Assessment of Performance of Wave Energy Conversion Systems

Foreword

This document has been prepared in consultation with The European Marine Energy Centre Ltd (EMEC) and with other interested parties in the UK marine energy community. It is one of twelve publications in the *Marine Renewable Energy Guides* series, included in the following figure.

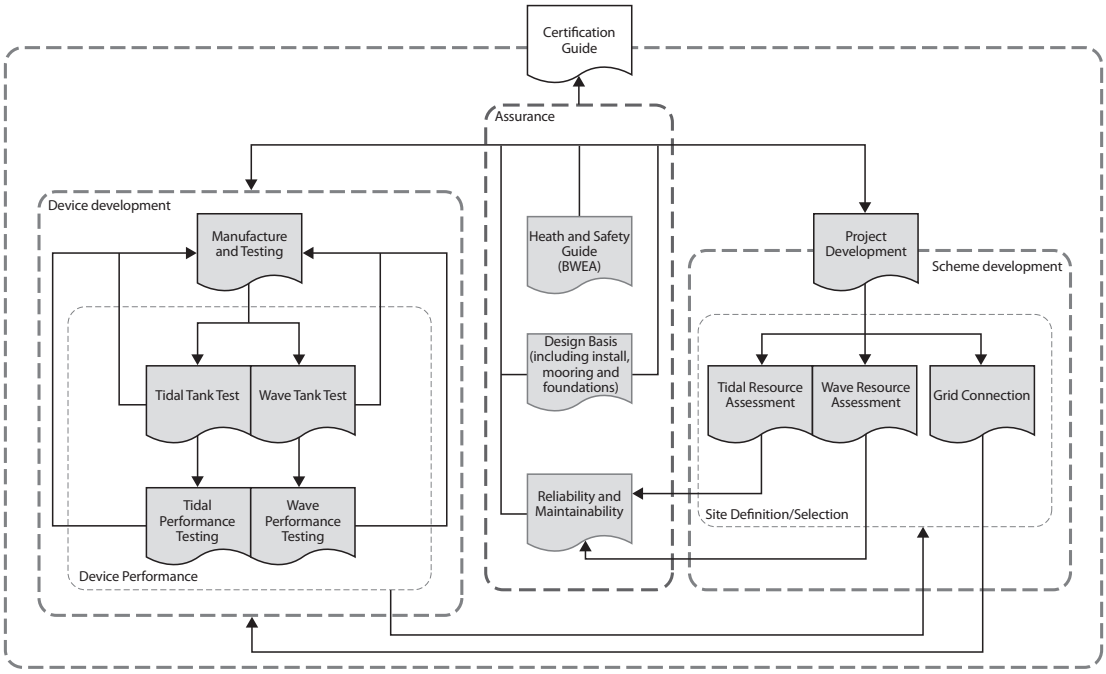

Figure 1 — Marine Renewable Energy Guides

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Marine Renewable Energy Guides

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EMEC ORKNEY™

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Introduction

This document outlines a methodology for assessing the performance of Wave Energy Conversion Systems (WECS) at open sea test sites. For the purposes of this document, a WECS is a system which generates electricity using the action of wind-generated waves and delivers that electricity to the shoreside grid by means of a cable connection.

The development of the wave power industry is at an early stage and very few data have been recorded by WECS in open sea conditions. As a result, this document is designated as in a developmental stage and will be subject to change as more data are collected and experience of testing WECS develops.

The purposes of performance assessment may be summarized as follows:

1. To provide an agreed methodology for the measurement of the power output of the WECS in a range of sea states.
2. To provide an agreed framework for the reporting of the results of these measurements.
3. To enable the estimation of the energy production of a WECS at a prospective site where wave power resource information of sufficient detail and quality exists.

The achievement of these aims will allow developers of WECS to demonstrate to potential operators that their systems meet their claimed performance. More generally, the development of rigorous and agreed performance standards will build the credibility of the wave power industry as a whole.

A primary aim of the testing procedure proposed in the document is that the performance results determined at the location of the tests should be *transferable* to the location at which the WECS will be installed for operational use. For WECS operating in deep or intermediate depth water this is achievable but for shore-line WECS and particularly for those built into structures such as breakwaters and harbour walls each installation is unique so that there may be limited value in testing at one location for subsequent use at another. In these cases this document may nevertheless be useful in investigating the performance of the WECS at the operational site. The results, while lacking strict transferability, will enable the assembly of a dossier of performance data for specific installations.

NOTE 1 The calculation of WECS productivity, mentioned in point 3 is discussed in Reference 2.

NOTE 2 Relationship of this document to the DTI Wave Protocol (see *Preliminary wave energy device performance protocol*, Reference 10) provides detailed instructions for both resource assessment and WECS performance monitoring for participants in the Department's Marine Renewables Deployment Fund. The Protocol is of great interest more generally to developers and operators of WECS although it is of necessity more prescriptive and narrowly focused than this document.

1. Scope

This document applies to floating WECS (compliantly moored and taut moored) and bottom-mounted WECS operating in all open sea resource zones.

It is not intended to apply to testing in enclosed tanks or test basins.

This document is aimed primarily at WECS which are post-prototype machines. That is to say they are at a stage of their development when it is possible to come to credible, quantitative conclusions about their performance. It may also prove useful in the testing of earlier versions of the technology, but that is not its main purpose.

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60068-8, *Power transducers*

IEC 60044-1, *Current transformers*

IEC 60044-2, *Voltage transformers*

3. Terms, definitions and symbols

For the purposes of this document, the following terms, definitions and symbols apply.

3.1 Terms and definitions

3.1.1
wave energy conversion system
generates electricity using the action of wind-generated waves and delivers that electricity to the shoreside grid by means of a cable connection

3.1.2
wavelength of principal component of wave climate
length of a sinusoidal wave with a period of Te_{peak} in the relevant depth

NOTE 1 This is intended to provide a length scale for the depth of deployment.

NOTE 2 Te_{peak} is the value of energy period at the peak energy part of the energy matrix for the site. An explanation of the energy matrix is given in Reference 1, Subclause 6.5.

