Assessment of Tidal Energy Resource

Foreword

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

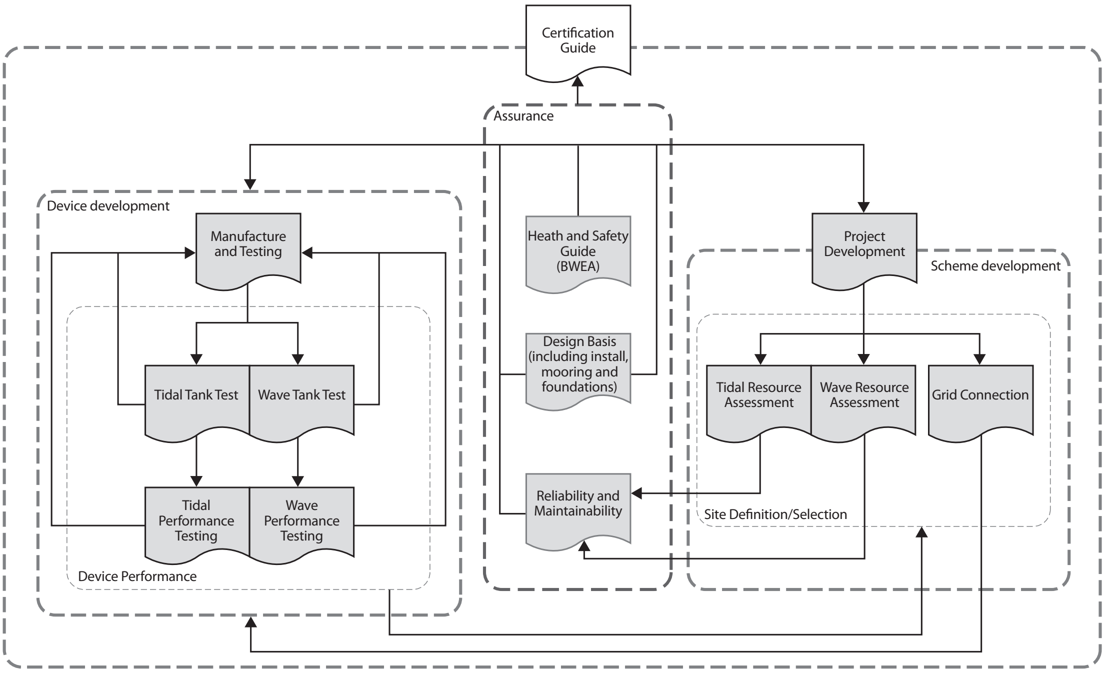

Figure 1 — Marine Renewable Energy Guides

Acknowledgements

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The author would like to acknowledge Scott Couch from Edinburgh University for his input and detailed review of this document. The document has been created with the input from many key people in the tidal industry through workshops, and all the participants are to be thanked.

Assessment of Tidal Energy Resource

Marine Renewable Energy Guides

The European Marine Energy Centre Ltd

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Contents

List of figures

List of tables

Assessment of Tidal Energy Resource

Introduction

This document 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 interface with this document. Relevant international work has been referenced, where appropriate, in the main body of the document and in the Bibliography which is located at the end.

This document provides guidance on how to perform a resource assessment study. The use of modal verbs is aimed at the entity that is assessing the tidal resource and writing the report.

This document is written in the same logical order as the assessment study is undertaken. It is organized such that each subclause in the document also represents a subclause in the report to be delivered, as described in Clause 10.

Please note that this document is a guide for tidal stream resource assessment only, and the use of tidal stream technologies only is considered in this document.

The purpose of this document is to provide a uniform methodology that will ensure consistency and accuracy in the estimation, measurement and analysis of the tidal stream resource at sites that could be suitable for the installation of Tidal Energy Conversion System (TECS).

The main aims of this document are to measure and describe the resource (by deriving a velocity distribution for a site), to understand the potential for the power extraction of an array of TECS (by combining the velocity distribution with the power curve of the TECS), and to ensure that the tidal resource available is not over-extracted.

This document provides guidance in the measurement, analysis and reporting of the tidal stream resource. Application by all parties of the estimation, measurement and analysis techniques recommended in this document will ensure that continuing resource assessment of potential development sites is undertaken in a consistent and accurate manner. This document presents techniques that are expected to provide fair and suitably accurate results that can be replicated by others.

1 Scope

This document establishes a system for estimating, measuring, analysing and reporting the tidal stream resource at sites potentially suitable for the installation of TECS. It is intended to be applied at various project development stages, from regional assessments to the various stages of site assessment (from initial investigations to detailed assessment), and to provide suitably accurate results for the resource assessment that can be used to derive 'annual energy production' assessments at the various project development stages.

The data collection provisions include the specific environmental conditions that determine the tidal stream resource and therefore potential energy production. Other conditions that might affect the proposed development of the site are also listed.

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.

Assessment of Performance of Tidal Energy Conversion Systems, EMEC, 2009

EA – 4/02 *Expression of the Uncertainty of Measurement in Calibration*

IEC 61400-12-1:2006, *Wind turbines — Power performance measurements of electricity producing wind turbines*

International Hydrographic Organisation. (2008): IHO Standards for Hydrographic Surveys. Special Publication No. 44. 5th Edition

Peter Croll, *Guidelines for Project Development in the Marine Energy Industry*, EMEC, 2009

Tedd Pitt, *Assessment of Wave Energy Resource*, EMEC, 2009

3 Terms, definitions, symbols, conventions and abbreviations

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

3.1 Terms and definitions

3.1.1
accuracy
closeness of agreement between the result of a measurement and the true value of the measurand

3.1.2
annual energy production (AEP)
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

3.1.3
availability (A_v)
ratio of the total number of hours during a certain 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

3.1.4
capture area
frontal area of the TECS that contributes to the power extracted by the TECS from the free tidal current stream

3.1.5
data set
collection of data that was sampled over a continuous period

3.1.6
mean spring peak velocity (*V*msp)
peak tidal velocity observed at a mean spring tide

NOTE Traditionally this has been taken to be at 5 m below the surface due to Admiralty measurement methods; however, it may be defined at any depth or on a depth-averaged basis.

3.1.7
measurand
quantity measured

3.1.8
median
middle value in a set of observations ordered by value

3.1.9
method of bins
method of data reduction that groups test data for a certain parameter into subsets typified by an independent underlying variable

3.1.10
net electric power output
measured portion of the TECS electric power output that is recorded at the TECS, where it is connected to the transmission voltage

3.1.11
power coefficient
ratio of the actual power produced by the TECS to that of the kinetic energy of a stream tube available after installation of the TECS with the same capture area as that of the TECS

3.1.12
rated power
quantity of power assigned, generally by the manufacturer, for a specified operating condition of a component, device, or item of equipment

3.1.13
root mean cubed velocity (*V*rmc)
cube root of the mean of the cubed velocities

3.1.14
significant impact factor (SIF)
percentage of the total resource that can be extracted without significant economic or environmental effects

3.1.15
standard
document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines and characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context

NOTE Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits.

[ISO/IEC Guide 2:2004, definition 3.2]

3.1.16
velocity (of current)
magnitude and direction of the current

NOTE 1 The magnitude is measured in m/s and the direction is measured in degrees.

NOTE 2 The term velocity is commonly used in the industry, even when only the magnitude of the current is actually utilized. The direction of the current is to be given where appropriate, as outlined in this document.

3.2 Symbols and units

A	Capture area of the TECS (m^2)
$A_{channel}$	Cross-sectional area of the channel (m^2)
A_v	Availability (%)
d	Rotor diameter (m)
$f(U_i)$	Time occurrence likelihood of a velocity in each 0.10 m/s bin (%)
H_s	Significant wave height (m). H_s was originally defined as the average height of the highest one-third waves in a wave spectrum. However, it is normally now taken as H_{M0} which is defined as four times the root-mean-square water elevation.
i	Index for velocity bin numbers
j	Index for number of time intervals
N	Number of time intervals

N_B	Number of velocity bins set in increments of 0.10 m/s
N_i	Number of data points in the i^{th} velocity bin
N_T	Number of TECS in a tidal farm
P	Electrical output power (kW)
P_{mean}	Average electrical power output over one year (kW)
$P(U_i)$	Mean electrical power per velocity bin (kW)
T_e	Energy period (s). Period of a monochromatic wave having the same energy as the real sea state.
U	Magnitude of the tidal current (m/s)
U_i	Central value velocity magnitude in the i^{th} bin (m/s)
z	Elevation above the seabed (m)
ρ	Density of the water (kg/m^3)
η_R	Efficiency of rotor (or equivalent) (%)
η_{PT}	Powertrain efficiency (%)

3.3 Conventions

Time: Coordinated universal time (UTC)

Date and time string format: DD/MM/YYYY HH:MM:SS

Coordinates: World Geodetic System 1984 (WGS 84)

Datum: Defined to the National Datum, referred to LAT

3.4 Abbreviations

ADP	Acoustic Doppler Profiler
AEP	Annual Energy Production (kWh/y)
APD	Average Power Density (kW/m^2)
GIS	Geographic Information Systems
HRCS	High Resolution Continental Shelf Model
LAT	Lowest Astronomical Tide (m)
MBES	Multi-Beam Echo Sounder
RGU	Robert Gordon University
ROV	Remotely Operated Vehicle
SBES	Single-Beam Echo Sounder
SIF	Significant Impact Factor (%)
SSS	Side Scan Sonar
TECS	Tidal Energy Conversion System
UTC	Coordinated Universal Time
Vmsp	Mean Spring Peak Velocity (m/s)

Vrmc Root Mean Cubed Velocity (m/s)

WGS 84 World Geodetic System 1984

4 Project description

4.1 Involved parties

The parties involved in undertaking the resource assessment shall be identified.

4.2 Previous work

This subclause of the report should briefly outline any resource assessment work that has already been carried out at, or nearby, the proposed site of the present resource assessment.

4.3 Objective and nature of resource assessment

4.3.1 General

This subclause of the report shall describe the objective and nature of the present resource assessment.

A list and description of the different development stages of a tidal resource assessment should be provided here to assist in the categorization of the nature of the project.

NOTE 1 This categorization is later used to determine appropriate techniques for the resource assessment.

NOTE 2 Table 1 lists the different stages of tidal resource assessment.

The following stages are in line with the *Guidelines for Project Development in the Marine Energy Industry* document of this series, and the resource assessment stages should be carried out in line with the stages numbered in that document.

NOTE 3 Stage 2 of tidal resource assessment described in *Guidelines for Project Development in the Marine Energy Industry* has been split in two parts for this guide, to separate a pre-feasibility stage resource assessment from that at a full-feasibility stage.

4.3.2 Resource assessment stages

4.3.2.1 Stage 1: Regional assessment – Site screening

If the project is in its initial stages and consists mainly of site screening, the resource assessment should be qualified as regional if the area of study is very large and incorporates many potential sites, i.e. a whole country or large portion thereof.

After a potential development area has been identified in a regional assessment and the resource assessment becomes focused on an individual area, the study is considered to have reached a 'site assessment' stage, which should include the three stages described in 4.3.2.2–4.3.2.4

4.3.2.2 Stage 2a: Site assessment – Pre-feasibility study

Stage 2a is deemed to be the first stage of a pre-feasibility study that should consider the resource identified in the site screening in more detail.

4.3.2.3 Stage 2b: Site assessment – Full-feasibility study

Stage 2b is a full-feasibility study that should result in a detailed economic model. At the end of this stage, all the constraints in the area should have been identified and assessed.

A permit request should be submitted if the project is attractive.

NOTE Please refer to the *Guidelines for Project Development in the Marine Energy Industry* document in this series.

4.3.2.4 Stage 3: Site assessment – Design development

At this point the exact area of development should have been identified, and a permit should have been obtained. The technology to be installed should be known and the resource assessment should determine the exact location of each TECS.

