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TECHNICAL SPECIFICATION

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Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization

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IEC TS 62600-201:2015-04(en)

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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CONTENTS

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MARINE ENERGY –
WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 201: Tidal energy resource assessment and characterization

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Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62600-201, which is a technical specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

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The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
114/142/DTS	114/151A/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy – Wave, tidal and other water current converters*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,
- replaced by a revised edition, or
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INTRODUCTION

This Technical Specification is for use by appropriately qualified and competent persons. The development of the tidal power industry is at an early stage and the significance of particular tidal energy resource characteristics is not well understood. This Technical Specification is intended to be updated as understanding of the resource and its response to power extraction becomes better understood. It is noted that it is presently particularly difficult to derive the uncertainty (within specified confidence limits) of the resource, given lack of field and model data for a statistically significant number of sites.

The purpose of this Technical Specification is to provide a uniform methodology that will ensure consistency and accuracy in the estimation, measurement, characterization and analysis of the theoretical tidal current resource at sites that could be suitable for the installation of an array of Tidal Energy Converters (TECs), together with defining a standardised methodology with which this resource can be described and reported. Application of the estimation, measurement and analysis techniques recommended in this Technical Specification will ensure that resource assessment is undertaken in a consistent and accurate manner. This Technical Specification presents techniques that are expected to provide fair and suitably accurate results that can be replicated by others.

The overall goal of the methodology is to enable calculation of the Annual Energy Production (AEP) for the proposed array of TECs at each TEC location in conjunction with IEC 62600-200.

In this Technical Specification, the theoretical tidal energy resource (undisturbed or disturbed by power extraction) is defined as the velocity probability distribution $f(U_i)$. For projects over c. 10 MW (circa 10 MW), the velocity probability distribution is calculated using hydrodynamic models that have been appropriately verified using measured data. The methodology for measuring the required data is also defined. For individual TECs within small projects of less than c. 10 MW, an alternative method which uses measured data at each TEC location may also be used to define the resource.

This Technical Specification describes only the aspects of the resource required to calculate AEP; e.g., it does not describe aspects of the resource required to evaluate design loads or to satisfy environmental regulations. Furthermore, this Technical Specification is not intended to cover every eventuality that may be relevant for any particular project. Therefore, this Technical Specification assumes that the user has access to, and reviews, other relevant IEC documentation before undertaking work (e.g., surveys and modelling) which could also satisfy other requirements.

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MARINE ENERGY –
WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 201: Tidal energy resource assessment and characterization

1 Scope

This part of IEC 62600 establishes a system for analysing and reporting, through estimation or direct measurement, the theoretical tidal current energy resource in oceanic areas including estuaries (to the limit of tidal influence) that may be suitable for the installation of arrays of TECs.

It is intended to be applied at various stages of project lifecycle to provide suitably accurate estimates of the tidal resource to enable the arrays' projected annual energy production to be calculated at each TEC location in conjunction with IEC 62600-200.

2 Normative references

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

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

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1: Terminology*

IEC TS 62600-200, *Marine energy – Wave, tidal and other water current converters – Part 200: Electricity producing tidal energy converters – Power performance assessment*

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

ICES, 2006, *Guidelines for Multibeam Echosounder Data*

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3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 apply.

4 Symbols, units and abbreviations

4.1 Symbols and units

$f(U_i)$ Time occurrence likelihood of a velocity in each magnitude bin (%)

$f(U_i, \theta_k)$ Time occurrence likelihood of a velocity in each magnitude and direction bin (%)

I Turbulence intensity

i Index for velocity magnitude bin numbers

j Index for number of time intervals

k Index for direction bin numbers

K Turbulent kinetic energy (m^2/s^2)

N Number of time intervals

N_B Number of velocity bins

u' Root-mean-square of the turbulent velocity fluctuations (m/s)

$\overline{U}$ Mean velocity magnitude (m/s)

U_i Central value velocity magnitude in the i^{th} bin (m/s)

U_j Central value velocity magnitude of time step j (m/s)

θ_k Direction for the k^{th} bin (deg)

V_{rmc} Root Mean Cubed Velocity (m/s)

ρ Density of the water (kg/m^3)

4.2 Abbreviations

AEP Annual Energy Production

ADV Acoustic Doppler Velocimeter

APD Average Power Density (kW/m^2)