3.1.3
wave power
time-averaged energy flux in a system of water waves

NOTE A derivation of power from the hydrodynamics is given in Reference 11.

3.1.3.1
unidirectional waves
time-averaged energy flux across a line of unit length which is parallel with the wave crests

3.1.3.2
multidirectional waves

3.1.3.2.1
omnidirectional (or gross) power
time averaged energy flux across a circle of unit diameter

3.1.3.2.2
directionally resolved (or nett) power
vector resultant of wave powers associated with all the component waves in the multidirectional wave field

NOTE 1 This is expressed as an energy flux per unit length normal to the direction of the resultant.

NOTE 2 In all cases, the measurement unit is kilowatts/metre (kW/m).

3.2 Symbols

f	Frequency
Δf	Frequency increment or interval
i	Index of frequency and spectral value
S_i	Spectral density of wave elevation variance at the ith frequency of the spectrum
P_i	Spectral density of power at the ith frequency of the spectrum
v_g	Group velocity
ρ	Density of seawater
g	Acceleration due to gravity
A_1, B_1, A_2, B_2	Normalized angular harmonics
θ_1	Mean direction
σ_1	Directional spread from first harmonics

σ_2	Directional spread from second centred harmonic
γ	Skewness of directional distribution
δ	Kurtosis of directional distribution
s_1	Spreading index from first harmonics
s_2	Spreading index from second harmonics
m_n	Spectral moment of order n
H_s, H_{m0}	Significant wave height estimated from the spectrum
T_z, $T_{0,2}$	Mean zero-crossing period estimated from the spectrum
T_e	Energy period
υ	Spectral width parameter
υ_p	Power-weighted spectral width parameter
P_{omni}	Omnidirectional (or gross) power
$Var(P)$	Variance of the estimate of power
D	Duration of sample
P_{nett}	Directionally resolved or nett power
θ_p	Power-weighted mean direction
UI	Unidirectivity index
P_{WECS}	Electrical power output of WECS
P_{SEA}	Sea state power (equal to either P_{omni} or P_{nett})

4. Test site

4.1 General

Waves are subject to a high degree of random variability and it is important that this is not compounded by systematic spatial and temporal variations due to the particular nature of the test site. In this regard the requirements for performance assessment may differ from the priorities during the production phase when a localized wave power maximum may be used to increase energy yield. For performance assessment purposes such small-scale 'hot spots' are undesirable in that they complicate the assessment process. The purpose of the provisions of Clause 4 is to identify conditions when significant systematic spatial and temporal variations of wave conditions can be expected. The action required in the light of this information is outlined in 4.7.

Systematic spatial variations are usually associated with bathymetric features with depths of less than one quarter of a wavelength, and with horizontal scales greater than a few wavelengths of the principal components of the wave power climate.

Systematic temporal variations are associated with strong tidal currents which affect the resource in at least two ways. They add to or subtract from the group velocity of the waves and thus affect the rate at which energy is transported. They may also lead to refraction of the waves and give spatial variation of the wave power. These effects become detectable when the current speed is an appreciable proportion (~10 % or

more) of the group velocity of the principal component of the wave climate. Such speeds will only occur at certain times of the tidal cycle at certain times of the lunar cycle and so the overall effect will be to increase the variability of the results.

4.2 Initial site selection

4.2.1 General

A preliminary review of prospective test sites should be undertaken. The prospective site should be well-exposed to the prevailing direction of the wave energy. The situation with regard to deeper water sites differs somewhat from shallower water sites and these are discussed in 4.2.2 and 4.2.3.

Once suitable sites have been identified, the initial selection may be followed up by more detailed investigations as specified in this clause.

4.2.2 Bathymetry of prospective deeper-water test sites

We refer to berths for floating WECS which would usually be on compliant moorings or possibly taut moorings in depths of order one half of the wavelength of the principal wave component. The depth should ideally be constant over the test area but in any case there should be an absence of bathymetric features which could lead to small-scale wave focusing or defocusing effects. Currents should be spatially uniform and of order 2 m/s maximum.

NOTE Deeper water sites have comparatively weak refraction effects. They should thus provide good performance assessment conditions and test results should be comparatively easy to interpret.

4.2.3 Bathymetry of prospective shallower-water sites

Here we are dealing with shallow water WECS which would usually be bottom-mounted or possibly on short taut moorings. The depth would in general be less than one quarter of the wavelength of the principal component. The depth is likely to be shoaling over the test area but ideally the bathymetry should be plane parallel. There should be an absence of bathymetric features which could lead to small-scale wave focusing or defocusing effects.

For shore line WECS at the operational (i.e. production) site, the accurate determination of the wave power at the position of the WECS may be difficult. It is suggested that a combination of modelling and measurements along the lines proposed in this clause could usefully form the basis of performance investigations.

NOTE Shallower water sites are much more influenced by refraction effects. If the bathymetry is 'plane parallel' and in particular if the depth depends only on the distance from the shoreline, the test results will be easier to interpret. For example, wave measurements made to the side of the WECS in water of similar depth can be directly used in the assessment. Wave measurements made in somewhat deeper water may require correction, but this can be accomplished with some confidence for simple bathymetry.

4.3 Bathymetric survey

A bathymetric survey of the area should be undertaken. The survey should extend over a wide area around the site, bearing in mind that its purpose is to provide a gridded bathymetry for local wave and current models.

NOTE The extent of the surveyed area and the design of the grid will depend on the type of modelling which is to be used. The grid should extend more than five kilometres in all directions around the WECS, or to the shoreline if this is within five kilometres of the WECS. For wave refraction models the grid cell size will be selected to resolve the salient detail of the bathymetry. For diffraction models several grid points per wavelength of the principal components should be used. The wave model grid should be adequate for the current modelling work as well.

4.4 Current measurements

Current measurements should be made at one or more locations in the test site area. The measurements should extend over at least 30 days. As a minimum, the measurements should be made at one level in the upper half of the water column. However, bearing in mind that their primary purpose is to help develop a tidal current model of the area, measurements at further levels would be advantageous.

The measurements should be analysed to give information about the main tidal constituents and also any non-tidal currents.

