dti

PRELIMINARY WAVE ENERGY DEVICE PERFORMANCE PROTOCOL

CONTRACT NUMBER:
MRF/02/00005/00/00

URN NUMBER: 07/807

dti

The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

PRELIMINARY

WAVE ENERGY

DEVICE PERFORMANCE PROTOCOL

Version 1.3 - March 2007

Commissioned by
The Department of Trade and Industry

MRF/02/00005/00/00

URN 07/807

Prepared by
Heriot-Watt University
The University of Edinburgh

The work described in this report was carried out under contract as part of the DTI Marine Renewables Deployment Fund, which is managed by AEA Energy & Environment. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or AEA Energy & Environment.

First published 2007

The Preliminary Wave Energy Device Performance Protocol that is reported in this document was commissioned by the Department of Trade and Industry (DTI) in April 2006. It was prepared by Dr. George Smith of Heriot-Watt University[1] 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 Wave Protocol described herein.

Acknowledgements

The authors gratefully acknowledge helpful discussions and correspondence with the following:

Fred Gardner & Miguel Goden de Sousa Prado - Teamwork Technology BV
Dr Tom Heath & Ben Yeats - Wavegen Ltd.
Simon Grey – AWS Ocean Ltd.
Dr. Ted Pitt - Applied Wave Research
John Griffiths - JWG Consulting Ltd.
Dr Andy Saulter & Catriona Williams – UK Met Office
Neil Kermode & Dr Jennifer Norris - European Marine Energy Centre Ltd.
Dr. Richard Yemm – Ocean Power Delivery Ltd.
Prof. Lucy Wyatt – University of Sheffield and Seaview Sensing Ltd.
Dr Bill Cooper – ABP Marine Environmental Research Ltd.
Lars Christensen & Erik Friis-Madsen – Wave Dragon ApS
Gregory Dudziak – Sgurr Energy Ltd.
Guy Nicholson – Econnect Ltd.
Brian Holmes – Hydraulics and Maritime Research Centre, Cork
Clare Lavelle, Alan Mortimer & Alan Wilson – Scottish Power plc
David Philip & Carolyn Heeps – The Crown Estate
Terry Sloane – Planet Ocean Ltd.
Tony Sanders – RS Aqua Ltd.
Prof. Julian Wolfram

[1] Dr George Smith is now at the University of Exeter

Contents

Background

A £42m share of the DTI's *Marine Renewables Deployment Fund* (MRDF) has been set aside for the *Wave and Tidal-stream Energy Demonstration Scheme*. This will provide up to 25% of the capital cost of eligible multi-device wave and tidal-current energy projects and revenue support payments of £100 per megawatt hour for electricity delivered to the network. The total value of the combined financial aid to any project will be capped at £9m. A maximum of two years will be allowed for the commissioning of projects after which revenue support payments will be paid for up to seven years.

A condition of project support from the Wave and Tidal-stream Energy Demonstration Scheme is that the performance of devices be monitored in accordance with an appropriate *protocol* such that all technologies can be assessed in a consistent manner. There will be one such protocol for tidal-stream devices and another for wave energy devices. The protocols, will form an appendix to any contract between MRDF Participants and the Secretary of State.

A *Draft* Wave Energy Device Performance Protocol was discussed by invited stakeholders at a *Protocols Workshop* in Edinburgh on the 19th of July 2006. It described how wave resources and wave energy device performances should be measured and reported to the DTI by early participants in the Wave and Tidal-stream Energy Demonstration Scheme. This document describes the *Preliminary* Wave Energy Device Performance Protocol and it incorporates responses to issues discussed at that workshop.

Key words used in this document (for example: *scheme*, *participant*, *device*, *facility*, *project*) have been chosen to match their usage in the DTI document 'Wave and Tidal-Stream Energy Demonstration Scheme' of May 2005.

Supporting Commentary

An associated document, referred to as the *Supporting Commentary*, provides: additional information and comments in parallel with this document; a guide to wave statistical calculations and the proposed method to describe device performance; a discussion of issues raised at the Protocols Workshop; a discussion of *gaps* and protocol management issues; a glossary; a list of symbols; and a bibliography.

The Supporting Commentary identifies a number of knowledge gaps where further research is needed. This Protocol may be updated in the future to take account of new research findings as and when they become available.

References

Note that where reference is made to other documents, details of these can be found in the bibliography, which is included in the Supporting Commentary.

1. Scope of the Protocol

The Protocol is designed to ensure the capture of data that will subsequently allow the varying power generated by wave energy devices to be considered in the context of the corresponding sea conditions.