Table 1 — Resource assessment stages

Stage	Category	Aim	Area	Constraints	Permit
Stage 1	**Regional assessment**	Site screening	Region or country	Limited constraints identified	No
Stage 2a	**Site assessment**	Pre-feasibility	Whole estuary, channel etc.	Major constraints identified	No
Stage 2b	**Site assessment**	Full-feasibility	Localized area in a channel, estuary etc.	All constraints identified and assessed	Applied for
Stage 3	**Site assessment**	Design development	Localized area in a channel, estuary etc.	All constraints assessed	Obtained

4.4 Specific or generic TECS characteristics

4.4.1 General

The following characteristics should be specified for the TECS:

- clearance between the sea surface at lowest astronomical tide (LAT) and the highest point of the capture area (top clearance);

  NOTE 1 For a ducted device the capture area is to be taken at the mouth of the duct, not at the throat.

- clearance between the seabed and the lowest point of the capture area (bottom clearance)

  The TECS' characteristics should ensure that the required top and bottom clearances can be achieved at the LAT;

- device spacing and geometry of array.

  NOTE 2 Depending on the stage of the project, a preferred technology might or might not have been selected. It is recommended in the *Guidelines for Project Development in the Marine Energy Industry* that the technology is chosen at Stage 2, so in this document both cases have to be considered, using a specific TECS or generic characteristics; these are discussed below.

4.4.2 Specific TECS

If the resource assessment is being undertaken with a specific TECS already identified, then the relevant characteristics of that TECS should be used.

If one (or more) of these characteristics is unknown, or the TECS is not yet identified, then the generic characteristics stated below should be used. If there are any major differences between the generic characteristics and those specified in the resource assessment, then a full explanation of the variation should be provided.

4.4.3 Generic characteristics

Although no single tidal stream technology is currently considered as the 'standard' technology and therefore the most appropriate for resource assessment, the most advanced tidal stream technology type is the horizontal axis turbine and therefore a horizontal axis turbine TECS should be considered in the event that no specific TECS has been identified.

If a specific TECS has not been identified, then generic characteristics should be used, and for each of the following items a clear explanation of the choice should be provided:

- maximum rotor diameter;

  NOTE 1 A reasonable diameter is to be considered, dependent on the state of the technology. The diameter is believed to be currently limited to c. 20–25 m for a standard horizontal axis turbine.

The maximum rotor diameter should be considered to be the present limit.

NOTE 2 As the technology matures, larger rotor sizes might become possible and provide more favourable economics.

- top clearance;

  A top clearance (for the capture area [of the rotor or equivalent]) should be considered – whether or not the location considered is deemed suitable for surface-breaking TECS.

  A minimum 5 m top clearance is normally recommended to allow for recreational activities (small boats, swimmers, etc.), and to minimize turbulence and wave loading effects on the TECS, as well as damage from floating materials. This is based on the assumption that an exclusion area could be created that (amongst other restrictions) restricts vessels that have a draught greater than 2 m. If this is not possible, then the top clearance should be based on known vessel movements in the area.

- bottom clearance;

  It is recommended that a bottom clearance of 25 % of the water depth (related to LAT), or 5 m, whichever is greater should be considered as a minimum to allow for potentially TECS-damaging materials that are moved along the seabed by the currents, and to minimize turbulence and shear loading from the bottom boundary layer.

- device spacing;

  The lateral spacing between devices (the distance between axes) should be two and a half times the rotor diameter (2.5*d*); the downstream spacing should be 10*d*. The devices should be positioned in an alternating downstream arrangement, as shown in Figure 2.

NOTE 3 These characteristics are based on a generic horizontal axis turbine and can vary.

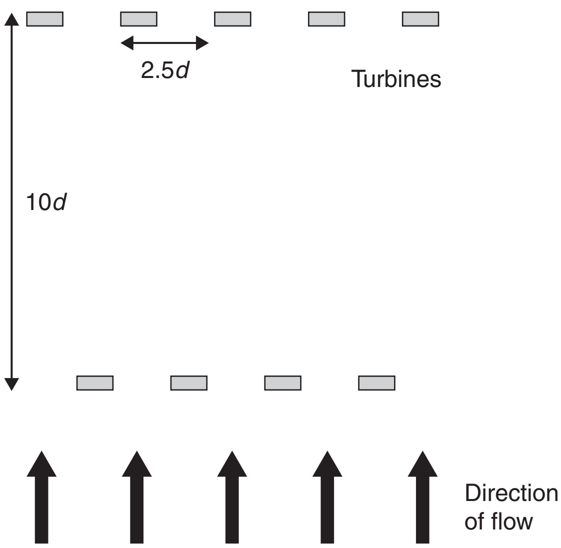

Figure 2 — Device spacing

NOTE 4 The configuration proposed in Figure 2 is thought to be close to optimal for a generic site, although it can be shown to be conservative once detailed modelling of wake effects is undertaken. It is noted that research is currently underway in this field by a group in the UK called SuperGen Marine Consortium, and the last published papers on this topic can be accessed on their website [1].

4.5 Extent of array

This subclause of the report shall describe the scale of the project, whether the project is for testing or commercial purposes, whether there will be more than one row of TECS and whether the scale of the project will be increased in later stages.

NOTE A description of possible project scales as a function of their rated capacity is provided here to assist in the categorization.

- single/few device(s) < 3 MW;
- small-scale farm ≥ 3 MW, < 20 MW
- medium-scale farm ≥ 20 MW, < 50 MW
- Large-scale farm ≥ 50 MW

4.6 Site conditions

4.6.1 Bathymetry

4.6.1.1 Data available

This subclause of the report shall describe the bathymetric data already available.

The oceanographic centres responsible for the region concerned should be contacted.

A list of all the surveys that have been undertaken, for which data is available, should be provided and the following information should be provided for each of them:

- date of survey;
- method used;
- precision.

4.6.1.2 Bathymetric survey

This subclause of the report shall first define whether a bathymetric survey should be conducted.

For a regional assessment (Stage 1), using the average depth over 1–2 km grids should be sufficient, considering the assessment techniques discussed below.

For a pre-feasibility assessment (Stage 2a), the bathymetry data should be from a data set with soundings of spacing approximately 100 m.

For the full-feasibility assessment (Stage 2b), the bathymetry data should be from a data set with soundings of spacing approximately 20 m.

For the development stage (Stage 3), the bathymetry data should be from a data set with soundings of spacing approximately 5 m.

In all these cases, a check should be made that the original data set was collected using modern techniques, and that as many of the bathymetric data sets available were collected without the use of modern (electronic) techniques. All data sets should be used with caution.

If a bathymetric survey is deemed to be required to complete the data available at the required resolution, the site should be surveyed in accordance to the IHO Standards for Hydrographic Surveys (2008).

The appropriate order of survey should be defined in accordance with Chapter 1 of the IHO Standard and the requirement stated in Table 1 of the same standard should be followed for this order.

Multi-beam echo sounder (MBES) is the recommended option in preference to single-beam echo sounder (SBES) or side scan sonar (SSS). An appropriate assessment of the accuracy of measurement with each beam shall be conducted for use in areas surveyed to Special Order and Order 1 Standards. A procedure for calibration of multibeam sonar shall be followed.

EXAMPLE An example of a procedure for calibrations described in the field calibration procedures for multibeam sonar systems [2].

If the study is at the development stage (Stage 3), a dive survey or a Remotely Operated Vehicle (ROV) deployment should be used to uncover issues that sonar surveys do not.

NOTE Sub-bottom profiling might also be required if there is significant suspended sediment, or layers of 'pluff' and liquefied mud, that may affect TECS installation.

The bathymetry should be processed using an approach similar to that described by Gardner et al (1998) [3].

4.6.1.3 Site bathymetric issues

This subclause of the report shall describe the bathymetric characteristics of the site. Using the data initially available or the survey that might have been carried out, a map with the bathymetric contours should be provided and the areas considered suitably homogeneous for TECS installation should be identified. The areas of steep gradients should be identified and highlighted on the map, as well as any features that could impact on the project feasibility (e.g. large rocks, reefs, etc.)

These issues should be summarized to assess the homogeneity of the site.

NOTE 1 The issues (and their severity) will vary depending on specific device requirements.

NOTE 2 Until further work has been carried out into the issues around homogeneity, Annex B of the IEC 61400-12-1:2000 can be consulted and a similar analysis can be carried out once potential locations of the TECS have been identified.

4.6.2 Tidal range

4.6.2.1 General

This subclause of the report shall describe the tidal range at the site. The data should come from the two closest tidal gauges, ideally in opposing directions from the area of interest. A basic map detailing the two locations should be included, along with a comparison of the two time series and the likely impact on the local tidal range and currents at the site.

NOTE There are many sources of tidal range information including, for the UK, Admiralty data. There are several software packages that can be used to obtain the tidal range at any global location. A list of such packages can be found at http://www.wxtide32.com/links.html [4].Tidal prediction packages only work at (or near) ports, where harmonic constituents are available from the tidal gauges. The distance from the tidal gauge used is hence crucial to assess the accuracy of the data.

4.6.2.2 Annual profile

An annual plot of the tidal range at the site shall be provided.

The seasonal variations in the tidal range at the site shall be described. A month that is representative of the average month for the chosen year shall be determined. To determine the average month, a table showing the average and maximum tidal range for each month of the year should be provided.

NOTE It is assumed that an average tidal month for the tidal range will also be an average tidal month for the tidal velocities. The identified month is used in 7.6.1 to estimate the average power density during a year.

4.6.2.3 Monthly profile

A 30-day plot of the tidal height above a datum at the site shall be provided, preferably from the month identified as an average month in 4.6.2.2. The spring cycles shall be identified clearly, along with the days where the maximum velocities are expected to be reached.

NOTE An example of this is shown in Figure 3, where it is clear that Brest is a location with a semi-diurnal tidal cycle.

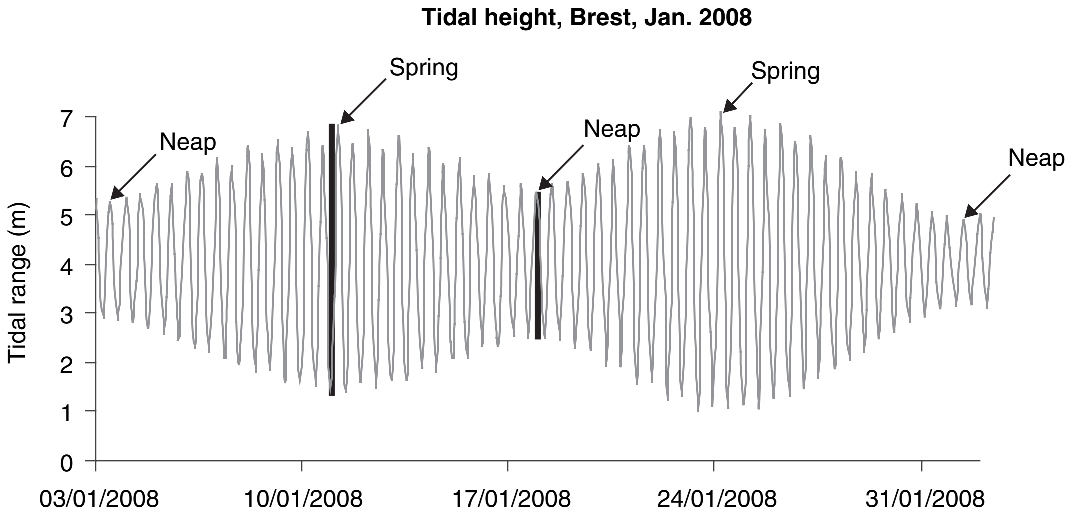

Figure 3 — 30 day tidal cycle

4.6.2.4 Daily profile

This subclause of the report shall describe the daily tidal profile at the site, with a 50-hour plot of the tidal range at spring tide – which has been identified in 4.6.2.3.

NOTE Figure 4 illustrates the three different daily profiles.