4.5 Tidal height measurements

Measurements of the tidal height should be made at the test site. The measurements should extend over at least 30 days and should be analysed to give information about the main tidal constituents and of any non-tidal variations.

NOTE For bottom-mounted devices in particular the depth is an important determinant of WECS performance. The measurements specified here will be used to predict the tidal height during the assessment programme.

4.6 Current modelling

In order to understand the spatial distribution of currents at the test site, it is recommended that a computer model of the currents be set up. In areas where tidal currents dominate this shall be a tidal current model, but for areas where there are significant non-tidal components of the current regime, these should also be considered.

4.7 Wave modelling

4.7.1 General

A series of runs of a competent wave transformation model should be carried out. The model should include the following physical processes as a minimum:

1. Sheltering by surface piercing obstructions;
2. Refraction by bathymetry;
3. Reflection by:
   i. Beaches;
   ii. Surface piercing obstructions;
4. Sea bed friction;
5. Wave-current interaction including refraction by currents;
6. Wave breaking and white capping.

The 'input' wave conditions shall be defined by a wave spectrum and also the state of the tide (see current modelling). The range of conditions (referred to the test site) is indicated in 4.7.2 to 4.7.6.

4.7.2 Wave spectrum

A recognized semi-empirical spectral formulation shall be used; examples are Pierson-Moskowitz, JONSWAP. A spectrum which is unimodal in frequency and direction would normally be adequate for these investigations. Very careful consideration should be given to the parameters of the spectrum, in particular, the degree of directional spreading.

4.7.3 Wave period

Runs should be carried out for values of Te corresponding to:

1. The maximum energy region of the expected energy matrix for the area, [2];
2. A representative long-period case, corresponding to the value of Te exceeded on 5 % of occasions.

NOTE The long-period case is to check the sensitivity of the site to refraction effects. If there appear to be strong effects at the long period selected, then runs at other (shorter) periods are to be made.

4.7.4 Wave height

Runs should be carried out for values of Hs corresponding to:

1. The maximum energy region of the expected energy matrix for the area;
2. A representative long-period case, corresponding to the value of Te exceeded on 5 % of occasions.

4.7.5 Wave direction

A representative range of wave directions shall be modelled.

4.7.6 Currents

Runs should be carried out for:

1. No-current conditions (slack water);
2. Maximum ebb at mean high water springs (MHWS);
3. Maximum flood at MHWS;
4. If the test site is in an area in which the current regime is dominated by non-tidal currents – a representative instance of non-tidal currents.

4.8 Pre-deployment wave measurements

In shallow water, for bottom-mounted WECS in particular, ascertaining the wave conditions at the site of the WECS during the assessment may be difficult. For this reason, a preliminary wave measurement programme should be carried out to verify the wave model and to compare conditions at the test measurement site and the projected WECS site. The object of this work is to derive a power transfer function between the two sites. Due to the inherent high variability of wave conditions, measurements should be made over several months, preferably in the winter.

4.9 Incorporation of site investigation results

4.9.1 Deeper water

The water depth would generally be greater than one quarter of the wavelength of the principal wave component. If strong systematic spatial or temporal variations are predicted by the modelling investigations, the site is probably not suitable for assessment purposes and another site should be sought.

4.9.2 Shallower water

This would usually apply to bottom-mounted or taut-moored systems in water whose depth is less than one quarter of the wavelength of the principal wave component. The challenge is to know the wave power at the position of the WECS. The wave measurements should of necessity be made some hundreds of metres away in the direction from which the wave is coming, or to the side of the WECS. In the former case the wave measurements would in general be in deeper water, while in the latter the depths would in general be similar. If the modelling investigation of 4.7 or the measurements of 4.8 show spatial changes between the positions of the wave measurements and the WECS which exceed 5 % in power a correction should be made.

5. Measurements – general considerations

5.1 General

Performance assessment consists of making sample measurements of the power in the wave field and of the resulting electrical power output of the WECS. This clause gives the ground rules for this operation; further details applicable to respectively WECS power measurements and wave measurements are given in Clauses 6 and 7.

The determination of the wave power for performance assessment purposes is part of the more general topic of wave power resource assessment. The guideline document *Assessment of wave energy resource* [1], should be read in conjunction with this clause.

5.2 Method of comparison

5.2.1 General

The WECS and the wave measuring instrument should be sited in an area where the site investigations have shown that there are no strong systematic spatial changes of wave power or current. They should thus, in principle at least, be subject to the same wave field, but because the individual wave phases are randomized, the statistical treatment shall be based on the comparison of samples from two random processes (see Clauses 7 and 9).

If the investigations of Clause 4 indicate that there are systematic differences between wave conditions at the site of the WECS and the site of the wave measurements, due allowance should be made for these differences in the assessment process.

The placement of wave measuring instruments is specified in 7.3.

5.2.2 Duration of testing programme

It is difficult to give hard and fast guidance on the duration of a performance test. Consideration of the following points may nevertheless be helpful:

- Enough data are needed to provide acceptable accuracy over that region of the energy matrix for the site which is considered to be important by the developer and/or the operator of the WECS;
- The testing process may be complicated by sensitivities to parameters other than Hs and Te;
- The test should be carried out over a period when the range of bins on the wave scatter diagram that describe the WECS operating envelope are likely to be adequately populated.

NOTE 1 An estimate of the variance of individual samples of the capture length is given in the Note at 9.4. This is an initial estimate and should be refined as more data become available.

NOTE 2 The sensitivity of WECS to parameters other than Hs and Te is discussed in 9.2.

NOTE 3 The effect of uncertainties in the capture length matrix on calculations of productivity are discussed in *Assessment of wave energy resource* [1].

5.3 Sample duration and frequency

Ideally, each sample should be one hour long, and the sample start times should be separated by one hour. This is considered to be a good compromise between the conflicting requirements for statistical stability and for adequate representation of changes in the underlying conditions. Note that this scheme makes use of all the data that can be recorded. Further discussion of sampling schemes is contained in Reference 3, where it is proposed that the basic recording unit is one half hour, with these being averaged two at a time to provide the final one-hour samples which are to be used in the performance calculations.

