Assessment of Wave Energy Resource

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.

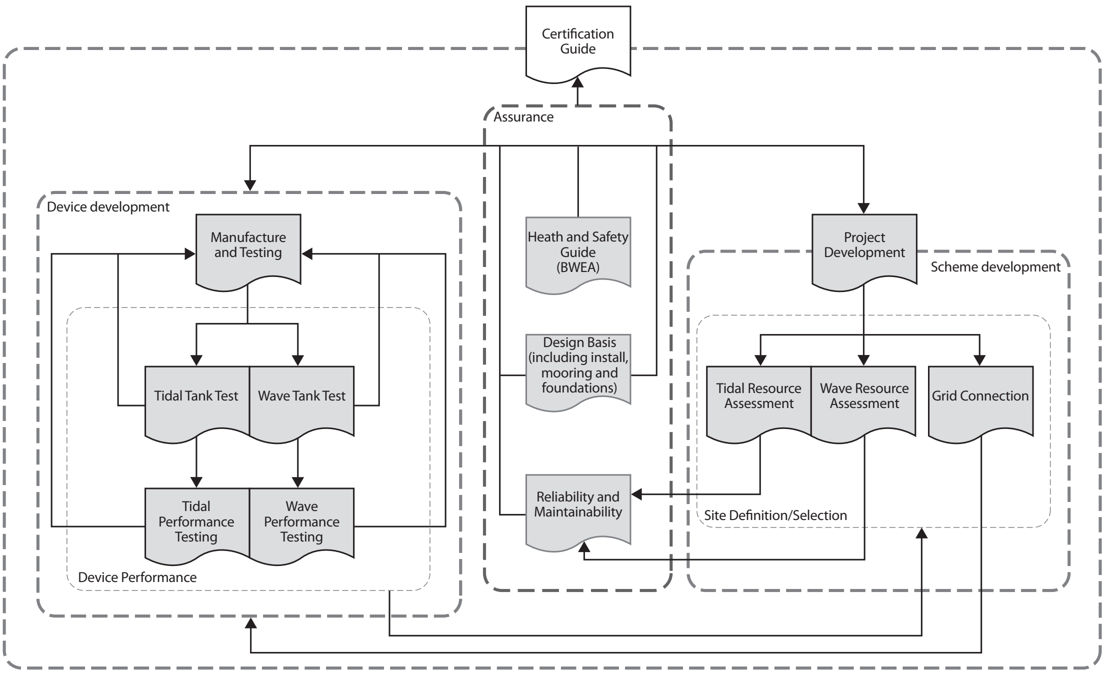

Figure 1 — Marine Renewable Energy Guides

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Assessment of Wave Energy Resource

Marine Renewable Energy Guides

EMEC ORKNEY™

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Introduction

There are two closely related but separate aspects of wave energy resource:

1. Wave power which is available at a particular location at a particular time, including information about its variability on short timescales (from hours to days). This can be assessed by making wave measurements at the position of interest.
2. Wave power climate at a particular location. The wave power climate includes the monthly, seasonal and annual statistics of wave power as well as a consideration of the variability of wave power on monthly, seasonal, annual and inter-annual timescales.

Assessment of the wave power climate can, in principle, be accomplished by measurement, however, because of the expense and difficulties of maintaining wave measuring instruments over a long period, and because of the requirement for information about the resource before a long-term measured climatology can be assembled, it is necessary to resort to other strategies – namely long-term wave modelling and other methods which use the meteorological archive.

NOTE 1 Wave power and wave energy. The wave energy is the time integral of the wave power and both of the terms 'power' and 'energy' are used in this document. Over a period of *N* hours in a sea state with a power of x kW/m the energy transfer is just Nx kWh/m, and the average is x kWh/m/h. So for time averages, 'power' and 'energy' are numerically equal. We will use the word 'energy', e.g. 'energy matrix', to emphasize that the presentation or statistic takes account of the duration of the relevant conditions as well as the power.

NOTE 2 Relationship of this document to the Department of Trade and Industry (DTI) wave protocol [1] provides detailed instructions for both resource assessment and Wave Energy Conversion Systems (WECS) performance monitoring for participants in the department's Marine Renewables Deployment Fund. The contents of the protocol are 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 guidance document specifies techniques which can be used to determine how much wave energy is available at a particular location or in a particular region.

It is intended for use by planners and developers of wave energy schemes and designers and developers of WECS.

The guidance given includes the derivation of wave energy resource information from both wave model results and from wave measurements. In the case of wave measurements the treatment includes descriptions of a number of measuring systems as well as the principles of quality control and spectral analysis.

The guidance is extended outside strict resource assessment to give a method for the calculation of WECS energy production which may be used when information on WECS performance is available.

The guidance does not include the derivation of WECS survival statistics. Although this is an important area it was decided that it could be dealt with more appropriately in a separate document.

2. Normative references

There are no normative references within this document.

3. Terms, definitions, symbols and units

3.1 Terms and definitions

3.1.1
wave power
time-averaged energy flux in a system of water waves

NOTE A derivation from the hydrodynamics is given in Reference 2.

3.1.1.1
unidirectional waves
time-averaged energy flux across a line of unit length which is parallel with the wave crests

3.1.1.2
multidirectional waves

3.1.1.2.1
omnidirectional (or gross) power
time-averaged energy flux across a circle of unit diameter

3.1.1.2.2
directionally resolved (or nett) power
vector resultant of wave powers associated with all the component waves in the multidirectional wave system

3.1.2
wave energy resource
wave power which occurs at a particular position or in a particular area integrated over whatever timescales are of interest

3.1.3
resource sample
estimate of the wave power at a particular time and a particular place that may be obtained by measurement or computer simulation

3.1.4
wave power climate
statistical description of the variation of wave power on timescales of the order of months or years which is obtained by forming the statistics of the resource samples

3.2 Symbols and units

f	Frequency (Hz)
Δf	Frequency increment or interval (Hz)
i	Index of frequency and spectral value
S_i	Spectral density of wave elevation variance at the i^{th} frequency of the spectrum (m^2/Hz)
P_i	Spectral density of power at the i^{th} frequency of the spectrum (kW/m/Hz)
v_g	Group velocity (m/s)
ρ	Density of sea water (kg/m^3)
g	Acceleration due to gravity (m/s^2)
A_1, B_1, A_2, B_2	Normalized angular harmonics
θ_1	Mean direction (degrees)
σ_1	Directional spread from first harmonics (degrees)
σ_2	Directional spread from second centred harmonic (degrees)
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 ($m^2 f^n$)
H_s, H_{m0}	Significant wave height estimated from the spectrum (m)
T_z, $T_{0,2}$	Mean zero-crossing period estimated from the spectrum (s)
T_e	Energy period (s)
υ	Spectral width parameter
υ_p	Power-weighted spectral width parameter

P_{omni}	Omnidirectional (or gross) power (kW/m)
$Var(P)$	Variance of the estimate of power (kW/m)
D	Duration of sample (s)
P_{nett}	Directionally resolved or nett power (kW/m)
θ_p	Power-weighted mean direction (degrees from true north)
UI	Unidirectivity index
P_{WECS}	Electrical power output of WECS (kW)
P_{SEA}	Sea-state power (equal to either P_{omni} or P_{nett}) (kW/m)

4. Overview of resource assessment procedure

This clause lists the steps normally required to assess the wave power resource at a given site. Cross references to relevant clauses of these guidelines are given and reference should also be made to *Guidelines for project development in the marine energy industry* [3]. The steps are as follows:

1. Make a preliminary assessment of the wave power resource in the area of interest. This can be done by using summary statistics derived from one of the global models, 7.3. The validity of these results are in general confined to water of intermediate depth or deeper.