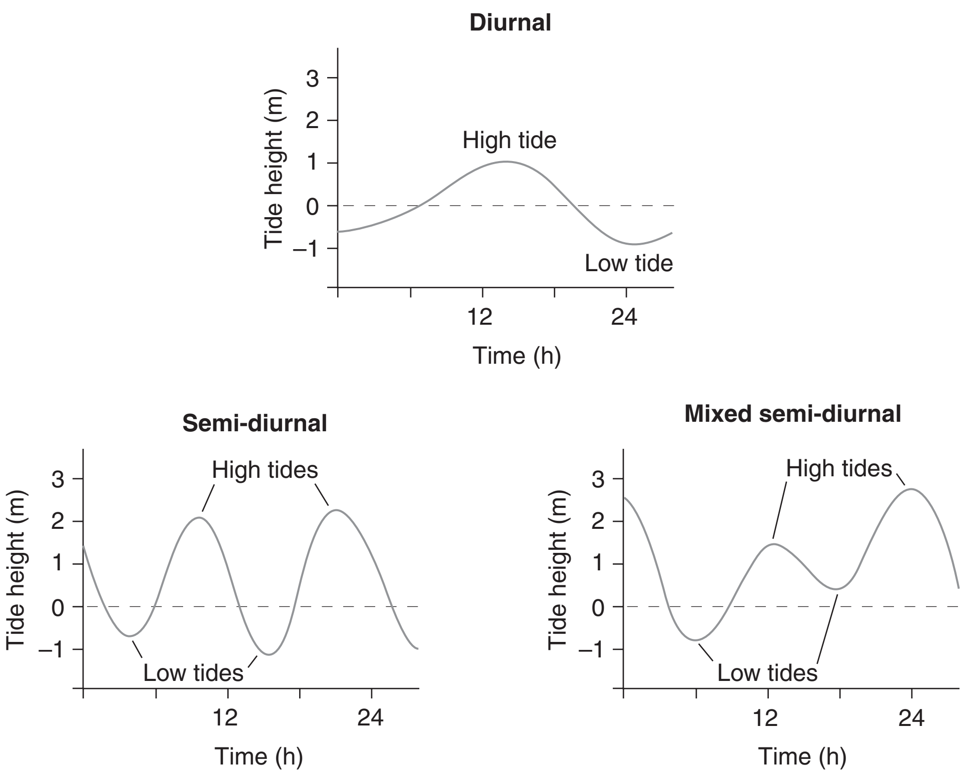

Figure 4 — Tidal daily profiles

Diurnal tidal cycle (Figure 4): An area has a diurnal tidal cycle if it experiences one high and one low tide every lunar day.

Semi-diurnal tidal cycle (Figure 4). An area has a semi-diurnal tidal cycle if it experiences two high and two low tides of approximately equal size every lunar day.

Mixed semi-diurnal tidal cycle (Figure 4). An area has a mixed semi-diurnal tidal cycle if it experiences two high and two low tides of different size every lunar day.

4.6.3 Tidal currents

4.6.3.1 Data available

This subclause of the report shall describe the tidal currents data already available.

The oceanographic centres responsible for the region concerned should be contacted.

A list of all the tidal current surveys that have been undertaken, for which data is available, should be provided and the following information is to be provided for each of them:

- date and duration of survey;
- data available;
- distance from the site;
- method used;
- precision.

A map of the measurement stations that have recorded tidal currents in the area of the site should be provided.

NOTE There are limited sources of tidal current information including, for the UK, Admiralty data. For the UK, a map of the data stations installed can be found on the oceannet website [5].

4.6.3.2 Correlation between tidal height and tidal currents

This subclause of the report shall describe the correlation (if any) between the available tidal current and tidal range data.

NOTE At some locations, tidal currents correlate well with the tidal range and a simple analysis of the tidal range might allow a rough prediction of the currents throughout the year. In these cases, the peak value of tidal current speed can be described by an approximately linear function of the tidal range, with the tidal currents and tidal range showing a correlation similar to that in Figure 5.

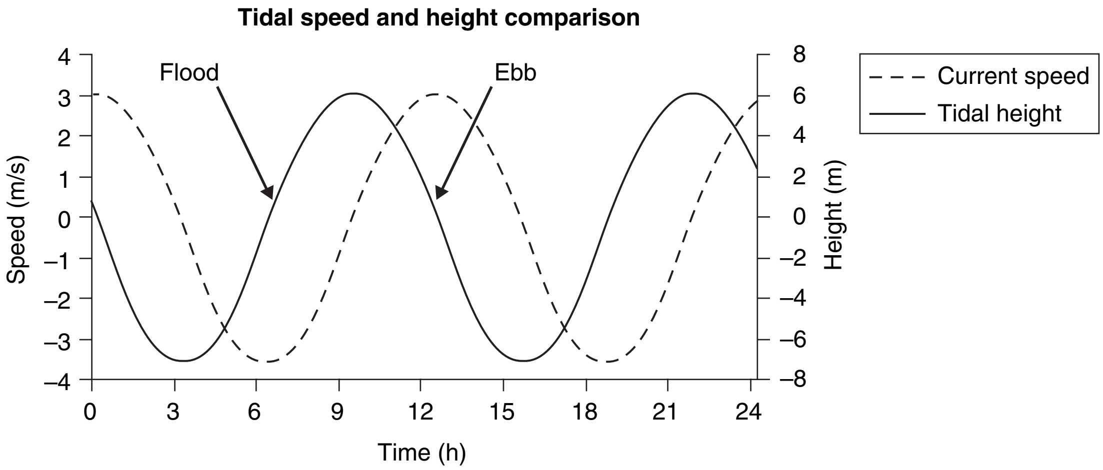

Figure 5 — Tidal current speed compared to tidal height

4.7 Constraints

Before starting Stage 2b of the resource assessment, the various constraints to the project in the area being considered should be checked.

NOTE 1 *Guidelines for Project Development in the Marine Energy Industry* recommends that an environmental scoping study is completed at Stage 2.

The major exclusion constraints should be identified at this stage so that the area of interest for tidal resource assessment can be narrowed.

NOTE 2 The probable exclusion constraints for tidal development are some protected sites, certain other renewable developments, MoD, pipelines and cables, dredging areas, oil and gas sub-surface installations, safety zones (sub-surface), wells.

4.8 Physical boundaries of assessment

This subclause of the report shall describe the method used to overlay all the applicable constraints (e.g. Geographic Information Systems (GIS) software) with the bathymetry, and thus the determination of the boundaries of the detailed resource assessment area so that sites that are excessively constrained are eliminated.

If the TECS to be installed has been identified, then the areas with a depth not deemed suitable for this TECS should be removed. If no specific TECS has been identified, all the areas with a suitable depth range (e.g. from 10 m to 150 m) should be considered.

5 Estimation of current speeds

5.1 Methods

NOTE The different methods that can be used to estimate current speeds are discussed in this subclause. The choice of method depends on the aim of the study and the scale of the assessment.

Table 2 should be used to help determine the appropriate method, which shall be specified in this subclause of the report and the appropriate details given in 5.1–5.4.

Table 2 — Methods to estimate current speeds

	Stages of the assessment			
	Stage 1	**Stage 2a**	**Stage 2b**	**Stage 3**
Harmonic analysis (minimum no. of constituents)	2*	4	20	20
Modelling (grid resolution)	<5 km	<500 m	<50 m	<50 m
Field survey (period of collection)	No	2 days (transects)	1 month	3 months

* Extracted from tidal range, whereas in Stages 2 and 3 they are extracted from current velocities.

5.2 Tidal harmonic analysis

5.2.1 General

Tidal range and/or currents at a site should be predicted by considering a finite number of harmonic constituents particular to a site, whose angular speeds and phases can be obtained from published tide tables, determined from navigational chart data, or by mathematical analysis of directly measured tidal range and/or current speeds.

NOTE 1 The basis of harmonic analysis is the assumption that the tidal variations can be represented by a finite number (N) of harmonic terms of the form:

$$v_n \cos(\sigma_n - g_n)$$

where v_n is amplitude, g_n is phase lag on the equilibrium tide at Greenwich, and σ_n is an angular speed.

Depending on the aim of the study, harmonic analysis may be simplified by considering only the principal tidal harmonics, or may be made more detailed by incorporating further tidal constituents, which should lead to greater accuracy in predictions. The harmonic constituents may then be used to predict the tidal range and/or currents at the site over any given period.

NOTE 2 Transient phenomena are eliminated in the analysis and only variations with a coherent phase are utilized.

5.2.2 Number of constituents and accuracy of the method

The number of tidal constituents that are used in the harmonic analysis shall be carefully assessed, depending on the tidal profile at the site.

NOTE 1 Usually, the greater the number of constituents included in the harmonic analysis, the more reliable the tidal predictions.

EXAMPLE As shown in Figure 6, for one particular site, predicting tidal levels using only the four main constituents (M2, S2, L2, N2) can lead to an underestimation of the tidal range by up to 0.8 m over 3.8 m, i.e. 20 % underestimation in tidal range.

There is also an overestimation (of c. 10 %) at certain times. For other sites, these errors will be different, and the intention of this example is merely to highlight the effect.

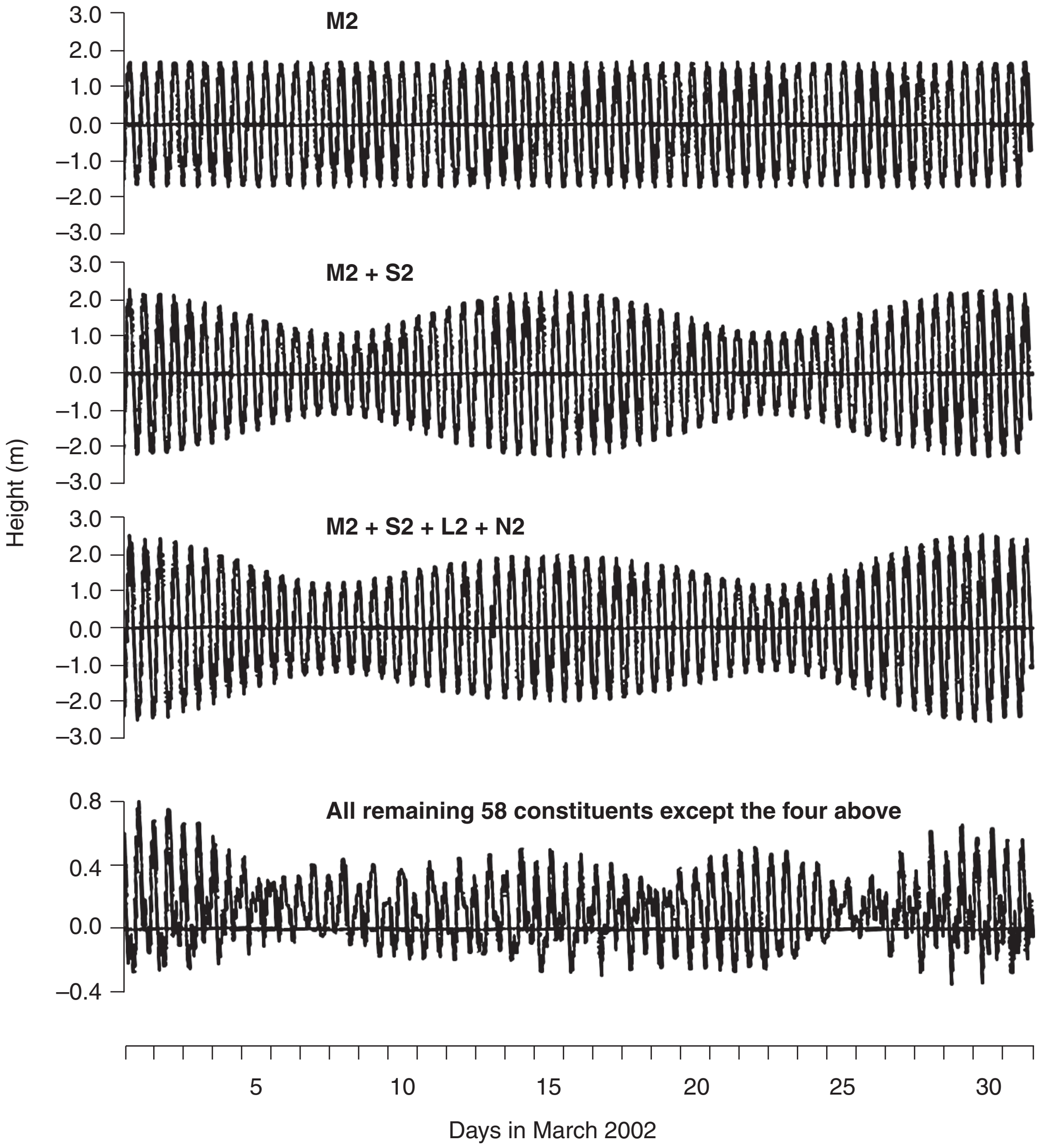

Figure 6 — The effect of predicting tides with 1, 2, 4 or 62 constituents [6]

Simplified harmonic analysis (with up to four constituents) is not a sufficiently accurate method to predict tidal stream resource at resource assessments beyond Stage 2a. However, in Stages 1 and 2a level assessments, simplified harmonic analysis (with up to four constituents) may be used. If more than four constituents are available, for instance from the Admiralty Charts, then all the constituents available should be used.

