Assessment of Performance of Tidal Energy Conversion Systems

Foreword

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

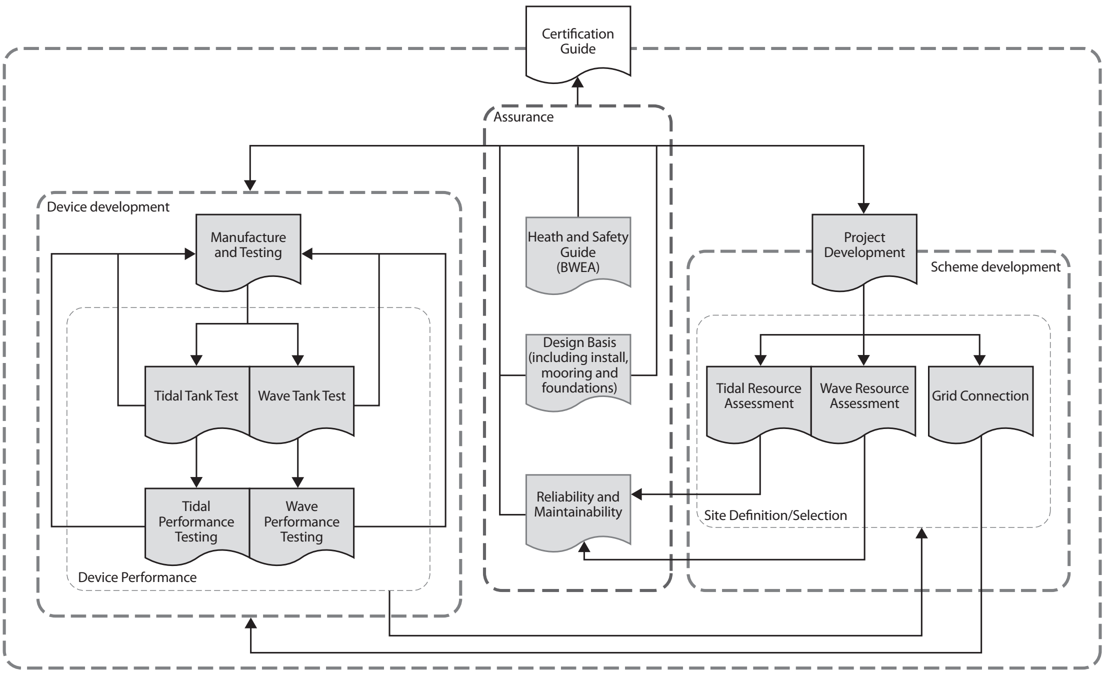

Figure 1 — Marine Renewable Energy Guides

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Assessment of Performance of Tidal Energy Conversion Systems

Marine Renewable Energy Guides

EMEC ORKNEY
The European Marine Energy Centre Ltd

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Contents

Assessment of Performance of Tidal Energy Conversion Systems

Introduction

This document has been prepared in consultation with The European Marine Energy Centre Ltd and with other interested parties in the UK tidal energy community and is designed for use by appropriately qualified and competent persons. Where appropriate, reference has been made in Clause 2 and at relevant locations in the main text, to national and European standards that form an interface to the present document. Relevant international work has been referenced, where appropriate, in the main document and in the Bibliography. Reference has been made to the relevant parts of the EMEC *Assessment of Tidal Energy Resource* publication, which is to document the stage of investigation to be undertaken at an intended tidal energy conversion systems (TECS) site, prior to the deployment of the device.

The measurement techniques recommended in this document should be applied by all parties to ensure that continuing development and operation of TECS is undertaken in a consistent and accurate manner. This document presents measurement and reporting procedures that are expected to provide fair and suitably accurate results that can be replicated by others, but without imposing excessively firm requirements that can add excessive cost to the testing process.

1 Scope

The document establishes a uniform methodology to ensure consistency and accuracy in the measurement and analysis of the power performance exhibited by tidal energy conversion systems (TECS). This document also provides guidance in the measurement, analysis and reporting of the performance testing of TECS.

2 Normative references

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

European Marine Energy Centre. *Assessment of Tidal Energy Resource*, 2009.

IEC 60044-1:1996, *Instrument transformers – Part 1: Current transformers*

IEC 60688:1992, *Electrical measuring transducers for converting a.c. electric quantities to analogue or digital signals*

International Hydrographic Organization. *IHO Standards for Hydrographic Surveys*. Special Publication No. 44. 5th Edition, 2008.

