PRELIMINARY WAVE ENERGY DEVICE PERFORMANCE PROTOCOL

SUPPORTING COMMENTARY

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This *Supporting Commentary* accompanies the report *Preliminary Wave Energy Device Performance Protocol* which was commissioned by the Department of Trade and Industry (DTI) in April 2006. This document was prepared by Dr. George Smith[1] of Heriot-Watt University and Jamie Taylor of the University of Edinburgh.

Disclaimer

This report is submitted in good faith only. Neither the University of Edinburgh nor Heriot-Watt University will accept responsibility or liability for third party use or interpretation of the Preliminary protocol described in this document.

The structure of this document

This document provides a supporting commentary to the *Preliminary Wave Energy Device Performance Protocol* (the *Protocol*). There are five distinct component parts as follows:

Sections 1 – 6 Parallel commentary
Additional information on the rationale that informed the preparation of the Protocol and detailed comments on certain aspects of it. This part of the Supporting Commentary should be read in conjunction with the Protocol and so the section numbers and titles are the same.

Section 7 Power and performance matrices
Discussion of probable preliminary analysis of performance data.

Section 8 Wave calculations
Notes on the calculation of certain wave parameters.

Section 9 Protocols Workshop
Summary of issues discussed at the *Protocols Workshop*, held at the MacDonald Roxburghe Hotel in Edinburgh on 19th July 2006 and the response to those issues in the preparation of the Protocol.

Section 10 Protocol management
Discussion of issues relating to the management of the Protocol.

Section 11 Technical issues for future consideration
Discussion of technical issues which warrant possible further research and development.

Section 12 - 14 Appendices
Glossary, symbols and bibliography.

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Contents

1. Scope of the Protocol – *Commentary*

The Protocol provides a methodology for the co-ordinated measurement of the wave resource by *wave-measuring instruments* and the electricity generating performance of individual wave energy *devices* within an array. It is designed to allow comparison between the declared or anticipated performance of a device and its actual performance, and takes into account the diverse nature and distinct deployment conditions of different devices. The data collected under the Protocol should ultimately improve the ability to predict performance of devices in other locations with different wave climates. High priority has been given to the compilation of good quality databases that will allow relatively straightforward annual assessment of overall performance whilst encouraging the investigation of the more complex relationships between resource and device performance through data filtering.

It is assumed throughout the Commentary and the Protocol that a *Project Monitoring Officer* has been assigned to the project by the DTI or its agent. The onus is on the Participant to demonstrate compliance with the Protocol to the Project Monitoring Officer.

1.1.1 ***The Protocol***

There is a significant body of research dealing with wave resource evaluation for wave energy converters [for example Hagerman & Bedard (2003), Swift (2003), Metoc (2004)]. Much of this work has been based on small amounts of real data supported by the results of numerical modelling. However none of these specifically relate to the situation where the resource is measured in parallel with device performance.

Four considerations have had particular influence on the preparation of the Protocol. The first is that the almost unlimited range of possible incident wave conditions frustrates the concise classification of sea-states. The second is the problem that a wave measuring instrument cannot measure exactly the same waves as are incident on a wave energy device. The third consideration is the wide range of wave energy device technologies and of their respective location requirements. The fourth and final consideration is of the challenge and difficulty of working at sea in all weathers.

In writing the Protocol, an attempt has therefore been made to avoid being unjustifiably prescriptive whilst ensuring that sufficient data is collected to allow a full and proper assessment of each wave energy device.

1.1.2 ***Standards***

A significant advance was made with the EMEC (European Marine Energy Centre Ltd.) Preliminary *Performance Assessment for Wave Energy Conversion Systems in Open Sea Test Facilities* (EMEC 2004). This was written as part of their need for accurate assessment of single devices and with a view to developing a suitable accreditation standard for the testing of wave energy converters. It therefore stipulates certain standards and procedures for components such as instrument transformers and power transducers and for the calibration of wave measuring instruments.

The EMEC document draws some of its methodology from the *International Standard for Power performance measurements of electricity producing wind turbines* [IEC(2005)], including the following *normative references* which apply to the instruments used to measure electrical parameters.

1. IEC 60688: 1992, Electrical measuring transducers for converting AC electrical quantities to analogue or digital signals
2. IEC 60044-1: 1996, Instrument transformers – Part 1: Current transformers
3. IEC 60186: 1987, Voltage transformers (amended 1988 and 1995)

Measurements of electrical parameters under the Protocol should be made to at least the standards specified by these documents or their successors.

1.2 Protocol start date

The beginning-of-the-month requirement for the Protocol start date is intended to simplify the bundling of individual data records into monthly folders.

1.3 Outline of Protocol requirements

The Protocol requires that participants make continuous measurements of waves and of device outputs and that they collect data from the electricity sold to the network. Depending on the project wave measuring system and on the types of devices, the compilation of half-hour records may take place in *real-time* (i.e. at the end of each half-hour period) or at a later date from the archived time-series.

2. Project information – *Commentary*

2.1 Rationale

The wave field encountered by each device and by any wave measuring instrument can be profoundly influenced by the local bathymetry and topography of the site where the array is deployed. The effects of refraction, diffraction, reflection, shoaling and shadowing along with energy loss due to bottom friction and wave breaking can significantly modify the local wave field and lead to complex spatial variations in wave power. The variation of tidal level and the presence of currents may also locally modify the wave field and affect the accuracy of wave recording instruments. These factors can be particularly relevant when considering shallow-water or shoreline devices as they complicate measurement of the incident wave power and its direct comparison with the power produced by a device.

Participants must provide a detailed bathymetric map of their project location with the nominal positions of their devices and wave measuring instruments indicated. They must demonstrate understanding of the physical characteristics of their project location, by identifying any features that may lead to significant resource variation between individual wave energy devices or between devices and wave measuring instruments.

After submission and consideration, the number and the placement of wave measurement instruments will be agreed with the *Project Monitoring Officer*.

Participants are required to provide information that shows how they expect the power generated by their devices to vary with different sea-states. Some information about the project cabling and electrical arrangements is also requested. This will allow estimation of the power losses within the project cables so that valid comparisons can be made between the average power measured at the terminals of individual devices and the energy exported from the project through the point of connection to the network.

2.2 Project-record

Eastings and Northings are specified for the indication of the locations of project features such as wave measuring instruments, devices and cable routes because they allow rapid appreciation of scale and easy calculation of dimensions.

Assessment of the physical characteristics (homogeneity, mean wave direction etc.) may be based on the use of wave models or from previous resource measurements at the location. This might be supplemented by discussions with appropriate persons with local knowledge, such as coastguard or port authorities. The intention of this information is to allow a decision as to the most appropriate instrument position and number. At inshore locations, specialised numerical modelling may be required to take account of bathymetric and topographic features.

In some cases, due to the nature of the locations or devices, deviations from the information requirements of the Protocol may be appropriate. Participants must then justify any such changes to the information contained within the Project Record.

Assessment of the *rated output* of a device is not necessarily straightforward. As defined for the protocol it is equivalent to the maximum power in kilowatts that can be supplied to the network, net of the corresponding power lost in the export cable and in the project-specific transformers and switchgear. If, for example, a device has a conventional generator with a *nameplate* rating of 1,250 kW and a minimum internal power requirement of 38.5 kW then its rated output would be assessed at 1211.5 kW.

If it can be shown that, by design, the generator is incapable of being driven to its nameplate rating and that the system over-current protection values are based on this reduced rating, then the reduced rating can be used in assessing the rated output.

For devices having variable-frequency, variable-voltage directly-driven generators, the value to use for rated output is less obvious. Grey (2005) considers this problem for a reciprocating directly-driven generator and points out the frequent confusion between *peak power* and rated power. Devices of the type that he considers will operate through a power-converter of some kind to convert their output to constant-frequency, constant-voltage current that can be supplied to the network. Whatever the arrangement, the rated output of the device would again be the maximum power in kilowatts that can be supplied to the network after allowing for the corresponding project specific cable, transformer and switchgear losses.

2.3 Project-log

The intention in stipulating that a project-log be kept is to ensure the systematic recording of all changes, modifications and problems that may have a bearing on how data is later interpreted.