For Stages 2b and 3, the harmonic analysis shall have a minimum resolution of 20 tidal constituents, including the 10 most significant constituents as defined in standard order [7] (see Table 3). At these stages, one month of current data should have been collected (see 5.4.3) from which a minimum of 23 fully resolved constituents should be extractable.

Table 3 — Tidal constituents in standard order

Common name	Period (hrs)	Rank
M2	12.42	1
S2	12.00	2
N2	12.66	3
K1	23.93	4
M4	6.21	5
O1	25.82	6
M6	4.14	7
MK3	8.18	8
S4	6.00	9
MN4	6.27	10

5.2.3 Methodology

5.2.3.1 Stage 1

At Stage 1 of a tidal resource assessment, a simple harmonic model may be developed. The aim of this methodology is to provide a rough estimation of the annual cycle, but it should be noted in each assessment using this method that an error of 50–100 % might remain in the expected velocities, depending on the distance from the navigational chart data point to the location of the project.

NOTE 1 This model uses only the principal lunar (M2) and solar (S2) constituents, and therefore requires a small number of input parameters, namely the mean spring and neap peak velocities (that can be obtained at most locations from navigational charts), and the flood/ebb ratio (that can be extrapolated from the tidal range data). This method is valid for diurnal and semi-diurnal sites but would have to be adapted for a mixed semi-diurnal site.

NOTE 2 An idealized representative spring-neap sinusoid can be approximated in the first instance using the peak velocities on mean spring and mean neap tides that can be obtained from the tidal diamonds on Admiralty Charts; the spring-neap cycle has a period of 14d18h. A semi-diurnal sinusoid can then be created with a period of around 12h25min, an adjustment can be made to account for differences in current velocity between the flood and the ebb tides.

EXAMPLE By superimposing these two (spring/neap and semi-diurnal) sinusoids together, the current velocity can be calculated at intervals of 10 minutes, and a simplified 14-day tidal cycle can be represented as shown in Figure 7. This figure has been created using an average site with a mean spring peak velocity of 3.19 m/s, a mean neap velocity of 2 m/s and a flood/ebb ratio of 0.85.

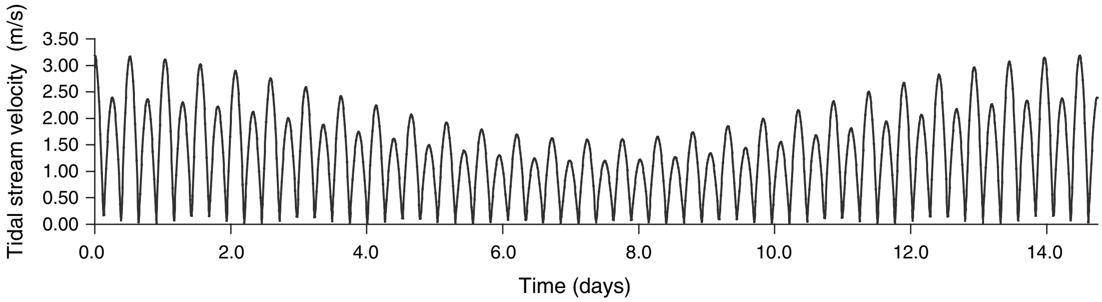

Figure 7 — Simplified 14-day tidal cycle

5.2.3.2 Stages 2 and 3

Using Fourier analysis and other mathematical procedures, more harmonic constants should be extracted. Depending on the stage of the assessment and what has been accomplished to date, the constituents should either be extracted from measured data or from the hydrodynamic model.

The harmonic analysis should be performed using software which follows a method recognized by the industry.

NOTE The methodology and software used by the National Oceanic and Atmospheric Administration are freely available on the web and the published memorandum *Tidal current analysis procedures and associated computer programs* [8] can be consulted to get a detailed description of harmonic analysis methods.

Time series of velocity at 10-minute intervals over the period (one month or one year) should be predicted.

Tidal range estimations should also be carried out with harmonic analysis to verify the accuracy of the different methods because tidal range data is available from tidal gauges at most locations and can also be estimated from a hydrodynamic model.

5.3 Modelling

5.3.1 Model choice

This subclause of the report shall describe the hydrodynamic models already available for the site (if any). The oceanographic centres responsible for the region concerned should be contacted.

This subclause of the report shall explain how the appropriate model has been chosen, as a function of its capabilities, which should include consideration of the following criteria:

- availability of the model and suitably qualified modellers;
- model complexity (i.e. 1-D, 2-D or 3-D) vs. site complexity;
- ease with which grid refinements can be made in zones of interest (implying time/cost reductions);
- ease with which the model can be calibrated to velocity data near to zones of interest;
- level of confidence in the model results, based on the underlying methodology and specific application to similar work;
- supplementary capabilities, such as power extraction modelling capability.

NOTE A list of potentially usable commercial models is provided in Table 4; this list is not exhaustive.

Table 4 — List of hydrodynamic models

Models	Dimensions	Grid structure
ADCIRC	2D/3D	unstructured
ADH	1D/2D/3D	structured
CH2D/CH3D	2D/3D	structured (curvilinear)
DELFT	2D/3D	structured (curvilinear, rectilinear and spherical)
DIVAST	2D	structured
ELCIRC	3D	unstructured, flexible
ELCOM	3D	structured (orthogonal)
GEMSS	1D/2D/3D	
GETM	3D	structured (orthogonal curvilinear)
HRCS	2D/3D	
Mars	2D/3D	structured
Mike Models (11, 21, 3)	1D/2D/3D	structured
RICOM	2D/3D	unstructured
RMA Models (2, 10, 11)	2D/3D	unstructured
ROMS	2D/3D	curvilinear structured
SELFE	3D	unstructured
SUNTANS	2D/3D	unstructured
TELEMAC	2D/3D	structured
TFD	1D/2D/3D	structured
TRIM	2D/3D	structured
UnTRIM	2D/3D	unstructured

If a different model is used, a comparison of the model chosen with a model well recognized by the industry should be undertaken.

5.3.2 Grid resolution and coverage

5.3.2.1 General

Table 2 defines a recommended maximum grid resolution for each stage of a resource assessment. It is assumed that the model should be refined as the assessment progresses through the different stages, and the level of refinement required should be determined and stated here, accounting for the accuracy requirements of the developer at each stage, the complexity and scale of the site and assessment, and the use of other predictive tools.

To refine the model grid, a reasonable growth rate per cell is recommended.

In general, the grid resolution should be decided in conjunction with the modellers to determine the optimal ratio between the time to run the model (dependent on many factors including the area that needs to be modelled) and the required accuracy. The same is true for the cell growth rate, which is the transition in cell size between adjacent cells.

NOTE 10 % has been recommended and used for some highly refined commercial models but this rate could be higher dependent on the model used and the complexity of the area studied.

The area covered by the model shall be sufficient to include all important hydrodynamic effects, and be such that calibration and validation of tidal range and/or currents is possible.

EXAMPLE The hydrodynamic model developed for Tacoma Narrows covers a wide area, from the open ocean boundary to the details of the Puget Sound estuary, as shown in Figure 8.

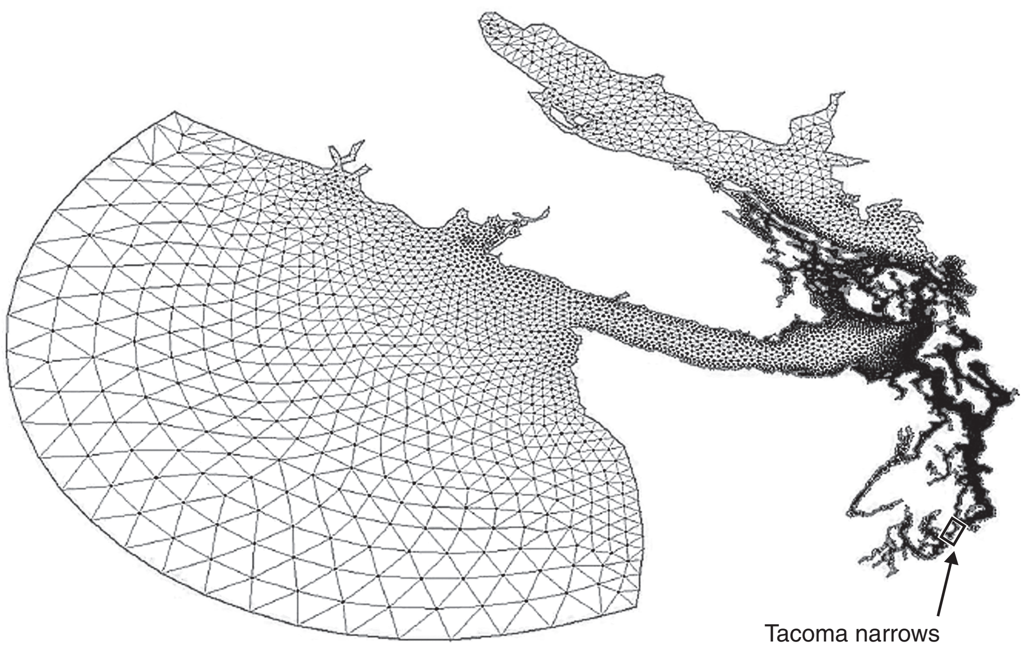

Figure 8 — Area modelled for Tacoma narrows [9]

5.3.2.2 Stage 1: Regional assessment

At the regional assessment stage, the model should be coarse to accommodate the large size of the area to be studied.

Where a suitable model already exists for the study area this may be utilized.

Otherwise, the model developed shall have a grid resolution finer than 5 km, and this shall be stated here.

EXAMPLE In the UK the High Resolution Continental Shelf Model (HRCS) used by POL is 3D and has a grid resolution of c. 1.8 km

The limitations of a coarse model should be recognized, both in terms of locating small sites and in terms of accuracy at larger sites.

NOTE Even where sites are sufficiently large that the grid cells of this coarse model are reasonably representative of actual site conditions in terms of boundary conditions and bathymetry changes a 30 % error in peak velocities can be expected.

5.3.2.3 Stage 2a: Site assessment pre-feasibility

The maximum cell length scale at the area of interest shall be finer than 500 m, and shall be stated. For sites where the bathymetry is highly irregular the model should be refined to 200 m. The maximum velocities predicted by the model should be validated against spring peak field survey data, as described in 7.8.

The limitations of a still relatively coarse model should be recognized, both in terms of locating very small sites and in terms of accuracy at larger sites.

NOTE Even where sites are sufficiently large that the grid cells of this relatively coarse model are reasonably representative of actual site conditions in terms of boundary conditions and bathymetry changes a 20 % error in peak velocities might be expected.

5.3.2.4 Stages 2b and 3: Site assessment full-feasibility

The grid resolution shall be as fine as reasonably practical, and should be determined based on the size of the area to be covered, the bathymetry available, and the computing time and cost compared to the time and costs of alternative methods of data collection such as field survey.

The maximum grid resolution at the area of interest should normally be finer than 50 m, and shall be stated. A monthly velocity profile predicted by the model is to be validated against field survey data, as described in 7.8.

NOTE At this stage, less than 10 % error in the peak and average velocities might be expected.

5.3.3 Model characteristics

5.3.3.1 Period

After allowing for appropriate spin-up time, the model is to be run for a minimum of 30 days, other than in the Stage 1 (regional assessment stage) where it may be run to determine only values for a spring peak velocity.

The 30-day period chosen shall be representative of a monthly tidal cycle with a typical tidal range, which should have been identified in 4.6.2.2. In Stage 2 onwards, the model shall be run for the same period as that of the field survey data to allow for model validation.