CTD Conductivity, Temperature, Depth

CFD Computational Fluid Dynamics

EEP Energy Extraction Plane

GPS Global Positioning System

IEC International Electrotechnical Commission

NOAA National Oceanic and Atmospheric Administration

PCA Projected Capture Area

RTK Real Time Kinematics

SAR Synthetic Aperture Radar

TEC Tidal Energy Converter

UTC Coordinated Universal Time

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5 Methodology overview

5.1 Project definition

5.1.1 General

This Technical Specification should be applied at various stages of the resource assessment process to provide velocity probability distributions for computing Annual Energy Production (AEP) with increasing accuracy or lower levels of uncertainty. This specification assumes that a region of interest has already been identified. Aspects of the methodology to be followed when undertaking a tidal resource assessment depend on the scope of the analysis and its objectives. Two distinct types of studies, feasibility and layout design, are defined as indicated in Table 1. The feasibility study generally has a focus on the whole estuary or channel with a medium level of uncertainty. The layout design study is expected to focus on the particular sites chosen through the feasibility studies.

Table 1 – Resource assessment stages

Stage	Aim	Area	Level of uncertainty
Stage 1	Feasibility	Whole estuary, channel, etc.	Medium
Stage 2	Layout design	Development site.	Low

The expected decrease in uncertainty as the resource assessment stages progress can result from:

- measurements and/or modelling over longer durations / periods;
- availability of additional, and/or higher quality measurements;
- use of more capable models, as outlined in 7.3;
- finer discretisation in space and time;
- use of improved boundary conditions;
- improvements in modelling techniques during the project's evolution.

5.1.2 Stage 1: Feasibility study

A Stage 1 study is focused on investigating the scale and attributes of the energy resource within a particular study area. The results of a Stage 1 resource assessment can be used to help assess the feasibility of constructing tidal energy arrays at sites within the study area by estimating the undisturbed site resource.

5.1.3 Stage 2: Layout design study

A Stage 2 study is focused on generating detailed and accurate information on the tidal energy resource in a specific area to determine AEP, through supporting the layout design of a tidal array, and may incorporate energy extraction impacts depending upon the project scale. The Stage 2 study should consider the technology to be installed and locations of TEC deployments in order to estimate AEP with lower uncertainty.

5.2 Methodology

The resource assessment requirements are defined depending on the scale of the project as well as the objective of the assessment (feasibility or design layout). The AEP (calculated using the method outlined in Annex A) may be assessed based on data from either direct measurements or from hydrodynamic modelling.

For projects where the total power output is expected to be less than c. 10 MW, or those where the proposed energy extraction is less than 2 % of the theoretical undisturbed tidal energy resource (see Note) and therefore there is expected to be little if any impact on the underlying hydrodynamics of the site, AEP may be estimated from direct resource measurements using static current profiler measurements and harmonic analysis as defined in 8.2.3. In order to use this method, measurements shall be made at each individual turbine location. Such projects may also use the hydrodynamic modelling required for larger projects. If the data collection indicates that the TECs should be deployed in different locations to

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where static current profiler data has been collected, then either additional data gathering at the new location or the modelling approach is required.

NOTE Understanding of the potential impact of energy extraction from TEC arrays is evolving; existing useful references include: Black & Veatch/Carbon Trust (2011); Garrett et al. (2004); Garrett et al. (2005); Sutherland et al. (2007); Polagye et al. (2008); Karsten et al. (2008); Draper et al. (2009); Vennell (2010); Vennell (2011); Polagye et al. (2011), Defne et al. (2011), Walters et al (2013).

For projects larger than c. 10 MW or 2 % of the theoretical undisturbed resource, AEP shall be assessed by hydrodynamic modelling, with appropriate verification by measurements. The first step in this process is to define the required model inputs, as described in 7.2. Subclause 7.3 describes the choice of numerical model. The next step is to assemble the information required to implement the model. If sufficient data does not exist for the model inputs, additional data shall be collected as described in Clause 6. The accuracy of the model may then be assessed as per 7.4. For feasibility studies, the model output may be used to produce the velocity probability distribution for AEP calculation. For layout design studies, if the level of energy extraction is to be small relative to the existing resource (see 7.6), the model data may be used directly. Otherwise, the model should be run with energy extraction to accurately specify velocity probability distributions for AEP estimation.