It is hoped that this will help to allay the fears of some potential participants that a *wholesale aggregation* of wave and electrical data will not enable critical assessment of their devices. It is possible that even minor events recorded in the project-log may later help to explain anomalies in device power generation.

3. Resource measurement - *Commentary*

3.1 Rationale

A general description of the random nature of the sea-state must include information on wave amplitude, frequency content and directional properties. Any particular wave energy device will have its own distinct sensitivities to each of these parameters and it is unlikely that all will be fully understood in advance of deployment - indeed one of the aims of the scheme is to advance this understanding. A main objective is to ensure that the details of the wave regime are recorded in sufficient detail to clarify these dependencies.

A frequency domain approach is prescribed to describe the sea-state. This implies treatment of sea-states as if they are statistically *stationary* over some time interval so that a wave energy spectrum can be calculated by use of the fast-Fourier transform (FFT). The reasons for using the frequency domain approach are:

1. It has wide acceptance as the appropriate method for the analysis of discretely-sampled waves;
2. The accuracies and errors are well understood;
3. Power density calculation is straightforward because the frequency- and depth-dependent variation of wave *group velocity* can be calculated;
4. The directional characteristics can be calculated and listed in terms of the wave spectrum;
5. The shape of the spectrum gives a very useful idea of the composition of a sea-state in terms for instance of swell, old wind-sea and new wind-sea.

3.2 Time coverage and data return

As the wave climate varies both seasonally and from year to year, the aim must be to measure wave data continuously – in all months of the year and throughout the life of the project. It is recognised however that it is impossible to guarantee a 100% data return from any wave measuring instrument. Specifying too high a data return might encourage participants to take excessive risks in trying to repair instruments in dangerous weather conditions. Setting a lower data return percentage will bias data in favour of calmer weather.

It is hoped that participants will themselves place such a high value on obtaining wave data that they will need little or no encouragement to maintain the highest possible data returns from their instruments. In any event, the Project Monitoring Officer will maintain a close watch regarding the rate of wave-data return and should be notified where instrument failure leads to loss of data recording.

3.3 Averaging period

The waves at any location are products to some degree or other of the action of all recent winds over all of the ocean surface. Sea-states are therefore constantly changing. Averaging parameters that are used to succinctly describe sea-states are calculated from time-series records from wave measuring instruments. Ideally the records would cover a time period short enough that the sea-state can be considered as being *stationary*.

However, the accuracy of calculation of power density and other statistically derived wave parameters depends on the time duration of the wave measurements. According to Pitt (2005) the *normalised standard error* in the calculation of wave power density from a 1600 second time-series is about 10 %, but is reduced to about 7 % if the observations cover a period of one-hour. In practise, averaging periods from 20 minutes up to 3 hours are common.

Any length of averaging period is bound to be a compromise. The half-hour period that is specified in the Protocol is influenced by the practise adopted by Datawell's *de-facto* standard measuring buoys and also reflects the practice within the electrical power industry to buy and sell energy in half hour blocks. Attendees at the Protocol Workshop expressed agreement with the choice of half-an-hour.

3.4 Time-keeping and synchronisation of data

Close synchronisation between resource and device data-recording is of very great importance when comparing the output of devices to the corresponding measured sea-states.

GPS systems appear to offer an effective way of enforcing a common timing discipline between physically separated data logging systems.

3.5 Type of Wave measuring instrument

Wave buoys are the standard means of measuring wave elevation and direction and there is considerable literature on the processing of their data. See for example the classic paper on the measurement of directional spectra by Longuett-Higgins, Cartwright and Smith (1963) or a synopsis of the data processing methodology used in the Waverider buoy system [Datawell (2005)]. General wave data processing and analysis techniques are described by Tucker and Pitt (2001).

The behaviour of buoys in shallow waters can be influenced by tidal and wind driven currents but they have been deployed successfully in water as shallow as 8m.

Acoustic Doppler current profiler (ADCP) systems have now been developed that are able to provide wave elevation time-series and directional information and it is possible that these may prove suitable in shallower water. Strong et al (2000) and Rorbaek and Andersen (2000), have made useful comparisons of ADCP-derived directional spectra with other measurements. It is also understood that EMEC and TUV NEL (ex *National Engineering Laboratory*) are hoping in the near future to make detailed comparisons of Waverider and ADCP measurements from the EMEC test site.

See also the comments on radar measurement of sea-states in Section 11.6.

3.6 Number of instruments and placement

For nearshore and shoreline sites where the bathymetry can change rapidly, a single wave measurement point may not be sufficiently representative of the incident power at each device in the array. In these cases measurements in deeper water will need to be transformed by a process based on the mathematical analysis of wave propagation from the measuring point to the device location.

Even for a site which can be considered to be relatively homogenous, the short-term statistical variations in wave parameters measured at two positions some distance apart can be large. As an example, some initial comparisons between the two EMEC buoys which were placed 1.5 km apart, show high temporal correlation but differences in absolute wave height at each position of up to 30%. At the other end of the scale, work has shown that measurement of H_{m0} averaged over 20 minutes at positions 70 m apart could also show variations of up to 20%.

Waves will be reflected or *radiated* from devices according to sea-states and according to device energy absorption characteristics. If the wave measuring instrument is too close the radiated waves may corrupt its measurement of the incident waves. This seems unlikely to be a significant problem if the sum of the angles subtended by the devices as seen from the measuring instrument position is less than 20 degrees.

In practise, the need to maintain safe distance between measuring instruments and devices means that buoys are unlikely to be significantly affected by reflections from devices.

3.7 Half-hour wave-records

The Protocol specifies that the half-hour wave-records be archived and included in the annual deliverables to the DTI. This requirement reflects the perceived high value of wave data and will allow further processing if required at a later date to recover information, for example, about extreme waves.

If post-processing of the time series is required, such as for instance to remove the effects of tidal level variation or instrument drift, the details must be noted in the project log.

A data validity flag has been included to allow indication that particular data may be in error. This could be due to a variety of reasons, including transmission error and instrument failure which are likely to be instrument dependent.

3.8 Half-hour sea-records

It is likely that most of the time-series data processing required to produce the half-hour sea-record will be a standard part of the automatic data processing routines implemented by the manufacturer of the wave-measuring instrument.

Most of the useful energy in waves falls into the range of wave periods from 5 seconds upwards and power density is proportional to period. Few devices will be efficient converters of energy at periods above 15 seconds but in these long powerful swell waves their output levels may still be high. A range of wave periods from at least 5 seconds to 20 seconds is therefore of greatest interest. This is equivalent to a frequency range of from 0.05 Hz to 0.2 Hz.

In this context, the methodology used by Datawell [Datawell (2005)] is instructive. For example, one of their standard systems samples waves at 1.28 Hz for 8 consecutive periods of 200 seconds. Each record thus contains 256 samples and a corresponding spectrum is calculated locally within the buoy by FFT (Datawell refer to this as the *internal wave spectrum*). The lowest frequency component is therefore at 1/200 s or 0.005 Hz with subsequent components at integer multiples of that frequency up to half of the 1.28 Hz sampling frequency. The spectrum thus ranges from 0.005 Hz to 0.64 Hz. A simple smoothing is applied to the components and then, to reduce data storage requirements for the internal wave spectrum, only every other component at frequencies greater than 0.1 Hz is kept. This leaves a total of 74 components in the spectrum. Finally, the average of eight consecutive 200 second spectra is filed as the half-hour internal wave spectrum.

In the Protocol, energy period T_e is the preferred period parameter. Its calculation is described in Section 8.4.

The derivation of power-weighted mean wave direction is described in Section 8.5.

4. Device measurement - *Commentary*

4.1 Rationale

The performance measurement of a wave energy device must be based on the net electrical power output of the device. Where external electronic equipment (a *power-converter*) is used to convert the output of a *network-incompatible* generator to *network-compatible* current, the device is considered to consist of the device itself plus its power-converter. It is assumed because of the difficulty of *manifolding* asynchronous currents that each such device will have its own dedicated power-converter.

The specification of the power cables and conventional power transformers that interconnect devices, power-converters, sub-stations, and network will be project specific and not properly part of the devices whose power generation characteristics are being monitored under the Protocol. However the cables and transformers will be sources of electrical losses and so it is important to make power output measurements in such a way that these are either not included in the measurement or that they can be corrected for.