At Stages 2b and 3 of the assessment, the model should be run for a minimum of three months. If computing time constraints prevent this, then the data from the longest available simulation, which shall be a minimum of 30 days, shall be extrapolated to a full year, as described in 7.6.

5.3.3.2 2D/3D

The model may be either 2D or 3D up to and including Stage 2. At Stage 3, the vertical dimension should be included in the model. If the model is 3D, each vertical bin should be sufficiently fine to resolve boundary layers and to include several vertical bins in the cross-sectional area of TECS.

In general, but depending on the depth, 1 m vertical bins are recommended.

Depth-averaged velocities output from 2D models will need to be converted to the velocity at the depth of the TECS; this may be done using the method described in 7.7.2.

5.3.3.3 Other characteristics

A description of the following items shall be given in the presentation of the results of the model, in 6.2. This shall include the following information:

- water levels used to drive ocean boundary of the model domain;
- open boundary conditions;
- closed boundary conditions;
- fresh water inflow locations and data used;
- bottom friction parameterization;
- wind stress formulation and data set applied;

- density structure and formulation;
- air/sea interaction (including evaporation).

5.3.4 Calibration and validation

For Stage 2 and onwards, the model used shall be calibrated and validated against tidal current data from a field survey. Prior to Stage 2, available tidal range data may be used for calibration and validation. In this case the best data available shall be used, either from a published source or from measured data.

Some field survey data for the study area might already exist, and this may be used if it is assessed to be of relevance, which shall principally depend on the location, the period of the survey and the age of the survey (if changes to bathymetry are possible).

5.4 Field study

5.4.1 General

Table 2 defines the recommended minimum field survey arrangements for each stage of a resource assessment.

5.4.2 Transect survey

5.4.2.1 General

The transect survey should be carried out during Stage 2 of the assessment.

The survey shall be carried out around the possible locations of the TECS that have been identified, making sure that all the crucial areas are covered.

The data collection should be carried out during a typical spring cycle, as identified in 4.6.2.3 during the two days with strongest currents. If time constraints or boat availability mean that the survey cannot be conducted during spring tides, the transect survey may be carried out at any peak flood or ebb cycle; however, the extrapolation to obtain the velocity during a mean spring peak cycle shall be carefully assessed and explained.

A transect survey shall be carried out by towing an acoustic instrument to measure the currents under a moving boat.

NOTE The aim of a transect survey is to provide an overview of the spatial variation in the velocity distribution over the site. This also allows validation of the spatial variation of the peak velocity estimated by the model used at this stage. Furthermore, the transect survey can help to evaluate the turbulence and flow reversal issues that can be associated with the site.

5.4.2.2 Characteristics

Transect velocity data shall be processed into suitable vertical and horizontal bins; these may be for instance 1 m vertical bins and 25–50 m horizontal bins.

The sampling frequency should be 2 Hz, and the depth of the first bin should be less than 5 m below the surface level.

NOTE It has been shown [10] that transects can show a bias in measured water velocities in the direction of vessel motion; this can be up to +/–5 cm/s and have vertical variability.

To overcome this bias, transects should be measured in both directions, back and forth, and data processing should average the two opposing transects to help remove this bias. Each transect should therefore consist of a traverse in both directions over a short time interval (< 10 min).

Each transect should not last for more than 10 minutes, otherwise the velocity at the start of the transect might have changed significantly by the time the boat returns to the start position.

5.4.2.3 Output data

For each time step, the following output shall be recorded:

- time (UTC) with year, month, day, h, min, s;
- location (latitude and longitude in WGS 84);
- velocities in the three directions;
- standard deviation in the three directions;
- signal to noise ratio (SNR) for the three directions;
- temperature;
- pressure;
- cell start depth (bottom cell) and cell stop depth (top cell);
- average velocity with direction;
- quality indicators and confidence levels for the horizontal positioning of the vessel.

5.4.3 Static survey

5.4.3.1 General

NOTE A static survey is so called because it consists of the deployment of a measurement device at a site, either floating or moored on the seabed.

5.4.3.2 Instrument numbers and locations

Depending on the stage and scale of the assessment and on the bathymetry complexity, the survey may require several velocity measurement instruments.

a) Stage 2b

NOTE 1 The aim of a static survey is generally to provide calibration and/or validation for the hydrodynamic model velocity results in the time dimension.

For a resource assessment of a TECS array, three months of data collection is recommended but one month is the required minimum; 15 days is required for a single TECS installation.

At least one instrument shall be deployed, but it is highly recommended to install two instruments.

NOTE 2 The redundancy is useful as the instrument will be deployed in a harsh environment, and total loss of data from the study is to be avoided. Moreover, the redundancy might provide more confidence in the data because the data from the two instruments can be compared.

The instrument(s) shall be located at one of the locations which the model has highlighted as having high velocity and/or that is deemed to be a representative location for a TECS installation. The modellers should be involved in the location decision, and site bathymetry should be considered.

The bathymetry data used to define the location shall be of sufficient resolution to ensure that the instrument can be deployed in an area without obstructions or sudden change in depth that might affect deployment. A bathymetric survey might be required, and the recommendations given in 4.6.1.2 should be followed.

b) Stage 3

NOTE 3 The aim of the field study is generally to collect a significant period of velocity data at the exact deployment location of the TECS.

For a resource assessment of a TECS array, data should be collected for one year, but three months is the required minimum; data shall be collected for 30 days for a single TECS installation.

At least one instrument shall be deployed, but it is highly recommended to install two instruments, for the reasons given above. For a single installation or for a small farm, the instrument(s) should be deployed at the centre of the array (or at key representative locations). For a medium or large-scale tidal farm, the number of instruments should be informed by the hydrodynamic modelling which will show the likely variations in velocity across the farm and/or the key representative locations for deployment.

5.4.3.3 Characteristics

The data collection interval should be between 2 and 10 min.

The velocity data should be processed into 1 m or 50 cm (depending on instrument used) vertical bins with u, v, w (the three current directions) and z (depth) in each bin for each time interval.

The sampling frequency should normally be 2 Hz.

The standard deviation in velocity measurement should be less than 5 cm/s and the current direction measurement shall be better than ±5 °.

The vertical bins should start as close to the seabed as possible and extend close to the sea surface.

5.4.3.4 Output data

For each time step, the following output shall be recorded:

- time (UTC) with year, month, day, h, min, s;
- velocities in the three directions;
- standard deviation in the three directions;
- signal to noise ration (SNR) for the three directions;
- temperature;
- pressure;
- cell start depth (bottom cell) and cell stop depth (top cell);
- average velocity with direction;
- turbulence intensity (where applicable).

The present instruments and techniques available shall be consulted in recent published papers, particularly for the measurement of turbulence intensity.

6 Results presentation

6.1 Tidal harmonic analysis

This subclause of the report shall describe the results from any harmonic analysis that has been undertaken, for tidal range and/or tidal velocities, and the results shall include for each site location:

- number of constituents used;
- method by which the constituents were extracted and utilized to generate time series data;
- data source from which constituents were extracted (hydrodynamic model/field survey);
- location reference for the data source (WGS 84);
- exact date and period of the analysis.

6.2 Hydrodynamic model

This subclause of the report shall describe the results obtained directly from any hydrodynamic model, for tidal range and/or tidal velocities, and the results shall include for each site location:

- location reference for the data source (WGS 84);
- exact date and period of the analysis;
- characteristics of model (as listed in 5.3.3).

6.3 Transect survey

This subclause of the report shall describe the results from any transect field survey, for tidal range and/or tidal velocities, and the results shall include the following information for each site location:

- location of survey (WGS 84), with exact coordinates of transect lines;
- exact date and period of survey, with time along each transect;
- maximum currents observed;
- any problems that occurred.

The analysis of the transect data should focus on providing data to allow calibration and/or validation of the spatial variation in the velocity distribution of the hydrodynamic model, and then focus on the areas where turbulence has been recorded. Charts that show an unexpected velocity profile shall be shown.

6.4 Static survey

This subclause of the report shall describe the results from any static field survey, for tidal range and/or tidal velocities, and the results shall include for each site location:

- location of survey (WGS 84);
- exact date and period of survey;
- maximum currents observed;
- depth-averaged tidal profiles during the whole period of collection;
- vertical profile during the maximum velocity observed during ebb and flood tides;
- any problems that occurred;
- details of filter used.

Based on the quality of the data collected and on the appropriate standard, which is EA – 4/02 *Expression of the Uncertainty of Measurement in Calibration*, the filtering of the data shall be explained and justified. The percentage of data that has been found to be good quality should be provided here. The data that is believed to be erroneous shall be removed, and the remaining valid data should be filtered.

A low pass filter should be applied to the remaining depth-averaged collected data, to remove instrument noise and turbulent motions.

NOTE A fourth order Butterworth filter with a cut-off frequency of 1/3 hours^{-1} is a specific filter that is commonly used for analysis.

The depth-averaged data for each horizontal component (e.g. north–south velocity component and east–west velocity component) shall be filtered first forward and then backward in time through the same filter to avoid introducing a phase shift. The depth-averaged current speed is then to be recalculated from the filtered component, and a comparison between the filtered and unfiltered data shall be plotted, as shown in Figure 9.

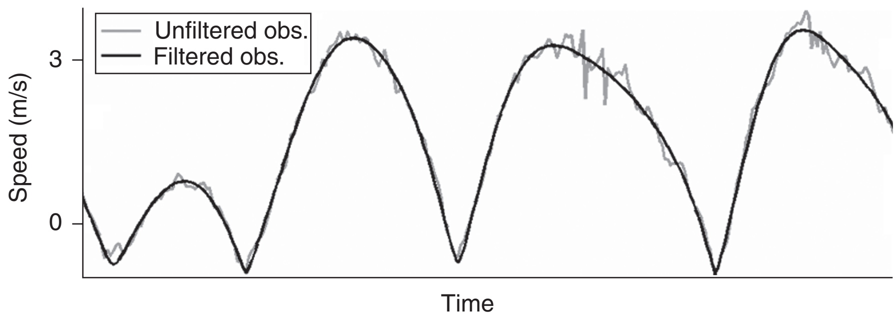

Figure 9 — Comparison between filtered and unfiltered data observed from a bottom Acoustic Doppler Profile

7 Data analysis

7.1 Velocity distribution

NOTE This subclause describes how to obtain $f(U_i)$, the velocity distribution.

A histogram analysis for the tidal current speed shall be carried out using the results from the tidal harmonic analysis, and from the hydrodynamic model if any.

The use of 10 min as the standard interval, and 0.1 m/s as the bin size, is recommended.

The percentage of time, $f(U_i)$, that the velocity falls within each bin shall be computed. A table, for each of the sites if several, shall be provided with the results of the histogram analysis, and the computed histograms should be used to plot the velocity distribution, or exceedance curve, at the site location(s).

The velocity distribution (or exceedance curve) should be plotted with data from as many sources as possible, and any difference in the shape of the exceedance curve shall be discussed.

The velocity distribution shall be averaged over different areas, depending on how the distribution will be used. When applied to a power curve for a TECS, the $f(U_i)$ shall be estimated over the same area as the $P(U_i)$. When the velocity distribution is to be applied to a cross-sectional area, either for a whole channel or for a cell (see 9.4), the $f(U_i)$ shall be estimated over the cross-sectional area considered.

EXAMPLE Figure 10 shows an example of the velocity distribution for three site locations from a one-month harmonic analysis. The three sites are less than 1 km apart.