Many of the external constraints that determine the assessment of the practical resource, such as acceptable environmental impacts, are beyond the scope of this Technical Specification. However, the modelling methodologies described within this Technical Specification may be used to assess some of the impacts of TEC deployments, including changes in tidal regime, tidal currents and bottom sediment movements, and may also provide data required for environmental studies. External constraints to be considered in determining the tidal resource should be determined in consultation with the appropriate regulators.

Table 2 should be used to help determine the appropriate model and survey requirements to estimate the tidal energy resource at any particular resource assessment Stage. Where appropriate, Table 2 references the relevant clause in this Technical Specification where the detailed information related to that activity is contained. These recommendations consider the practicalities of gathering the data to satisfy these requirements.

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Table 2 – Model and field survey recommendations (Overview)

		Stage 1	Stage 2
Modelling	Minimum number of harmonic constituents for modelling driving boundary (tidal amplitude)	4-8	8-12
	Grid resolution at the area(s) of interest	< 500 m or > 10 grid cells across a channel section	< 50 m
	Period of run	> 35 days	> 35 days
	Other model characteristics	7.2 and 7.3	Shall include energy extraction impacts as needed 7.6
Physical data requirement	Bathymetry	6.2	6.2
	Tidal height	6.3.3	6.3.3
	Wave characteristics	6.5	6.5
	Meteorological data	6.4	6.4
	Flow structure / Eddies / Turbulence	6.6	6.6
	Stratification, seawater density and sediment measurement	6.7	6.7
	Tidal currents – Mobile survey	6.3.4	6.3.4
	Tidal currents – Stationary survey	6.3.5	6.3.5
Data analysis	Harmonic analysis on available current data (minimum no. of constituents)	20	20

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6 Data collection

6.1 Introduction

For projects using hydrodynamic models for providing velocity distributions to support AEP calculations, field measurements are required to calibrate and validate numerical models of the tidal currents. This includes measurements of harmonic tidal currents, as well as non-tidal low frequency processes that may impact tidal resource assessment such as storm surge, residual flows and stratification, and high frequency processes such as turbulence. For projects smaller than c. 10 MW, the field measurements may be used to provide the velocity distributions to directly calculate AEP for individual turbines. Guidelines for current profiler measurements are provided in Annex B.

6.2 Bathymetry

The required resolution of the bathymetry data to feed into a hydrodynamic model is described in 7.2.1.

The bathymetric data already available shall be reviewed, e.g. contact with the oceanographic centres responsible for the region concerned is recommended. If existing data is to be used, then the collection techniques for the original data and their appropriateness shall be reviewed, e.g. by comparison to modern techniques. Such data should be used with an element of caution. If a bathymetric survey is required to complement and expand the available existing data in the specific region of interest, the survey should be conducted in accordance with the IHO *Standards for Hydrographic Surveys:*2008. Reporting of bathymetric survey activities shall be completed to the standard of the ICES *Guidelines for Multibeam Echosounder Data:*2006.

A map should be provided for all undertaken surveys for which data is available. The following information should be provided on each survey:

- date of survey;
- survey methods used;
- uncertainty of data;
- coordinate system and transformation used to convert to/from another coordinate system, as appropriate, for later use;
- method for accounting for stage of tide throughout survey and tidal reference (measurement or prediction) used;
- chart/tidal datum applied;
- calibrations applied;
- availability of data in electronic form.

There is no accepted world standard definition of tidal datum or chart datum used for navigation charts and tidal height graphs. Many nations have developed their own definitions. It is particularly important for numerical modelling purposes to have bathymetric depths referenced to a fixed geodetically determined datum, which can be referenced to true local mean sea level. Tidal or chart datum used on all worldwide navigation charts is not a fixed datum but may change from chart to chart and should be defined.

If new survey data is used in conjunction with existing data, the new data should overlap the existing data to allow for validation between the two datasets.

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6.3 Tidal characteristics

6.3.1 General

The tidal height and tidal current (both depth-averaged and depth varying) characteristics at the site shall be identified and reported. As a minimum this should include graphs of typical daily, monthly and annual tidal height, current speed and direction. These graphs may be generated directly from measured data or predictions may be calculated from tidal harmonic constituents derived from measured data using harmonic analysis software, according to the Stage of the investigation.

The usage of 'typical' is intended to convey the general conditions to be expected on site, for example a 'typical' daily cycle for a semi-diurnal or diurnal site will show the repetition in the expected pattern of high and low tides. A 'typical' daily cycle for a site with mixed tides may require several daily graphs to capture clearly the lower high water and higher low water cycles. A 'typical' monthly cycle should be selected for a 29 day period when solar semi-annual and annual constituents have minimal influence. A 'typical' annual cycle should be presented in the context of the longer term 18,6 year lunar-solar cycle.