2. Assess the inter-annual variability of wave power at the model site to ensure that the scheme is economically robust. If the model series is of adequate length this can be done by studying the inter-annual variability in the modelled data, Clause 9. If information on longer timescales is required, consider the use of pressure-based climate indices, Clause 9.

3. In general, the site of the Wave Energy Conversion System or Systems (WECS or WECSs) would be different from the global model grid point used for the preliminary assessment and moreover it would be in shallower water. The next step is therefore to transfer the modelled climate statistics from the global model grid point to the location of the WECS. Initially this can be done by using a local-area wave transformation model, 7.4.2. Part of this work will be to ensure that wave conditions at the measurement site (see point 4) are not systematically different from those at the WECS site.

4. If the modelling work mentioned in point 3 confirms the suitability of the WECS site, a programme of measurements to check the model results and to develop a measured climatology should be started, Clause 6.

5. The results of the resource assessment may be analysed using the methods of 6.5 and 7.6.

6. The wave power resource at the site of interest shall be subject to rolling review as more information becomes available.

5. Resource description

5.1 The directional spectrum

For resource characterization we adopt a frequency domain representation of the sea surface in which 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. The elevation ζ of the surface due to the waves at position (x, y) and time t can be written

$$\zeta(x,y,t)=\sum_n a_n \cos(l_n x+m_n y-\omega t-\varphi_n)$$

where the components a_n are densely distributed in frequency and direction and the phases φ_n are random and uniformly distributed. k_n is the wave number, i.e. 2π divided by the wavelength, and

$$l_n = k_n \cos\theta_n$$

$$m_n = k_n \sin\theta_n$$

where θ_n is the direction of travel of the n^{th} component.

The frequency and the wave number are related by the dispersion relation:

$$\omega^2 = gk\tanh kh \qquad h \text{ being the depth}$$

Each of the component wave trains satisfies the linearized hydrodynamic equations and the system is referred to as a random Gaussian 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, thus:

$$S(f,\theta)dfd\theta=\frac{1}{2}\sum a_n^2$$

where the sum includes all those elementary components in the frequency range f to $f+df$, and direction range θ to $\theta+d\theta$.

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.

NOTE Reconstruction of the directional spectrum. The complete directional spectrum of an individual sea state contains a vast amount of information so that almost all existing measuring systems provide only a parameterized version of it. In most single position sensors, this amounts to a listing by frequency of some well-defined, directionally integrated properties of the spectrum.

It is not necessary to reconstruct the directional spectrum in order to calculate the energy flux, mean direction, period parameters and so on, however, for design and tuning purposes it may be a requirement and there are a number of techniques available for this task. The maximum entropy method [4] has the important advantage that the reconstructed spectrum is consistent with the basic measurements. It should be noted that these techniques are approximations based on particular statistical assumptions.

5.2 Time domain description

The description of the sea state in terms of the heights and periods of individual waves is used in at least two areas of WECS design and operation. These are:

1. survival statistics, where statistics of the highest wave may be required;
2. wave group statistics, where runs of high waves and their impact on WECS operation may be assessed.

There are theoretical and semi-empirical treatments of both these topics which make use of a combination of time domain and frequency domain approaches. It is proposed that both of these topics should be addressed in a future guideline document.

6. Measurements

6.1 Role of measurements

6.1.1 Resource sampling

The wave power on a particular occasion may be derived from a sample measurement of wave conditions which is typically 30 minutes to one hour long. The value of the power or other characteristic derived from the sample is the average over the sample duration. The average value is unbiased but is subject to a rather high degree of variability and it is an important aspect of resource assessment to quantify the accuracy of individual sample measurements.

In this guide a record length of one hour is advocated as a reasonable compromise between the statistical stability of the measurements and adequate sampling of the underlying variation of the sea state. There will be occasions when the sea state, characterized for example by omnidirectional power, changes substantially over a period of two hours (the Nyquist period for one-hour sampling) but by and large changes during that period will be comparable with or smaller than the sampling errors in the individual records.

When making measurements to determine the resource, it is important to have a clear understanding of how representative the measurement is of the area in which the measuring instrument is situated. This depends on the exposure of the measurement site to the prevailing waves in terms of sheltering, and of the bathymetry of the area surrounding the wave measurement site.

6.1.2 Wave energy conversion system performance assessment

Resource sample measurement is an important part of the performance assessment of wave energy conversion systems. This is discussed in the *Assessment of performance of wave energy conversion systems*.

6.1.3 Comparison with model results

Wide area wave generation and propagation models are used extensively to help determine the wave power resource and these have been developed and tuned with the benefit of measurements. Small-scale spatial variations can be investigated with local wave transformation models and these can be checked with purpose-designed measurement programmes. Further discussion of these issues is contained in Clause 7.

6.2 Wave measuring instruments

6.2.1 General

Wave measuring instruments use many different principles of operation and different methods of recording and analysis. However, few are suitable for resource assessment in open sea and coastal situations. The basic requirement is for single point measurements extending over a period of months or years, although measurements made over an extensive area may be useful for project monitoring and short-term forecasting purposes. In the following subclauses, five types of instrument are described:

1. Surface-following buoys – suitable for monitoring at a fixed position in depths greater than 10 m.
2. Acoustic Doppler Current Profilers (ADP) – which may be particularly suitable for shallower water.
3. Pressure sensors – suitable for use in shallow water.
4. HF Radar – a medium to long range remote sensing method.
5. X-band radar – a short range high resolution remote sensing method.

Usually, the instrument manufacturer supplies a system for recording and processing the data. While it may not be practical for the user to understand every detail of the system which is offered, it is important that they are satisfied that it is adequate in terms of quality control, record length and calibration.

6.2.2 Surface-following buoys

6.2.2.1 Principle of operation

Surface-following buoys provide measurements of wave conditions at a fixed location and have been widely used for many years. There are two main approaches to measuring the waves:

1. Pitch-roll-heave buoys measure the slope of the surface (both its magnitude and direction) and the elevation of the surface. They are usually discus-shaped as an aid to following the surface slope.

2. Particle-following buoys follow the orbits of the water particles at the surface. They are usually spherical in shape and no attempt is made in their design to adopt any particular orientation with respect to the surface.

Both of these should follow the wave motions accurately so that the moorings should be compliant with respect to oscillatory wave motions but should maintain the buoy on-station in the face of steady currents and wave drift forces.

The second class, the particle-followers, divides into two further categories. They may:

- measure the acceleration of the buoy along three axes or;
- use satellite position-fixing to measure the displacement or velocity along three axes.

To accomplish this, the buoys (except for the category using satellite position-fixing) require, in addition to the basic measuring technology, a vertical reference and a compass. Further information on the techniques used is given in *Review of wave measurement technology* [5].

6.2.2.2 Form of data

The basic data consist of time series of the three fundamental measurements which may be one of the following triplets:

1. Heave (vertical displacement), slope north and slope east.
2. Vertical acceleration, north acceleration, east acceleration.
3. Vertical velocity, north velocity, east velocity.

These are processed on board the buoy or on shore into the auto- and cross-spectra between the pairs of basic measurements. The interpretation is thus in the frequency domain and the results (which may be looked upon as the fundamental observables) are the wave elevation variance density (usually referred to simply as 'the spectrum') and the first two harmonics of the Fourier series representation of the directional distribution at each analysed frequency. These may be related to a number of useful parameters of the directional spectrum as explained in 6.4.3.