The *Preliminary Wave Energy Device Performance Protocol* (*Protocol*) is addressed to developers (*participants*) of wave energy generating stations (facilities) that have or expect to have grants with the DTI under the *Wave and Tidal-stream Energy Demonstration Scheme* (*Scheme*). Such wave energy facilities will consist of arrays of independent wave energy converters (*devices*) that supply electricity to the *network* via a single grid supply-point.

Under the Scheme, all or some of the devices within a particular participant's facility constitute an *Eligible Facility.* In the context of this document, for clarity the term *Project* is used synonymously.

1.1 The Protocol

The Protocol specifies four sets of obligations for participants:

1. Provision of information to the DTI prior to the commencement of the project;
2. Continuous collection of data throughout the project;
3. Regular compilation of summarising data-records;
4. Submission of data and performance summaries to the DTI at annual intervals.

1.2 Standards

In the implementation of the measurements and procedures described in this Protocol, it is recommended that the document *Performance assessment for wave energy conversion systems in open sea test facilities.* [EMEC (2004)] be consulted.

In this document, specific standards are referred to where they are available: in the context of hydrographic surveys in Section 2.2 and in relation to the measurement of electrical power in Section 4.3.

1.3 Protocol start date

For the purposes of the Protocol, data collection will start at 00:00 hours Greenwich Mean Time on the first day of the calendar month following the *project commissioning date*.

1.4 Outline of Protocol requirements

Scheme participants must make continuous measurements and present collated information to the DTI at certain intervals. In outline, these requirements are as follows.

Prior to commencement of project

1. Provide *project information*, that describes the physical nature of the location, the proposed placement of wave energy devices and wave measuring instruments, the general characteristics of the devices and the electrical layout of the project. This requirement is detailed in Section 2.2 below.

On a continuous basis, from the Protocol start date

2. Maintain a project-log that records all significant events. This requirement is detailed in Section 2.3.
3. Record the incident waves at the project location with one or more wave measuring instruments and archive the information as half-hour *wave-records*. This requirement is detailed in Section 3.
4. Monitor the generated electrical power and certain operational status indicators from each project device. This requirement is detailed in Section 4.
5. Monitor the electrical energy exported to or imported from the network. This requirement is detailed in Section 5.

For every half-hour period, starting on the Protocol start date

6. Compile a *sea-record* that summarises the sea-state measured by one or more wave measuring instruments near to the devices. This requirement is detailed in Section 3.
7. For each device in the Project, compile a *device-record* that includes its average electrical power output and certain operational status indicators. This requirement is detailed in Section 4.
8. Compile an *export-record* that includes the average electrical power transfer between the project and the network. This requirement is detailed in Section 5.

At annual intervals after the Protocol start date

9. Deliver to the DTI, or its agent, the collated records from the preceding period with cumulative summaries of sea-states and device electrical generation. This requirement is detailed in Section 6.

2. Project information prior to commissioning

2.1 Rationale

Participants must supply information to the DTI prior to the commissioning of the project. This will describe the physical nature of the project location, the proposed positions of devices and wave measuring instruments and basic information about the devices and their connection to the network. In presenting this information, the participant must clearly demonstrate that the proposed wave measuring arrangements are consistent with the requirements of this Protocol. Throughout the project duration, Participants must also record significant events in a *project-log*.

2.2 Project-record

The project–record should provide the following location information

1. A bathymetric chart of the project location based on the UK National Grid using Eastings and Northings to identify project features. The horizontal and depth accuracies of the chart should be at least as specified for Order 1 Surveys in IHO(1998). This specifies accuracies of the order of 5 m horizontal and 1 m vertical. Higher accuracies may be required for projects that involve shoreline devices or that are in shallow water. The chart should show the nominal position and water depth of each device, of any associated external sea-based equipment such as transformers or sub-stations and all wave measuring instruments. Cable routes should be identified. For any moored device the maximum range of excursion from the nominal position should be indicated. Depending on the relative distances to land, the same chart or an additional smaller-scale chart should also show the coastlines, islands and any shallows that will have a significant effect on the wave climate in the project area. The location of onshore project equipment or buildings should be shown and the point of connection to the network or the direction and distance to it should be identified.
2. An assessment of any expected variations in the spatial homogeneity of the wave climate across the location due to variations in bathymetry and the effects of tidal currents.
3. The prevailing wave direction at the project location.
4. The maximum tidal range above and below mean sea level.
5. The maximum tidal velocity and direction.