3 Terms, definitions, symbols and abbreviations

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

3.1 Terms and definitions

3.1.1
accuracy
closeness of agreement between a measured quantity value and a true quantity value of measurand

3.1.2
availability
ratio of the total number of hours during a specified period excluding the number of hours that the TECS could not be operated owing to maintenance or fault conditions, to the total number of hours in the period, expressed as a percentage

3.1.3
capture area
frontal swept area of the TECS that contributes to the power extracted by the device from the free tidal current stream

3.1.4
data set
collection of data sampled over a continuous period

3.1.5
estimated annual energy production
estimate of the total energy production of a TECS during a one-year period obtained by applying the measured power curve to a set of tidal current predictions, at stated availability

3.1.6
measurand
quantity intended to be measured

3.1.7
measurement period
specified time period during which a statistically significant database was collected for the power performance test

3.1.8
method of bins
method of data reduction that groups test data for a certain parameter into subsets typified by an independent underlying variable

3.1.9
net electric power output
measured portion of the TECS electric power output that is recorded at the device, where it is connected to the transmission voltage

3.1.10
power coefficient
ratio of the actual power produced by the TECS to that of the kinetic energy of a stream tube with the same power-capture area as that of the rotor

3.1.11
rated power
quantity of power assigned, generally by the manufacturer, for a specified operating condition of a component, device, or item of equipment

3.1.12
standard uncertainty or standard error
measurement uncertainty expressed as a standard deviation

3.1.13
test site
location of the TECS under test and its surroundings

3.1.14
uncertainty in measurement
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

3.2 Symbols and units

A	Power – capturing area of the TECS (m^2)
A_v	Predicted availability
b_i	Width of horizontal slice i through the power capture surface (m)
E_i	Confidence limit in the data bin i
$f_i(U_i)$	Proportion of time during the year for which the average performance current velocity occupies a value within the data bin i of the device power curve

i	Data bin index number, used as a subscript
j	Data point index number in a given data bin
k	Index number of the horizontal slice through the power capture area
N_B	Number of measurement data bins
N_i	Number of data points in the data bin i of current speeds
P	Electrical power output (kW) from the TECS
P_i	Average electrical power (kW) from the TECS in the data bin i
$P_{(i,j)}$	Electrical power from the TECS at data point j in data bin i (kW)
P_{KE}	Power available from the kinetic energy active across the power capture area (kW)
S	Number of horizontal slices of the power capture surface, normal to the direction of tidal current flow
U	Speed of the tidal current (m/s)
U_i	Speed of flow of the tidal current normal to the power capture surface and flowing through the horizontal slice i of the power capture area (m/s)
U_{perf}	Average performance velocity of the tidal current (m/s)
$U_{perf(i)}$	Average performance velocity of data bin i (m/s)
$U_{(i,j)}$	Current velocity recorded for data point j in data bin i (m/s)
z	Elevation above the seabed (m)
z_i	Depth of horizontal slice i through the power capture surface (m)
ρ	Density of water (kg/m^3)

3.3 Abbreviations

AEP	Annual Energy Production in kWh/year
ASCII	American Standard Code for Information Interchange
CD	Chart Datum
CDF	Common Data Format
COP	Code of Practice
IHO	International Hydrographic Organization (Monaco)
LAT	Low Astronomical Tide
ODN	Ordnance Datum Newlyn
STP	Standard Temperature and Pressure
TECS	Tidal Energy Conversion System
UTC	Coordinated Universal Time
VHF	Very High Frequency (radio)
WGS84	World Geodetic System 1984

4 Test conditions

4.1 Tidal energy conversion system

The TECS shall be described and documented to identify uniquely the device that is under test. Clause 8 describes the reporting format that is to be adopted for this purpose.

4.2 The test site

A survey of the bathymetry of the test site shall be carried out to ensure that it is free from obstacles and topology that could affect the performance of the TECS, or adversely affect the local quality of the tidal currents.

NOTE Sub-bottom profiling might also be required in situations where there is a considerable volume of suspended sediment, or layers of liquefied mud that may affect the device installation.

The site shall be surveyed in accordance with IHO Order 1 hydrographic survey standard, as described in Chapter 1 of the *IHO Standards for Hydrographic Surveys* (2008), and which is summarized in Table 1 of the IHO Standard.

NOTE Prior to the detailed design stage, an additional survey is likely to be necessary, as this may uncover issues that sonar surveys do not.

4.3 Local site considerations in resource assessment at the pre-deployment stage

The effects of seasonal migration of currents need to be considered, since they do not necessarily retain the same position throughout the year and their potential capacity to relocate may exert an influence upon predicted long-term power capture. Tidal stratification might also need to be taken into consideration, and the scale of its existence and the need to consider it should be inferred from numerical modelling [1].

Wave–current interaction also exerts an influence upon the total current resource, through the Stokes drift and also through wave-induced temporal fluctuations, and the magnitude of these effects shall be assessed and, where significant, shall be taken into account in the resource assessment stage. This shall be accomplished through the application of a suitable nonlinear numerical wave analysis in respect of Stokes drift and by at least a linear wave–current interaction analytical technique to assess the magnitude of wave-induced temporal fluctuations.

In general, the area to be considered in this respect typically shall be of the order of 10 TECS diameters up and downstream and 5 diameters either side of the test site.

4.4 Data measurement of speed and direction at the resource assessment stage

Recording devices shall be installed at positions close to the intended TECS test location, to provide an accurate measure of tidal current conditions experienced in operation. The device(s) to be installed shall be capable of recording the temporal variation in horizontal current velocity vertically throughout the water column.