6.2.2.3 Mooring

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 seabeds, especially where there are fast currents, the use of a mooring in two parts with a robust subsurface float system may be required.

6.2.2.4 Data recovery

The data recovery options for wave buoys include some or all of the following:

- Real-time HF or VHF radio telemetry of the basic time history measurements.
- Radio telemetry of the processed spectral data.
- On-board recording of the processed data.
- Satellite collection of a subset of the processed data.

In the case of on-board recording, the data is not recovered until the buoy is recovered.

6.2.3 Acoustic doppler velocity profilers

6.2.3.1 Principle of operation

The ADP was developed to provide measurements of current speed and direction through the water column. It works by firing pulses of acoustic energy (typical acoustic frequency of one MHz) along typically four beams (three mutually inclined and one vertical) upwards towards the surface. Typical pulse repetition rates are of the order of a few Hertz. The acoustic energy in the inclined beams is scattered by particles in the water (plankton or perhaps sediment particles) and some of this is received by the instrument. The received signal is Doppler shifted with respect to the transmitted signal and this allows the along-beam velocity to be calculated. By range-gating the return signal a profile of measurements through the water column is obtained. The vertical beam is reflected by the surface essentially as in an inverted echo sounder.

6.2.3.2 Form of data

The vertical beam provides a time history of surface elevation from which the omnidirectional variance spectrum can be derived. The inclined beams can be processed to provide a near-surface array of three velocity vectors and from these (and the surface elevation) the directional properties of the waves can be determined. In a depth of 10 m, with beams inclined at 25 ° to the vertical, the low period cut-off for the directional information is about three seconds. This is adequate for wave power resource determination and, for periods of greater than this limit, it should be possible to determine the mean direction and directional spread and also detect reflections, although the latter depends on the details of the processing method.

6.2.3.3 Data recovery

Since the ADP is submerged, recovery of the data and its effect on the design of the deployment require some consideration. There are two main approaches:

1. Record internally and recover the data by recovering the whole instrument at intervals of two months or so. This is particularly suitable for the case where the instrument is deployed on a subsurface float, as an acoustic release can be inserted in the mooring below the float.
2. Provide data telemetry to a surface buoy where it can be retransmitted by radio to a satellite or a shore station. This can provide real time or almost real-time data, but at the cost of the vulnerability of the surface buoy.

6.2.4 Pressure sensors

Measuring the pressure fluctuations due to waves provides a robust and comparatively simple measurement method. As the pressure variations are attenuated with depth, the method is only suitable for measuring long waves in shallow water, but under those circumstances it can be very effective. To determine the directional properties of the waves requires the use of an array of pressure sensors. Further details of these techniques are available in References 6 and 7.

The pressure p measured by a bottom-mounted sensor in a depth h due to the elevation of the surface η by a wave with wave number k is given by:

$$p = \frac{\eta \rho g}{\cosh(kh)}$$, i.e. the hydrostatic pressure divided by cosh(kh)

Table 1 lists cosh(kh) for waves of various periods in 5 m depth. These are the factors which convert the measured bottom pressure to a pressure equivalent to $\eta \rho g$ where η is the instantaneous wave surface elevation and ρ and g have their usual meanings. It is generally safe to use amplitude corrections up to about 5, implying corrections to the spectrum of up to 25. The use of factors bigger than this risks exaggerating any noise (including spectral leakage) which may be present.

Table 1 — Pressure attenuation in a depth of 5 m

T (s)	Deep-water wavelength (m)	*kh* in 5 m	Amplitude correction factor
2	6.24	5.031	76.53
4	25.0	1.415	2.18
6	56.2	0.825	1.36
8	99.8	0.592	1.18
10	156.0	0.464	1.11

6.2.5 HF Radar

HF radar is a shore-based remote sensing system using radio waves in the 6–20 MHz region to measure waves and currents. It requires two transmitter/receiver stations to be set up so that the look directions are approximately at right angles. The primary observable is the Doppler spectrum of the radio waves which are backscattered from the ocean waves. This is then 'inverted' (using a complex numerical procedure), to give the directional spectrum of the ocean waves.

Subject to a number of limitations the full directional spectrum can be measured on a grid defined by the intersection of the radar beams with a spatial resolution which while dependent on the design of the radar is typically between 1 km and 5 km. The measurement limitations are concerned with the highest wave frequency for which information is available and the range of H_s which can be observed. Both of these depend on the radar operating frequency. Operating range can be from 10 km to 100 km.

On most occasions the spectrum can be measured accurately, but there are occasions when this is not so. This is because the data interpretation (inversion) technique is rather sensitive to imperfections in the radar data. Of the directional parameters, mean direction is reasonably reliable but directional spread is not very accurate. Comparisons of power suggest that differences between buoy and radar measurements are mostly comparable with the (joint) sampling errors associated with the two methods.

6.2.6 X-band radar

This is a remote sensing technique in which information about the wave field is extracted from X-band (wavelength 3 cm) marine radar. The technique allows high-resolution directional spectra to be derived from radar images over ranges of a few kilometres. The wave information obtained is the average over an area of the order of one half kilometre square, rather than a point measurement.

X-band radar could be very valuable because it allows measurements of wave power to be made in near-shore reflective environments where other techniques are unlikely to be successful. There are, however, two particular difficulties with the method:

1. There is no definitive scaling between the radar intensity and the wave height. While an overall scaling can be inferred from the observed radar signal-to-noise ratio, for the best accuracy an ancillary source of scaling is required.

2. The system does not work for very small waves.

Both of these problems can be addressed by deploying a wave buoy within the analysis area.

6.3 Spectral analysis

6.3.1 General

Due to the many different principles upon which wave measuring systems are based, it is not possible to specify the preliminary processing of them all even in outline, let alone in useful detail. Moreover, the measurements may well be undertaken by specialist contractors using systems and software which are already in place. Nevertheless, it may be useful to give an outline of the principles involved in forming the spectrum of the wave surface elevation.

Waves in ocean engineering [8] discusses the calculation of spectra in detail and Appendix 7 of the same title [9] contains detailed practical proposals for the analysis and recording of wave data. These should be studied by anyone charged with setting up a recording and analysis scheme.

The elementary sample estimate of the (auto-) spectrum is defined by:

$$\hat{S}(f)\Delta f = \frac{1}{2}(a_i^2 + b_i^2)$$

where the *a*s and *b*s are the cosine and sine parts of the discrete Fourier transform of the elevation time history.

$$f = i\Delta f \text{, and } \Delta f = 1/D$$

where D is the time series length. $\hat{S}$ is highly variable (it has a negative exponential distribution) and should be subjected to an averaging process to give the 'smoothed' estimate of the spectrum which is of practical value.

Where it is required to investigate the amplitude and phase relationships between two time histories, as is the case when analysing directional measurements, it is conventional to calculate the Co-spectrum and Quad-spectrum. If a_i and b_i are the Fourier transform of series 1, and c_i and d_i the Fourier transform of series 2 then the elementary sample estimates of the Co- and Quad-spectra are defined as follows:

$$\hat{C}_{12}(f)\Delta f = \frac{1}{2}(a_i c_i + b_i d_i)$$

$$\hat{Q}_{12}(f)\Delta f = \frac{1}{2}(a_i d_i - b_i c_i)$$

Again, these should be smoothed to give usable estimates of the spectra.

The practical application of these principles involves many design decisions and these are discussed in 6.3.2.