The project-record should provide the following device information

6. The number of devices in the project and the total number of devices in the facility, if greater than the number of devices in the project.
7. An outline single-line electrical diagram of the project that shows all devices, any external power-converters (see Section 4.2), and the cables, transformers and switchgear up to the point of connection of the project to the network. Any additional import cables that provide power to control or ancillary systems within devices or

power-converters (see Section 4.2) should also be included. Voltages, lengths, cross-sections and conductor material should be shown for cables.

8. The *declared performance* of the type of device to be used in the project. This will indicate the predicted power output from devices installed at the project location over a tabulated range of the sea-states likely to be encountered. As a minimum, the declared performance will be in the form of a power-matrix (see Section 7 of the Supporting Commentary) that tabulates device power output against parametric wave height H_{m0} and parametric wave period T_e. Where the performance characteristic of individual devices is expected to vary, due for instance, to variations in water depth, a declared performance should be provided for each distinct class of location.
9. An assessment of the sensitivity of device output to other sea-state parameters such as spectral width and wave directionality.
10. An assessment of the expected sensitivity of the device output to the device position within the proposed array.
11. Identification of any specific environmental variables, apart from wave conditions, which would be expected to have a significant effect on the power generated by the device type. For example air-turbine devices may be sensitive to air-density, temperature and humidity.
12. The nominal output voltage and the *rated output* (in kW) of each device. If the output is not in the form of network-frequency, constant-voltage, three-phase alternating current, the range of voltages and frequencies should be provided.
13. The *quiescent power* drawn by each device. This is the mean electrical power that is required to operate the device. Depending on operating conditions this will be taken from the generated power output, or from the network when there is not enough wave power to generate.
14. For devices that use *power-converters* (see Section 4.2), the proposed methodology for dealing with cable power losses in the calculation of device power production.
15. Details of planned outage and maintenance programme for devices.

2.3 Project-log

The project-log will be used to record *significant events* during the life of the project. This will take the form of a spreadsheet or text file with date-stamped entries on events that will include the following.

1. Removal, addition or change of position of wave measuring instruments.
2. Removal, addition or change of position of devices.
3. Failure, repair and reinstatement of wave measuring instruments.
4. Failure, repair and reinstatement of devices.
5. Modifications to device hardware, operating policies, or software that may affect device power conversion characteristics. These aspects are discussed in Section 4.7.
6. Any other changes or events that it will be necessary to recall during the later interpretation of performance data.

3. Resource measurement

The Protocol specifies an *averaging period* of half-an-hour for measurements of the wave resource, device power generation and exports to the network.

3.1 Rationale

Knowledge of the wave conditions that are incident on project devices will depend on the continuous deployment and operation of one or more wave *measuring instruments* that can sample wave motions at a suitable sampling frequency in all weather conditions. The time-series of data from the instruments should be stored as calibrated SI-unit variables in a time and date-stamped *wave-record* for each half-hour recording period – as specified in section 3.7.

The time-series data will be processed by conversion to frequency-domain spectra for the calculation of power-density and other statistically-descriptive variables. These will be stored as a time and date-stamped *sea-record* corresponding to each half-hour averaging-period – as specified in section 3.8.

Participants will be required to supply both the wave-records and the sea-records to the DTI, as specified in Section 6.

3.2 Time coverage and data return

From the Protocol start date, participants should use their best endeavour to maintain continuous resource measurements for the duration of the project and in all months of the year. The Participant must notify the Project Monitoring Officer of any instrument failure leading to loss of recorded data, for whatever reason and explain how resource measurement is planned to be restored as quickly as possible.

3.3 Averaging period

The choice of a half-hour as the averaging period for the Protocol, is a trade-off between the length of time for which the characteristics of any sea-state can reasonably be treated as if unchanging and the length of wave-record required to reduce uncertainty in the calculation of wave power-density and other parameters to an acceptable value.

3.4 Time-keeping and synchronisation of data

The time and date-stamp on each record will refer to the *start* of the half-hour wave recording period and these start times should be locked to the nominal hours and half-hours of the GMT system with a maximum time-drift of plus or minus five minutes. The Participant should be able to demonstrate that this is being achieved.

It is likely that time and date-stamping will be by record file-name, but all records will ideally include a time and date field derived from GPS information.

3.5 Type of Wave measuring instrument

In the majority of cases, the most appropriate type of instrument will be a directional wave-buoy system fitted with a mooring appropriate to the water depth.

In addition to responding to wave elevation, the wave measuring instrument(s) must record waves in such a way that wave directionality can be calculated.

The instrument(s) should have amplitude resolution of 1 cm or less and accuracy of at least 0.5%. Wave data should be captured at a sampling frequency of greater than 1 Hz, and an anti-aliasing filter should be used prior to logging to prevent data corruption by signals or noise above half the sampling frequency.

