minimum amount of data required to produce a reasonable estimate of the average annual wave power (see Section 5).

As noted in the Introduction, the wave data used as a basis for the resource assessment shall be generated using a numerical model. The Specification does not define the model to be used, but does define the minimum set of hydrodynamic processes that should be represented in the model at the three different stages of resource assessment. Examples of the hydrodynamic processes that need to be modelled include bottom friction, white-capping, refraction, etc. Clearly, a numerical model that does not include representations of a required hydrodynamic process is not adequate for the resource assessment and therefore cannot be used. As would be expected, as the assessment stage progresses from *Reconnaissance* to *Design* there is a requirement for more hydrodynamic processes to be included in the model.

It has been recognised by the Project Team that in some cases particular hydrodynamic processes may have an insignificant impact on the wave energy resource and inclusion in the model only results in additional computational effort and cost. To account for this the Specification does allow hydrodynamic processes to be omitted, but only if it can be shown by sensitivity analysis or scientific reasoning that their influence is insignificant. As would be expected the measure of significance depends on the assessment stage and is defined as a percentage of the wave power and significant wave height. The wave resource can then be defined as insensitive to a particular modelling element if the percentage of sea states where the modelling element is found to have a significant influence is below a particular threshold.

The Specification also defines the minimum resolutions that may be used for the different resource assessment stages. The minimum spatial resolution also depends on both the water depth and the steepness of the seabed, which aims to ensure that wave propagation is correctly modelled. The minimum temporal resolution is defined as three hours for the *Reconnaissance* and *Feasibility* stages and one hour for the *Design* stage. This higher resolution at the *Design* stage is specified because of the short-term peaks in a sea-state that can be missed using a three hour time-step. The Specification also defines the minimum number of frequency components (25) and directional components (24) to use in the numerical modelling, which have been chosen to ensure that the spectral shape is adequately defined.

The Project Team recognized that predicting wave conditions within the surf zone is especially challenging, and for this reason the Specification recommends that the study domain be restricted to depths where depth-limited wave breaking rarely occurs. Guidance concerning modelling the near-shore wave energy resource is given in an informative Annex. The Project Team also recognized that an array of WECs may have considerable influence on the local wave energy resource. In this case, the effects of a WEC array on wave propagation may be simulated in the numerical modelling; however, the best methodology for doing so remains unresolved and so has not been specified explicitly.

Although the Specification provides relatively detailed guidance on what should be included in a suitable numerical model this is not intended as a substitute for experience in the construction and application of the numerical models used to produce the wave data. The flexibility of wave propagation models means that a skilled operator is always required and that care must always be taken to ensure that the numerical model used has the necessary features and is able to correctly reproduce the unique wave transformations over the entire study area.

The Specification requires that the numerical model is validated using measured wave data and that this data should be from locations close to where wave energy converters may be deployed. It is recognised that the accuracy of the numerical model output may not be constant and so the validation is limited to a region around the measurement location. The extent of this region is defined in the Specification by a maximum variation in the average annual wave power. Although this is not a true measure of the extent of validity, which is significantly more complex to define, it is expected to provide a reasonable indication of the extent of validity.

The wave parameters used to validate the numerical model shall include the significant wave height, the energy period and the wave power. The maximum allowable RMS error in the numerical model output for these parameters depends on the assessment stage and ranges from 30% (*feasibility*) to 10% (*design*). In addition, the Specification requires that the sea states used for validation include a full range of wave conditions at the measurement site. The required coverage of possible wave conditions is dependent on the assessment stage and defined by a minimum percentage of sea states represented by the validation data, using the omni-directional scatter table to define the representativeness of each particular sea state.

4. Analysis of the wave energy resource

The Specification requires that the model output be analysed, stored and reported in a specific manner to facilitate inter-comparison between studies, to avoid potential confusion arising from the use of different parameter definitions and reporting formats, and to ensure that the results are available for use in future studies. The numerical model output used to estimate the wave energy resource contains a vast amount of information, which requires organisation and analysis so that it can be stored in a convenient format. The Specification defines two basic structures for storing the wave energy resource data; the temporal variation at reference sites and the spatial variation over the study area. The Specification also defines a number of parameters derived from the spectral moments of the directional spectra that are considered to adequately characterise the sea state. The spectral moment of a discretized spectrum is given by Equation (1) below

$$m_n = \sum_i f_i^n S_i \Delta f_i \tag{1}$$

where

- S_i is the variance density over the i^{th} discrete frequency;
- n is the order of the spectral moment;
- m_n is the spectral moment of n^{th} order;
- f_i is the i^{th} discrete frequency;
- Δf_i is the frequency width of the variance density over the i^{th} discrete frequency.