Existing long-term data sets and tidal constituent data maintained by the national hydrographic office or oceanographic data centre responsible for the region should be accessed where available. Tidal characteristics from all tidal height stations and tidal current stations in the area of interest shall be determined. Further tidal height data including tidal constituents may also be obtained from appropriate satellite databases. If additional location specific tidal height data is required, an appropriate survey should be conducted (see 6.3.3). These approaches to obtaining data require use of appropriate methodologies, and an appropriate assessment of the uncertainty in the data should be reported.

NOTE 1 A standard text on the theory of tides and tidal currents, including what constitutes a typical spring tidal cycle, and tidal harmonic analyses and prediction may be consulted before any substantive work is completed on this tidal resource analysis. Several good references are freely available including the straightforward Forrester (1983), and the more mathematically complex Foreman (2004). The latter manual includes freely available tidal height and current prediction and analysis software. Alternative analysis and prediction software is available, e.g. T-Tide, (Pawlowicz et al., 2002)
(http://www.eos.ubc.ca/~rich/) or UTide (Codiga 2011).

NOTE 2 Tidal height and tidal current constituent data can be obtained from a number of sources. These are freely available in the USA and many other localities but some countries, including the UK, protect the raw constituent data and only make them available for a fee.

NOTE 3 Examples of appropriate satellite databases include TOPEX/POSEIDON, and ERS-1. For those unfamiliar with satellite imagery the following references may be useful: http://sealevel.jpl.nasa.gov, http://podaac.jpl.nasa.gov/OceanSurfaceTopography.

NOTE 4 Preliminary tidal characteristics such as the spatial structure of persistent tidal eddies may be evaluated for a project site through the use of surface drifters.

6.3.2 Assessment of data quality

Ideally, an overall assessment of tidal current data quality would be conducted according to the standardised approach presented in ISO/IEC Guide 98-3:2008. However, application of this method to current profiler non-steady (turbulent) flow data is itself subject to debate. Current profiler manufacturers can prescribe a given uncertainty in measurement for the selected instrument configuration, but this value is applicable only for homogeneous flow across layers of constant depth. Hence, this prescribed uncertainty value does not account for the error caused when separate beams detect spatially varying flow, yet transform the data into a velocity vector at a single point. The ISO/IEC Guide 98-3 provides a method for characterizing measurement uncertainty using the standard deviation of multiple measurements. However, this method relies upon the measurement of fluctuations from an observed steady mean value. At many sites, the approximately 12 h period of the tidal cycle, in combination with large-scale eddies with time scales of just a few minutes and small-scale turbulence with timescales of a few seconds, precludes an averaging period over which the underlying velocity can be considered a truly steady value. Thus it is generally not possible to rigorously conduct propagation of uncertainty for values dependent on the tidal velocities

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measured as described in various subclauses below. Instead, it is suggested that standard deviation of velocity measurements over the averaging period be simply reported to provide a qualitative assessment of uncertainty due to inhomogeneous flow.

6.3.3 Tidal height

Tidal height data is required for: model calibration and validation analyses, hindcasting and future prediction of tidal heights, production of tide tables and assistance in inferring tidal current tidal constituents where appropriate. Tidal height data will also be required to define, refine or confirm the model boundary conditions and for calibration of the model at both the proposed development site and other locations within the model domain. The number of locations required for tidal boundary conditions depends on the complexity of the model domain and the length of any open boundaries. The number of locations required for calibration purposes depends on the extent of the model domain, the number of interconnected channels and/or the size of any enclosed embayments and channels connecting to the open ocean within the modelled domain.

The data at each location shall include:

- location;
- date and length of measurement;
- measurement methods;
- calibration reports/ calibrations applied to the data;
- tidal range and vertical datum;
- analysed tidal constituent data, including the amplitude and phase of all constituents identified as important such that at least 95 % of the total variance is captured by the constituents;
- an assessment of the overall quality of data collected should be conducted. The percentage of data that has been found to be good quality should be calculated. Data that is believed to be erroneous shall be highlighted, and for purposes of further data manipulation, can be removed from the record. All Quality Assurance / Quality Control practices applied to the data sets shall be noted.