The wave measurement instrument(s) must have a valid certificate of calibration (such as from HR Wallingford or Delft Hydraulics) and must be maintained as prescribed by the manufacturer.

In shallow inshore locations, including those of shoreline devices, a bottom-standing acoustic Doppler current profiler (ADCP) may be suitable if an instrument that is adapted and calibrated for directional wave measurement is used.

3.6 Number of instruments and placement

In the first instance wave conditions should be recorded by placing a measuring instrument at a single position where the conditions are representative of those across all devices. Locations with bathymetric, topographic or tidal influences that might be expected to cause significant variation in the time averaged resource across all devices should generally be avoided as sites for the deployment of facilities under the Scheme. Where such locations cannot be avoided, the Participant must deploy sufficient number of instruments to adequately characterise the wave energy resource seen by the devices in the facility. The Participant must demonstrate that the proposed number and location of the instruments are adequate to do this.

Each wave measuring instrument should be placed such that:

1. It is in water at least as deep as the average depth found under the array of devices;
2. It is subject to the same prevailing wave conditions as the array;
3. It has the same nominal angular exposure to the ocean as has the array;
4. The bathymetry is either flat or has an even reduction in depth between the instrument and the array.

The best position for a single wave-measuring instrument will generally be on a line seaward from the geometric centre of the array in the direction of the prevailing wave direction as described in Section 2.2 item 3.

The minimum distance between a wave measuring instrument and the nearest device should be such that:

5. Waves radiated by devices will have little effect on the waves at the measuring instrument location;

6. If the measuring instrument is in the form of a buoy, the minimum distance between the envelope of its maximum excursion from its equilibrium position and the equivalent envelope of the nearest device is at least 100 metres;
7. If the measuring instrument is in the form of a bottom mounted ADCP, it should be at least 100 metres outside the envelope of possible movement of the nearest device;

The *maximum* distance of a wave-measuring instrument from the furthest device should be 1 km.

3.7 Half-hour wave-records

The time and date-stamped *wave-records* will contain calibrated wave elevation time-series and such data that is required to calculate the directional wave spectrum.

Each wave-record will contain the following fields:

1. Wave elevation time-series
2. Directional time-series as appropriate to the type of wave measuring instrument (e.g. a *north* and a *west* time-series for accelerometer based buoys)
3. Data validity time-series (*1 = valid*, *0 = not valid*)

A *wave header-file* that identifies the fields of the wave-records will be maintained and will form part of the annual deliverables. (see Section 6.1)

The data validity flag will be helpful in the subsequent data analysis process. It will allow error-checking algorithms to identify discontinuity or invalid points within the time series.

3.8 Half-hour sea-records

A time and date-stamped half-hour averaged *sea-record* will be compiled from each half-hour wave-record after computing the directional spectral density function. From this, the omni-directional spectral density, the spectral moments and other statistical parameters will be calculated. Some of these parameters are robustly defined in terms of the spectral moments.

The spectrum should extend from at least 0.05 Hz to 0.5 Hz (equivalent to wave periods in the range of 2 seconds to 20 seconds). The frequency resolution of the energy spectrum should be at least as good as the *internal wave spectrum* of the Waverider buoy (0.005 Hz for frequencies less than 0.1 Hz, 0.01 Hz for frequencies above 0.1 Hz).

Each sea-record will contain the following fields:

1. Directional spectrum listing - spectral density, mean direction and directional-spread at each spectrum frequency
2. Seven consecutive spectral moment values - m_{-2} to m_4
3. Sea-state height parameter - H_{m0}
4. Sea-state period parameters: energy - T_e , zero-crossing - T_z , calculated-peak - T_{pc}

5. Omni-directional (gross) wave power-density - P_w
6. Sea-state bandwidth parameter - ν
7. Power-weighted mean wave direction - θ_p
8. Sea-state mean directional spread - σ_m

A sea-record may also include additional fields such as:

9. GPS derived position (if the wave-measuring instrument is a buoy)
10. GPS derived time and date-stamp
11. Sea surface temperature - $Temp_s$
12. Quality control parameters
13. Device specific environmental variables

A *sea-state header-file* that identifies the fields and calibrations of the sea-records will be maintained and will form part of the annual deliverables (see Section 6.1).

To summarise these requirements, Table 3.1 illustrates the logical structure of the mandatory section of a sea-record.