It is recognised that the performance of a device cannot be adequately assessed by simply logging all sea-states and the corresponding half-hour device power outputs and then producing a single *universal* performance indicator such as a power matrix. Complete performance assessment will require active *filtering* of data and the methodology of the Protocol has been designed to preserve the original data so to make this possible. As an example, control strategies and algorithms are likely to evolve as operational confidence is gained and it will be important to be able to separate the performance indicators from before and after a particular software update. Another example might be the need to exclude periods when, due to faults, a device was only partially enabled for electricity generation. The inclusion of *device-status* and *system-identifier* fields in the device record is designed to facilitate this kind of data filtering.

4.2 Power-converters

All devices will deliver current to the network *point of connection* as constant frequency (50 Hz) nominally constant-voltage, three-phase current. In some devices however, particularly those with direct-drive *power-take-off* systems, the range of current, voltage and frequency will be such that the power will not be suitable for the network until processed by a power-converter. An example of a power-converter would be a rectifier, DC-bus and inverter system that changes variable-voltage and variable-frequency electricity to constant-voltage three-phase alternating-current at network-frequency.

Other devices, such as oscillating water columns (OWC), may use more or less standard electronic *variable-speed drives* to allow the generator to deviate from network frequency. For the purposes of the Protocol, such a system is treated as a power-converter.

The project-dependent cable losses between devices and power-converters during half-hour periods will usually be calculable from knowledge of the cable characteristics and of the average RMS current flowing in it during the half-hour. This current can be measured at the *input* terminals of power-converters.

4.3 Power measurements

Typically, the instantaneous electrical power will vary cyclically at twice mains frequency and depending on the number of generators within the device and the degree of energy storage within the power-take-off system there will be further gross variation of power at wave frequency. The power signal that is provided for the performance monitoring of the device must be the *average* value of the instantaneous power during each half hour period.

4.4 Quiescent power

The requirement to record negative power values that correspond to net *quiescent* consumption in small seas is consistent with the methodology used for the power performance measurements of wind turbines [IEC (2005)].

4.5 Power-variability

The instantaneous electrical power in any single phase of the output will vary cyclically at twice network mains frequency (i.e. 100 Hz). However, when the power in the three individual phases are summed by the power transducer, this network-frequency modulation will largely cancel out.

Although wave energy devices will only be able to remain connected with the network by maintaining voltages across the three phases that are balanced within decreed tolerances and at network frequency as specified (for example) by Engineering Recommendation G59 [Electricity Association (1991)], the current and power from a single device will obviously vary according to sea-states and incident waves. Depending on the number of electrical generators within the device and the degree of energy storage within the power-take-off system, there is likely to be residual modulation of power at wave frequencies and there will certainly be power modulation over time periods comparable with the time-constant of the storage.

It is likely that projects that are able to deliver wave generated energy with power values that change relatively slowly will more easily be able to negotiate network connection. The relative highs and lows of short-term power variation will be reduced to some extent when the outputs of a number of devices within a project are aggregated. The quality of power delivered to the network will also be higher when the device power-take-offs have sufficient storage capacity to buffer power output from wave to wave.

4.6 Device-status and network-status

By keeping a structured record of the device status it will be possible when compiling performance summaries to include or exclude certain periods of operation which might otherwise unfairly misrepresent device performance. This kind of data *filtering* will also allow the availability and maintenance history of devices to be readily examined.

There may be times when the network operator is not able to take all the available power, and the participants will be required to *constrain* the output of certain devices.

Sometimes the underlying reason for a device being off-line will be related to issues or problems *within* the device. At other times, it will be off-line because of *external* factors.

If a device has parallel redundancy in its power-take-off system, there may be times following a component failure or storm damage, when it will be operating at a *reduced capacity* setting or with a *work-around* setting.

4.7 System identifier

It was noted by one of the authors during a visit to a wind farm that each of twenty-six identical looking turbines had one of six different makes of gearbox and one of four different makes of alternator. In wave energy devices, there may be similar variations in the detailed hardware composition of power-take-off systems and there are very likely to be changes in operational procedures and control algorithms during the life of a project.

The *system identifier* tracks such variations through its various *hardware*, *policy* and *software* sub-fields.

4.8 Half-hour device-records

The detailed structure of the device-record will vary from project to project and will be indexed by the device *header-file.* This will, for instance, list the implied meanings of flag values that are used in the device-status and network-status fields as well as any additional fields that may be included in the records.

5. Export measurement - *Commentary*

5.1 Rationale

The metering of electricity exports at the point of connection to the network is usually based on half-hour *energy totals* and is carried out by an *accredited meter operator.* Arrangements will be required to obtain regular data from the meter operator. To facilitate comparison with *power* measurements made elsewhere, these half-hour energy totals will be converted to equivalent mean power values.

Power-factor correction and purchase of reactive power will be a matter between the participant and the network operator and so measurements of reactive power flows to and from the network are not required under the Protocol.

5.2 Quiescent power and ancillary supply

Where there is only a single connection between project and network, the associated energy or power will at times be negative to indicate a net draw of energy from the network by the project.

However, in addition to the *export* connection, some facilities may have an *ancillary* power import connection to the network that must also be monitored. In the case of off-shore devices with variable-voltage and variable-frequency generators and external power-conditioning, such an ancillary supply may be routed through to devices independently of their generated output cable to provide a conventional mains supply.

5.3 Network-status

The network-status field provides additional information with regard to the project connection to the network. This can be used for data filtering when compiling performance summaries.

5.4 Half-hour export-records

Note that the half-hour *energy* exports should be converted to half-hour average *power* values.

6. Deliverables - *Commentary*

6.1 Header files

The detailed format of the wave-, sea-, device- and export-records is not specified in the Protocol. They are likely to be text files with comma or tab spacing between fields but without any explicit labelling. The header files therefore provide a means to *decode* the contents of those files by supplying *labels* and *calibrations*.

6.2 Returns file

The returns file should have explicit labelling of the sort shown in Table 6.1 of the Protocol document. The top fifteen or so lines of the file will give a quick visual summary of the degree of compliance with Protocol requirements that a participant has managed to achieve. The rest of the file can be *machine-read* during automated processing of records.

6.3 Headline numbers

The headline numbers for individual months should be laid out in the order of their occurrence during the project year. For example, if the Project start date is 1st November, the months should be listed in the order: November, December, January ... etc.

6.4 Time-series plots

The intention behind the formatting instructions is to encourage visual presentation of resource and performance information in a relatively standardized way that makes it as easy as possible to compare results from different devices within a project and to compare results from different projects. The details of graphical presentation will depend amongst other factors on the number of devices in a project, and the instructions are intended to convey the *spirit* rather than the *letter* of how data should be presented.

6.5 Scatter diagrams

The data presented in the *bins* of scatter diagrams are sometimes reported as the actual number of occurrences of sea-states with a particular combination of height and period. Alternatively, the data is sometimes normalised, typically as integer *per-mil* values, i.e. as probabilities in parts per thousand. Tucker and Pitt (2001) present scatter diagram data in this way. However, to retain comparative resolution for rarely visited bins, they suggest that all per-mil values of less than one be replaced by an underlined number that represents the actual number of observations. This kind of mixed presentation can be tricky to read and the format specified in the Protocol and illustrated with the fictional example of Figure 6.1 is based on the actual numbers of occurrences.

With the axes shown, the right top-most bin represents sea-states having power densities of just over 1 MW/m and greater. The lower left-most bin represents power densities of around 600 W/m and less. Note that the total number of observations is indicated on the diagram.