5.4 Simultaneity

The samples of power from respectively the WECS and wave measurement system should ideally be within 15 minutes of each other. However, in the interests of capturing as many data as possible this requirement may on occasions be relaxed so that the records may be considered simultaneous if their start times are within one half hour. In cases where one of the pair of records is missing, the allowable time-slip may be further extended to one hour if this captures a replacement valid sample; see 7.1 and its note for a discussion of the statistical background to this requirement.

5.5 Data recording

5.5.1 General

The data shall be recorded or consolidated in files each of which shall contain data and/or no-data records for one calendar month. The monthly data files shall consist of a header and a number of data and/or no-data records (744 for a 31-day month). The use of a calendar month as the basic archive unit is not a fixed requirement, but has been found to be convenient.

The header shall contain details of the measurement, processing and recording of both the wave and WECS data. The documentation should be sufficiently comprehensive to ensure the intelligibility of the data to all interested parties.

The data records shall be derived from nominally one hour long digital samples of respectively the wave conditions and the output power of the WECS.

Each record shall be stamped with the time of the start of the sample.

Each record shall be annotated with quality control flags giving the results of the quality control checks carried out during the recording and analysis path.

A sequence of nominal times shall be maintained and the wave data and WECS power records shall be ascribed to the nearest nominal time in their respective sequences. A missing record shall be generated for each nominal time in each sequence which is greater than one half hour from the nearest data record.

Suitable recording formats include plain ASCII which may be organized as Net-CDF.

The data content for respectively the WECS power records and the wave records are summarized in 5.5.2 and 5.5.3 and specified in detail in Clauses 6 and 7.

5.5.2 Wave energy conversion system data

Each sample shall consist of a time history of measurements of output electrical power in kW, or of such quantities as are required to calculate it. The average power and its standard deviation over the sample shall be calculated and recorded. The maximum and minimum values shall also be recorded.

Some further details are given in Clause 6.

5.5.3 Wave data

The directional spectrum of each sample should be recorded in the form given by pitch-roll buoys and equivalent systems, i.e. a frequency listing of the principal observables. The frequency listing shall ideally cover the range 0.04 Hz to 0.5 Hz, although some variation of this range may be necessary depending on the measurement system. Some measurement systems give the directional spectrum as a function of vector wavenumber on a kx,ky grid. It is suggested that these spectra are converted into the form of a frequency listing.

In addition to the variance spectrum a number of other derived quantities should be recorded, including:

- Power spectrum. A listing by frequency of the power per unit frequency (kW/m/Hz). This quantity can be included in the directional spectrum listing.
- Omnidirectional or gross power. Scalar sum of power over frequency (kW/m).
- Directionally resolved or Nett power. Vector sum of power over frequency (kW/m).
- Average power direction (degrees from true north).
- Hs, Tz, Te derived from the spectrum.

Further details are contained in Clause 7.

6. Wave energy conversion system power output measurements

6.1 General

The WECS output power (nett of system energizing power and of any power generated by on-board ancillary generators) shall be measured at a point where it is in the form of AC at network frequency. The primary requirement is the average output power (and its standard deviation) of the WECS over the one-hour sample. However, to facilitate more detailed study of the characteristics of the WECS power, the time series of power should be recorded once every 24 hours. The power shall be digitized at 2 Hz, the power signal having been subjected to a suitable anti-aliasing filter. The maximum and minimum of the 2 Hz values to occur in each one-hour sample shall be recorded in addition to the mean and standard deviation.

6.2 Definition of the wave energy conversion system for electrical export purposes

Ideally power output should be measured at the output terminals of the WECS, however, some WECS use electronic power converters that are external to the WECS itself but should be considered as a part of it for the purposes of performance assessment. Where remote power converters are used the WECS power should be measured at the output terminals of the power converter wherever it is situated. Losses due to cables and other components between the WECS and the power converter should be estimated or otherwise determined and the power output should be adjusted accordingly. The methodology for these corrections should be fully explained in the file header and accompanied by supporting documentation as necessary.

6.3 Instruments and calibration

The accuracy of the measurements from the power transducer shall be equal to or better than 0.5 % of the rated power of the WECS.

Electrical transducers used in the electrical measurements shall be class 0.5 or better, shall be calibrated to traceable standards and shall meet the requirements of the following standards:

Power transducers	IEC 60068-8
Current transformers	IEC 60044-1
Voltage transformers	IEC 60044-2

The operating range of the power transducer shall be sufficient to include all positive peaks corresponding to nett generation and all negative peaks corresponding to nett imported power. As current transformers become non-linear for low currents (≤ 5 % of their range or thereabouts) it is important that they are specified correctly.

6.4 Wave energy conversion system power data processing

The mean and standard deviation of the WECS output power over the one-hour sample shall be calculated and recorded. Other quality control data should be recorded as appropriate.

7. Wave measurements

7.1 Specification of the wave field

Following convention, the wave system is represented as the sum of a large number of elementary component wave trains with different frequencies and directions and random phases. Each of the component wave trains satisfies the linearized hydrodynamic equations and the system is referred to as a random Guassian process. Such a system is described by the directional spectrum which provides information on how the wave elevation variance is distributed with frequency and direction. The directional spectrum is fundamental in the sense that all the important statistics of the wave field, including those concerned with energy propagation, can be derived from it. Analysis in the time domain is very important for some applications, but for the determination of power the frequency domain description is more appropriate.

NOTE The adoption of a Guassian model has been shown to be reasonably successful in reproducing the observed variability of wave conditions. The geophysical source of this variability is associated with the fact that the waves observed at a point are the sum of randomly phased contributions from a wide area with continual minor changes in generation and propagation conditions. Such studies that have been done in 'constant' generating conditions suggest that the natural variability is rather greater than the Gaussian model would imply.

Thus, a wave recording extending over 1000 seconds differs from another made over the next 1000 seconds while one made over the next 1000 seconds may be more like the first record and so on. Calculations using data from the EMEC Waverider show that the standard deviation of the power for samples of 30 minutes duration was about 10 % of the mean. For one-hour samples this would be reduced to about 7 %. These figures were derived from each spectrum using the theoretical formula for the variance. The alternative approach of estimating the power from successive records and calculating the variation directly is not available because one cannot rely on the underlying conditions remaining constant for long enough to establish the 'true' power.