The location of each tidal station shall be shown on a geo-referenced map with the bathymetric data and shoreline, given in a coordinate system consistent with the bathymetry data in 6.2. The tidal range and tidal datum shall be expressed using standard definitions used on navigational or hydrographic charts in the project country, and those definitions shall be clearly explained in terms of the region over which the datum is valid, the location or port to which it is referenced, and its offset from a definitive phase of the tidal cycle, such as mean sea level or lowest astronomical tide. The latter requirements concerning the datum enable consistent application of the tidal height data to the hydrodynamic models.

6.3.4 Tidal current mobile survey

6.3.4.1 General

Mobile surveys using vessel mounted current profiler measurements should be undertaken for all proposed TEC sites at Stage 1. It should be noted that a mobile current survey, in itself, is not an adequate data source to specify an annual velocity distribution, but used with model simulations may be able to provide useful information about the spatial variability in tidal currents at a proposed TEC site. If collected synoptically, this information can be used for model validation or to plan the deployment of further stationary current profiler measurements described in 6.3.5. Synoptic measurements may be readily obtained over sites with a characteristic size in the order of several hundred metres, but may be more difficult to collect over larger areas (Palodichuk et al.: 2013). The current profiler should be mounted and operated by competent operators with experience using such devices because there can be severe degradation in data quality with a poorly mounted and/or configured system. Mobile surveys may also be helpful at other locations to characterize flow conditions across model

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boundaries or to assist in model validation at key regions of highly dynamic flow. Mobile surveys should be designed to take into account the size, bathymetric shape and volume of the site under investigation. The surveys shall use appropriate scales to capture local variability.

The data collection should preferably be conducted during a typical Spring tidal cycle as a minimum (see 6.3.1, Note 1 for guidance on what constitutes a typical Spring tidal cycle). If a full data set cannot be obtained on a spring tide, results can be interpolated from other data that may be available. The methodology should be justified and fully reported. Wherever possible, data collection on a typical Neap tidal cycle should be performed as well in order to identify any significant changes in tidal characteristics (e.g., spatial extent of eddy structures) between Spring and Neap tides.

6.3.4.2 Characteristics

The details of the mobile survey work will be determined by the scale of the hydrodynamic system under investigation. These moving vessel current profiler surveys need to continually traverse a single line, or undertake a ladder survey or box-circuit, for a full diurnal or semi-diurnal tidal cycle. The objective is to revisit each part of the circuit with sufficient frequency to resolve variations in the current amplitude and phase. This condition typically restricts circuit times to 1 h to 1,5 h or less. Vessel speed governs the balance between horizontal resolution of the current measurements and the area covered by the circuit. Mobile velocity data shall be processed into suitable vertical and horizontal bins; these may be for instance 1 m vertical bins and 25 m to 50 m horizontal bins. Current profiler averaging times should be set to record at least one ensemble velocity profile per horizontal bin, although more would be desirable. The horizontal bin size shall be selected to resolve the significant flow features within the survey area.

Unless multiple vessels are available, wide straits or a large TEC site will likely require the survey work to be distributed over a number of separate tidal cycles. A 25 m to 50 m spatial resolution means that bottom-tracking derived vessel speeds are essential. Deep locations will typically require low frequency current profiler's (perhaps 300 kHz) and hence larger depth bin sizes and also larger horizontal bins.

NOTE 1 It may be possible to conduct harmonic analysis of the mobile current profiler data. See Simpson et al (1990), Vennell (1994), Vennell and Beatson (2006), Vennell and Beatson (2009) for details of how to conduct such an analysis.

NOTE 2 Accurate vessel positioning, both in the horizontal and vertical directions, is a critical factor in undertaking a successful mobile current survey.

Some caution should be exercised in the use of mobile transect data. Since current profiler equipment spreads a number of beams through the water column, the horizontal footprint of these beams expands (each beam and the collective scale of all beams) as the range from the device increases. In some cases, this spread can be proportional to the range, i.e., over 50 m depth the horizontal width across the beams may be up to 50 m as well. The processed information per time step is then a statement of the 'average' value over vertical bin increments and also across the horizontal sampling widths. In cases where eddies of this scale are present, standard 'averaging' may lose certain relevant details. Further, in cases where fine scale models are being considered with length scales of the order of 50 m or less, sufficient understanding of what has been described in the field versus what is being described in the model shall also be achieved. Where possible, a mobile current profiler transect (looking down) should attempt to cross a static deployment (looking up) on several occasions to provide further data to aid uncertainty definition.