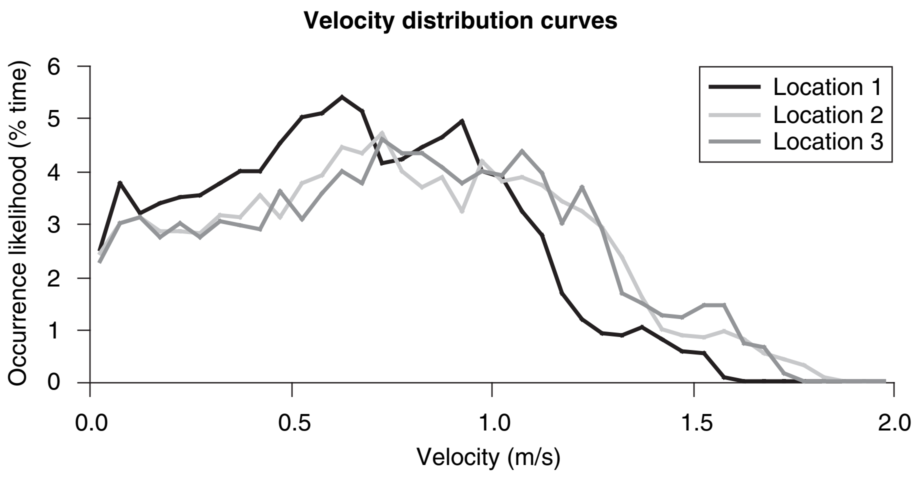

Figure 10 — Velocity distribution curves

7.2 Maximum velocities

7.2.1 One-month data

From any results that are available for a typical month (e.g. static field survey, model, harmonic analysis), that month's *V*msp shall be taken as the peak velocity that has been reached for 10 min during the whole month. The average month *V*msp shall be estimated, to obtain the maximum velocity that would occur during an average month. This should be compared to *V*msp values that have been derived in other related, or earlier, work.

The one-month data in this subclause of the report shall be given only for one particular depth, as the depth profile analysis occurs later. Depending on the data available, the velocity should be given either as depth averaged, at hub height, or averaged over the cross-sectional area of the TECS.

7.2.2 From transect survey

For each survey that has been undertaken the *V*msp shall be estimated.

If the boat survey has been carried out during the two strongest days of a representative spring tide, the maximum velocities (10 min average) that have been recorded shall be given as the *V*msp. Otherwise the *V*msp shall be extrapolated as accurately as possible with the data available; however, this extrapolation will add uncertainty which should therefore be defined.

Depending on what is required for validation purposes, the *V*msp should either be depth averaged or given at the depth used in the model.

7.3 Tidal range

The tidal range over the period shall be provided using the results of each of the methods that have been undertaken. This should be compared to tidal range values that have been derived in other related, or earlier, work.

7.4 Tidal ellipse

For TECS that are not able to extract energy from all directions (at different times), an understanding of the tidal ellipse is required to determine the optimum orientation.

The tidal ellipse should be generated using the model, and, if available, the static field data.

Once the major axis has been determined with the tidal ellipse, a table with the percentage of occurrence in a different direction (compared with the major axis) shall be provided. An ellipse shall be generated separately for flood and for ebb, and in either case if the flow direction is off the major axis by more than 10 % for more than 5 % of the time, a directionality offset in the resource available shall be applied, as a function of the TECS to be installed.

NOTE Whilst many tidal flows are approximately bidirectional (i.e. the flood and ebb are at 180° to each other, +/–10°), some are not, and it is therefore important to determine the optimum orientation of the TECS for energy extraction if the TECS is not able to extract energy from all directions (at different times).

If the TECS to be installed has already been identified and is a vertical axis machine, or one that is able to yaw into the direction of the current flow, this subclause is less relevant, but the issue of directionality should still be considered as the support structure might not be symmetric and the yaw tracking might not be perfect.

EXAMPLE Table 5 shows an example of the possible directionality offset for a fixed orientation horizontal axis turbine. No test results are available, so the table shows the percentage of the velocity that would be resolved as the scalar component of the velocity vector onto the major axis the turbine, using a simple cosine relationship.

Table 5 — Influence of directionality of flow on resource

Degrees off the major axis	Directionality offset
0	100 %
5	100 %
10	98 %
15	97 %
20	94 %
25	91 %
30	87 %
35	82 %
40	77 %

7.5 Power density

The average power density (APD) available across the surface area considered should be calculated from the time series of the measured/predicted velocity distribution $f(U_i)$. The velocity distribution shall be calculated over the appropriate area as described in 7.1.

The APD shall be calculated with the equation below where N_B is the number of bins and the index *i* refers to the bin number:

$$APD = \frac{1}{2} \cdot \rho \cdot \sum_{i=1}^{N_B} \left(U_i^3 \cdot f(U_i) \right) = \frac{1}{2} \rho \cdot V_{rmc}^3 \quad (\text{kW/m}^2)$$

U_i is the central value of the i^{th} bin, and V_{rmc} is the root mean cubed velocity, to be calculated with the equation below:

$$V_{rmc} = \sqrt[3]{\sum_{i=1}^{N_B} \left(U_i^3 \cdot f(U_i) \right)} \quad \text{(m/s)}$$

NOTE Note that the power density can be calculated directly from the time series coming from the model, before the histogram analysis, as this will give the most accurate results.

$$APD = \frac{1}{2} \cdot \frac{1}{N} \cdot \rho \cdot \sum_{j=1}^{N} \left(V_j^3 \right) \text{ and } V_{rmc} = \sqrt[3]{\frac{1}{N} \cdot \sum_{j=1}^{N} \left(V_j^3 \right)}$$

Where j is the index of the 10 min increments, V_j is the velocity recorded every 10 min, and N is the total number of time intervals (= total period of simulation divided by 10 min).

7.6 Extrapolation of data to a longer period

7.6.1 Typical month

NOTE This subclause describes how to extrapolate the results from the model/field survey to a longer period with the harmonic analysis.

The month chosen for the field survey shall be compared with the annual distribution generated with the harmonic analysis. In both cases the power density flux shall be calculated, and the difference between one-month and one-year distribution shall be calculated.

In case the difference between the power density resulting from a monthly distribution and the annual distribution is more than 5 %, the reasons shall be assessed as to why the month that was thought to be an average month is not representative of the yearly distribution. In this case the power density that is to be used further in the study should be calculated with the annual distribution.

7.6.2 Accuracy

The uncertainty in the method to extrapolate the monthly distribution to one-year distribution with the tidal constituents shall be estimated here, depending on the number of constituents used and on the source of the constituents' extraction.

7.7 Comparison of model with static field survey

7.7.1 General

The velocities obtained directly from the model, and/or from harmonic analysis of the model results, shall be compared to the actual data from the static field survey.

7.7.2 Depth profile

The depth profile should be plotted at different critical locations to compare the model (if 3D), the field data and the different depth velocity distribution laws commonly used in the industry.

A similar plot as on Figure 11 shall be provided here with the different depth profiles.

NOTE 1 Three power laws are generally used to describe the velocity reduction with depth.

The first is the '1/7th' law as shown below, where V_0 is the speed at the surface (m/s), z is the distance above the seabed (m) and d is the depth (m). The second law is the same formula but with 1/10th rather than 1/7th.

$$V = V_0 \left(\frac{z}{d}\right)^{1/7}$$

The third law was developed in the JOULE 1996 resource study [11], which has considered a different velocity profile that gives a higher average flow.

NOTE 2 Figure 11 shows that the 1/10th power law profile falls between the 1/7th power law and that used in the JOULE study. If no other information on the velocity profile at the site is available at this stage of the resource assessment, the 1/10th law can be used to offset the averaged velocity to the vertical area considered in the study. These profiles are not always accurate but if no 3D profile is available at the site they can be used to extrapolate the surface current to the average current over the whole section area of the channel or over the area of the TECS, depending on what is required in the assessment.

If at some locations the velocity profile is highly different from the expected one, an explanation should be given.

If the model was only 2D, or only harmonic analysis was conducted, the law to extrapolate the velocity from the surface (or from the chosen depth) to the hub height shall be defined in this subclause of the report. The use of such a law is a significant assumption and this shall be taken into account in the uncertainty of the final results.

7.7.3 Maximum velocities

7.7.3.1 3D model

*V*msp in each vertical bin should be compared between the model and the measured data for the peak flood and ebb velocity periods. Where the difference is more than 10 %, a short explanation should be given to justify the uncertainty.

7.7.3.2 2D model

*V*msp at the chosen model depth should be compared between the modelled and the measured data for the peak flood and ebb velocity periods. Where the difference is more than 10 %, a short explanation should be given to justify the error.

The peak ebb and flood velocities at the chosen model depth should also be compared to the depth-averaged velocities over the whole water column and to the depth-averaged velocities over the capture area of the TECS.

NOTE Depending on the result of the comparison and the explanation of the error, an offset might be necessary to adjust the velocities from the 2D model to the depth-averaged velocity over the capture area of the TECS.

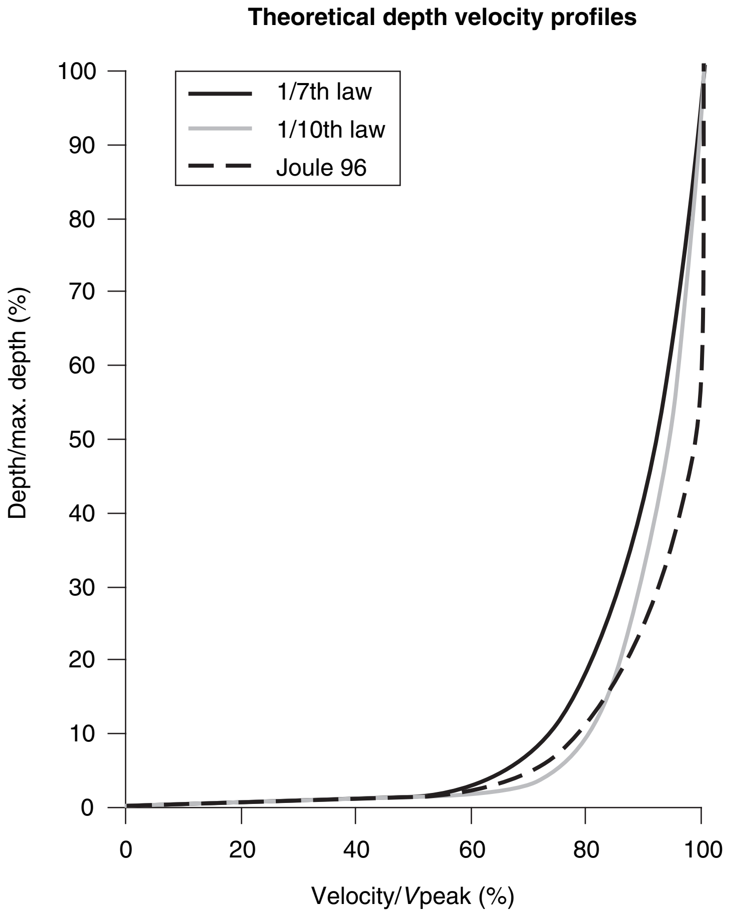

Figure 11 — Velocity profiles using different laws

7.7.4 Times series

The quality of fit between the predicted model results and the observed data for tidal velocity time series data shall be assessed using a cross-correlation procedure similar to the one described below.

Statistics shall be derived to quantify the differences between predicted and observed time series data. Four sets of statistics should be presented.

- Mean – comparison of sample mean values of the predicted and observed time series.
- Phase shift – average shift in time between the predicted and observed time series.

- Amplitude ratio – comparison of the time series range, which ideally would equal 1.

  NOTE 1 This value is estimated after removing the phase shift between predicted and observed time series.

- Scatter – remaining difference between predicted and observed time series after phase and amplitude errors are removed.

  NOTE 2 One measure of the scatter is the goodness of fit parameter, R^2, from a linear regression performed on the observed and predicted time series with phase and amplitude errors removed.

  NOTE 3 The phase shift process entails repeatedly shifting the predicted time series record at one-minute increments relative to the observed time series and computing the correlation coefficient, R^2, at each time shift. The shifted model time series best matches the observed time series when the correlation coefficient, R^2, has a maximum value. The time shift when the maximum correlation occurs represents the phase difference between the predicted and observed data. The linear regression is then performed between the time shifted model results and observed data record to yield the amplitude ratio, best-fit line and correlation coefficient.

The observed and predicted means, phase shift, amplitude ratio and R^2 value shall all be summarized for each simulation period.

Different plots shall be provided for ease of comparison, and should include the following:

- Monthly velocity comparison, as shown on Figure 12.