This subclause along with Subclause 5.2 describes the required minimum specification and performance characteristics of devices that are to be used for the measurement of current speed and direction at the site. The following deployment procedure shall be adopted:

1. A 10 min resolution time series of water level, current speed and direction, covering the entire duration of the measurement period, shall be recorded, with a view to predicting the long-term energy potential at the site.
2. The difference in total water depth between the sampling location and the intended TEC position shall be less than ±10% of the water depth to Chart Datum.
3. The recording device shall be bottom mounted.
4. Maximum vertical distance between sampling levels up the water column shall be 1 m.
5. The recording period required in order to establish an accurate resource assessment shall be determined, taking due consideration of the nature of the tides and the complexity of the ambient tidal signal in the project area. Due consideration shall be given to the possible stochastic influence of surges upon the tidal currents recorded during the resource measurement stage, and to the temporal position of the recording period within the equinoctial and the nodal cycles. A period of 30 days of output power is regarded as the minimum acceptable recording period and the validity of this minimum choice should be substantiated. Preferably, the tidal current regime should be monitored from an early a date as possible in the development process.

4.5 Data analysis at the resource assessment stage

In respect of fixed axis devices, the principal current direction is to be extracted from the current data and the data to be then converted to the principal direction by resolution. The resolved data shall be harmonically analysed using an established and accepted method, to obtain a sufficient number of constituents to provide a converged fit to the data.

NOTE A minimum of 20 current velocity constituents is normally expected to be required for the long-term prediction of annual energy production to be effective.

The tidal velocity constituents obtained shall be used to predict a time series of current speeds to a maximum temporal resolution of 10 min, at the TECS, for the lifetime of the deployment to enable the annual energy production calculation to proceed. An established and accepted method should be used for this purpose, capable of including all of the tidal constituents derived from the analysis procedure.

The power flux available from the kinetic energy at the device shall be calculated from the time series of harmonically predicted current speeds based upon Equation 1, which shall be subsequently integrated over time to obtain an estimate of mean annual power availability. The seawater density value used in Equation 1 shall be obtained using the method as described in Subclause 5.3.

4.6 Transposing performance between sites and sea areas

At any test location, the proximity of the tidal current measuring device(s) relative to the TECS may vary. Consequently, consideration shall be given to the differences between the tidal current recording site and the TECS deployment sites, especially in respect of:

- the adoption of a suitable agreed tolerance on the distance between the devices and the proposed measuring locations;
- water depth and/or morphological features that could lead to local spatial variations in the mean tidal current behaviour.

5 Test equipment

5.1 Electric power

The net electric power of the TECS shall be measured using a 3- or 2-phase power measurement device, such as a transducer, and be based upon measurements of current and voltage on each phase. The class of current transformers and the class of voltage transformers shall conform to Class 0.5, or better, as defined in IEC 60044-1.

The accuracy of the power measurement device, if it is a transducer, shall conform to Class 0.5, or better, as defined in IEC 60688. If the power measurement device is not a transducer, then the accuracy shall be equivalent to Class 0.5 power transducers. The operating range of the measuring device shall be set to measure all positive and negative instantaneous power peaks generated by the TECS.

NOTE As a guide, the full-scale range of the power measurement device needs to be set at -50% to 200% of the TECS full rated power. All data needs to be periodically reviewed during the test to ensure that the range limits of the power measurement device have not been exceeded.

The power measurement device shall be mounted as close to the network connection point of the device as is practicable to ensure that only the net active power output, delivered to the electrical power network, is measured. Losses in cables and transforming equipment should be calculated by a method that is acceptable to a relevant accreditation body.

5.2 Tidal stream and current measurement

Recording devices shall be installed at positions close to the location of the TECS under test, to provide an accurate measure of tidal current conditions experienced in operation. A device shall be installed that is capable of recording the temporal variation in horizontal current velocity at vertical increments covering the power capture area of the TECS.

NOTE It might be helpful to obtain measurements showing the spatial variability of the currents in order to ascertain an appropriate measure of closeness, for example with an array of in-situ sensors or using a remote sensing technology.

The time stamp on the device logger shall be set immediately before instrument deployment and shall further be checked immediately after recovery. Any discrepancies exhibited by the recorded times of deployment and recovery shall be reported, alongside the data repair techniques.

The minimum specification for the device shall be as follows:

1. It shall be capable of recording temporal variation in water depth throughout the tidal cycle.
2. It shall be capable of recording the temporal variation in horizontal current velocity profile and the current direction, vertically through the water column.
3. The device shall be specified to measure velocity to ±2% or better and be verified by traceable calibration.
4. It shall have a recording velocity range capable of covering the maximum and minimum current speeds identified at the Tidal Resource Assessment stage and with a resolution better than ±0,05m/s
5. It shall report discrete samples at a maximum temporal interval that is commensurate with the known scale of temporal fluctuations in the tidal speed at the site.
6. The recording equipment shall be capable of collecting and transmitting data at a sampling rate of 2 Hz or more, and the data ensemble binning interval should be 2 min or more.
7. The absolute accuracy of the current direction measurement shall be better than ±5 degrees, without compromising the accuracy of current speed recording.
8. Water level, current speed and direction ensemble data should be reported every 10 min or less.
9. The record shall be binned at a maximum vertical spatial increment of 1 m through the depth of the power capture area. It should be demonstrated prior to installing the recording device that a spatial sampling increment of 1 m is sufficient to resolve the variation in current speed across the power capture area of the TECS, especially in areas where it is believed that the scale and location of the TECS power capture

area might render it susceptible to the more rapid variations in current speed and also lower current speeds, associated with closer proximity to the seabed. A finer spatial sampling resolution should be adopted if necessary.