6.3.4.3 Output data

For each recorded time step, the following output shall be recorded, as specified by the recording device:

- time (UTC) with year, month, day, hour, minute, seconds;
- location (given in a coordinate system consistent with the bathymetry data in 6.2);

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- velocities in the three directions (Cartesian coordinates, x,y,z with z positive upward) corrected for declination and deviation;
- measures of accuracy provided by the current profiler measurement unit (e.g., signal–to-noise ratio, error velocity);
- cell start depth (top cell) and cell stop depth (bottom cell);
- tidal height (reported in a reference frame consistent with that in 6.3.3);
- quality indicators and uncertainty levels for the horizontal positioning of the vessel.

6.3.4.4 Results presentation

The results from any mobile field survey, for tidal range and/or tidal velocities shall include the following information for each site location:

- location of the survey (given in a coordinate system consistent with the bathymetry data in 6.2), with exact coordinates of track lines;
- exact date and period of survey, with time along each track;
- tidal range observed during survey(s) relative to maximum and minimum annual (or 18,6 year) tidal range;
- synoptic maps of currents at specific depths and different stages of the tide, along the survey track and/or interpolated between adjacent transect lines in the case of a ladder survey;
- all images (e.g., survey tracks, etc.) should be presented with a consistent reference abscissa (e.g., plotted West to East on the x-axis).
- details of any problems or issues arising during the survey. Any manipulation of current profiler output data shall be reported and justified.
- an assessment of the overall quality of data collected should be conducted. The percentage of data that has been found to be good quality should be calculated. Data that is believed to be erroneous shall be highlighted, and for purposes of further data manipulation, can be removed from the record. All Quality Assurance / Quality Control practices applied to the data sets shall be noted. The original raw data should be retained for future reference.

6.3.5 Tidal current stationary survey

6.3.5.1 General

The aim of a stationary survey is to provide a temporally evolving dataset at a specific location. Gathering current velocity data during a stationary survey enables the output time-series to be used to provide primary validation and/or calibration data for an accompanying hydrodynamic model, or to directly calculate AEP for individual turbines through combination with the turbine’s power curve, and to derive harmonic constituents. Guidelines for current profiler measurements are provided in Annex B.

It is recommended that all current measurement instruments should record water level data simultaneously with currents to provide additional data for model validation and/or calibration.

Where feasible, the measurements should be acquired during periods which are subjected to less metrological forcing.

6.3.5.2 Instrument numbers and locations

6.3.5.2.1 General

Instrument deployment numbers and locations depend on the stage and scale of the assessment. If the data collected will be used for computing the AEP directly, then the data shall be collected at the location of the proposed TEC for a minimum of 90 days, ideally over the projected capture area of the TEC.

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If possible, multiple deployments across the project site should also have a sufficient temporal overlap so that they may be cross-correlated so that cross-correlations between different data sets can produce sufficiently strong correlations.

6.3.5.2.2 Stage 1 – Feasibility

A minimum of one instrument shall be deployed at the intended development site. The pre-requisite of extracting 20 harmonic constituents from a data set can be achieved with a minimum of a 35 day data set.

NOTE 1 While 20 constituents can be formally resolved from a 35 day data set, longer data sets will often improve the accuracy of the amplitude and phase estimates for these constituents. It is not yet possible to provide specific guidance on the required length of data collection to achieve a desired uncertainty in AEP.

The instrument(s) shall be positioned at locations suitable for model calibration/validation. This may include representative location(s) (e.g., based on available information about velocity, depth and bathymetry) for the intended TEC array installation. Field measurements may also be required for locations distant from the proposed site, but within the modelled domain, to provide or check the boundary conditions used in the model and provide information for model calibration and validation. Tidal eddies may impact the selection of TEC locations at the project site; therefore, eddy locations need to be considered when selecting locations for detailed static current profiler deployments.

NOTE 2 Eddies may be identified by a number of techniques, including tidal current mobile surveys, shore-based radar, current drifters, or inspection in the visual or infrared spectrum.

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 changes in depth that might affect the quality of data collection. A bathymetric survey might be required, and the recommendations given in 6.2 should be followed.