ALL YEAR **17518 half-hour observations**

H_{m0} \ T_e	<=5	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	>=15
>=12																				1	
11.5																			1		
11.0																		1	2	1	
10.5																	2	14	2		
10.0															8	9	9	11	5		
9.5													7		6	3	5	7	2	1	
9.0													17	14	11	21	7	21	1		
8.5													22	34	23	17	12	15	4	1	2
8.0												17	34	18	31	42	21	13	3	4	
7.5											19	21	15	34	34	51	18	8	2		
7.0											21	32	45	42	35	18	16	7	4	1	
6.5											34	34	68	119	42	24	21	3	1		2
6.0										4	51	68	51	51	25	23	34	11	1	1	
5.5								3	27	18	64	85	85	68	41	31	18	1	6		1
5.0							34	23	34	102	85	153	85	102	41	34	22	5	1	3	
4.5						9	15	34	68	238	119	135	102	68	56	51	17	9	2	1	
4.0						21	17	68	68	221	153	170	162	136	68	51	15	5	3		
3.5						28	34	136	101	299	238	231	153	85	68	34	13	11	3	2	
3.0					34	34	68	221	306	408	374	272	136	85	51	21	11	7	7		
2.5				12	23	34	204	357	427	563	408	204	136	51	22	11	8	2	4		
2.0			9	21	51	85	221	562	374	714	340	221	85	34	16	7	5	8	4		
1.5		11	14	34	68	119	408	582	408	372	173	102	23	22	12	8	12	7			
1.0	1	9	21	51	59	51	204	289	272	204	85	34	21	15	11	5	9	3			
0.5	2	3	7	9	16	20	21	34	23	24	34	12	15	21	9	3	5				

Figure 6.1 Example all-year scatter diagram with the ranges of the height and period as specified in the Protocol and with the data binned as frequency of occurrence of half-hour sea-states.

6.6 Power-weighted wave rose

The directionality of waves and sea states is a complex issue and hard to adequately represent diagrammatically. Power-weighted wave roses with their petal *area* proportional to the number of observations rather than the petal radial *length* are thought by the authors to give a better feeling for the variability of the wave power resource with direction. However, many other formats are possible. Boehme *et al* (2006) use a rose device where the lengths of petals show the relative proportion of time that the average wave direction was in a particular sector. But they also show, by alternating black and white banding within each petal, how the wave power density was distributed within certain intervals (>25 kW/m, 25 – 50 kW/m, 50 – 75 kW/m and > 75 kW/m).

7. Power and performance matrices

7.1 The power matrix

It is likely that sea-state and device performance data provided to the DTI will be used to produce power matrices.

The power matrix is well established as an indicator of commercial wave energy device performance. Its use reflects an experimental tank-testing methodology that was referred to by earlier wave energy experimenters as *scatter diagram exploring* (Salter & Taylor, 1984). Several wave energy device-developers have published a power matrix for their device as a concise way to present its predicted performance in full-scale seas. The popularity of the power matrix also reflects the important part played by *power curves* in the marketing of wind-turbines and in the development of wind-energy projects. An example power matrix based on an imaginary device is shown in Figure 7.1.

For any combination of values of parametric wave height (typically significant wave height H_s or H_{m0}) and parametric period (typically energy period T_e) the power matrix tabulates an average power output figure for the device. The numbers so far published by device developers are presumed to be from tank testing or numerical modelling or from a combination of both. The sea-states referred to by the height and period parameters are therefore usually two-parameter idealised models (such as the Bretschneider spectrum) combined with a simple *spreading function*. (A cosine weighting function $\cos^{2s}$ is sometimes used for spread, where s is the parametric spread factor with a value of $s = 1$ corresponding to a short-crested sea).

H_{m0}	<=5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13	13.5	14	14.5	>+15	T_e
>=12																2025	2025	2025	2025	2025	2025	
11.5															2025	2025	2025	2025	2025	2025	2025	
11.0															2025	2025	2025	2025	2025	2025	2025	
10.5														2025	2025	2025	2025	2025	2025	2025	2025	
10.0														2025	2025	2025	2025	2025	2025	2025	2025	
9.5													2025	2025	2025	2025	2025	2025	2025	2025	2025	
9.0													2025	2025	2025	2025	2025	2025	2025	2025	2025	
8.5													2025	2025	2025	2025	2025	2025	2025	2025	2025	
8.0												2000	2025	2025	2025	2025	2025	2025	2025	2025	2025	
7.5											1928	1987	2025	2025	2025	2025	2025	2025	2025	2025	2025	
7.0											1855	2026	2025	2025	2025	2025	2025	2025	1912	1996	1983	
6.5									1478	1679	1672	1790	1866	1976	1833	1696	1800	1672	1754	1836	1712	
6.0									1245	1347	1488	1540	1731	1627	1666	1618	1600	1673	1592	1512	1545	
5.5									1083	1179	1325	1395	1567	1549	1523	1495	1479	1520	1471	1368	1463	
5.0							787	892	920	1106	1161	1271	1402	1336	1380	1383	1358	1251	1279	1162	1200	
4.5							619	632	721	784	947	1108	1174	1183	1151	1230	1129	1031	1051	1037	973	
4.0					380	426	451	523	521	612	733	831	945	936	923	917	900	921	823	820	745	
3.5					299	307	352	368	405	465	573	653	741	730	717	742	694	633	638	587	583	
3.0			183	202	218	218	254	275	289	362	413	489	537	550	512	515	487	498	454	414	420	
2.5			129	154	158	169	187	202	216	244	295	316	374	398	364	343	354	319	326	314	298	
2.0			74	86	97	116	119	133	142	151	176	205	210	203	215	202	220	217	198	181	175	
1.5	22	33	45	55	59	62	73	73	87	97	109	117	132	139	133	137	134	129	120	121	107	
1.0	8	11	15	16	20	23	26	29	31	38	42	50	53	51	50	47	47	42	43	39	38	
0.5	0	1	2	2	3	4	5	7	10	10	12	15	15	13	11	10	9	11	12	9	7	

Figure 7.1 Example power-matrix for an imaginary 2025 kW device. Each cell gives a power output prediction (in kW) for a rounded value of parametric wave height (usually H_{m0}) and wave period (usually T_e). The occurrence of seas with high H values and low T values is generally limited by breaking – hence the blanks at the top of column on the left.

7.2 Performance matrices

A power matrix says nothing about the sensitivity of device performance to variations in sea-state parameters such as spectral width and directional spread. A single power matrix also reveals nothing about variation in power output in *different* sea-states that may have had the *same* nominal height and period. It is possible therefore that additional *performance matrices* will be created as a first step in understanding the performance of a device.

Figure 7.2 illustrates a simplified set of five such performance matrices that respectively show the mean power, maximum power, minimum power, standard deviation of power values about the mean and the total number of records.

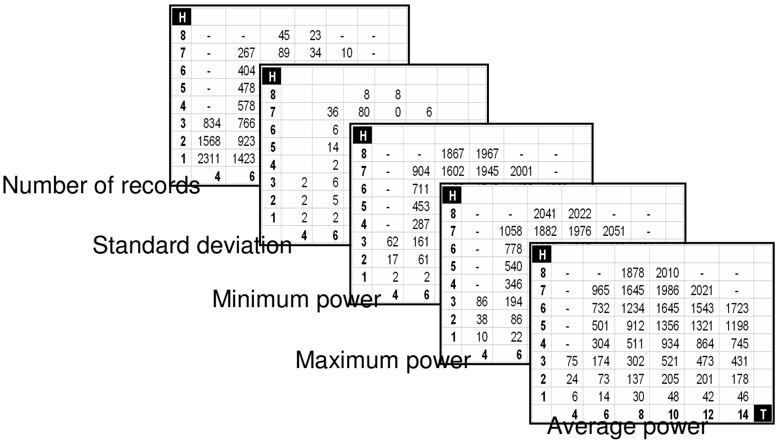

Figure 7.2 Example set of performance matrices for an imaginary single device. To simplify illustration, the numbers of bins have been reduced.

The last of these (the number of records) will be very similar to the wave resource scatter-diagram for the corresponding time period, though there will usually be differences due to losses of wave data at certain times and losses of device availability at other times.

For a device that is relatively insensitive to wave directionality and sea-state spectral shape, the average, maximum and minimum power values will be fairly close for each *H/T* bin. In that case the standard deviation values will also be low. Such results would show that the device behaviour is relatively easy to predict and that the conventional power matrix will usually suffice to describe the relationship between sea-states and generated power.

For devices that are more sensitive to directional and spectral variation, there may be considerable differences between average, maximum and minimum power values and relatively high values for the standard deviations. Such results would suggest that more sophisticated techniques will be required to tabulate device power generation in terms of sea-state parameters.

It is, therefore, suggested that sets of performance matrices of the sort suggested in Figure 7.2, may provide a relatively easy first check on the relationship between sea-states and device performance.