As well as varying from sample to sample in time, the wave conditions vary from place to place. This is important in WECS performance assessment, as the waves at the measurement position would in general differ from those occurring simultaneously at the WECS position. However, by making the assumption that spatial variability and temporal variability are equivalent, i.e. that the wave field is an ergodic process, we may in principle quantify the accuracy with which the performance results can be determined.

7.2 Placement of instruments

7.2.1 General

The wave measuring instrument or instruments must be placed close enough to the WECS to ensure that the climate at the measuring position is the same as at the WECS position, but not so close that the measurements are contaminated by radiation or shadowing effects.

7.2.2 Deeper water sites

Assuming that the preliminary site investigations have not revealed significant small-scale variations in wave patterns at the site, these requirements shall be satisfied if

- the instrument and the WECS are in similar depths;
- the instrument is on the same side of the WECS as the prevailing wave direction, i.e. to the 'front' or 'side' of the WECS;
- the WECS does not subtend an angle of greater than 20 ° at the measurement position.

NOTE The stipulation of a minimum subtended angle is a concise way of expressing the twin requirements for a minimum distance between the WECS and the wave measuring position and a maximum horizontal aspect of the WECS (which is related to the power of the radiated waves).

7.2.3 Shallower water sites

The wave measuring instrument should be placed in water which is deep enough to allow accurate wave measurements on most occasions. Many wave measuring systems work satisfactorily in a depth of order 10 m, but in shallower water of order 5 m wave

breaking, wave reflection, sediment suspension and other non-linear effects become more problematical.

Where the WECS is in shallow water rapid spatial changes in wave conditions are to be expected. In this case it is necessary to assess the changes which might occur between the positions of the WECS and of the wave measurements before deployment of the WECS. A power transfer function will be developed following the provisions of 4.7 and 4.8.

7.2.4 Number of wave measuring instruments

For sites where there are more than one source of significant wave energy which are separated in direction, it may be necessary to have more than one wave measuring instrument.

NOTE This situation could occur at an island site such as EMEC's at Billia Croo where waves may approach from the west and southwest on some occasions and from the north and even northeast on others.

7.2.5 Redundancy

In view of the very considerable expense of carrying out tests on WECS in open sea conditions it is vital that wave measurements are available when required. To this end the provision of some redundancy in the measuring system is highly desirable.

7.3 Instrument types

The requirement is for sample measurements to be made at a single position over a considerable time period (months or years). In view of this, the most suitable system is a fixed position sensor which is capable of reliable operation with both on-board recording and automatic data telemetry.

Making accurate measurements in very shallow water is particularly challenging because the wave field may be contaminated by reflections and may also be subject to breaking. However, the range of directions would be smaller than in deep water so that the directional performance of the measuring system is less important.

Further information about wave measuring systems is contained in Reference 4.

NOTE The most widely used sensor type is the wave surface following buoy. This may either be a pitch-roll buoy which measures the elevation and the slope of the surface, or a particle following buoy which measures the elevation and the orbital motions at the surface.

Another type of fixed instrument is the Acoustic Doppler Current Profiler. These have been in use for wave measurement for a comparatively short time, but may offer advantages in shallower water (depth ~10m) . They are usually bottom-mounted and work by transmitting pulses of acoustic energy upwards towards the surface. The acoustic energy is scattered by particles in the water (plankton or perhaps sediment particles) and some of this is received by the instrument. If the water is moving the

backscattered signal is Doppler shifted, allowing calculation of the along-beam velocity. They typically use three mutually inclined beams and also a vertical central beam which is essentially an upward looking echo sounder. The acoustic return is range-gated so that a profile of current measurements through depth is obtained. The directional information is derived from the velocity measurements from the near-surface range-gates which form a horizontal array of vector measurements.

A remote sensing (i.e. non-contact) system which should be considered for near shore test sites (range ~ a few km) is X-band radar, which can provide high-resolution directional spectra when used in conjunction with an additional instrument to provide absolute scaling. The system provides directional spectra which are averages over an area of sea of order half a kilometre square.

For very shallow water the use of an array of pressure sensors should be considered.

7.4 Wave buoy moorings

Wave buoys should be moored so that they are free to respond to the waves, but at the same time can survive the highest waves that are likely to occur at the site. For deeper sites and for sites with rocky sea beds, especially where there are fast currents, the use of a mooring in two parts with a robust subsurface float system may be required. Wave buoys are rather vulnerable to accidental collisions and malicious interference and all precautions should be taken to ensure their survival. Precautions should include the deployment of marker buoys and the wide dissemination of information regarding the deployment.

7.5 Specification and calibration of instruments

The wave measuring instrument of whatever type must be capable of measuring the waves accurately and reliably with minimal data dropouts.

The instrument must have traceable calibration standards for the basic physical measurements. For the case of buoys this would include such quantities as direction, surface slope, positional displacement and data rate.

For ADCPs the accuracy of the depth of the measurement cells and of the velocity measurements must be verified. Because the instrument is submerged, data recovery from ADCPs should be given careful consideration.

The data analysis system of the instrument must be capable of providing directional spectral data in the form required in 7.6.3.

7.6 Wave data analysis and presentation

7.6.1 General

The principles of the quality control and analysis of wave measurements are discussed in Reference 5. The present clause outlines the information which should be included in

the data records which are to be used for performance assessment. The definitions of the quantities are included here for reference and also in Reference 6.

NOTE A comprehensive list of sea state descriptors including many time-domain parameters can be found in Reference 7. However, for WECS performance assessment the quantities listed here and in Reference 6 shall be adequate in most instances.

7.6.2 Information content of the sample data records

The sample shall be ascribed to one of the series of nominal times. Where the record for a particular nominal time is missing a specially formatted 'no-data' entry shall be recorded.

The sample data record shall consist of the following components:

i. Date and time stamp.

ii. Depth in m. If tidal variations lead to changes in group velocity of greater than 5 %, referred to as the maximum energy value of Te in the expected energy matrix, this should be the actual depth at the site taking account of tidal variations. Otherwise the mean depth shall suffice.

iii. A frequency listing containing information about the variance spectrum and its directional characteristics as well as the power spectrum.

iv. A number of derived parameters including the power, mean direction, wave height and period.

v. Quality control flags.