10. Time stamping shall be to UTC throughout the recording periods(s).

5.3 Seawater density

In areas where the freshwater contribution from land is insignificant, for instance when the TECS is located well away from any estuary or any semi-enclosed area with a large freshwater input, a representative value for the density of seawater (1 025 kg/m^3) may be used. However, in areas where the density of seawater would be expected to vary, a device for measuring the temperature and salinity should be deployed alongside the current meter. The recorded dataset of temperature and salinity should be investigated to consider the effects of varying water density upon the power resource.

5.4 Tidal energy conversion system operational status

At least one parameter indicating the operational status of the TECS shall be monitored continuously or frequently. The status information shall be used in the estimation of the TECS availability.

NOTE The non-production of electric power is not a suitable parameter to monitor, because there may be separate factors inhibiting production, other than the availability of the TECS, e.g. a grid failure.

The total number of hours for which the device was available for energy production should be logged, along with the corresponding figure of unavailability due to a device fault. Unavailability time due to planned maintenance as specified in the test scheme should also be recorded. The duration for which the device was unavailable due to external factors arising from third parties, such as grid faults, should also be documented, substantiated and logged.

5.5 Data acquisition system

A digital data acquisition system having a minimum resolution commensurate with the known scale of temporal fluctuations at the site shall be applied to gather measurements and to store pre-processed data. End-to-end checking of any installed remote data acquisition system shall be performed for each signal.

The uncertainty introduced by the data acquisition system shall be demonstrated as being negligible compared to that due to the sensors.

6 Measurement procedures for TECS device performance

6.1 General

The objective of the measurement procedure is to collect data that meet a set of clearly defined criteria. This ensures that the data are of sufficient quantity and quality to enable the performance characteristics of the TECS to be represented. The measurement procedure shall be documented in compliance with Clause 8, so that every procedural step can be reviewed and, if necessary, repeated.

The ambient resource shall be recorded during the TECS performance test, along with the power capture performance of the device.

6.2 Tidal energy conversion system operation

During the measurement period, the TECS shall be in normal operation as prescribed in the TECS operations manual, which is to form part of the test scheme. The machine configuration shall not be changed during the measurement period. All data collected when the TECS is unavailable, under the definitions described in Subclause 5.4, shall be eliminated from the power calculation, notwithstanding the obligation to correctly establish the percentage of availability of the TECS device during the test period. The control algorithm can exert a significant effect on energy capture and shall not be changed during the test period.

6.3 Data collection

6.3.1 General

The minimum measuring period necessary to reliably define TECS performance shall be considered from the outset of the trial, by reference to the resource assessment data and shall not in any event be less than 15 days. The data shall be of sufficient quality to enable a reliable prediction of the power curve, as described in Subclause 7.2, to be obtained.

The data acquisition system shall store the sampled data unprocessed, or in pre-processed format, or both. The pre-processed data sets shall consist of the following items of information on the sampled data within each averaging period as defined in Subclause 5.2:

- the mean value;
- the standard deviation;
- maximum value;
- minimum value.

NOTE It is desirable to incorporate redundancy in the sensor systems where possible, to allow cross-checks to be implemented, thus ensuring that data sets do not have to be discarded because of the failure of a single sensor.

6.3.2 Incident resource measurement during TECS deployment

Data shall be sampled continuously using devices that conform, as a minimum, to the description provided in Subclause 5.2. The positioning of the resource measurement devices(s) shall be such that they capture the ambient current behaviour without modification due to the proximity of the TECS, but sufficiently close to the TECS to be representative of the local current regime. Maximum and minimum distances between the recording device and the TECS need to be agreed, on the basis of TECS size and geometry and on a consideration of the potential for spatial variation in current speed distribution at the site.

EXAMPLE Two bottom-mounted recording devices could be deployed near to the TECS, and located appropriately up- and downstream of the device, along the line of the major principal axis of the tidal current. Alternatively, a recording device could be deployed near to the TECS, and located perpendicular to the TECS along the minor principal axis of the tidal current.

In all cases, the difference in water depths between the TECS and the recording devices shall be demonstrated from the pre-installation survey to be less than ±10% of the depth to Chart Datum.

A floating TECS that is free to move on a compliant mooring should ideally be equipped also with a downward-looking acoustic device mounted on the TECS itself.