Table 3.1. Sea-record: the mandatory fields. Additional project-specific fields may be required.

			symb	unit	notes
1	**Directional spectral density**	Omni-directional spectral density components	$S(f_1)$	m^2/Hz	See Tucker & Pitt (2001) p 30 equations 2.2-4 and 2.2-7.
			$S(f_2)$		
			$S(f_3)$		
			...		
			$S(f_n)$		
		component mean wave direction	$\theta(f_1)$	degrees from north	
			$\theta(f_2)$		
			$\theta(f_3)$		
			...		
			$\theta(f_n)$		
		component mean wave spread	$\sigma(f_1)$	degrees	
			$\sigma(f_2)$		
			$\sigma(f_3)$		
			...		
			$\sigma(f_n)$		
2	**Spectral moments**		m_{-2}	m^2s^2	$m_n = \int_0^\infty f^n S(f) \mathrm{d}f$
			m_{-1}	m^2s	
			m_0	m^2	
			m_1	m^2s^{-1}	
			m_2	m^2s^{-2}	
			m_3	m^2s^{-3}	
			m_4	m^2s^{-4}	
3	**Sea-state height parameter**		H_{m0}	m	$H_{m0} = 4\sqrt{m_0}$
4	**Sea-state period parameters**	*energy period*	T_e	s	$T_e = \frac{64\pi}{\rho g^2}\frac{P}{H_{m0}^2}$
		zero-crossing period	T_z	s	$T_z = \sqrt{(m_0 / m_2)}$
		calculated-peak period	T_{pc}	s	$T_{pc} = m_{-2} m_1 / m_0^2$
5	**Omni-directional wave power density**		P_w	kW/m	$P_w = \rho g \sum_{i=1}^{n} c_g(f_i, h) S(f_i) df_i$ See section 8.1 and 8.2 of the Supporting Commentary
6	**Sea-state bandwidth parameter**			Dimensionless	$\nu = \sqrt{m_0 m_2 / m_1^2 - 1}$
7	**Power-weighted mean wave direction**		θ_p	deg. from N.	See Section 8.5 of the Supporting Commentary
8	**Sea-state mean directional spread**		σ_m	degrees	$\sigma_m = \frac{1}{n}\sum_{i=1}^{n} \sigma_i$

4. Device measurement

4.1 Rationale

The average electrical power from each device in the project during every half-hour period must be recorded in a time and date-stamped *device-record*.

Performance measurements should be based on device electrical power output values that exclude electrical losses due to the external project-specific cables and transformers that connect the device to the network. For most devices the power measurements should therefore be made as near as possible to the point where the device connects to its external electrical power cable.

Device-records will include information on the operational status of devices. A *system identifier* field will be used to keep track of changes. Systematic logging of this data will ultimately allow data to be *filtered* to include or exclude certain conditions that should be taken into account when assessing device performance.

4.2 Power-converters

Some device types may use special electronic *power-converters* that are external to the device but that should be considered as part of it in the context of performance assessment.

Where remote power-converters are used, device power should be measured at the output terminals of the power-converter wherever it is situated. Due to the project-dependent cable losses between device and converter, such measurements will underestimate the device performance. The measured average power values from devices will subsequently be adjusted to allow for those losses.

This adjustment must be done using a rigorous and transparent methodology that has been approved by the Project Monitoring Officer before use.

4.3 Power measurements

The net electrical power (i.e. generated power minus system energising power) of the device or its power-converter will be measured at a point near to the output cable terminals where it is in the form of constant-voltage network-frequency AC. A power transducer will be used that computes the instantaneous total power based on continuous monitoring of the current and voltage of each phase.

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

Electrical transducers used in the measurement of power should be class 0.5 or better, should meet the requirements of the following standards, and should be calibrated to traceable standards:

Power transducers	IEC 60688
Current transformers	IEC 60044-1
Voltage transformers	IEC 60044-2

The operating range of the power transducer will be sufficient to include all positive peaks corresponding to net generation and all negative peaks corresponding to net imported power.

4.4 Quiescent power

When the device is generating, the power will usually be positive to indicate export. In very small waves however, the device may be available but not generating. The range of the power transducer must therefore be sufficient to include negative values due to quiescent power being drawn by the device from the network through the export cable.

If the device or its power-converter has any auxiliary electrical cables that import power from the network (or from other devices in the project) in order to energise control or ancillary equipment, the power so drawn must be measured and averaged over each half-hour period in the same manner as described above for the exported power.

The quiescent power measurements should be made to a minimum accuracy of plus or minus 1 kW.

4.5 Power-variability

A *power-variability* figure computed as the standard deviation of the instantaneous output power relative to the half-hour average power will be used to record the variation of device power delivery to the network.

4.6 Device-status and network-status

Devices will normally either be *generating*, when the incident wave energy is sufficient, or *available for generation*, when waves are too small. However, there will be a number of other possible *device-status* conditions that should be recorded.