These requirements are expanded in the following clauses. Further details are contained in Reference 4

NOTE Spectral and non-spectral data: since it is recommended that the fundamental interpretation method is in the frequency domain all the parameters proposed can be traced back to the (directional) spectrum. They are called 'spectral' when they are listed by frequency and 'non-spectral' when they are not. In the latter case they are based on integrated properties of the spectrum.

7.6.3 Spectral data

A listing of the following quantities shall be recorded. The index *i* shall run from 1 to N, the number of estimates in the spectrum.

Frequency f_i The frequency listing shall ideally cover the range 0.04 Hz to 0.5 Hz, usually on a linear scale. The frequency spacing should not exceed 0.01 Hz, but more closely spaced frequencies may be useful near the spectral peak and at lower frequencies. If the frequency spacing is non-linear, for example logarithmic, the scale shall be designed so that the integrated properties of the spectrum can be evaluated with adequate precision.

Frequency increment Δf_i The frequency width in Hz of each spectral estimate shall be given. Alternatively, sufficient information shall be included in the file header to enable the calculation of the frequency width to be ascribed to each estimate.

Variance spectrum S_i The wave elevation variance density in m^2/Hz shall be given at each frequency.

Power spectrum P_i Here, $P_i = \rho g S_i v_g(f_i)$
v_g is the group velocity
ρ and g are the density of seawater and the acceleration due to gravity respectively

The power (energy flux) for each frequency is expressed as a density by length and frequency, i.e. it has units of kW/m/Hz.

Normalized angular harmonics $(A_1, B_1, A_2, B_2)_i$ The complex angular harmonics of the Fourier series representation of the directional distribution of variance shall be recorded for each frequency. For pitch-roll buoys and equivalent systems this shall be the first two complex harmonics. Where more angular harmonics are available, these shall also be recorded. Reference 8 describes the calculation of these quantities.

Mean direction $(\theta_1)_i$ The mean direction in degrees from true north shall be given. This shall be derived from the first angular harmonic at each frequency as

$$\theta_1 = ATAN2(B_1, A_1)(+2\pi) \text{ (radians)}$$

where ATAN2 is a four-quadrant inverse tangent algorithm

Model-free directional parameters A number of model-free parameters, Reference 9, of the directional distribution can usefully be calculated and recorded. The following centred harmonics are required for subsequent definitions but need not be recorded:

$$M_1 = C_1 = \sqrt{A_1^2 + B_1^2}$$

$$M_2 = \frac{A_2(A_1^2 - B_1^2) + 2A_1B_1B_2}{A_1^2 + B_1^2}$$

$$N_2 = \frac{B_2(A_1^2 - B_1^2) - 2A_1A_2B_1}{A_1^2 + B_1^2}$$

Directional spread (model-free) $(\sigma_1)_i$ The root mean square (rms) angular width (in degrees) of the directional distribution of the spectrum, calculated from the first harmonic, shall be recorded at each frequency

$$\sigma_1 = \sqrt{2(1 - M_1)} \text{ (radians)}$$

Directional spread (model-free) $(\sigma_2)_i$ The rms angular width (in degrees) of the directional distribution of the spectrum, calculated from the second centred harmonic, shall be recorded at each frequency

$$\sigma_2 = \sqrt{\tfrac{1}{2}(1 - M_2)} \text{ (radians)}$$

Skewness (model-free) γ_i The skewness shall be recorded for each frequency

$$\gamma = -\frac{2\sqrt{2}N_2}{\left(1-M_2\right)^{3/2}}$$

Kurtosis (model-free) δ_i The kurtosis shall be recorded for each frequency

$$\delta = \frac{3-4M_1+M_2}{2(1-M_1)^2}$$

Spreading index $(s_1)_i$ This is the estimate from the first harmonic of the parameter *s* in the following model for the directional distribution:

$$D(\theta) = F(s)\cos^{2s}\frac{(\theta-\theta_1)}{2}$$

where *F* is a normalizing function. It shall be calculated and recorded for each frequency as

$$s_1 = \frac{C_1}{1-C_1}$$

Spreading index $(s_2)_i$ This is the corresponding estimate of *s* from the second harmonic which is to be calculated and recorded for each frequency as

$$s_2 = \frac{1+3C_2+\sqrt{1+14C_2+C_2^2}}{1(1-C_2)} \text{ where } C_2 = \sqrt{A_2^2+B_2^2}$$

7.6.4 Non-spectral data

The following quantities shall be recorded:

Frequency moments of the variance spectrum m_n The moments of the spectrum from n=-1 to n=2 shall be calculated from

$$m_n = \sum_{i=1}^{N} S_i f_i^n \Delta f_i$$

Significant wave height H_s, defined from the moments (also called H_{m0}), shall be recorded

$$H_s = H_{m0} = 4\sqrt{m_0}$$

Mean zero-crossing period T_z defined from the moments also called $T_{0,2}$

$$T_z = T_{0,2} = \sqrt{\frac{m_0}{m_2}}$$

Energy period T_e The energy period shall be defined from the moments as

$$T_e = \frac{m_{-1}}{m_0}$$

Spectral width parameter v This is defined from the moments as

$$v = \sqrt{\frac{m_0 m_2}{m_1^2} - 1}$$

Spectral width parameter (power weighted) v_P Defined from the moments as

$$\upsilon_P = \sqrt{\frac{m_{-1} m_1}{m_0^2} - 1}$$

This is a similar parameter to *v* but calculated from *S/f*. In deep water it is the normalized radius of gyration of the spectrum of power.

Omnidirectional (or gross) power The total power in the spectrum, irrespective of direction, shall be recorded. This is calculated as the scalar sum over frequency

$$P_{omni} = \sum_{i=1}^{N} P_i \Delta f_i$$

Variance of the estimate of power Var(P) The variance of the estimate of P_{omni} shall be calculated and recorded from:

$$Var(P) = \frac{1}{D} \sum_{i=1}^{N} P_i^2 \Delta f_i$$

where *D* is the duration of the record.