6.3.3 Power production measurement

The power measurement equipment shall conform to Subclause 5.1. The voltage and current shall be reported as an average over the same averaging period as that adopted for the resource measurement as described in Subclause 6.3.1 and referenced to Subclause 5.2. The power production data shall be supplied in time stamped format over the measurement period and simultaneous in date and time with the tidal current resource records, thus enabling direct comparison between the calculated resource and the power capture of the TECS. The record of the meter operator shall also be supplied covering the measurement period, at hourly and half-hourly temporal resolution. Where several facilities use a common connection point, metering that conforms to the relevant COP standard shall be installed at a point before the output from the facilities combines, in order to produce the same standard of data relating to each facility.

6.4 Data issues

6.4.1 General

Selected data sets shall be based upon 10 min periods derived from the contiguous measured data. Data sets shall be excluded from the database under the following circumstances:

- TECS wholly or partially unavailable;
- failure of the test equipment;
- failure of the tidal current resource recording equipment.

Data sets collected under special operational conditions occurring during the measurement period may be selected as the contents for a special database and the selection criteria shall be stated in the measurement report.

The total duration of each data set shall be 10 min and the data set shall not be separated by time delays. Data shall be collected until the criteria in Subclauses 7.1 and 7.2.2 are satisfied.

6.4.2 Data Filtering

It is permitted to filter the data, but the full filtering algorithm shall be reproduced within the benchmarking documentation. Active frequency rejection systems are the preferred option, using frequency domain-based signal processing techniques.

6.4.3 Data Validation

Once the accuracy of the data has been fully defined and the data acquisition system calibrated, this can be used in basic models of the product to enable validation of the data as well as sensor validation.

Data from all measurement channels shall be synchronized as far as practicable in order that data from separate acquisition units can be fully locked onto a consistent time frame.

NOTE This will require a separate trigger signal to be distributed within the data logging system, either by a hard-wired analogue signal, or through a data synchronization protocol via a communication network.

This technology shall also enable multiple sampling regimes to be incorporated into the data logging system.

EXAMPLE Electrical power flow will need to be monitored on a slow time frame if steady-state power flow is required, but if harmonic content is to be fully analysed, then the power will need to be sampled in the kHz range.

Adequate data protection should also be enabled within the data logging function, that is, protection of data integrity as well as electrical signal integrity.

NOTE In an electrically noisy environment, and subject to the harsh marine conditions, the operation of electromechanical hardware can become affected.

The tidal constituents of current velocity, derived from the Resource Assessment Stage described in the EMEC *Assessment of Tidal Energy Resource* document, shall be used to predict a 10 min time series of current speeds likely to apply during the TECS device performance measuring period. Such results are likely to provide a close approximation to the records that will be taken during the test period and will assist in validating the results.

6.4.4 Data Correction

Using the harmonic predictions, it shall be possible to identify tidal current data that are corrupted or suspect. Corrupted or missing data should be removed from consideration.

NOTE Data irregularities connected with turbulence in the free stream flow need to be addressed. Tidal turbulence is complex both in time and space and it cannot necessarily be expressed as a constant fraction of the mean flow. Furthermore, turbulent behavioural traits can contain signatures of earlier flow conditions, thus rendering the interpretation of data behaviour more complex.

6.4.5 Possible contribution from waves

The possible contribution of waves may be of relevance in establishing the performance characteristics of the same device at different sites.

NOTE There may be circumstances in which the tidal currents are at times affected by wave-induced phenomena, such as the Stokes drift, arising from surface waves of long or moderate period and of sufficient amplitude to penetrate to the level of the TECS power capture surface. If the site is known to be subject to bursts of wave activity of sufficient intensity as to affect the numerical values of the tidal currents at that level, then it is advisable for a wave measurement instrument with traceable calibration to be installed at the site, recording at the same time stamp interval as the TECS recording device.

A comparative study between a wave buoy and an acoustic sensing device [2] showed that whilst the two devices agreed well in respect of significant wave height, the records of peak period showed a more considerable departure, both in terms of the mean and the standard deviation of peak period. If wave–current interaction and its influence upon TECS power capture were to be studied, correct knowledge of the peak wave period would be essential. This is true if the site has good tidal stream power capability but is also active in terms of ambient wave energy.

It may also be necessary to consider the influence of the pulsating flow contributed by waves, upon the performance of the TECS. There may even be flow reversals arising due to waves at times when the current is weaker and the TECS is still in operation.

6.4.6 Potential contribution from baroclinic forcing and other effects

Thermal stratification can occur over large expanses of the sea, giving rise to further variations in potential energy capture of TECS. The existence of such effects in the project area should be defined and quantified. The effects of seasonal migration of currents also need to be considered as any relocation of the device could exert an influence upon predicted long-term power capture.

Additional records shall be taken where there is doubt concerning the homogeneity of the current regime and due consideration shall also be given to the possible influence of surges upon the tidal currents recorded during the test.

6.5 Database

6.5.1 Data Format

In order to enable the widest availability of the data, simple ASCII text files or net CDF are the preferred options. Data shall be produced in terms of:

- post-conversion fixed point data;
- scaling factors;
- data resolution;
- data accuracy;
- time stamp, expressed in UTC.

NOTE Once stored in text-based spreadsheet format, further analysis can be performed using a variety of bespoke or custom signal processing systems and techniques.