It is also hoped that, by use of the device-status, network-status and system-identifier fields of the device-records it will be relatively easy to *pre-filter* the data that is plotted within a set of performance matrices. As a simple example, it would be possible to look at the performance of a device, based only on times when it had been fully available and under automatic control and to exclude all of the times when it had only been partially available (e.g. due to non-fatal faults) or under manual control. Similarly the performance under distinct software versions might be compared.

Some of these issues are further discussed in Section 11.8.

8. Wave calculations

For reference, this section shows recommended processes for the calculation of gross power density, group velocity, spectral moments, energy period and mean direction.

8.1 Gross wave power density

The theoretical *gross* or *omni-directional* power density of a sea-state is given by:

$$P_w = \rho g \int S(f) c_g(f,h) \mathrm{d}f \qquad 8.1$$

where:

P_w = gross wave power density (W/m)

ρ = density of sea-water (kg/m^3)

g = Acceleration of gravity (m/s^2)

$S(f)$ = spectral density at frequency f (m^2/Hz)

$c_g(f,h)$ = group velocity at frequency f (m/s)

h = water depth (m)

In modern practise, wave data is obtained as discretized time-series and transformed into the frequency domain by the *fast Fourier transform* (FFT). The energy at each discrete frequency is then represented by the product of the corresponding spectral density component S, the density of seawater and the acceleration of gravity g. The power at each frequency is obtained by multiplying this energy by the speed at which it is transported by the wave, the so-called *group velocity* c_g. In deep water, where group velocity depends only on wave frequency, the calculation is straightforward. In intermediate water depths it is complicated by the additional dependence of group velocity on water depth.

The discretized form of the gross power density equation is:

$$P_w = \rho g \sum_{i=1}^{n} S_i c_g(f_i) \Delta f_i \qquad 8.2$$

where:

S_i = spectral density of the i^{th} component (m^2/Hz)

f_i = frequency of the i^{th} component (Hz)

$c_g(f_i)$ = group velocity of the i^{th} component (m/s)

Δf_i = frequency width of i^{th} component (Hz)

n number of components

8.2 Group velocity

Wave group velocity is calculated from the *dispersion relation*, either by direct solution or via a look-up table of velocity as a function of frequency and depth.

The dispersion relation generally shows group velocity as a function of *phase velocity* and of wave number *k*. However *k* is itself a function of frequency and the group velocity can be expressed directly as:

$$c_g(f_i) = \left(\frac{g}{k(f_i)}\tanh(k(f_i)h\right)^{\frac{1}{2}}\left(1+\frac{2k(f_i)h}{\sinh(2k(f_i)h)}\right) \qquad 8.3$$

where:

$k(f_i)$ = wave number of the i^{th} component (m^{-1})

In general, the *wave number* is defined in terms of the reciprocal of wavelength:

$$k = \frac{2\pi}{\lambda} \qquad 8.4$$

where:

λ = wavelength (m)

The deep water wave number $k_0(f_i)$ can be found from:

$$k_0(f_i) = \frac{(2\pi f_i)}{g} \qquad 8.5$$

$k(f_i)$ for any depth can be found by an iterative solution of the following equation, which uses the value of k_0 from *8.5* as an initial guess:

$$k(f_i) = \frac{(2\pi f_i)^2}{g\tanh(k(f_i)h)} \qquad 8.6$$

Equations *8.5* and *8.6* can be used to create a table of wave number values for the depth of the water where the wave measuring instrument is located and for all of the discrete frequencies in the wave spectrum. These values can then be used to calculate group velocity at each frequency from equation *8.3*. Finally, the gross power density can be calculated from equation 8.2.

8.3 Spectral moments

The n^{th} spectral moment is defined from the omni-directional spectrum as:

$$m_n = \int f^n S(f)\mathrm{d}f \qquad 8.7$$

In practice, these will be calculated in a discretized form from the derived spectrum, as follows:

$$m_n = \sum_{i=1}^{n} f_i^n S(f_i)\Delta f_i \tag{8.8}$$

Where

m_n = n^{th} spectral moment (Unit depends on degree of n)

In calculating spectral moments from a discretized spectrum there is danger, particularly for the higher order moments, that higher frequency spectral density components may bias the result out of proportion to their actual contribution to the power available to wave energy devices. There is a similar danger from the effects of *noise*. Accordingly, an upper cut off 0.5 Hz should be used in calculations. i.e. spectral density components corresponding to frequencies above 0.5 Hz should be ignored.

8.4 Energy period

In deep water, energy period can be defined in terms of the *minus-one* and the *zeroth* spectral moments:

$$T_e = \frac{m_{-1}}{m_0} \tag{8.9}$$

Where

T_e = energy period (s)

In intermediate depths it is important to take account of the effect of water depth on wave group velocity. The most appropriate way to consider energy period is to then recall the conceptual definition of energy period as the period of the regular wave that has the same parametric height and the same power density as the sea-state under consideration. If the gross power density and the parametric wave height H_{mo} are already known, this leads to:

$$T_e = \frac{64\pi}{\rho g^2}\frac{P_w}{H_{m0}^2} \tag{8.10}$$

8.5 Mean wave direction

For discretized spectra, the mean wave direction is given by:

$$\theta_m = \arctan\left(\frac{\sum_{i=1}^{n}\sin(\theta_i)\Delta f_i}{\sum_{i=1}^{n}\cos(\theta_i)\Delta f_i}\right) \tag{8.11}$$

where:

θ_m = mean wave direction (degrees)

and *arctan* is the *four-quadrant inverse tangent* function implemented as *atan2* in Matlab and other programming languages.

The mean power-weighted wave direction is given by:

$$\theta_p = \arctan\left(\frac{\sum_{i=1}^{n}\sin(\theta_i)S(f_i)c_g(f_i,h)\Delta f_i}{\sum_{i=1}^{n}\cos(\theta_i)S(f_i)c_g(f_i,h)\Delta f_i}\right) \qquad 8.12$$

where:

θ_p Power-weighted mean direction wave direction (degrees)

9. Protocols workshop

During preparation of the Protocol, a *Protocols Workshop*, was held at the MacDonald Roxburghe Hotel in Edinburgh on 19th July 2006. This was a combined event at which the Wave Energy Device Performance Protocol and the Tidal-Current Energy Device Performance Protocol were discussed in plenary sessions and in separate wave and tidal-current workshops.

The attendees were as follows:

George Aggidis	Lancaster University
David Ainsworth	Marine Current Turbines
William Batten	University of Southampton
Cuan Boake	Queen's University Belfast
Ian Bryden	The University of Edinburgh
Scott Couch	The University of Edinburgh
Fred Gardner	Teamwork Technologies
George Gibberd	Tidal Generation Ltd
Andrew Grant	University of Strathclyde
John Griffiths	JWG Consulting Ltd
Tom Heath	Wavegen
Henry Jeffrey	The University of Edinburgh
Neil Kermode	EMEC
Clare Lavelle	Scottish Power
Simon Meade	Lunar Energy
Phil Michael	Future Energy Solutions
Robin Murray	Future Energy Solutions
Norman Perner	Voith Siemens Hydro
Ted Pitt	Applied Wave Research
Chris Retzler	Ocean Power Delivery Ltd
Emma Robinson	OpenHydro
Howard Rudd	Future Energy Solutions
Gary Shanahan	Department of Trade & Industry
George Smith	Heriot-Watt University
Jeremy Thake	Marine Current Turbines
Vengatesan Venugopal	The University of Edinburgh

The issues raised and discussed with reference to the wave energy Protocol are addressed below.

9.1 Data disclosure

There was general concern regarding the public disclosure of project performance information. This issue is considered in Section 10.4.

9.2 Near-shore devices

The difficulties of near shore wave measurement were discussed. There is a problem in dealing with the possible effects of reflections and in making measurements that are representative of the incident waves on an entire array. This issue is considered in Section 11.4.

9.3 Wholesale data gathering

Concern was expressed regarding the "wholesale gathering" of data and its subsequent use in the production of power matrices, without regard for the "background story" behind each result. One workshop participant felt that to lose this would drastically reduce the scientific output from the measurement exercise.

After the meeting an email was received suggesting that the process should be carried out in two stages as follows.