6.3.2 Record length, sampling rate and spectral resolution

6.3.2.1 General

The design of the analysis scheme is subject to the following constraints and requirements:

1. The basic Fourier transform is done using the Fast Fourier Transform (FFT) which is fundamentally a binary algorithm so that the number of data values in the input time history should be a binary number.
2. The frequency width of the variance estimates in the final spectrum (the frequency resolution) should ideally be 0.005 Hz or less, and certainly no greater that 0.01 Hz.
3. The frequency range of the spectrum should ideally be 0.04 Hz to 0.5 Hz. The upper frequency limit of the range may be lower if constrained by the instrumental technique, but should not be less than 0.3 Hz.
4. To avoid aliasing, the input should be low pass filtered with a cut-off of $1/(2\Delta t)$, where Δt is the sampling interval. It may be convenient to sample the signal at a much higher rate than is required for the calculation of the spectrum and apply a digital filter before analysis.
5. Contamination of one part of the spectrum by 'leakage' of variance from other parts of the spectrum should be minimized. This requires that the section of data which Fourier transformed is ideally no shorter than 1000 seconds. This is particularly important for pressure and other subsurface records in which contamination of the higher frequency estimates should be minimized.
6. The statistical variability of the spectral estimates should be as low as is practicable. It turns out (see ahead) that each estimate should be defined with a minimum of 20 degrees of freedom (d.f.) and ideally with 40 d.f.

6.3.2.2 Example Scheme A with a sampling interval of exactly 0.5 seconds

Suppose the data section contains N values (or points) sampled at interval Δt, the record length is $D=N\Delta t$ and the resolution of the 'periodogram' or unsmoothed spectrum is $1/D$. If N is 4096 and Δt is 0.5 s then D=2048 s (34 min and 8 s), and the frequency resolution Δf is 0.00048828125 Hz. To achieve the target resolution, the elementary estimates are averaged 10 at a time to give a smoothed resolution of 0.0048828125 Hz. This is called frequency domain averaging, and each elementary estimate which enters the average contributes 2 d.f. so that the smoothed estimates are defined with 20 d.f. They are chi-squared variables and have a standard error of $\sqrt{2/d.f.} = \sqrt{1/m}$ where m is the number of elementary estimates in the average. For estimates smoothed over 10 harmonics this is equal to 32 %. Each smoothed spectral estimate is ascribed to the average frequency of its band.

Finally, we may average the spectra arising from two such sections (this is called time domain averaging) to give a total record length of 68 min and 16 s with a spectrum defined with 40 d.f. and a standard error of 22 %.

6.3.2.3 Example Scheme B with a frequency resolution of exactly 0.005 Hz

Some people prefer to see their spectra defined with a resolution of exactly 0.005 Hz, and moreover with the sequence 0.005 Hz, 0.010 Hz, 0.015 Hz,…. While defining the spectrum on arbitrary frequency values as in Scheme A is only a minor inconvenience, the requirement for a record length of exactly 30 minutes is more fundamental because of the requirement for one-hourly 'final' records. Scheme A would require overlapping records to be started at half-hourly intervals. To resolve this problem requires that the digitization rate can be selected arbitrarily. For this example D=30×60=1800 s and the sampling interval Δt = 1800/4096 = 0.439453125 s or a sampling rate of 2.27555…Hz. Then, by averaging over 9 elementary harmonics we get smoothed estimates at multiples of 0.005 Hz. These are defined with 18 d.f., and after time domain averaging over two half-hour sections this becomes 36 d.f., giving a normalized standard error of 24 %.

6.3.3 Tapering

With a record length of 2048 s, or even 1024 s, spectral leakage for surface records is not really a problem and tapering is not strictly necessary, however, for subsurface records it can be important and so it has become conventional to use a taper and it is suggested that a length of one eighth of the series at each end is cosine tapered.

The use of a taper reduces the variance of the record and the spectrum should be adjusted for this effect. It can be shown that the spectrum can be corrected by the application of a scaling factor. The scaling required varies with each spectrum because the taper interacts with each time history differently and so the correction required is a statistical quantity. Its expected value is the reciprocal of the variance of the taper function which for a one eighth taper is 1.1852 and the spectrum can be scaled by this number. This is the conventional approach but builds in the (admittedly small) extra variability associated with the tapering process.

NOTE Effect of taper on the variability of the spectra. The use of a taper causes an increase in the variability of the spectral estimates, but for a one eighth taper this is acceptable and may be minimized by following the correction procedure recommended.

Another approach is to scale the spectrum using the fundamental property (Parseval's theorem) that the total variance of the spectrum is equal to the variance of the time history. Therefore:

$$Correction = \frac{Var}{\sum_{i=1}^{N/2} \frac{1}{2}\left(a_i^2 + b_i^2\right)}$$

Here the as and bs are the Fourier transform, $N/2$ is the number of harmonics in the transform and Var is the variance of the time history. The correction varies from spectrum to spectrum (it has an F distribution) but within quite close limits, and its average value should be around 1.1852 for a one eighth taper.

6.3.4 Quality control

6.3.4.1 General

For most measurement systems, errors can occur due to instrument or telemetry failures resulting in 'spikes', i.e. large erroneous values or 'flat spots' where the reading remains constant for a few samples. These errors can be detected by well designed range and rate of change checks on the time history. They also have an effect on the spectrum, resulting in anomalously high values at low and high frequencies. For gross errors the spectrum is corrupted to the extent that Parseval's theorem is not obeyed and the taper correction has an anomalous value.

6.3.4.2 Time series checks

These consist of range and rate of change tests which are designed on the assumption of Gaussian statistics for both the surface elevation and the rate of change of the surface elevation. They may also be used for other wave properties such as orbital velocities and pressure.

For the elevation we may set $x = \frac{\eta}{\sigma}$ where η is the surface elevation with respect to the mean and σ is the standard deviation of the surface elevation.

We estimate the rate of change by the difference between adjacent points divided by the sampling interval, so that:

$$x = \frac{\Delta\eta / \Delta t}{\sigma_s}$$

where $\Delta\eta$ is the change in elevation between adjacent samples which are separated by time Δt. σ_s is the standard deviation of the rate of change of surface elevation and is equal to $2\pi\sqrt{m_2}$, where m_2 is the second moment of the spectrum.

From standard statistical tables [10] we may estimate how frequently a given test will be satisfied by legitimate data. As an example, for x=4, P(X>x)=0.9999683288, so P(X<x)=3.1671×10^{-5}. (Trivial adjustments are required for negative ordinates.)

Also $P = \frac{M}{N \times 744}$ where M is the number of points per month exceeding x times the standard deviation of the record and 744 is the number of hourly records in a month. For x=4 and N=4096, M~96, which is too high. Increasing x to 5 reduces this to about one per month which is reasonable.

A difficulty with implementing these tests is that errors in the data will disturb the statistics (standard deviations) on which the tests are based, however, since the record start times are separated by only half an hour it is acceptable to use the previous good data sample.

Another test which should be undertaken is for successive equal values. This will reveal the presence of flat spots.

6.3.4.3 Spectral tests

Data errors are reflected in corruption of the spectrum. A good way of detecting this is to look for anomalously large amounts of variance at high and low frequencies. This can be done by comparing the variance near the peak of the spectrum with the variance in a band at low frequencies (say in the first 3 or 4 estimates) and also at high frequencies (the last few estimates). These comparisons can be expressed as signal to noise ratios in dB.

The taper correction can also be used as an indication of errors in the spectrum, although there has to be gross corruption for it to be severely affected.

6.3.4.4 Interpretation of quality control results

An important principle is that no data should be discarded by the quality control procedure. The results of the quality control tests should be appended to the record as a series of 'flags'. These can then be scrutinized by the user of the data so that a decision can be taken as to whether the data are of adequate quality for the application.