The device-status field will indicate conditions such as the following:

1. Device available
2. Off-line for maintenance
3. Constrained availability – (reduced output requested by network operator)
4. Off-site for maintenance
5. Off-line for device fault
6. Off-line for project fault
7. Off-line for network fault
8. Available at reduced capacity (partial fault)
9. Device under manual operation

It will be important to distinguish loss of availability due to factors on the project side of the network connection from loss of availability due to factors on the network side. The *network-status* field therefore provides additional information about the status of the network connection.

The network-status field will indicate conditions such as the following:

1. Device connected to network
2. Electrical fault on the project side of the network connection
3. Network lost
4. Constrained generation requested by the network operator

4.7 System identifier

The device-status and network-status fields record events that will affect the way that performance data should be interpreted, it is important that *device variations* should also be systematically recorded.

Such variations may be in the *hardware* of the system, in the *operating policy* or in the *control algorithm* and will be recorded by at least a three-component *system identifier* field.

Devices will not necessarily be identical in terms of their component parts, particularly following repair or scheduled maintenance. Variant component combinations should be identified by a *hardware version*.

Device *operating policy* may change as participants gain experience and confidence. This can be tracked by a *policy version* identifier. An example might be the average wave height at which a stress-reduction procedure is triggered.

Control software is very likely to go through many revisions and these can be recorded in the familiar way through the use of an incrementing *version number*.

Note that device variation information should also be recorded verbosely in the project-log, which is discussed in Section 2.3.

4.8 Half-hour device-records

Device data for each half-hour will be stored as calibrated SI-unit variables in a time and date-stamped *device-record*.

Each device-record will contain the following fields:

1. Mean power generated – P_{mean}
2. Maximum power generated - P_{max}
3. Minimum power generated - P_{min}
4. Power variability - standard deviation about the average power – σ_P
5. Device-status - *DS*
6. System identifier - *SI*
7. Device compass heading - *DH*

The device-record may also include additional fields such as:

8. RMS current at input to power-converter (see Section 4.2 of Supporting Commentary) - I_{rms}

9. Average power import from auxiliary cable - P_i
10. GPS derived time and date-stamp - t_{gps}

A device header-file that identifies the fields of the device-records will be maintained and will form part of the annual deliverables. (see Section 6.1) Table 4.1 illustrates the logical structure of a device-record.

Table 4.1. Device-record format

		symbol	Example values & field identifier	unit	notes
1	**Mean power**	P_{mean}	275.4	kW	Can go negative
2	**Maximum power**	P_{max}	312.5	kW	
3	**Minimum power**	P_{min}	179.3	kW	Can go negative
4	**Power variability**	σ_P	31.4	kW	Standard deviation about average power.
5	**Device status**	*DS*	1 *Available* 2 *Off-line for maintenance* 3 *Constrained availability* 4 *Off-site for maintenance* 5 *Off-line for device fault* 6 *Off-line for project fault* 7 *Off-line for network fault* 8 *Available at reduced capacity* 9 *Manual operation*		These options will be device and project dependent.
6	**Network status**	*NS*	1 *Device connected to network* 2 *Electrical fault on project side* 3 *Network lost* 4 *Constrained generation requested*		Ditto.
7	**System identifier** (3-part)	*SI*	7 *Hardware version number* 45 *Policy version number* 4.01 *Software version number*		Ditto. For the example values shown, the system identifier would
8	**Device heading**	*DH*	275	deg	From north

---------- *Device dependent additional field examples* ------------

9	**RMS cable current**	I_{rms}	12.56	A	For devices with external power-converters
10	**Average power import**	P_i	0.8	kW	If ancillary cable is used
11	**GPS time**	T_{gps}	2009-09-26 16:03		

5. Export measurement

5.1 Rationale

Details of the metered electricity exported from the project into the network will provide a valuable check against aggregates of the device power measurements specified in Section 4.8. When the devices within a *project* are a subset of a larger *facility*, it is a requirement of the Scheme that the devices within the project must be metered separately. Export-records will include information on the operational status of the connection between project and network.

5.2 Quiescent power and ancillary supply

Where net energy is drawn *from* rather than delivered *to* the network during any half-hour period, this must be shown in the export-record by negative values. If quiescent power for energising the project is drawn from an ancillary supply, the corresponding half-hour average power from that source must be recorded.

5.3 Network-status

The electrical connection from the device to the network will normally be closed. There is a number of possible conditions that will require this connection to be opened.