The *first-stage* would be validation of the power matrix based on the highest power output in any half-hour period for each (H,T) bin. Interpolated and extrapolated values would be used to fill in those (H,T) bins that had not accrued any measurements. These decisions would be well documented and open to outside validation.

The *second-stage* would involve the production of a more comprehensive set of half-hour records of wave and machine parameters.

We can understand concern regarding the use of averages of all of the data rather than only the highest output figures. However we believe that this is the correct approach for the following reasons.

1. The Scheme is targeted at devices that have passed through the main research phase of their development and so the results from the Protocol should provide a realistic view of the overall performance of the device under real operating conditions. As such it would not be appropriate to present only the best data to describe the performance.
2. Any further calculations such as the production of a power matrix should be based on an unadulterated representation of the measured data. It should be possible to make an unbiased assessment of the reliability of the data. As such, *missing* bins in a power matrix should not be filled by interpolation or extrapolation, but rather noted as part of the uncertainty in the prediction of annual power.
3. This scheme does not preclude participants analysing the data to provide their own estimation of the *best* production.

Power production in the first year after commissioning may very well be less than that initially predicted by participants due to the challenges inherent in the deployment of devices. Participants may also initially adopt conservative operating policies so as to reduce device stresses.

Equally, it is expected that over the seven years of device deployment under the Scheme, participants will gain increasing understanding of the behaviour of their devices and average performance will be improved. This will be reflected by year-on-year improvements in the device performance and closer correspondence between updated predictions and measured values.

We believe that the data collected under the terms of the Protocol will be suitable for *filtering* during analysis to highlight the different aspects of the performance of devices.

These issues are further discussed in Section 10.3.

The requirement for a *project-log* that has been introduced since the Protocols Workshop should help to ensure that any physical, software or operational modification to a device is recorded in a systematic way that will aid later interpretation of performance information.

10. Protocol management

Arising from the Workshop and individual meetings with developers during the preparation of the Protocol, certain issues relevant to the way in which it will be managed have been raised and require further discussion.

10.1 Project Monitoring Officer

Because devices, projects and locations will vary greatly, it has not been possible to provide a completely prescriptive Protocol specification. It is inevitable that informed judgements will be required at various stages in assessing the suitability of wave or device monitoring arrangements. The Project Monitoring Officer will make such judgements either personally or through consultation with experts, based on the information provided by the Participant. It is not known at this stage whether the Project Monitoring Officer will be a member of DTI staff or of a third-party agency.

10.2 Data collection and management

There was a strong consensus at the workshop that data collection and its subsequent analysis and presentation to the DTI represented an unwanted burden on Scheme participants, and the desire was expressed that this work should be undertaken by a separately funded organisation. This would also have the benefit of ensuring that data collection and reporting are done consistently across all participants.

10.3 Data-mining and filtering

As discussed in Section 7, there is unlikely to be such a thing as a *single* power-matrix that can summarise the performance of a device over the entire course of its deployment under the Scheme. There is also such a wide range of possible variation in the spectral and directional structure of sea-states that an attempt must be made to understand the effect of distinct sea-state variables on the behaviour of devices.

Accordingly, the data collection methodology has been designed for flexibility in subsequent interpretation through the use of customised software.

The *filtering* concept is made possible by the collection of status and operational information on devices and of a reasonable range of descriptive sea-state parameters.

Filtering should allow the analysis of performance against distinct criteria such as mean wave direction or a particular control algorithm. By clarifying links between detailed performance data and the underlying causes, it will help developers to understand and explain their devices more fully.

10.4 Confidentiality of data

The Protocol requires that a large amount of data is recorded by participants and submitted to the DTI. Some of this data will emerge into the public domain as *processed presentations* that summarise device performance. Other data may remain out of the public domain but available to consultants or to DTI staff. Consideration must be given to how the acceptance and handling of data will be affected by the current Freedom of Information legislation.

11. Technical issues for future consideration

During the preparation of the preliminary Protocol, the authors have sought to identify technical issues that require further study.

11.1 Use of wave models

The achievement of continuous unbroken wave data collection will be virtually impossible due to data drop-out and possible instrument failure. Based on past experience, data buoys may break their moorings or mysteriously disappear. Although their movements will often be identifiable through GPS data, recovery and re-installation will be strongly weather dependent especially in winter. Where gaps are only of the order of several hours it may be possible to interpolate missing data. However, much longer gaps may occur.

In discussions during the preparation of the protocol it became clear that it was simply not realistic to impose a fixed *data return target*. If, for example, the Protocol specified a 80 % target, how would it be defined, how would it be enforced and what might be the possible consequences? If the 80 % was an *all-year* target, wave data would likely become biased in favour of summer months. If the target figure was to be achieved in each *season* or in each *month*, it might lead to unwise decisions to attempt buoy repair or replacement in deteriorating sea conditions.

It would benefit generic full-scale performance assessment if data from numerical *wave models* were collected in parallel with wave measurement. Under normal operation, when the wave measuring instruments are working properly, it would be of great scientific interest to be able to compare the measured data and the modelled data to determine the degree to which such models can replace in-situ measurement. There would be the added value, when the recording instruments suffered failure, that the wave model data might permit some level of continuity in device performance assessment and so provide a modest form of insurance.

When considering the use of wave models, two important issues are the *spatial* and the *temporal* resolution. Currently the best spatial resolution available from the Standard Met Office wave models is thought to be one-ninth of a degree of latitude by one-sixth of a degree of longitude, an area typically around 12 km square. The best temporal resolution, when the data is obtained in retrospect, is thought to be 3 hours. These compare poorly with the spatial resolution required for projects that are expected to generally be located at the most at tens of kilometres from coastlines, and with the half-hour averaging time-frame of the Protocol. However additional wave tracing through the known bathymetry and topography of Scheme locations could improve the accuracy of the wave models. Furthermore, it is understood that if wave model data is obtained from the Met Office on a continuous (possibly daily) basis it can be acquired with a higher temporal resolution than 3 hours. This constitutes a rich area of possible collaboration between research Institutes and device developers.

11.2 Statistical variations

The averaged sea-state determined by a wave measuring instrument during a half-hour period can never be *exactly* the same as that seen by a device. It is known that the statistical variation between waves measured at two positions of roughly the same depth and within hundreds of metres of each other (for example between the two Waverider Buoys deployed at EMEC) can be quite significant.

This has obvious implications for the quantification of device performance. For instance, in extreme cases, device averaged output power might be binned to an H_{m0} and T_e address which does not correspond to the actual incident sea-state. In all cases, the variations in measured and actual sea-states will be comparable to the effect of a varying level of *noise* that will affect the accuracy of binning.

Further investigation should be carried out to understand localised variations in sea-state measurements and to determine how to quantify the effect in the calculation of device performance.

11.3 Half-hour averaging period

The trade-off between the *accuracy* of measurements and the *steadiness* of any sea-state during the Protocol's half-hour averaging periods is discussed in Section 3.3. The choice of half-an-hour is strongly influenced by it being the *de facto* time-base for electricity sales and for standard wave measuring systems such as Datawell's Waverider buoys. Continuing effort should be made to quantify the uncertainties implicit in making sea-state measurements over a particular averaging period and to understand how those may affect the accuracy of device performance assessment.

Given the statistical variation described in Section 11.2 above and the observation by Pitt (2005) that the accuracies of power measurement is improved through the use of a one-hour averaging period, the output from the MRDF could be used to investigate this aspect further.

11.4 Incident waves in nearshore locations

Measurement of device performance in nearshore and shoreline locations is complicated by the difficulty of measuring incident waves in comparatively shallow water (*intermediate and shallow* depths). The effects of relative variations in bathymetry, tidal and wind-driven currents and reflections from devices and from land may make it very hard to make resource measurements that adequately represent incident wave conditions at devices. The use of a single measurement close to a particular device may not adequately quantify the resource for other devices in the array.

Although buoys can be used in shallow water, their motions will be affected by nearshore and wind-driven currents. Acoustic Doppler devices may be appropriate in such conditions and are discussed in Section 3.5.

Reflections may be a particular problem where devices form part of a breakwater. Changing depths and coastlines may cause complex frequency- and direction-dependent wave variation through refraction, diffraction, attenuation and breaking.