6.5.2 Storage format

All data shall be stored in a text format that is universally readable, such as HTML or XML.

NOTE Net CDF is the preferred compact data format.

6.5.3 Data Security

The test results data shall be retained in a secure state using a method agreed at the time of the test design.

6.5.4 Data storage and telemetry

Consideration shall be given at the test planning stage, and an agreement should be made, regarding the location of stored data, whether or not it should be stored on site and the safe means of data recovery or transmission to shore.

7 Derived results

7.1 General

The performance envelope of the TECS device shall be described by a power curve produced using the measured in-situ data, analysis of the operational status of the device, and the annual energy generated by the facility. The power curve relates the electrical power produced by the TECS to the value of the simultaneous incident resource, which is characterized by the tidal current velocity.

The power available from the kinetic energy active across the power capture area shall be calculated from a time series of the measured current speeds as:

$$P_{KE} = \tfrac{1}{2}\rho A U^{3}_{perf} \quad (1)$$

where

U_{perf} average performance velocity as defined in Equation 2.

The minimum resource measuring period necessary to reliably define TECS performance shall be established from the outset of the trial, by a consideration of the resource assessment data and shall not in any event be less than 15 days. The data shall be of sufficient quality to enable a reliable prediction of the converged power curve, as described in Subclause 7.3, to be obtained. Therefore the deployment period should be 15 days or the time required to prove convergence of the performance curve, whichever is the longest period of time.

7.2 Prediction of the power curve from measurements

7.2.1 Method of bins

The power curve constitutes a plot of the power production record (*y*-axis) against the incident current resource (*x*-axis).

NOTE The recommended approach is similar to that adopted in the wind industry standard IEC 61400-12-1:2005.

The power production in this context is represented by the recorded power at the individual TECS output point and therefore includes the reduction in transmission arising from the drive train efficiency and any other device equipment contributions. Where it is impracticable to measure power at the TECS output point then power should be measured at a suitable location such as the substation onshore, and the losses due to cables, transformers and power conditioning should be accounted for accordingly.

The resource tidal current records shall be available at temporal increments of 10 min or similar, at spatial increments of 1 m or less, working up the water column from the seabed. It shall be assumed that the record at any elevation above the seabed is representative of the tidal current speed across the entire width of the power capture surface at that elevation. The vertical variation of the tidal current at each time interval shall be integrated across the power capture area, to provide an average performance velocity for plotting on the power curve, based upon the following identity:

$$U_{perf} = \left[\frac{1}{A}\sum_{k=S}^{k=1} U_k^3 \cdot b_k \cdot z_k\right]^{1/3}$$
$$A = \sum_{k=S}^{k=1} b_k \cdot z_k \quad (2)$$

where

A	area of the capture surface
b_k	width of horizontal slice k through the power capture surface
S	number of horizontal slices of the power capture area, normal to the direction of tidal current flow
k	subscript number of the horizontal slice centred around speed U_k
U_k	speed of flow of the tidal current normal to the power capture surface and flowing through the k^{th} horizontal slice of the power capture surface
z_k	height of slice k taken horizontally through the power capture surface

If the TECS is fixed, i.e. it has no yaw capability, then only the component of velocity perpendicular to the power capture surface should be used for the identity of U in Equation 2. However, if the TECS device is capable of orientating to the dominant tidal current direction prevailing at a given time, the recorded velocity vector irrespective of direction should be used for the identity of U.

The measured power curve is to be derived by applying the method of bins to the current velocity data in bin increments of 0,10 m/s and by calculation of the mean values of current resource across the power capture surface and device power output for each current resource bin as follows:

$$U_{\text{perf}(i)} = \frac{1}{N_i} \sum_{j=1}^{N_i} U_{\text{perf}(i,\,j)}$$
$$P_i = \frac{1}{N_i} \sum_{j=1}^{N(i)} P_{(i,\,j)} \qquad (3)$$

where

N_i	number of data sets in bin i
P_i	average recorded TECS power output in bin i
$P_{(i,j)}$	TECS power output recorded at data point j in bin i
$U_{\text{perf}(i)}$	average current velocity in bin i
$U_{\text{perf}(i,j)}$	current velocity recorded for data point j in bin i

The power curve shall be presented in graphical and in tabular format. The table shall list the following items:

- Velocity bin value for the i bins;
- Average current velocity in each of the i bins: $U_{\text{perf}(i)}$;
- Average power output in each of the i bins: P_i;
- The number of data sets in each of the i bins: N_i;
- The standard deviation of the values of P_i in bin i.

7.2.2 Levels of uncertainty

It should be noted that the value of P_i for each bin, is a mean, or expected, value based upon an ensemble average of the collected values in that bin. Consequently, there will be a distribution of values scattered randomly around the mean value given in Equation 3, with a standard deviation attached to that distribution, relating to that bin. The standard deviation on each bin in the power curve will provide one of the levels of uncertainty associated with the behaviour of the device at the site.