The network-status field will indicate conditions such as the following:

1. Device connected to network
2. Electrical fault on project side of network connection
3. Loss of network
4. Constrained generation requested by network operator

5.4 Half-hour export-records

Export data for each half-hour will be stored as calibrated SI-unit variables in a time and date-stamped *export-record*.

Each export-record will contain the following field:

5. Mean power exported or imported through export connection - P_E
6. Network-status - *NS*

Where an ancillary supply is taken from the network:

7. Mean power imported through ancillary connection - P_I

An export *header-file* that identifies the fields of the export-records will be maintained and will form part of the annual deliverables. (see Section 6.1)

Table 5.1 illustrates the export-record format.

Table 5.1. Export-record format

		symbol		unit	notes
1	**Network export power**	P_e		kW	Can go negative
2	**Network status**	*NS*	1 *device connected to network* 2 *electrical fault on project side* 3 *network lost* 4 *constrained generation requested*		These options will be device and project dependent.
	------------------ *If ancillary supply is taken* --------------------				
3	**Network import power**	P_i		kW	

6. Deliverables

Prior to the commissioning of their project, participants must submit to the DTI or to their nominated agent:

1. The project-record as already specified in Section 2.2.

Each year *within 3 months of the anniversary of the Protocol start date*, participants must submit to the DTI or their nominated agent:

2. An up-to-date version of the *project-log*, as already specified in Section 2.3.
3. A set of half-hour *wave-records*, as already specified in Section 3.7.
4. A set of half-hour *sea-records*, as already specified in Section 3.8.
5. A set of half-hour *device-records*, for each device in the array as already specified in Section 4.8.
6. A set of half-hour *export-records*, as already specified in Section 5.4.
7. A set of four *header files*, as specified in Section 6.1 below.
8. A *returns file*, as specified in Section 6.2 below.
9. A set of *headline numbers*, as specified in Section 6.3 below.
10. A set of *time-series plots*, as specified in Section 6.4 below.
11. A set of *scatter diagrams*, as specified in Section 6.5 below.
12. A *power-weighted wave rose* for each wave measuring instrument, as specified in Section 6.6.

The deliverables specified in this section do not include any device performance analysis, but it is likely that data delivered under the Protocol to the DTI will be used to prepare *power matrices* of the sort published by several device developers. Further performance matrices may also be used to investigate the variability of device generated power with sea state. This issue is discussed in Section 7 of the Supporting Commentary.

6.1 Header files

The wave header-file, sea-state header-file, device header-file and export header-file are described in Sections 3.7, 3.8, 4.8 and 5.4. These are required to make sense of the information in the wave-, sea-, device- and export-records respectively. For each field of each record type, they will identify the corresponding parameter and provide scaling and units information. The header files may remain the same throughout the course of a project, or they may change if additional fields are added to any of the records or if any calibrations are changed.

6.2 Returns file

For each half-hour of the year and for each of the four half-hour record types the returns-file indicates whether a valid record is available. This will be a comma- or tab-separated text-file or a spreadsheet file with one column for each wave measuring instrument and for each device. Table 6.1 indicates the logical structure of the annual returns-file.

Period	*Buoy 1*		*Buoy 2*		*Dev. 1*	*Dev. 2*	*Dev. 3*	*Export*
	Wave	*Sea*	*Wave*	*Sea*				
2007/8 Year	92.4[1]	92.4	92.4	92.4	99.6	98.6	99.6	100
2007 March	100	100	100	100	100	100	100	100
2007 April	89	89	89	89	100	100	100	100
2007 May	90	90	90	90	98	97	96	100
2007 June	100	100	100	100	100	100	100	100
2007 July	98	98	98	98	100	100	100	100
2007 August	97	97	97	97	100	100	100	100
2007 September	92	92	92	92	97	86	99	100
2007 October	100	100	100	100	100	100	100	100
2007 November	86	86	86	86	100	100	100	100
2007 December	90	90	90	90	100	100	100	100
2008 January	67	67	67	67	100	100	100	100
2008 February	100	100	100	100	100	100	100	100
2007-03-01[2] 00:00	1[3]	1	1	1	1	1	1	1
2007-03-01 00:30	0	1	1	1	1	1	0	1
2007-03-01 01:00	1	1	1	1	0	1	1	1
(followed by 17,565 more entries through to 23:30 hrs on 29th February 2008)								

Table 6.1 Example of annual returns-file structure. The first three half-hour summaries are shown at the bottom. '1' indicates valid data.

Dev 1, Dev 2 etc: Device 1, device 2

[1]Numbers are percentage values.(e.g. 92.4 % of wave records for the year 2007/8 have been obtained)

[2]In this example, the anniversary of the Protocol start date falls on 1st March

[3]1 indicates record exists, 0 indicates missing or erroneous data.