Further work is required to be able to provide adequate wave monitoring advice for such locations. The test programme proposed by EMEC (see Section 3.5 of this document) to study the comparative performance of acoustic Doppler and buoy-based measuring devices is welcomed. Additional studies should be undertaken to examine how well the latest shallow water wave models perform so that

measurements made further offshore might be transformed into incident sea-states in complex inshore waters.

The modification of waves by currents has considerable consequences both for the measurement of sea-states and in the way that this will affect device performance. Efforts should be made to understand these effects and it is noted that work is planned on this topic in the anticipated next stage of the Supergen Marine research programme.

11.5 Sea-state transforms

Implicit in the Protocol is the measurement of waves at one or more positions and the use of the corresponding derived sea-state data as being representative of the wave conditions that are incident on devices. It is easy to imagine circumstances where this assumption is too simplistic. The issue is closely related to the nearshore problem discussed in section 11.4 above but reasonably distinct from it.

It is routine practise in the wind energy industry to transform the wind climate measured over the long-term at a Met Office anemometer site to the climate expected at the location of a proposed wind farm. The process is typically based on a detailed initial comparison of concurrent measurements at the Met Office site and at the wind farm site.

Similar transform processes should be developed for wave energy. In the context of the Protocol, effort should be made to at least assess the current state-of-the-art in this area.

11.6 Wave measuring radar

Phased-array high-frequency radar has been developed for the remote measurement of wind, waves and currents from pairs of land-based stations. Professor Lucy Wyatt's Sheffield based company Seaview Sensing Ltd is a leader in this area. There are obvious advantages to being able to make real-time wave measurements from land although the cost of the equipment may be an order of magnitude greater than for wave buoys and the power required for each base station is greater than 5 kW [Wyatt (2006)]. The precision of radar measurements of wave height are currently less than from buoy based systems, but they can measure wave directionality. Indeed Professor Wyatt claims to be able to resolve more than one wave component at a particular frequency.

A possible advantage of radar-based wave measurements is that the data so obtained describes conditions over sea areas that are larger than those measured by buoy or acoustic Doppler systems. It is possible that this could lead to improved estimations of the averaged incident wave conditions across different devices in an array.

As in the case of the acoustic Doppler technique, a watching brief should be maintained on the capability of radar systems and their possible relevance to device assessment.

11.7 Location specifics

When considering the performance of a particular model of wind-turbine, its power generation can generally be adequately characterised entirely in terms of wind-velocity. However it may not be so easy to decouple the power capture behaviour of a wave energy device from the specifics of its location. The most obvious location-specific variable is water depth. As depth decreases, an increasing fraction is dissipated through bottom-friction, but the balance of the energy that is conserved is squeezed into less and less depth, so that wave height increases. The relative amplitude of the surge to heave motions of water particles also increases as their orbits, that are circular in deep water, become increasingly oval. The directions of waves change through refraction. A shoreline device may be sensitive to diffraction caused by waves bending around adjacent landmasses.

Except in water depths that are greater than say 100 m it may be necessary to qualify any performance description such as a power-matrix with an indication of the water depth that it applies to. This *location-effect* aspect of performance measurement needs further consideration.

11.8 Power matrices

A power matrix can be used in conjunction with a scatter diagram to estimate the *annual energy production* for a particular site. The method derives from the practice used in the wind turbine industry. However, the description of a wave resource is considerably more complex than the description of a wind resource. The power matrix method considers response to parametric wave height and period but does not consider wave directionality or spectral width. Nor does it necessarily take into account variations between the bathymetry of the reference device for which the power matrix was obtained and the bathymetry of the site for which the scatter diagram has been obtained. If the power matrix is based on measured rather than calculated performance, the power values in bins that correspond to higher wave heights and longer periods may be based on very few observations and so may be comparatively unreliable.

Work is required to determine the limits of the power matrix method, to analyse its sensitivity to errors in the input data and to find reasonably concise ways to extend its applicability to more complex sea-state descriptions.

Appendix A
Glossary

12. APPENDIX A - Glossary

AC	Alternating current (electricity).
Annual energy production (AEP)	A prediction of the total electrical energy that would be produced in a year (in MWh or GWh) at the terminals of a device that has a measured or calculated generation characteristic (such as a power matrix) if situated in a location for which an all-year reference wave climate is available. AEP figures are based on the assumption that devices are always available for generation. Reference wave climates are typically in the form of long-term all-year scatter diagrams. An AEP figure is likely to be a simplification because of the difficulties of taking into account the effects of the varying spectral and directional characteristics of sea-states and the variations due to the bathymetry of the proposed device location.
Array	A group of independently operating and spatially separated wave energy devices.
Availability	The percentage of time for which a device is enabled for generation expressed as average over a certain period. This number will be greater than the percentage of time for which the device actually generates, because the incident wave power level will at times be too low for generation.
Averaging period	The period over which sea-state parameters and device outputs will be averaged. A half-hour averaging period is prescribed in the Protocol.
Bathymetry	The underwater equivalent of topography. Bathymetry describes the spatial variations of water depth measured from the sea surface to the sea-bed.
Capacity factor	The mean net power generated by a device over a certain period divided by its rated power and expressed as a percentage value.
Constrained	As, for example, in *constrained availability*. Refers to any circumstances where the network operator sets an upper limit on the power that a project is allowed to deliver to the network in order to protect the network from overload.
DC	Direct current (electricity).
Declared performance	Within the Protocol, a table, formula or algorithm that will be submitted as part of the pre-commissioning

	project-record and that predicts the power output from the type of wave energy device that will be deployed in the range of sea-states likely to be encountered. This will generally be in the form of a power-matrix.
Device	A machine or system that converts wave energy into electricity and delivers it into an external cable. Elsewhere, often referred to as a wave energy converter or WEC.
Device fault	A fault occurring within a particular device of the array, or its corresponding power converter, that leads to the loss of electrical generation to the network from a single device.
Device-record	Within the Protocol, a time and date-stamped file, containing specified parameters that summarise the electrical output and service conditions of a wave energy device during a half-hour period.
Direction	All directions are measured clockwise in degrees from true north.
Diffraction	The angular spread of waves into open areas of water after passage through channels or around land-masses.
DTI	The UK Department of Trade and Industry
Envelope	The range of movement of wave energy devices and measuring instruments from their equilibrium positions, due to wave, current and wind action.
EMEC	European Marine Energy Centre, Ltd. (Orkney)
Export-record	Within the Protocol, a time and date-stamped file, based on energy readings collected by an *accredited meter operator*, that summarises the electrical power flow between a project and the network during a half-hour period.
Facility	An array of devices and their associated infrastructure located within a limited geographical area and supplying electricity to the network via a single grid supply-point. Within the Scheme, *all* or *some* of the devices within a *facility* constitute an *eligible facility*.
Frequency-domain	Indicates wave analysis on the basis that a *spectrum* of regular waves of different frequencies and amplitudes can be considered equivalent to a particular sea-state. As opposed to *time domain* analysis but usually linked to it through the forward and reverse fast Fourier transform (FFT).
GMT	Greenwich Mean Time. Same as Zulu time,