The standard deviations for each of the velocity bins are best estimates of the true standard deviation, which will itself possess a distribution, and which will become increasingly accurate as the number of points in the bin increases. The duration of the test period is therefore likely to exert an influence upon the level of uncertainty attached to the expected performance of the device at that site.

The derivation of overall system performance uncertainty should account for the contributions made by the measuring instruments, cables, transformers and other equipment, in accordance with the methods described in EA-4/02 [3].

7.2.3 Proof of convergence

The graphical representation of the power curve shall display the averaged power output as a function of the averaged tidal stream velocity, and the upper and lower bands of standard deviation, which shall be deemed to be represented by the standard deviation of power capture applying to the bin under consideration.

In addition to providing a power curve at the end of the test period, a set of intermediate power curves shall be calculated based upon accumulations of each successive 24 h of valid operation, which, if the test is uninterrupted, will constitute 144 new readings added in total for each day of the deployment period. As the data contents of each tidal velocity bin increases in volume, it shall be demonstrated that the power curve converges towards a stable shape and set of values, so that at the end of the test period, it has been demonstrated that the final test result for the power curve represents a statistically stable and reliable result. In this manner, the optimum duration of the test shall be established based upon a continual assessment of the convergence of the power curve towards a stable result and, consequently, a longer period than the minimum acceptable duration of 15 days may be required for the test, on this basis.

7.3 Power coefficient

7.3.1 General

The power coefficient of the device shall be expressed as:

$$C_p = P/\left[\rho A U^3_{\text{perf}} /2\right] \quad (4)$$

where

A	power capture area of the device
P	recorded power output (kW)
U_{perf}	average performance velocity of the tidal current (Equation 2)

The power coefficient is a function of the tip speed ratio, defined as the ratio of the speed of the tip of the device rotor, to that of the free current. P is the electrical power output.

In general, the performance of the device is likely to fall below the theoretical Betz limit [see web references in the Bibliography], owing to turbulent interference between the blades of the device at high tip speed ratios, and to capture drop-off at very low rates of rotation. However, owing to the close proximity of the two boundaries provided by the seabed and free surface, the streamlines of flow around the device may on occasions be such that the theoretical Betz limit, which applies to an infinite stream, can be achieved, or even exceeded.

NOTE For an example, see DTI (2005)-URN 1698 [4].

7.3.2 Proof of convergence of the power coefficient

If it is agreed from the outset that a power coefficient curve is to be provided as output from the test, then the method of bins should again be used to develop the curve, which should also be shown to have converged to a stable value during the test. This will require that the rotational frequency of the TECS be monitored during the test period and reported at date stamps that are simultaneous with those of the resource monitoring equipment and the power capture monitoring system. Date stamps shall be on the hour and half-hour to match electrical measurements.

7.4 Annual energy production

The expected annual energy production (AEP) in kWh for a device with a defined power curve shall be obtained by combining the power curve described in Subclauses 7.2 and 7.3 with a frequency distribution of velocity for the site:

$$\mathrm{AEP} = 8760 \cdot A_{\nu} \cdot \sum_{i=1}^{N_B} P_i\left(U_{\mathrm{perf}\,(i)}\right) \cdot f_i\left(U_{\mathrm{perf}\,(i)}\right) \tag{5}$$

where

A_v	the predicted availability
AEP	expected annual power production in kWh
N_B	total number of velocity bins set in increments of 0,10 m/s, in the device power curve
$P_i(U_{perf(i)})$	the power in kW generated by velocity bin *i* of the power device curve

$U_{perf(i)}$ the average performance current velocity of bin *i* of the power device curve

$f_i(U_{perf(i)})$ the proportion of time during the year for which the average performance current velocity occupies a value within bin *i* of the device power curve

If the TECS is fixed, having no yaw capability, only the component of velocity perpendicular to the power capture surface should be used for the identity of $U_{perf(i)}$ in Equation 5. However, if the TECS device is capable of orientating to the dominant tidal current direction prevailing at a given time, the velocity vector irrespective of direction should be used. This consideration also arises in the derivation of the device power curve, as discussed in Subclauses 7.2 and 7.3.

Alternatively, the expected AEP may be predicted on a year-by-year basis, using the constituents of tidal current speed calculated for the various levels up the water column, to first obtain the average performance velocity at each time step during the year, by the application of Equation 2. The power capture at that velocity may then be obtained from the power curve, and the results integrated for the whole year accordingly.

It is important to note that the expected AEP is a robust estimator of the expected power and it has attached to it a level of uncertainty in each of the N_B bins of tidal current velocity at the test site. Generally it may be expected that the AEP can be calculated for another site provided that the set of $f_i(U_{perf(i)})$ is known. However, the AEP shall be quoted with an expected margin of error either side of the mean value. In this way, estimations of uncertainty in AEP can be calculated on the basis of upper and lower confidence limits ($P_{(i)} \pm E_{(i)}$) in each bin, where $E_{(i)}$ denotes the confidence increment of the bin i.

The uncertainties in the AEP only consider those factors from the power performance test and not the uncertainties arising from other important effects. These other factors should be reported if allowances need to be made and/or caveats provided in the test report. Practical AEP forecasting should account for other uncertainties and include availability of the TECS due to environmental effects associated with storm damage and other influences.