6.3 Headline numbers

The *headline-numbers* give a concise numerical overview of the wave power resource incident on the project location and of the overall performance of the devices. Information on five aspects of the project will be provided.

The following parameter will be calculated from the wave-records for every wave measuring instrument. An *all-year* figure and a figure for *each month* should be provided.

1. Mean gross wave power density, in kW/m.

The following parameters will be calculated from the device-records for every device in the project. An *all-year* figure and a figure for *each month* should be provided.

2. Mean net generated power from each device, in kW.
3. Mean availability of each device, in %.
4. Mean capacity factor of each device, in %.

The following parameter will be calculated from the export-records for the year as an *all-year* figure and as a figure for *each month*.

5. Net energy exported from the project to the network, in MWh.

6.4 Time-series plots

Time-series plots will be drawn from the half-hour average values of the wave-records and the device-records to provide a graphic overview of the temporal variability of the wave resource over the year and the response of each device to it. The following plot(s) will be drawn for each wave measuring instrument.

1. Gross wave power density in kW/m.

The following plot will be drawn for each device.

2. Mean generated power in kW.

The plots should be drawn one below the other as composite landscape-format images on A4 paper with identical horizontal time-scaling. There should be a maximum of six such plots on a page. If the total of wave measuring instruments and devices is more than six, the upper plot on each page each page should be the same as the upper wave plot of the first page.

The vertical axes of the wave power density plot(s) should be to the same scale with the maximum value being a *rounded* value equal to or greater than the maximum recorded value. The vertical axes of the generated power plots should all be to the same scale with the maximum value being a *rounded* value equal to or greater than the device rated power.

6.5 Scatter diagrams

For each wave measuring instrument, the half-hour averages of height H_{m0} and energy period T_e will be binned as scatter diagrams. A set of five such scatter diagrams should be provided for each wave measuring instrument. The first will be an *all-year* scatter diagram. The other four will correspond to *winter*, *spring*, *summer* and *autumn*, defined as follows:

Winter	December	January	February
Spring	March	April	May
Summer	June	July	August
Autumn	September	October	November

An example scatter diagram (for an imaginary location and time) with the specified axes, resolution and format is shown in Section 6.5 of the Supporting Commentary.

The H_{m0} bins will be from 0.5 to 12 m in steps of 0.5 m. The occurrences of each H_{m0} will be allocated to a particular bin if it satisfies the relation $LL < H_{m0} \leq UL$, where *LL* is the lower limit for a particular bin and *UL* is the upper limit. The bin label will be defined as the *upper cut-off* height for the particular bin. As an example, an H_{m0} value of 4.01 m would be assigned to the 4.5 m row. Any H_{m0} value greater than 12.5 m will be assigned to the 12 m row.

The T_e bins will be from 5 to 15 s in steps of 0.5 s. The occurrences of each T_e will be allocated to a particular bin such if it satisfies the relation $LL < T_e \leq UL$, where LL is the lower limit for a particular bin and UL is the upper limit. The bin label will be defined by upper cut-off period. As an example, a T_e value of 12.01 s would be assigned to the 12.5 s column. Any T_e value less than 5 s will be assigned to the 5 s column. Any T_e value greater than 15 s will be assigned to the 15 s column.

The values reported in the Protocol scatter-diagrams *should not be normalised*. They will indicate cumulative numbers of half-hour sea-state observations. The total number of observations for each time period should also be shown.

6.6 Power-weighted wave rose

A sixteen-sector all-year *power-weighted wave rose* should be provided for each wave measuring instrument. These plots are a form of histogram and will be based on the *power-weighted mean wave direction* figure that is contained within each half-hour sea-record. An example based on synthetic data is shown in Figure 6.1 to illustrate the required format.

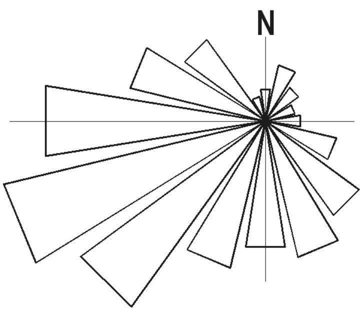

Figure 6.1 Sixteen-sector power-weighted wave rose plot. The *area* of each *petal* is proportional to the respective number of observations.

The individual power-weighted mean wave direction values from the set of sea-records for the year are binned into sixteen bins, each of which represents one of the 22.5 degree sectors. The *area* of each drawn sector in the plot is then made proportional to the number of entries assigned to it. This is achieved by making the *radius* of each sector proportional to the *square-root* of the number of binned observations.