Directionally resolved or nett power P_{nett} The directionally resolved or nett power shall be recorded. This is the modulus of the vector sum of P_i over frequency:

$$P_{nett} = \sqrt{P_N^2 + P_E^2}$$

where $$P_N = \sum_{i=1}^{N} P_i (A_1)_i \Delta f_i$$

and $$P_E = \sum_{i=1}^{N} P_i (B_1)_i \Delta f_i$$

Power-weighted mean direction θ_P The power-weighted mean direction, i.e. the direction of the directionally resolved or nett power vector, shall be recorded in degrees from true north

$$\theta_P = ATAN2(P_N, P_E)(+2\pi) \text{ (radians)}$$

Unidirectivity index UI The unidirectivity index shall be calculated and recorded as

$$UI = \frac{P_{nett}}{P_{omni}}$$

8. Meteorological measurements

8.1 General

A full suite of meteorological measurements is not essential, but recordings of wind speed and direction should be made at a well-exposed land-based location on or near the shore at the test site. The recordings should be made routinely over the period during which the test site is in operation.

8.2 Measurements of wind speed and direction

8.2.1 General

The main use of the meteorological measurements is in retrospective studies of the performance of individual WECS and arrays of WECS. These often require information about the wind speed and direction particularly for analysis of the sea state in terms of sea and swell. It is also useful to have a local measurement of wind speed and direction during the operation of the scheme.

8.2.2 Selection of instrument

The anemometer and wind vane should be suitable for long term use in the marine environment. They should be manufactured and calibrated to professional standards and provide electrical outputs for automatic data recording.

8.2.3 Exposure of instruments

The anemometer and wind vane should be mounted on a pole at a site which is as far as possible level and free of obstructions within a radius of at least 300 m. The height of the pole should preferably be 10 m, which is the standard height for wind measurements, but may be reduced to a minimum of 4 m if the standard height is not practicable. The instrument site may be land-based, but as near the shore and the test site as is practicable.

If the test site is more than say 20 km from shore, the use of buoy-mounted instruments at or near the wave measurement site should be considered.

8.2.4 Recording and data processing

The primary purpose of the measurements is to provide a time series of one-hour means of wind speed at hourly intervals to accompany the wave and WECS output power measurements. However, because of the gustiness of the wind it may also be useful to record more frequently.

It is suggested that the 10-minute scalar mean of the wind speed and the 10-minute vector mean of wind speed and direction should be recorded at 10-minute intervals. The one-hour means can be calculated from these. The units should be metres per second and degrees from true north.

8.3 Measurements of temperature, pressure and humidity

These are optional, and at the discretion of the WECS developer.

9. Calculation of performance indicators

9.1 General

In this clause a method is given for estimating and reporting the performance of a WECS from the recordings of wave power and WECS output specified in Clauses 5, 6 and 7.

Although the wave power industry is at an early stage these specifications are designed for testing post-prototype versions of their respective technologies. The objective is to produce results which are credible in both technical and economic contexts.

9.2 Sensitivity of performance to factors other than Hs and Te

As there is very little experience of testing WECS in open sea conditions the methodology is at an early stage of development. Since the power in the sea state is closely dependent on Hs^2 and Te, the practice has developed of indexing the performance on Hs and Te. Other attributes of the sea state such as mean direction, directional spread and the frequency width of the spectrum must also be important and the sensitivity of performance to these factors may vary from one class of WECS to another. For bottom-mounted WECS in shallow water, depth (including tidal and other long-period variations) is likely to be important. As yet there are very few data on the performance of WECS and still fewer recording their dependencies on these properties. If there is excessive variability of performance these dependencies should be explored and sufficient information is specified in Clauses 5 to 8 to enable this. The aim is to reduce the uncertainties in the performance results.

9.3 Measured power matrix

This is the method for the presentation of the performance results which has become conventional. It is a bivariate histogram of Hs and Te in which each cell contains the average value of the power output of the WECS for all the sea states falling within that cell. The measured power matrix may be presented to give an overall picture of the

performance of the WECS during the test period which has the advantage of familiarity. It is recommended that the cells of the matrix should be 0.5 m width for Hs and 1.0 s for Te, but these may be varied depending on the local wave climate.

NOTE A disadvantage of this method which may not be immediately apparent is concerned with the statistics of this process. As the sea state is highly variable and the power output from the WECS is dependent on a large number of factors, some of them unknown or at least imperfectly known, it is important to be able to specify the uncertainty of the power output for each Hs, Te cell. But the wave power samples included in each cell are not identically distributed because they vary strongly and systematically with Hs in particular and also Te. In fact the variation of power in each cell is likely to have as much to do with the range of Hs and Te as it has on the variability of the performance of the WECS.

Another related disadvantage is that the sea state power is not specifically involved in the presentation. The very idea of 'performance' would seem to imply measuring the output of a WECS in a sea state with a known and stated power. The wave power is not a simple function of Hs and Te except in deep water, so that the power is not uniquely defined in each cell even if we ignore the variability.

9.4 Capture length

9.4.1 General

The measure of performance advocated in this document is the ratio of electrical power output of the WECS to the power in the sea state. The wave power has units of kW/m and the power output of the WECS has units of kW so the ratio has dimensions of 'length', and we call it 'capture length'. It is not intended that this quantity should posses any connotations of 'efficiency', in the sense of a desirable quality of the particular WECS, or that it can or should be related to any physical dimension of the WECS.

$$\text{Capture length, } L = \frac{P_{WECS}(kW)}{P_{sea}(kW/m)}$$

where P_{WECS} is the one-hour average of the electrical power output of the WECS (Clause 6)
P_{sea} is the corresponding one-hour average of wave power (7.6). Here P_{sea} is either P_{nett} or P_{omni} as appropriate (see 9.4.2).

We may reasonably expect this quantity not to vary too abruptly with Hs and Te so that its expected value in each cell shall be well defined. We estimate this by the mean of L over all sea states in the cell in question. Although the expected value of L is well defined, as explained in the note, it is likely to be quite variable, with a standard error of the order of 14 %. In view of this the standard deviation of L in each cell should be reported in a separate variability matrix.