8 Reporting format

8.1 Description of tidal energy conversion system

The specific TECS under test shall be described, including, as a minimum, the following:

- make, type, serial number and production year of the device and control algorithm;
- description of energy capture technology, including cut-off levels, depth below surface (or above the seabed) of the energy capture axis of the TECS;
- description of power take-off system and its rating – power, voltage, type of generator, etc;

- normal range of operating parameters;
- standard dimensions of the TECS.

8.2 Description of the test site

The test site arrangement and general facilities shall be reported. A map shall be provided showing the berth location, water depth, plus tidal current ellipse, wind and wave roses. The map shall show locations of the measurement devices and any nearby met station and standard tide gauge installations. A general summary of the instrumentation and equipment at the test site shall be provided, details of which are given in Subclause 8.4.

The site survey report detailing the results obtained under Subclause 4.2 shall be included, along with the position of the TECS device, expressed in degrees latitude and longitude in WGS84 coordinates of degrees, minutes and seconds to three decimal places.

8.3 Grid conditions

The voltage, frequency and the permitted tolerances shall be recorded here. Any prevailing grid conditions that may have limited the power output during the test period should also be documented.

8.4 Test equipment

The test equipment, conforming to the general requirements in Subclause 5, shall be described in full, along with any user-defined settings that have been applied. The sensors, data acquisition system and communication links shall be described, and documentation showing the calibration details prevailing at the time of the testing shall be provided.

8.5 Measurement procedure

A description of the measurement procedure, as outlined in Subclause 6, shall be provided, including the following: procedural steps, test conditions, sampling rates and the measurement period. A copy of the test logbook, showing all significant events that may affect the test results, shall be appended to the report.

8.6 Presentation of the data

A spreadsheet or similar medium shall be provided, describing in detail the measured record from the monitoring device(s). The spreadsheet shall cover the entire period of the deployment, including details of the signal to noise ratio, where appropriate and the standard deviation, where available.

The principal direction of the tidal current shall be reported in degrees, relative to an agreed reference direction such as True North.

NOTE The usual convention for the sense of direction of a current is the direction towards which it is going. The data needs to be documented to clearly delineate the sense of the direction.

The report shall present the record of net electrical power produced by the TECS for the entire measurement period.

8.7 Provision of estimated AEP

The predicted value of the expected annual power availability across the power capture surface, obtained at the Tidal Resource Assessment stage, shall be provided, along with predictions of the expected power capture for each year of the system lifetime, all based upon the application of the harmonic analysis.

The uncertainties underlying the data used to produce the power curve shall be used to provide an upper and lower bound estimate of the AEP for each year of the system lifetime.

8.8 Presentation of power curve and coefficients

The power curve shall be provided in accordance with Subclause 7, showing the convergence of the expected power curve to a stable value during the test period. The final uncertainties applying to each bin of the power curve shall be stated, along with the mean value. If it is agreed from the outset that a power coefficient curve is to be also obtained, then it is to be developed in compliance with Subclause 7.3 and reported to the same standard as the power curve.

8.9 Uncertainty assumptions

The uncertainty assumptions underlying all uncertainty components shall be reported. In particular, an uncertainty budget shall be formulated as shown in Section 4 of EA-4/02 [3] and the calculation of uncertainty in measurement should be made by reference to Section 7 of the same document.

8.10 Deviations

Any deviations from the requirements of this document shall be clearly documented in the test report and supported with a technical rationale for each item.

Bibliography

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[3] European Co-operation for Accreditation. *Expression of the Uncertainty of Measurement in Calibration*. EA-4/02, 1999.

[4] Department of Trade and Industry. *Development, installation and testing of a large scale tidal current machine*. Report URN 05/1698. Crown Copyright, 2005.

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IEC 61400-12-1:2005, *Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines*

Background references

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International Organization for Standardization (ISO). *Guide to the expression of uncertainty in measurement*. ISO information publications. (1995): ISBN 92-67-10188-9

Web-based references

http://www.pol.ac.uk/ntslf/networks.html – UK Class A tide gauge network

http://www.plansys.com/buoys.cfm – Typical technical details of modern wave rider buoys

http://www.carbontrust.co.uk/TECShnology/TECShnologyaccelerator/ME_guide3.htm – For general TECS behaviour

http://www.axysTECShnologies.com/pdf/TriaxysADCParticleinHydroInternational.pdf – For a comparison between wave buoy and ADCP wave data

http://hfradarlab.cse.ucsc.edu/publications/Measurements_of_Near_Surface_Ocean_Currents_using_HF_Radar.pdf – For a detailed discussion of Stokes Drift

http://ams.allenpress.com/perlserv/?request=get-document&doi=10.1175%2F1520-0485(1998)028%3C1803:IOSUDT%3E2.0.CO%3B2 – For research by Xing and Davies on tidal stratification

http://www.windpower.org/en/stat/betzpro.htm – By the Danish Wind Industry Association – for a derivation of the Betz Law