It is valuable to give a preliminary assessment of the data automatically and to append a 'go'/'no-go' flag which in effect summarizes the quality control procedure for each record. This should be tuned to the instrument and data on a continuing basis until the assessment is reliable enough to be useful.

6.4 Data archive

6.4.1 General

Whatever the type of instrument, the data archive shall have a common basic structure and content, although the details may vary. The information arising from an individual sample measurement is referred to as a data record and these shall be ascribed a series of nominal times which will usually be on the hour, one hour apart. Where the data record for a particular nominal time is missing, a specially formatted 'no-data' record shall be substituted.

The data records shall be consolidated into data files typically containing one month's worth of data records and/or no-data records. This is not a fixed requirement, but monthly files have proved to be a useful length to handle.

The data files shall thus contain a series of data and no-data records and these shall be preceded by a header record. The file header shall contain details of the measurement, processing and recording of the wave data. The documentation should be sufficiently comprehensive to ensure the intelligibility of the data to all interested parties.

6.4.2 Information content of the data records

The sample data record shall consist of the following components:

1. Date and time stamp.
2. Depth in m. If tidal variations lead to changes in group velocity of greater than 5 %, referred to the maximum energy value of T_e in the expected Hs:Te scatter diagram this should be the actual depth at the site taking account of tidal variations. Otherwise the mean depth shall suffice.
3. A frequency listing containing information about the variance spectrum and its directional characteristics as well as the power spectrum.
4. A number of derived parameters including the power, mean direction, wave height and period.
5. Quality control flags.

These requirements are expanded in the following subclauses.

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 usually involve integrated properties of the spectrum.

6.4.3 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 typically cover the range 0.04 Hz to 0.5 Hz, usually on a linear scale. The frequency spacing should not exceed 0.01 Hz, and 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. The calculation of the harmonics from the measured Co- and Quad-spectra is described in [11].

Mean direction (θ_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 [12] 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) (σ_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) (σ_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:

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

6.4.4 Non-spectral data

The following quantities shall be recorded.

Frequency moments of the variance spectrum m_n – The moments of the spectrum for n=-1, 0, 1 and 2 shall be calculated from:

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

Significant wave height H_s, also called H_{m0} – The significant wave height defined as:

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

Mean zero-crossing period defined from the moments, T_z, also called $T_{0,2}$ – The mean zero-crossing period shall be defined from the moments as:

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

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 v_P – Defined from the moments as:

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

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:

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

Other power-weighted averages – As an example we give the formula for the power-weighted directional spread (model-free from 2nd harmonic).

$$\bar{\sigma}_2 = \frac{1}{P_{omni}} \sum_{i=1}^{N} (\sigma_2)_i P_i \Delta f_i$$

6.5 Interpretation of measurements

6.5.1 General

For resource assessment the primary variable is the measured power: either or both of omnidirectional (gross) power or directionally resolved (nett) power. The calculation of power from measured spectra is outlined in 6.4.3 and 6.4.4. In this subclause are described some statistical presentations in which power is indexed on H_s and T_e.

6.5.2 Energy matrices

6.5.2.1 General

This is an analysis of long-term (duration of order months or years) power data in terms of H_s, T_e and direction. Other divisions of the data may be appropriate in particular cases and the principles described here can be applied to those as well. The purpose of this analysis is to determine the available energy at a particular site in terms of parameters which affect the performance of the WECS. In particular, the productivity of a particular WECS can be assessed by multiplying the energy matrix for the site by the performance matrix of the WECS, see Clause 8.

6.5.2.2 Bin sizes

The matrix should cover the complete range of both H_s and T_e which occur in the data. It is common practice to set the bin sizes to 0.5 m for H_s and 1.0 s for T_e. Since the power is closely proportional to H_s^2 this leads to a large proportional change in power for the lower values of H_s. If a finer breakdown is required then smaller bin sizes can be used.

6.5.2.3 Definitions

Let n_{ij} be the number of measurements falling within an H_s, T_e cell (H_{si}, $T_{e\,j}$). Then:
$\sum_i \sum_j n_{ij} = N$, the total number of measurements. Each measurement within (H_{si}, $T_{e\,j}$) has a power p_k. Note that in this formulation p_k is the power calculated from the spectrum NOT an estimate from H_{si} and $T_{e\,i}$. Then the total power within the cell is $P_{ij} = \sum_{k=1}^{n_{ij}} p_k$ and the mean power in the cell is $\bar{P}_{ij} = \frac{P_{ij}}{n_{ij}}$.

The total energy within each cell E_{ij} is given by $P_{ij}\Delta t$ (kWh/m) where Δt is the observation interval (nominally one hour). The total measured energy is then:

$$\sum_i \sum_j E_{ij} = \Delta t \sum_i \sum_j P_{ij} = \Delta t P_{TOT}$$

where we have defined P_{TOT} as $\sum_i \sum_j P_{ij}$

The proportion of measured energy falling within each cell is thus:

$$\frac{\Delta t P_{ij}}{\Delta t P_{TOT}} = \frac{P_{ij}}{P_{TOT}} \qquad \left(= \frac{P_{ij}}{N\bar{P}} \right)$$

where $\bar{P}$ is the overall average measured power.

We refer to this as the energy matrix.

6.5.2.4 Variability

The mean power in each bin as calculated above is unbiased, and when multiplied by Δt and scaled as above is an unbiased estimate of the mean proportional energy in that bin. This is true whatever the dimensions of the bin. However, because of the variation of H_s (and to a lesser extent T_e) within each bin, some care is required in estimating the uncertainties in the energy matrix.

The variability consists of the following components:

1. The sampling variability of individual estimates of power;
2. Variability due to the finite size of each (H_s, T_e) cell;
3. Variability in the number of occurrences, i.e. the climatic sampling variability.

Items 1 and 2 are discussed in the Note. Item 3 is the most important and can be approached in the following way:

The energy matrices calculated from two different years are always different – sometimes fundamentally different. It would be useful to model these differences formally perhaps using modelled wave data, however, a worthwhile initial approach is to study the variability of energy productivity for a particular device or possibly for a generic device. This would give a one-number description for each climatic unit (month/season/year) in kWh. Calculation of device productivity is outlined in Clause 8.

NOTE Variance of energy matrix. Neglecting climatic sampling variability, the variance of the energy in each bin can be decomposed as follows:

$Var(E_{ij}) = Av(Var\left\langle e_k \middle| (Hs_i, Te_j)\right\rangle) + Var(Av\left\langle e_k \middle| (Hs_i, Te_j)\right\rangle)$ where e_k denotes the individual values of measured energy, *Var* denotes the variance and *Av* denotes the average (strictly, the expectation). The second term on the right-hand side (RHS) is the variance due to the range of H_s and T_e included in each bin. It is a consequence of, and varies with, the design of the analysis and is not therefore a relevant measure of uncertainty. The first term on the RHS is the average of the variances of the individual values of energy and we adopt this as the measure of uncertainty:

$$Var(E_{ij}) = \frac{\left(\Delta t^2\right)}{n_{ij}} \sum_{k=1}^{n_{ij}} Var(p_k) \text{ and so}$$

the proportional standard error is just $\dfrac{\sqrt{Var(E_{ij})}}{\Delta t \bar{P}_{ij}} = \dfrac{\sqrt{\dfrac{1}{n_{ij}} \sum_{k=1}^{n_{ij}} Var(p_k)}}{\dfrac{1}{n_{ij}} \sum_{k=1}^{n_{ij}} p_k}$

It is recommended in 6.4.4 that the variances of the individual measured values of power are calculated as routine.