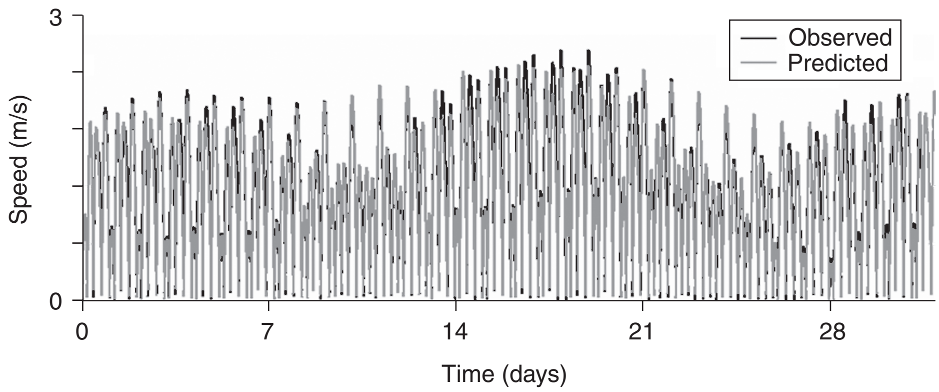

Figure 12 — Monthly speed comparison

- A tidally-averaged speed comparison for the full analysis period, as shown in Figure 13, which should be used to evaluate spring-neap and other relatively long timescale variability, as well as non-tidal forcing such as storm surge.
- A scatter comparison between the observed and predicted data over the analysis period, as shown in Figure 14, after compensating for phase shift.

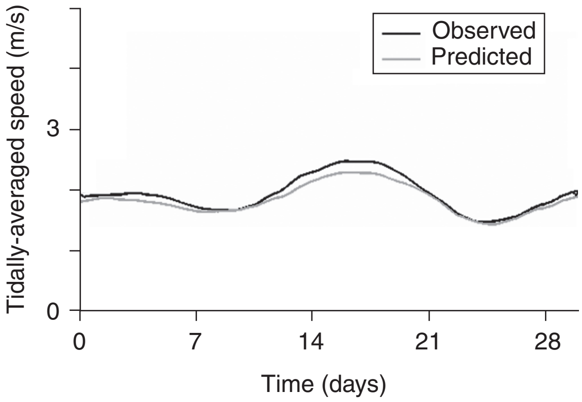

Figure 13 — Tidally averaged speed comparison

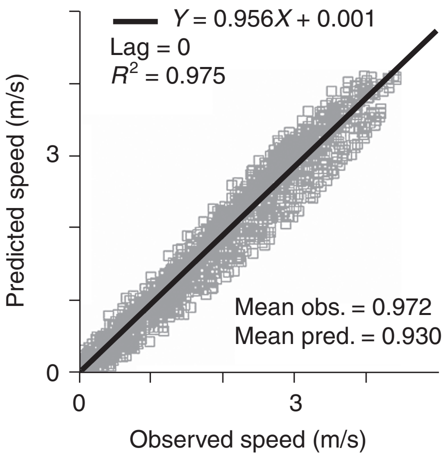

Figure 14 — Scatter plot comparison between observed and predicted speed

7.7.5 Velocity distribution curves and power density

Using the results from the model, and/or from harmonic analysis of the model results, and the actual data from the static field survey, the velocity distributions for one month should be determined, and the average power density (APD), in kW/m^2 (see 7.5) calculated in order to make a comparison between the different results.

The percentage difference between the different methods shall be summarized in a table.

7.8 Comparison of static field survey and model with transect field survey

7.8.1 General

The data sampling location(s) shall be compared to the overall site characteristics and this subclause of the report shall clarify how to demonstrate that sampling locations are representative. The results from the model/harmonic analysis shall be checked at critical locations and depths.

7.8.2 Comparison with static field survey results

If a static field survey has been carried out, and if the transects covered the static location(s), a comparison of the results should be used to verify that the chosen static location(s) are representative of the overall site under investigation and to verify the quality of the two surveys.

7.8.3 Comparison with predicted velocities

NOTE The transect survey will normally have been conducted at the period of peak flood and ebb velocity.

For each transect the average observed velocity shall be computed using all the valid velocity observation data and compared to the predicted velocity averaged at the same depth.

A table should summarize for each transect the average predicted velocity, the average observed velocity and the difference in magnitude between both.

For each transect, the predicted and observed data during the peak flood and peak ebb shall be compared by plotting their respective velocities.

Any discrepancy between the observed and predicted data shall be explained and taken into account in the uncertainty analysis.

7.9 Uncertainty analysis

This subclause of the report shall summarize the uncertainty associated with each of the current estimation methods that will be used to determine the energy resource available, particularly on the data and methods used for long-term histogram analysis (normally the model and/or static installations).

Wherever possible, this summary should be based on the uncertainty at the locations where it is intended that a TECS will be installed.

7.10 External effects on tidal current speed

7.10.1 General

The results from the harmonic analysis describe the predicted stream currents during the tidal cycles without considering the influence of meteorological effects. The results may be used for comparison with actual recorded field survey data to allow an estimate of these effects, such as wind, wave and surge, and other interactions on the tidal currents.

7.10.2 Maximum current velocity

Maximum 1-year, 10-year and 50-year currents shall be supplied in the site metocean study, considering storm, wind, wave and atmospheric effects.

NOTE The maximum current velocity is a critical parameter and is fundamental in evaluating both the structural integrity of the device and its functional loads. The parameter is critical in estimating the maximum drag loads imposed upon submerged structures and allows functional loads such as rotor thrust and torque to be determined at maximum current.

Whether or not the maximum current velocity equates to the maximum functional loads is dependent on the rotor power regulation system that is in place. It might be necessary to ensure that the rotor power regulation system can safely accommodate the maximum current. Shutdown currents might need to be defined for extreme cases.

EXAMPLE Ten-year currents are often considered for the design of structures.

7.10.3 Wave

7.10.3.1 General

Wave conditions such as wave height and period can be required for tidal current estimation.

7.10.3.2 Data available

The wave data that is available in the location of interest shall be summarized here. This should include:

- buoy locations;
- period of record;
- graphs of the significant wave height H_s and the energy period T_e with the data available.

If sufficient information is already available at a specific location, there might not be a need for further measurements and, equally, if the area of interest is not exposed to swell waves, or it is considered that the wave climate can be calculated from a locally collected long-term wind data set, there might be no need for a wave monitoring device, but the decision shall be explained.

There is still some uncertainty as to the effect that wave-induced motion will have on tidal stream devices, and data from the early prototypes shall be required to assess it.

Wave–current interaction is a complex process; with the area currently a research topic it is recommended that the latest research papers published on this topic should be consulted.

NOTE Some ongoing research is being undertaken by a group in the UK called SuperGen Marine Consortium, and the last published papers on this topic can be accessed on their website [12] .

7.10.3.3 Extreme wave

The 50 and 100-year storm waves shall be considered by a developer.

NOTE Turbines are likely to shut down or have the survival mode engaged in such extreme storm conditions because

(i) the wave-induced power oscillations might become too severe (+/– 80 % of mean);

(ii) the forces and stresses imposed on a device in operation might approach allowable design conditions; and

(iii) the stability of the device might become compromised.

This will influence the resource available, but as the effect on the tidal resource is limited, it is not deemed necessary to consider the extreme wave before Stage 3 of the resource assessment.

7.10.3.4 Wave measurements

In the case where no accurate data is available at the site area for waves, wave data measurements should be recorded at the same time as the current measurements.

In this case, one wave measuring instrument should be installed at an appropriate position in the area. The buoy should measure accelerations in three directions to allow wave heights and periods, together with their directionality, to be calculated by a specified method.

NOTE These measurements will allow the directional wave spectrum to be estimated.

The buoys should be capable of recording data at 5 Hz.

For more information on wave measurement procedures, the *Assessment of Wave Energy Resource* document in this series should be consulted.

7.10.4 Wind

7.10.4.1 Available data at location

Similarly to wave and current data, the details of available wind data at the specific location shall be listed here with reference to the location of the monitoring wind mast, the period of measurements and the quality of the data available.

There are reasonably reliable numerical model wind simulation outputs and processed satellite derived wind field data available across the world. If this is to be used, details of the model used, its characteristics and accuracy of the predictions shall be described here as well.

7.10.4.2 Wind measurement

If a hydrodynamic model has been developed, the influence of wind on the results should be assessed through including a generic set of wind velocities (from published data as described above) within the model to compare the results against those calculated without a wind component.

NOTE 1 If, as expected for strong tidal zones, the influence of wind is minimal, then a decision can be made not to acquire real wind measurements.

NOTE 2 The influence of wind can be considered as minimal if doubling the generic wind velocities in the model changes the depth-averaged speed results by less than 2 %.

However, if there is no wind data available to use in the model, or wind is shown to significantly influence the current velocity, wind measurements may be carried out at the same time as the current measurements. In this case the measurements should be undertaken following the methodology described in IEC 61400-12-1.

7.10.5 Turbulence

This subclause of the report should describe different levels of turbulence that have been observed, and those that would have been expected but haven't yet been observed.

As this is currently a research topic, recent papers that might have been published in this area should be consulted and reference should be made to them in this subclause of the report.

8 Mean annual electrical power

8.1 Definition and characteristics

NOTE The main aims of this draft methodology are to measure and describe the resource (by deriving a velocity distribution for a site), to understand the potential for the power extraction of an array of TECS (by combining the velocity distribution with the power curve of the TECS) and to ensure that the tidal resource available is not over-extracted.

Once the velocity distribution has been calculated, it can be applied to the TECS' power curve to estimate the annual energy output.

8.2 Velocity distribution

The velocity distribution $f(U_i)$ shall be estimated considering the different velocity distribution curves that have been derived from the different methods. The velocities shall be averaged over the appropriate cross-sectional area, as described in 7.1

From the analysis carried out as described in Clause 7, the results of the analysis shall take account of the directionality, the depth profile, the external effects on the currents, and the uncertainties.

8.3 Power curve

8.3.1 General

This subclause of the report shall describe how to obtain the average electrical power for each velocity bin $P(U_i)$.

8.3.2 Case 1: TECS not tested

A generic device shall be used if no device has yet been chosen.

The generic characteristics of the device are described in 4.4.2. The other characteristics required are as follows:

- the power generated in each velocity bin and the efficiency of the device;
- the rated velocity shall be estimated, at which the device will produce the maximum power output;
- the electrical efficiencies shall be estimated for the powertrain, including where relevant the gearbox, the generator and the power electronics.

NOTE If the TECS has not been identified, or has been identified but not been tested, this subclause gives a methodology to obtain a power curve for a generic device. The power curve calculated here is not deemed to be accurate, but will be sufficient to determine whether the resource that is planned to be extracted by a tidal farm doesn't exceed the resource available.

The rotor efficiency can be considered to rise from 38 % at cut-in speed to reach 45 % at the rated velocity.

The rated velocity can be taken as 71 % of the V_{msp} at the hub height, as determined in this document.

The average powertrain efficiency (η_{PT}) can be considered at this stage to be 90 %.

The cut-in speed (the minimum velocity required for device operation) is assumed constant at 0.5 m/s. This assumption greatly simplifies the analysis and does not impose significant limitations on accuracy, since the available energy from tidal currents at speeds below 0.5 m/s is usually less than 5 % of the total available energy.

EXAMPLE Table 6 shows an example of the calculation of $P(U_i)$ for a site with a V_{msp} at hub height of 2.5 m/s. The rated velocity is then 1.775 m/s, and above this value the electrical power is assumed constant. In the example the rotor diameter is 22 m, so the swept area A, is 380 m^2.