The spectral moments can then be used to calculate the significant wave height, the energy period, the spectral bandwidth and the omni-directional wave power as given in Equations (2) to (5) below

$$H_{m0} = 4\sqrt{m_0} \tag{2}$$

$$T_{-10} \equiv T_e = \frac{m_{-1}}{m_0} \tag{3}$$

$$\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{m_{-1}^2} - 1} \tag{4}$$

$$J = \rho g \sum_{i,j} c_{g,i} S_{ij}\, \Delta f_i \Delta\theta_j \tag{5}$$

where

- H_{m0} is the spectrally estimated significant wave height;
- T_e is the energy period;
- ϵ_0 is the spectral width;
- J is the omnidirectional wave power;
- S_{ij} is the variance density over the i^{th} discrete frequency and the j^{th} discrete direction;
- $c_{g,i}$ is the group velocity of the i^{th} discrete frequency;
- ρ is the reference sea water density;
- g is the acceleration due to gravity;
- $\Delta\theta_j$ is the angular width of the variance density over the j^{th} discrete direction.

The Specification also requires the calculation of the maximum directionally-resolved wave power, the direction of maximum directionally resolved wave power and the directionality coefficient. Equations (6) to (8) defined these three parameters.

$$J_\theta = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j \cos(\theta - \theta_j)\delta \tag{6}$$

$$\begin{cases} \delta = 1, & \cos\left(\theta - \theta_j\right) \geq 0 \\ \delta = 0, & \cos\left(\theta - \theta_j\right) < 0 \end{cases}$$

$$\psi = \angle\{\max\left(J_\theta\right)\} \tag{7}$$

$$d = \frac{J_\psi}{J} \tag{8}$$

where

- J_θ is the wave power density resolved along the direction θ;
- θ is the direction of resolution;
- θ_j is the j^{th} discrete direction;
- δ is a factor insuring that only positive components are summed;
- ψ is the direction of maximum directionally resolved wave power
- J_ψ is the maximum directionally resolved wave power;
- d is the directionality coefficient;

A number of reference sites shall be selected such that the spatial variability of the study area is adequately represented. Because of the very large amount of data associated with the raw directional spectra this is only stored as a temporal variation for the reference sites. In addition, the temporal variation of the parameterised wave energy resource (as defined by Equations (2) to (8) are also stored for the reference sites. Finally, aggregated data in the form of monthly and annual scatter tables (omni-directional and directionally resolved) are required by the Specification, as well as monthly mean values of the sea state parameters and directional aggregations such as wave roses. These spectral parameters and aggregations are required by the Specification; however, many other parameters and aggregations exist. By requiring that the temporal variation of the directional spectra is stored these can be generated subsequently if the need arises.

The same spectral parameters, defined by Equations (2) to (8) are aggregated (monthly, yearly, etc.) and maps are prepared to show their spatial variation over the study area. Unlike the reference points there is a loss of data in this process and the Specification defines the minimum aggregated parameter maps that must be produced at each assessment stage. These aggregated parameters include the mean, standard deviation, 10^{th} and 90^{th} percentiles of the wave resource parameters. The parameters for which this is required include the wave power (onmi-directional and directionally resolved), the significant wave height, the energy period, the direction of maximum directionally resolved wave power and the directionality coefficient.

5. Estimation of uncertainty

Obtaining an estimate of the uncertainty of the wave energy resource prediction is essential to fully understand the resource and to provide proper context. The Specification separates the uncertainty into two types; aleatory and epistemic. The aleatory uncertainty is associated with the variability of the wave climate from year to year, and arises because the period chosen for numerical analysis may not be fully representative of the long-term wave climate. The epistemic uncertainty reflects the net effect of all errors inherent in the numerical modelling and arises because at any instant the model output may not be a completely accurate representation of the actual sea state.

The Specification suggests that a minimum of 50 years of data is used to calculate the aleatory uncertainty. It is recognised that it would be overly burdensome for this to be calculated specifically for the wave energy resource study and so it is acceptable to use other data from the region, either measured or modelled. The aleatory uncertainty is defined as the standard deviation of the *n*-year average wave power, where the average is calculated from consecutive years. It is important to recognise that this standard deviation is larger than the standard deviation of the 1-year average divided by the square root of the number of years due to correlation in the inter-annual wave climate. Figure 1 shows the average wave power at WaveHub from 1960 to 2000 [15]. It can be seen that even using a 5-year average the aleatory uncertainty is high. In this example the normalised standard deviation of the 10-year average is ±4.5%, which assuming a normal distribution means that there is a 95% confidence level it is within ±9.0% of the long-term average. This aleatory uncertainty is the primary reason why at least 10 years of data is required for the resource analysis.