	Universal Time and Co-ordinated Time.
GPS	Global positioning system
Grid supply point	An electrical substation where interconnection is made between a project and the network.
Intermediate depth	See under *shallow water*.
Location	An area of sea that includes all of the project devices and wave-measuring instruments. For inshore or shoreline devices, it also includes land features that are likely to have a significant effect on the wave climate.
MRDF	The DTI's Marine Renewable Deployment Fund.
Network	The electricity transmission or distribution system to which the project is connected. Synonymous term to *grid*.
Network faults	A fault arising within the network that constrains the export of electricity from the entire Project.
Omni-directional spectral density function	S(f) represents the distribution of wave elevation variance with frequency. The units are m^2/Hz
OS	Ordinance Survey
Parametric	Of wave height, period etc, indicates a representative value that is statistically based on all of the measurements within a recorded time-series from a wave-measuring instrument. Of a wave spectrum (Pierson-Moskowitz, Bretschneider etc), indicates an idealised sea-state having an energy spectrum that can be calculated from a simple algebraic formula with one or more input variables such as nominal wind-speed, period or spectral width.
Participant	The company which enters into contract with the DTI under the Wave and Tidal Stream Energy Demonstration Scheme. It may be the lead partner of a consortium or a joint venture company.
Peak frequency	The wave frequency at which the value of energy spectral-density is highest.
Point of connection	The electrical location at which an accredited meter operator makes records of electrical energy flows so as to determine the payments for electricity bought from and sold to a project.
Power-converter	Electronic equipment that is used to convert variable-voltage variable-frequency current into

	constant-voltage constant-frequency current suitable for supply to the network.
Power matrix	A table showing the predicted or measured power output of a wave energy device against joint combinations of parametric wave height (typically H_{m0}) and parametric period (typically T_e).
Power-take-off	The system that absorbs power from the primary moving part(s) of a wave-energy device and transmits that power to the electrical generator, by direct-connection, by mechanical, hydraulic or pneumatic means or by combination of any of these. The power-take-off may incorporate storage devices such as hydraulic accumulators to smooth some of the wave-by-wave power variation.
Prevailing wave direction	Ideally, the average direction of the wave power that is incident on the project location. At the outset of a project, this will generally not be known in detail and so may be based on general Met Office information or on local knowledge.
Project	An array of wave energy devices and associated physical assets, contracts and arrangements that is contracted into the DTI's Wave and Tidal-stream Energy Demonstration Scheme and that supplies electricity to the network via a single grid supply-point.
Project commissioning date	The date on which the participant declares their project to be commissioned and from which day revenue support payments will be payable.
Project fault	A fault arising from within the general electrical infrastructure that connects devices to the point of connection to the network, and excluding faults within individual devices or their associated power converters. Such a fault may constrain generation from one, several or all devices within the Project.
Project monitoring officer	An individual assigned by the DTI to monitor the compliance of a Project with the Protocol.
Protocol	Preliminary Wave Energy Device Performance Protocol. (The present document.)
Protocol start date	The date from which data collection will start: 00:00 hours Greenwich Mean Time on the first day of the calendar month following the *project commissioning date*.
Quiescent power	The mean electrical power that is required to operate a device.

Rated power	Defined in the context of the Protocol as the maximum power that can be supplied by a device to the network after allowing for project specific cable, transformer and switchgear losses.
Refraction	The process whereby the angle of a wave travelling obliquely in relatively shallow water is reduced by decreasing water depth and increased by increasing water depths. Commonly observed as the tendency for waves coming in to shallower water to progressively align themselves with a beach.
Reflection	The energy in waves is conserved except where breaking occurs or through friction at the seabed. Hence discontinuities such as rapid depth changes in shallow water or solid boundaries cause partial or near complete wave reflection.
Regular wave	An idealised water wave of constant height, period and direction.
Rms	Root mean square. (Equivalent to standard deviation about the mean).
Scatter diagram	A bivariate graphical representation of the frequency of occurrence of sea-states, at some location and over some time interval (e.g. all-year, winter, ten-years), in terms of parametric wave period (typically T_e) and height (typically H_{m0}). A scatter diagram thus consists of a two-dimensional array of *bins* each of which represents a *sub-range* of periods combined with a *sub-range* of heights. The values that are binned are based on individual sea-state recordings of fixed duration, such as half-an-hour or three-hours. The numbers may show the actual number of observations or they may show a normalised number such as the frequency in parts per thousand (*per mil*).
Sea-state	The wave conditions prevailing at a particular location, treated as if statistically unchanging in terms of parametric height, period, spectral composition and directional structure.
Sea-state mean wave direction	The power-weighted mean wave direction, calculated from the directional wave spectrum.
Sea-record	Within the Protocol, a time and date-stamped file containing a set of specified parameters that statistically summarise a sea-state during a half-hour period.
Scheme	The DTI's *Wave and Tidal Stream Energy Demonstration Scheme*.

Shallow water	When the water depth is less than one-half of the deep-water wavelength, it is often described as being *shallow*. Some writers use one-third of wavelength as the transition depth. In fact, it more useful to refer to such depths as being *intermediate* and to reserve use of *shallow* for depths of less than one-twentieth of the deep water wavelength. In the context of wave analysis, *deep*, *intermediate* & *shallow* depths are usually distinguished from each other by requiring separate mathematical treatments. A ten-second wave has a deep water wavelength of 156 m ($\lambda = gT^2/2\pi$) so a depth of less than 78 m would be considered intermediate. However 25 m depth would be considered as deep water for a 5 second wave.
Shoaling	Any variation in bathymetry that reduces water depth to levels that may be considered to be *shallow* as defined above. Where local shoaling occurs in deep water it may be indicated by wave breaking (*white-caps*).
Spectral moments	A set of parameters, that are easily defined in terms of the spectral density function *S(f)*, and that are useful for calculating certain sea-state averaging parameters. The n_{th} spectral moment m_n is defined as follows: $m_n = \int_0^\infty f^n S(f) df$ Tucker and Pitt (2001) gives examples of sea-state parameters expressed in terms of spectral moments.
Spread	A measure of the extent to which wave components within a sea-state are travelling in directions other than the mean direction.
Topography	In the context of this document, the local distribution of land masses around the project location.
Wave-measuring instrument	A buoy, acoustic Doppler current profiler or other system, that is capable of making directional wave measurements with a sampling rate of at least 1 Hz.
Wave model	The process used to predict the directional sea-state within a given area by mathematical calculation from reported atmospheric observations. When wave models are run from archived data for times earlier than the present, they are sometimes referred to as *hindcasts*. The Met Office *UK Waters Wave Model* currently resolves to sea areas that are approximately 12 km square with averaging time

	periods of three hours.
Wave-record	Within the Protocol, a time and date-stamped file containing directional wave time-series data measured by a single wave-measuring instrument during a half-hour period. For example, each wave-record from a project that uses Waverider buoys will contain separate half-hour time-series for *heave (elevation)*, *north* and *west* directions.
Wave rose plot	Within the protocol, a graphic device that indicates, for 16 discrete 22.5 degree sectors of the compass, the relative wave power density that is incident from that direction.

Appendix B
Symbols

13. APPENDIX B - Symbols

$c_g\ (f, h)$	Wave *group-velocity* at frequency f and water depth h - (m/s)
f	Frequency - (Hz)
g	Gravitational acceleration - (9.81 m/s^2)
h	Water depth - (m)
H_{m0}	An averaging wave height parameter that, because of its clear statistical definition, based on the zeroth spectral moment; $H_{m0} = 4\sqrt{m_0}$ (m), is preferred to *significant* wave height H_s.
k	Wave number. A property of a regular wave, or of a discrete frequency component, inversely proportional to its wavelength - $k = \lambda / 2\pi$ (m^{-1})
m_n	The n^{th} *spectral moment* of the wave energy spectrum $m_n = \int f^n S(f) df$
$S(f)$	Sea-state *omni-directional spectral density* at frequency f - (m^2/Hz)
P_{mean}	Mean power generated by a device during one averaging period - (kW)
P_{max}	Maximum power generated by a device during one averaging period - (kW)
P_{min}	Minimum power generated by a device during one averaging period - (kW)
P_e	Mean power exported from project to network - (kW).
P_i	Mean power imported from network to project - (kW).
t_{gps}	GPS derived time
T_e	Wave energy period - $T_e = \frac{64\pi}{\rho g^2} \frac{P}{H_{m0}^2}$ (s)
T_z	Wave zero-crossing period - $T_z = \sqrt{(m_0 / m_2)}$ (s)
T_{pc}	Wave calculated peak period - $T_{pc} = m_{-2} m_1 / m_0^{2}$ (s)
$Temp_s$	Sea temperature - (^{0}C)
λ	Wavelength – (m)
ν	Sea-state bandwidth parameter - $\nu = \sqrt{m_0 m_2 / m_1^2 - 1}$ (dimensionless)
$\theta(f)$	Sea-state mean direction at frequency f - (degrees)

θ_m	Mean wave direction - (degrees)
θ_p	Power-weighted mean wave direction - (degrees)
	Sea-water density – usually taken as 1025 kg/m^3 for UK waters
$\sigma(f)$	Sea-state rms angular spread at frequency f - (degrees)
σ_m	rms angular spread about the estimated mean wave direction - (degrees)
σ_p	Power variability

Appendix C
Bibliography

14. APPENDIX C - Bibliography

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