6.5.2.5 Division by direction

The energy matrix can be divided in as many ways as required. This may be by analysis period (season and number of years) as well as by direction, directional spread and so on. In the case of direction we may use the power-weighted mean direction θ_p and sort the data into eight sectors centred on N, NE, NW…. The north octant would range from 337.5 to 22.5 degrees, the north-east from 22.5 to 67.5 degrees and so on. The sectors are conventionally indexed as 0 to 7.

6.5.3 Percentage exceedance of power

This is the most fundamental of the resource statistics and gives the exceedance probability for the sample. In other words we calculate the percentage of the sample data which exceeds a given power level. The 'sample' may be any of:

- all the whole years, i.e. annual;
- all the winters, or springs, or summers, or autumns, i.e. seasonal;
- all the Januaries, or Februaries, … , or Decembers, i.e. monthly;
- any other period which is of interest.

The power data, p_k, is sorted into bins with width Δp. The number of values in each bin in general falls very quickly as the value of p increases so that there tends to be more variability in the results at the higher powers. For this reason some approaches use bin widths which increase with power level.

In the interests of simplicity this explanation is confined to the case of equal bin widths. The j^{th} bin includes the range $(j-1)\Delta p$ to $j\Delta p$ and contains n_j measurements. The total number of measurements N is given by $N=\sum_{j=1}^{n_b} n_j$ where n_b is the number of bins, and the sample probability density (or proportional occurrence) at the midpoint of the j^{th} bin is given by $\frac{n_j}{N}$. To calculate the sample percentage exceedance we begin at the bottom of the bin in question and add the proportional occurence for each higher bin i.e.:

$Exc(p_j)=\frac{1}{N}\sum_{i=j}^{n_b} n_i \times 100\,\%$ where p_j refers to the bottom end of the bin.

6.5.4 The probability distribution of power

The cumulative non-exceedance sample probability is given by:

$$\Pr(P<p_j)=\frac{1}{N}\sum_{i=1}^{i=j} n_i$$

Note that this probability relates to the value of power at the top of the j^{th} bin. It will be seen that the probability summed to the highest bin is identically equal to one. While this is true for the sample, for the population from which the sample was drawn it cannot be true since there are always other (unsampled) values of power which exceed those which have been observed. This problem is circumvented by omitting the top bin from the plotted results.

6.6 Archiving statistical analyses

The statistical analyses described in the preceding subclauses are given in normalized form and this is probably the most accessible way to present the results, however, some users may prefer to leave the results in un-normalized form. If it is required to archive the results they should be stored in a format which preserves the full precision of the original analysis and this is most conveniently the un-normalized data.

7. Wave models

7.1 General

Wave models provide computer simulations of wave generation, propagation and dissipation on all spatial scales from global to the detailed anatomy of a single breaking wave. They have been developed for use in research, operational wave forecasting for marine operations and for the production of data sets from which long-term wave statistics can be simulated. The last application, often called hindcasting, has been used primarily for the investigation of survival statistics for the offshore oil and gas industry. The result of this is that some of the most extensive hindcast data sets have concentrated on simulating 'storms', or discrete severe weather events. The requirement of wave power resource characterization is rather different since it is the whole population of sea states and their associated powers which are of interest. We therefore require hindcasts to be carried out at evenly spaced time steps (typically three hours or six hours) throughout the hindcast period.

7.2 Role of wave models

Wave models can be used in resource determination in the following ways:

1. To provide long-term time series of wave data from which wave power statistics can be derived. This is often the only long-term source of wave climate data which is available for a position or area of interest. In effect the models turn long-term meteorological data into wave data.

2. To allow calculations of wave transformation to be made in coastal areas. This is useful for the assessment of a prospective WECS site and is often combined with a measurement programme.

7.3 Global models

7.3.1 General

These are wave models which are run by meteorological agencies on a routine basis to provide forecasts for marine operations. As part of their routine use, a simulation of the wave conditions is made using the meteorological analysis (rather than a forecast) for a regular sequence of times and these simulations (hindcasts or perhaps more appropriately nowcasts) are archived and form the basic information for wave climate studies.

There is a useful discussion on the formulation of global models and in particular the differences of the several 'generations' of models in [13].

In the following subclauses, a number of global wave models are listed along with wave power climate studies which have been based on them. The models and projects mentioned are given as examples of the use of global models and the list is not intended to be exhaustive.

7.3.2 UK Met Office model

7.3.2.1 General

In the United Kingdom the models developed, implemented and run by the UK Meteorological Office (UKMO) have assumed particular significance. A description of these can be found on http://www.metoffice.gov.uk/research/ncof/wave/index.html and information on a number of wave power studies which have incorporated their results is given below.

7.3.2.2 DTI atlas of marine renewable energy resources

The presently available version of this was published by DTI in 2004 and gives wave power results for the whole of the UK continental shelf including its extension to the Rockall Shelf. The UKMO Coastal Waters wave model was used to simulate the wave conditions at six-hourly intervals on a 12 km grid over the period 1 June 2000 to 30 September 2003. Note that in common with almost all of the available wave data sets this is a rather short period. Further discussion of this problem is contained in Clause 9.

The results have been published in an atlas as a series of maps of annual and seasonal mean power. In addition a technical report has been published giving details of the derivation of power and comparisons with other studies. These two reports (the atlas and the technical report) are available on a CD in PDF format. The atlas database is not generally available, but can be accessed for the purpose of producing other statistical analyses on application to DTI (now DECC).

An updated and enhanced version 2 of the atlas is now available. This will be based on an extended database of approximately seven years.

7.3.2.3 Seapower south-west review

This study, which was published in 2004, concentrates on wave and tidal power in the seas around the south west of England and was funded by the South West of England Regional Development Agency (SWRDA). It includes a detailed analysis of UKMO wave model data for a total of 11 grid points: seven from the European Waters Model (35 km grid size) and four from the UK Coastal Waters Model (12 km grid size). The European Waters Model data were available for the period June 1991 to November 2003 and the UK Coastal Waters Model for March 2000 to December 2003. The objective was to define the wave power climate along the 50 m depth contour. Appendix A of the report contains the analysis results, while Appendix B describes a number of ancillary studies which were undertaken to validate the accuracy of the methods used.

The report is available on the SWRDA Wavehub website [16].

7.3.3 The WAM Model

7.3.3.1 General

The WAM model was developed in the 1980s by a group of European scientists with a view to incorporating the advances which had recently been made in wave generation and propagation theory. It is a third-generation model, meaning it calculates explicitly the effects of non-linear wave-wave interactions. It is run as routine at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading. The next subclause describes studies which have used the WAM model results.

7.3.3.2 WERATLAS

This project was funded by the European Union (EU) under the Joule programme with a view to producing an atlas of the wave energy resource in waters around the EU. The project was led by INETI in Lisbon and included a number of other mainly academic bodies. The results were published in 1997.

A total of 41 rather widely spaced grid points in the Atlantic (and a similar number in the Mediterranean) from the WAM model were analysed using data from the period 1987–1994. A wide range of wave statistical analyses, including power and T_e, are available using an interactive software package.

At the time of writing, the WERATLAS and users' guide can be purchased for €200 and the technical report costs €50. For more information, please contact atendimento@ineti.pt.

7.3.3.3 North Atlantic 50-year hindcast, NATL50

This project used a model developed by Oceanweather Inc, Cos Cob, CT., which is essentially a reimplementation of the WAM model. The model covers the whole of the North Atlantic on a half degree grid, i.e. about 55 km north by (at 50 °N latitude) 36 km east. The work was funded by The Climate Research Branch of Environment Canada. The hindcast runs from 1 July 1954 to 30 June 2004. The purpose of the hindcast was to improve on earlier studies particularly with regard to the waters of the Canadian east coast.