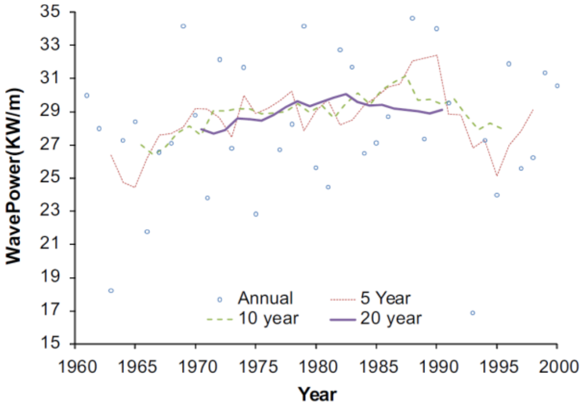

Figure 1: Variation in wave power at the WaveHub site 1960-2000 [15]

Estimation of the epistemic uncertainty is highly complex because it depends on many factors associated with the application of the numerical model. External sources of uncertainty include the boundary wave data, the wind field, the bathymetric data and the marine currents. Internal sources of uncertainty include the formulation of the model physics together with the temporal, spectral and spatial resolution. In addition, coupling between the factors that influence the epistemic uncertainty means that it is problematic to propagate the uncertainty through the model. Consequently, the Specification defines the epistemic uncertainty as the root-mean-square error obtained from model validation. It is recognised that the uncertainty is likely to vary with the sea-state and so the Specification requires that it is calculated separately for each cell in the scatter table. The epistemic uncertainty can be calculated for all parameters; however, the Specification only requires that it is calculated for the significant wave height, energy period and wave power.

6. Relationship to the IEC Technical Specification of Power Performance Assessment

It is clearly important that the *IEC Technical Specification of Wave Energy Resource Assessment and Characterisation* can be used in conjunction with the *IEC Technical Specification of Power Performance Assessment of a Wave Energy Converter* to produce an estimate of the mean annual energy production. The Power Performance Technical Specification defines a wave energy converter's power performance using a power matrix indexed by at least the significant wave height and energy period. The same document also defines a method for calculating the mean annual energy production that involves summing the power production of all sea states and dividing by the number of sea states, as given in Equation (9)

$$MAEP = \frac{8766}{n}\sum_{i=1}^{n} L_i J_i \qquad (9)$$

where

MAEP	is the mean annual energy production
n	is the number of sea states
L_i	is the capture length of wave energy converter in sea state i
J_i	is the power capture in sea state i

Because this Specification requires the significant wave height and energy period to be calculated for each sea state then it is clear that the resource assessment can be used directly in the calculation of the mean annual energy production. It is also possible, with the information produced following both specifications, to calculate the uncertainty of the mean annual energy production at any resource assessment stage, which is particularly important when looking at investment decisions.

7. Discussion and future work

It is difficult in an emerging industry to produce standardised procedures because there is generally a lack of experience that can be drawn upon. Although the science of wave modelling is well developed the requirements for wave energy projects differ from more traditional projects, such as oil rigs and breakwaters, so that this knowledge cannot necessarily be used directly. However, to achieve continuing investment in wave energy it is important that stakeholders have full confidence in the resource assessments that are developed; such confidence can be gained by following robust standardised procedures. In developing the Specification the Project Team has tried to develop robust procedures whilst maintaining flexibility to allow for developments in the industry (such as new wave modelling tools and measurement technologies) as well as in the understanding of the wave energy resource. Notwithstanding, there remain a number of areas where further work is clearly required.

A range of different methods are available for measuring waves, including buoys, acoustic dopplers, satellites and radars. Clearly, since measured wave data is to be used for validation of the numerical modelling, it is important that the measured data be highly accurate and reliable. However, for many of the wave measurement instruments in use today there is a lack of well-established and reliable procedures for verification and validation. Development of a common validation procedure is challenging because generating a pre-defined sea state against which the output of a wave measuring instrument can be compared is not practicable. It would be desirable for wave measuring instruments to be checked against a universally accepted standard measurement device, but unfortunately such a device does not currently exist. This is an area where further work is required.

The Project Team recognizes that in many locations, the accuracy of the wave modelling and hence the accuracy of the resource assessment will be limited by a lack of available good-quality boundary condition data (offshore directional waves, winds, currents and bathymetry). An excellent wave propagation model with lots of advanced physics cannot be expected to make up for sparse or inaccurate boundary condition data. Hence, in many regions, further work is required to improve the availability of, and access to high-quality boundary condition data, including directional wave spectra.

Quantification of epistemic uncertainty is also an area where further work is required. Calibration of a wave model is often viewed as a “black art”, where understanding how different parameters may influence the accuracy of the model is esoteric knowledge, often developed over many years of wave modelling practice. The diversity of bathymetries and wave conditions mean that it will never be possible to be totally prescriptive regarding the model requirements to achieve a particular accuracy; however, a better understanding of the key requirements and how they may be related to uncertainty could undoubtedly be developed.

Finally, it is inevitable that as the Specification is used it will be become apparent that some parts of it require modification, either to improve usability, to increase accuracy or to make it more appropriate. It is also possible that some parts will be found to be redundant and/or that there is a requirement for additional parts. It is intended that the Specification will in future be modified and improved in response to these findings. However, the current Specification, described in this paper is a necessary starting point for this development process, which hopefully the whole wave energy community recognises as vital for the continued advancement of the industry.

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