Table 6 — Electrical power per bin

Average bin velocity	Available power	Rotor efficiency	Electrical power per bin
U_i	$P_{av(i)}=0.5 \cdot \rho \cdot A \cdot U_i^3$	η_R	$P(U_i) = P_{av(i)} \cdot \eta_R$
m/s	kW	%	kW
0.05	0	0	0
0.15	1	0	0
0.25	3	0	0
0.35	8	0	0
0.45	18	0	0
0.55	32	38	11
0.65	53	39	19
0.75	82	40	30
0.85	120	41	44
0.95	167	42	63
1.05	225	42	86
1.15	296	43	114
1.25	380	44	150
1.35	479	45	194
1.45	593	45	240
1.55	725	45	293
1.65	874	45	354
1.75	1043	45	422
1.85	1232	x	422
1.95	1443	x	422
2.05	1677	x	422
2.15	1934	x	422
2.25	2217	x	422
2.35	2526	x	422
2.45	2862	x	422
2.55	3227	x	422

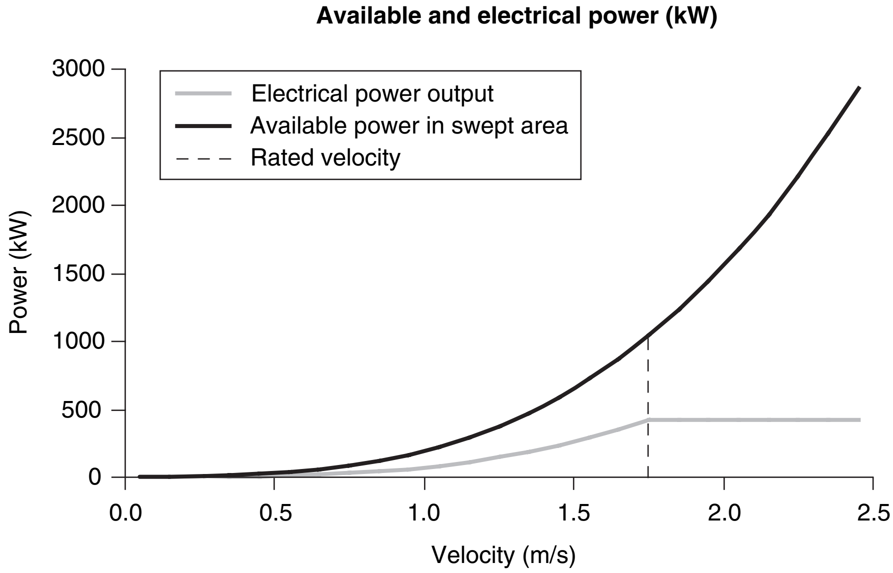

Figure 15 — Electrical power curve

8.3.3 Case 2: TECS has been tested

This subclause of the report shall be used by the entity that carries out the resource assessment if the TECS planned to be installed has already been identified and tested, in which case the power curve should be available as determined using the *Assessment of Performance of Tidal Energy Conversion Systems* document in this series.

The characteristics of the device should be used here, i.e. the rated velocity, the rotor efficiency, and the cut-in-speed, and should be compared to the generic values described in 8.3.2. Any major differences between the values used for the chosen TECS and the generic values shall be justified carefully here.

The power curve should be shown here, as obtained from the *Assessment of Performance of Tidal Energy Conversion Systems* document in this series. It should be presented in graphical and in tabular format.

The table shall list the following items:

- current velocity passing through the swept area averaged in each of the *i* bins: $U_{perf(i)}$;
- average electrical power generated in each of the *i* bins: $P_i(U_{perf(i)})$;
- number of data sets in each of the i^{th} bins: N_i;
- standard deviation of the values of P_i in the i_{th} bin.

The power curve plotted should be similar in shape to the one plotted in Figure 15, but with error bars to represent the standard deviation for each point, as described in IEC 61400-12-1. The level of uncertainty shall be calculated following the relevant Clause in the *Assessment of Performance of Tidal Energy Conversion Systems* document in this series.

Reference should be made to the *Assessment of Performance of Tidal Energy Conversion Systems* document to derive the energy output of a specific TECS(s) under specific resource conditions experienced by the TECS(s).

8.4 Mean annual electrical power

The mean annual electrical power (P_{mean}) shall be obtained by combining the velocity distribution $f(U_i)$ obtained with this document with the average absorbed power for each velocity bin $P(U_i)$ calculated as described in 8.3 by using the following equation:

$$P_{mean} = \sum_{i=i}^{N_B} P(U_i) \cdot f(U_i)$$

NOTE 1 In the example shown in Table 7, the same device characteristics as described in 8.3.2 have been used to calculate P_{mean}.

NOTE 2 If the TECS has already been tested and the *Assessment of Performance of Tidal Energy Conversion Systems* document has been used, note that in the performance results $U_{perf(i)}$ is the mean value of the measured velocities in the i^{th} bin, which might not be the central value of the bin, especially for the first and last bins, as values measured might not have been evenly distributed around the centre of the bin. In this case, either the velocity distribution bins can be centred on the $U_{perf(i)}$ bins to get $f(U_{perf(i)})$ which is preferred, or one can apply the distribution $f(U_i)$ to the respective $U_{perf(i)}$ bin.

8.5 Annual energy production

For each TECS, the annual energy production (AEP) shall be obtained by combining the P_{mean} with the available hours per year:

$$AEP = 8760 \cdot A_v \cdot P_{mean} \quad \text{(kWh)}$$

Table 7 — Mean electrical power

Average bin velocity	Velocity occurrence likelihood	Electrical power per bin	Mean annual electrical power per bin
U_i	$f(U_i)$	$P(U_i)$	$P(U_i) \times f(U_i)$
m/s	%	kW	kW
0.05	0.3	0	0
0.15	0.9	0	0
0.25	1.5	0	0
0.35	2.2	0	0
0.45	3.0	0	0
0.55	4.0	11	0
0.65	5.2	19	1
0.75	6.4	30	2
0.85	7.4	44	3
0.95	8.0	63	5
1.05	8.1	86	7
1.15	8.1	114	9
1.25	7.9	150	12
1.35	7.5	194	15
1.45	6.9	240	17
1.55	5.9	293	17
1.65	4.9	354	17
1.75	3.9	422	16
1.85	2.9	422	12
1.95	2.1	422	9
2.05	1.3	422	0
2.15	0.8	422	5
2.25	0.4	422	3
2.35	0.2	422	2
2.45	0.1	422	1
2.55	0.0	422	0
	Mean annual electrical power, P_{mean}		**155 kW**

9 Available and extractable energy

9.1 General

NOTE This subclause describes two methods that are commonly used to calculate the energy that could be generated by a TECS array.

The first method, called the farm method should be used to calculate the energy generated by an array by simply multiplying the electrical energy output for each TECS by the number of TECS that could be installed, or by calculating the electrical energy output of each TECS and summing the results. The second method, called the flux method, should be used to check that the use of the farm method will not result in an alteration of the flow speeds that would have a significant adverse effect on the economics of the project or on the environment.

9.2 Site characteristics (energy extraction effects)

The channel shape and friction coefficient shall be described in this subclause of the report.

Other site characteristics might be required. This is currently a research subject, so latest research should be consulted.

9.3 Resource assessment with farm method

NOTE 1 The farm method for estimating energy extraction using tidal stream farms is based on the concept of an array of tidal stream devices, each of which extracts an amount of energy related to the incoming energy. The resulting extracted energy is therefore purely dependent on the size and number of the devices, conversion efficiency and the packing density within the site area.

The aim of comparing the two methods is to assess how much power is extracted from the sea, so the electrical power needs to be divided by the powertrain efficiency η_{PT} in order to obtain the power extracted from the sea (as the powertrain losses will be returned to the sea as heat energy rather than as kinetic energy).

To estimate the resource at a site with the farm method, one should first determine the size of the farm that could potentially be installed in the selected area, in order to estimate the number of turbines that can be installed and the farm output power.

NOTE 2 The number of TECS (N_T) that can be installed can be determined by dividing the total available surface area estimated in 4.8 by the device spacing and farm layout described in 4.4.3.

The annual mean electrical power (P_{mean}) of each device shall be calculated in each grid cell or area where a velocity distribution has been calculated, as described in 8.4

The total resource estimated by the farm method shall be calculated simply by adding the P_{mean} divided by η_{PT} of each device that can be installed in the area. In the following equation n is an index that represents a TECS.

$$P_{farm} = \sum_{n=1}^{N_T} P_{mean}(n) / \eta_{PT}(n) \qquad \text{(kW)}$$

NOTE 3 Depending on the number of different grid cells for which a velocity distribution is available, this formula is in practice hard to apply for each device, as it would mean that each device would be designed with a different rated power to best fit the velocity distribution. This is unlikely to be the best method in practice as economies of scale would normally be lost. The devices would hence normally be grouped in areas of similar velocity distributions.

9.4 Resource assessment with flux method

NOTE 1 The flux method is based on the calculation of the incoming kinetic energy flux through the frontal cross-sectional area of a flow channel. The resulting available resource estimate is independent of the device type, efficiency, and packing density, taking only the energy flowing in the channel into account. The extractable portion of the resource is then estimated using a significant impact factor (SIF), which may be informed by detailed hydrodynamic or other modelling.

The P_{farm} calculated with the method in 9.3 shall be compared to P_{flux}, which is the total power available in the cross-sectional area of the channel considered for the TECS installation.

The P_{flux} shall be calculated across the whole channel cross-sectional area by multiplying the average power density (APD) (calculated with the velocity distribution as described in 7.5) by the cross-sectional area of the channel considered.

$$P_{flux} = APD \cdot A_{channel} \qquad \text{(kW)}$$

where

APD = average power density (kW/m^2)

A_{channel} = cross-sectional area of the channel (m^2)

Depending on the stage of the assessment, the P_{flux} shall be calculated across the cross-sectional area as accurately as possible. If a different velocity distribution is available in several grid cells for the cross-sectional area considered, then the annual average kinetic power flux (P_{fluxcell}) should be calculated for each cell, where APD is then calculated with the velocity distribution averaged over the cross-sectional area of the cell as below:

$$P_{fluxcell} = APD \cdot d_{cell} \cdot w_{cell} \qquad \text{(kW)}$$

where:

APD = average power density (kW/m^2)

d_{cell} = depth of the cell (m)

w_{cell} = width of the cell (m)

The total power flux through the site (P_{flux}) is then obtained by summing the power flux calculated for each cell across the site, along a line perpendicular to the main flow direction.

$$P_{flux} = \sum_{cross\text{-}sectional\ area} P_{fluxcell} \qquad \text{(kW)}$$

Where feasible, this calculation should be carried out for several cross sections along the longitudinal axis of the site. An average is then taken to be a representative value for the total power flux through the site.

The annual average available power ($P_{available}$) is then the product of the power flux passing through the site and the significant impact factor (SIF):

$$P_{available} = P_{Flux} \cdot SIF \qquad \text{(kW)}$$

NOTE 2 The SIF represents the percentage of the total resource at a site that can be extracted without significant economic or environmental effects. There is clearly only a percentage of the total energy in a site that can be extracted without significant alteration to flow speed. Alteration to flow speed has an important effect on the economics of energy generation in addition to possible environmental impacts.

Previous work by Black & Veatch in conjunction with Robert Gordon University (RGU) [13] has suggested that the SIF will be dependent on the type of site. In channels where the flow is governed by a head difference at either end of the channel, and the flow cannot affect the tidal elevation in the bodies of water at either end, significant effects on the flow can be noted when this percentage is around 10 %. Other modelling by RGU has suggested that in areas where the flow has more freedom within its elevation boundary conditions, up to 50 % extraction could be possible without significant effects. It is important to note that these percentages are based on theoretical modelling results, which have yet to be validated by physical experiment.

Given the presently limited understanding of the SIF, and the current research on this critical issue, this document cannot give a methodology to calculate the SIF for a site.

As a minimum, the power available calculated with the flux method can be compared with the power extractable obtained with the farm method, to verify that the power extractable is not more than 50 % of the power available.

10 Reporting

10.1 Purpose of reporting

The reporting shall serve a number of purposes:

- to provide a periodic report of the advancement of the resource assessment programme;
- to provide periodic updates of the tidal resource available as more data becomes available;
- to provide a consolidated final report that will describe the tidal resource and the velocity distribution at the site of interest at the end of the resource assessment programme to be used in correlation with the *Assessment of Performance of Tidal Energy Conversion Systems* document in this series to predict the output power of a TECS or a farm of TECS at a chosen location.

10.2 Contents of the report

The report should contain all the clauses and subclauses that have been presented in this document, following the same order. Some of the items might not be relevant to the resource assessment carried out, depending on the stage and the purpose of the assessment, but in this case the clause/subclause should still be included and a short explanation given.

10.3 Frequency of reporting

A report should be prepared at each stage of the programme.

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