While the resolution is rather coarse for resource determination in coastal areas, its great strength is the length of the hindcast which should allow for the first time accurate studies of the inter-annual variability of power.

NOTE Further information is available from Oceanweather Inc at www.oceanweather.com (follow the link to 'Metocean Studies', NATL50).

7.4 Local models

7.4.1 General

We refer here to wave models which can be used in coastal and near-shore areas to investigate the detailed distribution of wave power under particular conditions. Typically, but not always, they might use the output from the global models for their offshore boundary conditions and calculate the wave conditions at an array of grid points in the near-shore zone.

The following paragraphs describe two examples of local models. There are of course many others.

An example of this type of model which has been used extensively for coastal wave power studies is the SWAN model from the Technical University of Delft. This is a refraction model and includes many of the important shallow water processes as well as generation by the wind. There is thus a lot of overlap between models such as this and the global models; the difference is essentially in the long-term use of the global models by the meteorological agencies.

The SWAN model can be obtained from the Technical University of Delft website (www.citg.tudelft.nl). Go to the SWAN home page.

Another local model is the Mike21 suite which is available on a commercial basis from the Danish Hydraulics Institute. This is a linear refraction/diffraction model based on the mild-slope equation.

7.4.2 Transfer of wave climate to the WECS site

The transfer of the wave climate from a global model grid point (i.e. the 'offshore grid point') to the site of the wave power scheme (the target site) can be approached in a number of ways including the following:

1. Use the global model results as the offshore boundary conditions for the local model and run the local model on a sufficient number of occasions to define the wave climate at the target site. The number of sea states could include the whole of the global model database but this would be expensive.

2. An alternative approach is to undertake sufficient modelling to define a set of transformation matrices between the offshore grid point and the target site. This requires that a methodology is developed for selecting a representative subset of

sea states. The objective of this approach is to relate the sea state parameters at the target site to those at the offshore grid point. The transformation matrix or matrices can then be used to derive the energy matrix of the target site from the energy matrix of the offshore grid point.

As part of this procedure a transfer function confined to wave power may be developed. Whether this is a viable approach depends on how variable the relationship proves to be.

3. For plain parallel bathymetry, the transformation problem can be reduced to a set of algebraic equations involving the depths of the two sites. This follows on from the fact that, in the absence of losses, the on-shore component of the power is continuous. Changes in directional spreading vary closely as the changes in wavelength between the two sites. Approximate corrections can be made for losses due to wave breaking and bottom friction. This approach provides a method for the approximate transformation of the offshore sea state parameters to the target site. The whole of the offshore data series can be economically processed using this approach.

   The transformation process should be developed and checked with the aid of a purpose-designed measurement programme.

7.5 Comparison with measurements

7.5.1 Global models

All the available wave models were developed with the aid of wave measurements. The measurements were sometimes designed specifically to study wave generation and propagation theory, e.g. the JONSWAP project and its successors. In addition all the models have been validated by measurements made over many years as part of commercial and publicly funded wave climate programmes. It was found that the models were least accurate in rapidly changing winds (in both speed and direction) and this led to errors in the very high sea states which are of particular interest for survival statistics. Improvements to the models in terms of better model physics and better wind fields have led to greater accuracy in extreme conditions. For the more general run of wave conditions the improvements due to model physics have been less pronounced, and the accuracy of the wind fields is now the limiting factor. One area, however, which is of great importance to wave power resource determination is the way in which swell wave energy is handled by the models and recent studies suggest that there is still room for improvement here.

7.5.2 Local models

A purpose-designed measurement programme should be used to check the calculations and modelling used to transfer the offshore wave climate to the shallow water target site.

7.6 Interpretation of model results

7.6.1 General

Subclause 7.3 gave examples of studies undertaken using global models which give wave power and other statistics which in principle may be used directly for wave energy resource assessment. More generally, however, it may be necessary to process the model output to satisfy particular requirements.

7.6.2 Calculation of power from model spectra

Just as the power may be calculated from measured data, so it can be calculated from model results. When the model result for a particular simulation is available as a spectrum in the frequency domain, the method of 6.4 may be used. If the results are given on a k_x, k_y wave number grid it is probably easiest to convert the results to the frequency domain. In undertaking these transformations the following relations should be noted [15]:

$$S(f,\theta) = S(k_x, k_y) k \frac{dk}{df}$$

$$k_x = k\cos(\theta)$$
$$k_y = k\sin(\theta)$$

When using the definitions of 6.4 with model data we require values for the frequency widths Δf_j. These are not usually included explicitly in the spectral list, but may be calculated from the frequency information, either by successive differencing of the frequency values, or (preferably) by using the calculus. For example, the frequency list in the UKMO models may be calculated from:

$f_j = \exp(\frac{j-C}{D})$ where j is the frequency index, C=19.48 and D=5.747 then

$\frac{\Delta f_j}{\Delta j} = \frac{1}{D}\exp(\frac{j-C}{D})$ in applying this equation Δj is set to unity so that

$$\Delta f_j = \frac{1}{D}\exp(\frac{j-C}{D}) = \frac{f_j}{D}$$

7.6.3 Calculation of power from height/period data

It sometimes happens that the model results are not available as spectra, or that they are expensive and difficult to handle in that form. In such cases the power may be estimated from height/period data (usually H_s and T_Z), although with some loss of accuracy and without detailed directional information. A method for estimating power from height/period data which is not confined to deep water and is reasonably accurate for unimodal and particularly narrow spectra is given in *Seapower Southwest Review* [16]. The formula is:

$$P \approx 0.6286 c_g\left(T_e, h\right) H_s^2 \text{ kW/m}$$

where cg is the group velocity and h is the depth.

Since this formula is given in terms of T_e whereas the wave period is usually given as T_z, T_e should be derived from T_z either using the relationship appropriate for a particular spectral shape (e.g. the Pierson-Moskowitz) or by correlation between T_z and T_e for a sample of spectral data for the model grid point. Further details can be obtained from *Seapower southwest review* [17].

7.6.4 Calculation of energy matrices from Hs:Tz scatter diagrams

If the height/period data have been summarized into bivariate histograms (scatter diagrams) of H_s and T_z, it may be convenient and cost-effective to convert these directly into energy matrices. Clearly there are disadvantages with this approach compared with the method outlined in 6.5 and these are listed here:

- As the energy in each bin is derived from the height/period values for the bin there will inevitably be some inaccuracy and bias in the value ascribed to the bin.
- The scatter diagram may have been sorted by direction so that a 'mean' or 'predominant' direction will be available, however, usually information on directional spread will not be available.
- The energy matrix is indexed on H_s and T_z, rather than H_s and T_e.

In spite of these limitations, with care, useful preliminary information can be derived using this approach. Details are given in Appendix B2 of *Seapower southwest review* [17].

8. WECS productivity calculations

8.1 General

This clause outlines how the energy matrices described in 6.5.2 and the capture length matrices [18] can be used to estimate the productivity of a WECS.

8.2 Productivity calculations

To determine productivity we multiply the energy matrix for the site (6.5.2 and 7.6.4) and the capture length matrix for the WECS to produce a productivity matrix.

For simplicity we consider data which is sorted by H_s and T_e only, (H_{si},T_{ej}). Then donating the annual (i.e. all-year) energy matrix (normalized and in parts per thousand (ppt)) by e_{ij} and the capture length matrix by L_{ij} the annual productivity matrix is given by $e_{ij} \times L_{ij}$. We then form the sum and denormalize to get the annual productivity, thus:

$$\text{annual energy production} = \sum_i \sum_j (e_{ij} \times L_{ij}) \times 10^{-3} \times \overline{P} \times 365.25 \times 24 \text{ (kWh)}$$

where $\overline{P}$ is the annual average power for the site.