NOTE Statistics of capture length. L is the ratio of two random quantities. The wave power is distributed as chi-squared, and the WECS power must also be a chi-squared type of quantity, although its statistics are not well known and will vary from one class of WECS to another (and even from one control strategy to another in the same WECS). If, for the sake of simplicity, we assume that the WECS power is also chi-squared then L will be F-distributed. The mean and variance of the F-distribution are given by:

$$\mu = \frac{v_2}{v_2 - 2}$$

$$\sigma^2 = \frac{2v_2^2(v_1 + v_2 - 2)}{v_1(v_2 - 2)^2(v_2 - 4)}$$

Where v_1, v_2 are the number of degrees of freedom in respectively the WECS power and the wave power.

We may estimate the effective number of degrees of freedom in the wave power estimate from the calculated proportional standard deviation of the power as

$$v_2 = \frac{1}{(psd)^2} = \frac{1}{(0.07)^2} \approx 200$$

For simplicity and in the absence of other information we will assume the number of degrees of freedom in the numerator is about the same, i.e.

$$v_1 \approx 200$$

Then the mean is very close to unity (i.e. the estimate of L is unbiased), and the normalized standard error is about 14 %. In general the cells will contain n estimates of the ratio L so that the error will be reduced by a factor $1/\sqrt{n}$.

9.4.2 Choice of omnidirectional or directionally resolved power

For deeper water test sites the choice of whether to use P_{omni} or P_{nett} depends to some extent upon the type of WECS under test, but generally speaking for single WECS P_{omni} is more appropriate. However, in shallower water P_{nett} has some advantages as it takes account of reflections and is thus more likely to give consistent results.

9.4.3 Subdivision of the capture length matrix

If investigations as proposed in 9.2 suggest that factors such as direction and/or spectral shape have a marked effect on the capture length or if there is excessive variability in the mean values of L, the capture length matrix should be subdivided to take account of the other factors. For example there may be several matrices, each for a different mean direction or range of mean directions, another for different values of unidirectivity index and so on. Each subdivision shall have its associated uncertainty matrix. The degree and nature of the subdivision is a matter for the developer of the WECS under test, but clearly it is desirable for a prospective operator to understand the uncertainties in the assessment.

9.4.4 Effect of tidal currents

The effect of tidal currents has been discussed in the note on Clause 4. Potentially more important is the effect on the orientation of some devices with respect to the wave field.

It may be possible to detect this and other effects by looking for modulation of WECS performance at tidal frequencies.

9.4.5 Presentation of capture length matrices

The capture length matrix and associated uncertainty matrices should be indexed as bivariate histograms on Hs and Te. Typically, Hs shall be on the ordinate in 0.5 m cells and Te on the abscissa in 1.0 second cells although the precise resolution shall depend on the wave climate at the test site.

10. Reporting

10.1 Purpose of reporting

The reporting schedule shall serve a number of purposes:

1. To provide a periodic report of the operational aspects of the testing programme;
2. To provide periodic updates of the performance measures of the WECS as more data become available;
3. To provide a consolidated final report which shall describe the performance of the WECS at the end of the assessment programme.

10.2 Contents of the reports

10.2.1 General

The reports shall contain some or all of the following items (depending on the purpose of the report, see 10.1). Many of the presentations specified are described in detail in Reference 1.

10.2.2 Operational history of the deployment of the wave energy conversion system and the wave measuring instrument(s)

This shall include the following:

1. Wave measuring instrument deployments, recoveries and losses.
2. A catalogue of the wave measurements made during the recording period. This shall include the start and end dates of instrument deployments and any periods of data loss.

3. Information about the deployment of the WECS and the start and end dates of power recordings and the dates and nature of any changes to the WECS operating set-up.
4. Periods for which data from both systems were available, and conversely those periods for which data of sufficient quality were not available.

10.2.3 The wave measurements during the reporting period

This section shall give a presentation of the wave power climate during the reporting period and shall include the following:

1. Time series plots of wave power. These shall be both directionally resolved power and omnidirectional power. The time resolution of these plots shall be chosen to provide an overview of the power resource during the reporting period, rather than multiple pages of indigestible plots. So, for example, it may be sensible to plot time averages of power rather than the hourly values in some instances.
2. Hs:Te matrices showing the proportion of wave energy (directionally resolved) in each cell. These are the energy matrices described in Reference 4. Contours of wave power can be drawn as an aid to interpretation, and the mean or total power during the reporting period shall be shown for denormalizing purposes.
3. Hs:Tz scatter diagrams: i.e. bivariate histograms giving the proportional occurrence of ranges of the main parameters. Steepness lines may be shown in the conventional way.
4. The proportion of the measured wave energy falling within certain direction ranges. The direction of the vector resultant of power shall be used (7.6.3).
5. An account of the preliminary processing of the data including methods of quality control and spectral analysis.

10.2.4 The wave energy conversion system power output during the reporting period

This section shall give an overview of the WECS power output during the reporting period.

1. Time series of WECS power. The same considerations regarding averaging and time resolution as discussed in 10.2.2 (1.) apply. It may be useful to plot the WECS and wave power on the same axes.
2. The measured power matrix 9.3 for the reporting period.

10.2.5 Wind speed and direction information during the reporting period

A section shall be included to report the wind measurements made during the reporting period and shall include the following as a minimum:

1. A data catalogue giving the dates and times of successful data collection and of any data loss.
2. Monthly statistics of wind speed and direction, including mean wind speed and direction and maximum wind speed (10-minute mean and hourly mean).

10.2.6 The capture length data during the reporting period

This section reports the main quantitative results of the test programme. For the whole reporting period and for such subdivisions of the reporting period which are appropriate the following shall be included:

1. The capture length matrix;
2. The capture length variability matrix;
3. Capture length matrices for subdivisions of the data as necessary;
4. The corresponding variability matrices.

10.3 Frequency of reporting

The frequency of reporting depends on the stage of the project which has been reached. In the initial stages of a project it may be useful to have frequent reports on progress, but as the programme becomes more mature annual reporting should be the objective. In addition there should be a consolidated report at the end of the testing programme.

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