For other periods, for example winter (defined as the three months: December, January, February) we take the average winter energy matrix for the site, multiply this by the capture length matrix, sum and denormalize, thus:

$$\text{winter energy production} = \sum_i \sum_j (e_{ij} \times L_{ij}) \times 10^{-3} \times \bar{P}_W \times 90.25 \times 24 \text{ (kWh)}$$

where $\bar{P}_W$ is the average winter power for the site.

8.2.1 Uncertainties in productivity calculations

Uncertainties in estimates of productivity feed through from those in the energy matrices and from the capture length matrices. Leaving aside the issue of year-to-year variability for the moment, we may estimate the variability in the calculation of the productivity by summing the variability in the energy matrix and the variability in the capture length matrix. This assumes that they are uncorrelated and very small.

If $(v_L)_{i,j}$ is the proportional variance in the capture length for cell (H_{si}, T_{ej}) and $(v_e)_{i,j}$ the corresponding proportional variance in the energy then the variance in the productivity can be approximated as:

$$VarE = \sum_i \sum_j \left\{ \left(v_L\right)_{i,j} + \left(v_e\right)_{i,j} \right\} e_{i,j} \quad \text{(ppt)}$$

This result can be denormalized as required. Subclause 6.5.2.4 discusses the variability of energy matrices.

9. Meteorological archive

9.1 General

Wave models are the principal way in which wave power resource information can be obtained from the meteorological archive. The advantage of this approach is of course that the meteorological archive is essentially complete and is usually longer than measured series. Even so the lengths of modelled data series (hindcasts) are in most instances quite short. The UKMO European Waters model extends over almost two decades, while the UK Coastal Waters Model is not yet one decade long. Preliminary studies of these series have shown that inter-annual variability is large, and is likely to affect the economics of any wave energy scheme. The Environment Canada/Oceanweather 50-year hindcast provides one of the longest series available at present and studies of inter-annual variability using these data would be valuable.

To investigate variability on longer timescales it is necessary to look at broader indicators of wave climate. The use of pressure-based indices relies on the availability of estimates of monthly mean barometric pressure over most of the globe for a period exceeding 150 years.

9.2 Climate indices

9.2.1 General

These are based on the idea that the pressure gradient and the wind speed over the sea surface are closely related. Because the relationship between the two is linear to a first approximation, the average wind speed and the average pressure gradient should also be related.

9.2.2 North Atlantic Oscillation Index

The North Atlantic Oscillation (NAO) is a long-term variation in the strength of the westerlies. It has far-reaching implications for the climate of the whole northern hemisphere, particularly that of north-west Europe. The 'strength' of the NAO is characterized by an index which is based on the difference between average mean sea level (MSL) pressures from a station near the Azores and another near Iceland. Usually the difference is positive corresponding to a mean flow from the west.

9.2.3 Other pressure-based indices

The relationship between wind speed and wave power is far from simple and neither is it linear. Therefore the relationship between monthly averages of the NAO Index and wave power is not strong, however, it is possible to construct other pressure-based indices which correlate reasonably well with wave power and these can be used to study the inter-annual variability of wave power over timescales of many decades. A preliminary study along these lines is contained in [14].

10. Presentation of resource data

10.1 General

The results of investigations into the wave power resource should be presented in a report or series of reports. The reports should include the following:

1. A full description of the wave power resource at the position of interest.
2. A description of the techniques used to quantify the resource.
3. The operational history of any wave measurement programme undertaken as part of the resource determination.
4. A presentation of the results of the measurement programme.

These requirements are expanded in 10.2.

10.2 Contents of the reports

10.2.1 Wave power resource

10.2.1.1 General

The best estimate of the characteristics of the wave power climate shall be reported using the following presentations. These shall include a consideration of information from all sources including models and measurements.

Subclause 10.2.4 deals specifically with information about the short-term climate obtained from local measurements.

10.2.1.2 The energy matrices for the position of interest

This shall include the following:

1. Annual and seasonal energy matrices (see 6.5.2). These shall be in normalized form. For convenience of presentation, the values may be given in parts per thousand (ppt). The archived results given in un-normalized form should also be available.

   Power contours may be added as an aid to interpretation.

   A denormalizing quantity, usually the mean power, should be shown.

   The measure of power used may be either or both of the omni-directional power, P_{omni}, or the directionally resolved power, P_{nett}. In the case of the P_{nett}, divisions of the matrices in terms of direction may be given. Subclause 6.5.2 indicates how this can be done, but the precise design of the directional presentation should be tailored to the case in hand.

2. For measured data, uncertainty matrices should accompany the energy matrices. These will give the normalized standard deviation arising from sampling variability in the individual measurements in per cent for the values in each cell. It may be helpful to use colour coding to indicate values with comparatively high levels of uncertainty. For model-derived data it is not clear at this stage how to quantify the uncertainty in the results.

3. As far as possible, a discussion of the year-to-year variability in the energy matrix should be given.

10.2.1.3 Percentage exceedance of power

The following shall be presented:

1. The annual and seasonal percentage exceedance of power, 6.5.3. This may be either or both of P_{omni} and P_{nett}. The results may be plotted on logarithmic or semi-logarithmic axes.

2. For the case of P_{nett} the data may be presented by direction θ_p, although care should be taken to ensure that the available data are not over-divided. For example, with eight directional sectors and four seasons plus annual we have 40 plots.

10.2.1.4 Directional distribution of energy

This should give the percentage occurrence of energy by direction, using the directionally resolved value of power, P_{nett}. Either a compass-rose or a bar-chart method of presentation may be used. In either case an eight-sector division may be used and the graphical presentation can be supplemented by a tabular presentation.

10.2.1.5 Variation of power on monthly, seasonal, annual and inter-annual timescales

Some or all of the following time series of P_{omni} may be plotted. For very long data series, e.g. the NATL50 database, it may not be practical to plot all of the recommended series. The aim is to provide an oversight of the temporal variability of wave power at the site, such as:

1. Monthly means, i.e. mean of measured or modelled power for each available month;
2. Monthly means (overall), i.e. mean over available years for each month;
3. Annual means, i.e. a plot by year of the available annual means.

These may be derived from measurements, by long-term modelling or by other methods. Wherever possible, suitable measures of uncertainty shall be given. The graphical presentations shall be supplemented by tabular data as necessary.

10.2.2 Explanation of methods

The methods used to derive the resource information shall be fully described. For the case of measured data the explanations shall include brief details of the measurement techniques including the data rate, analysis method and quality control checks. The method used to calculate the power shall be given.

For resource data derived from modelled data, the methods used to calculate the power shall be given, for example, whether model spectra, height/period data, time series data or scatter diagram data were used. Where data from a wave power atlas or similar source are used, reference shall be made to the source.

If information on inter-annual variability of wave power is included, it is particularly important that the derivations used are reported in view of the early state of development of these techniques.

10.2.3 Operational history of wave measurement programme

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.

10.2.4 The wave measurements during the reporting period

This subclause gives a presentation of the wave power climate during the measurement 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. Energy matrices for the deployment period. Contours of wave power can be drawn as an aid to interpretation, and the mean or total power during the reporting period will be shown for denormalizing purposes.
3. Hs:Tz or Hs:Te scatter diagrams, i.e. bivariate histograms giving the proportional occurrence in 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 ranges of θ_p.

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