6.3.5.2.3 Stage 2 – Layout design

Depending on the scale of the tidal development array, a number of short-term deployments of a period not less than 35 days shall be deployed across the region of the TEC array. The short-term deployments should encompass the intended array in a manner that allows for validation of the hydrodynamic model at scales commensurate to the TEC scale and the array extent. Where possible, to inform the robust resource assessment of potential annual energy production from a TEC array using validated hydrodynamic models, data should be collected over a 12 month period with the frequency of data acquisition higher than during Stage 1.

NOTE As noted in 6.3.5.3, deployments longer than 35 days would reduce the uncertainty in both harmonic and time-series analysis of the data.

The variability of local topographic and bathymetric features shall be considered when selecting the number and location of instrument deployments.

For a small array, the instrument(s) should be deployed at the centre of the array (or at key representative locations). For a medium or large-scale tidal array, the number of instruments should be informed by the hydrodynamic modelling which will show the likely variations in velocity across the array.

6.3.5.3 Characteristics

Current profiler deployments shall span a minimum of 35 days if being used for calibration/validation of the model simulations and 90 days if being used to directly compute the AEP through combination with the turbine's power curve. Modern current measurement instruments (e.g., current profiler) have limited data storage capacity available to record current data. The duration of the deployment for the units therefore depends on the recording interval which may be as short as 1 s to 10 s or longer such as 1 min to 10 min. In any case, an averaging period of 10 min or less, but greater than or equal to 2 min shall be used (to filter the majority of turbulence from observations). A suitable integer divisor of 10 min, or

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600 s, should be used for consistency with AEP calculation. The sampling frequency should be maximised within the constraints of battery life and memory storage (where applicable) and ensure a minimum sample rate of at least once every 20 s.

The velocity data should be processed into vertical bins (resolution will depend on the instrument used and depth of water) with u, v, w (the three current directions) and z (depth) in each bin for each time interval and the bin averaging method should be noted.

The vertical bins should start as close to the seabed as possible and extend close to the sea surface, ensuring full coverage at the likely deployment depth.

In general, a longer recording period (with lower frequency recording intervals) is suitable for informing tidal resource assessment and for providing verification of data from tidal modelling studies. A shorter recording period (with higher frequency recording intervals) provides additional information on higher frequency current variability that is generally only required for TEC turbine design (but this data may also be important for tidal resource assessment). The impact of high frequency flow variability (in particular turbulence and short-period waves) on energy yield assessment is not yet well understood and hence the latest literature may be consulted.

In sites with a large tidal range or with strong surface effects (e.g. waves), care shall be taken when analysing the near-surface bins.

The heading of the instrument should be recorded over the course of the deployment, corrected for declination and deviation and analysed to assess whether movement occurred during the deployment that might compromise the accuracy of the velocity data. Review of pitch and roll can also be used to assess movement of the device during the deployment period.

The frame for the current profiler should be designed to minimise magnetic deflection (i.e. constructed with non-ferrous materials). The compass calibration should be carried out with the unit mounted within the deployment frame/pod.

Vertical bins for which more than 5 % of the data have been rejected due to quality control should be excluded from the analysis. This can occur close to the surface, particularly for sites with large tidal ranges. Inclusion of these bins can result in erroneous calculations if, for example, measurements of that bin are only possible around high tide, rather than evenly distributed over ebb and flood.

6.3.5.4 Output data

The measuring instrument should be defined and described, together with a description of how data collection was conducted. An assessment of the overall accuracy of the data shall be presented for each time step, and the following output shall be recorded:

- location of survey (given in a coordinate system consistent with the bathymetry data in 6.2), taking account of any local/national regulatory requirements;
- time (UTC) with year, month, day, hour, minute, second;
- all applied data calibrations;
- velocities in the three directions for all depth bins;
- measures of accuracy provided by the current profiler measurement unit (e.g., signal-to-noise ratio, error velocity);
- measures of current profiler orientation (e.g., roll and tilt) that can be used to interpret, correct and/or reject data during processing;
- measures of current profiler heading;
- cell start depth (bottom cell) and cell stop depth (top cell);

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- total water depth and tidal height above the project chart datum.

6.3.5.5 Results presentation

The results from any static field survey for tidal range and/or tidal velocities shall include for each deployment:

- location shown on a geo-referenced map with the bathymetric data and shoreline, given in a coordinate system consistent with the bathymetry data in 6.2;
- exact date and period of survey;
- maximum and minimum tidal range observed during survey, preferably relative to maximum and minimum annual (or 18,6 year) tidal range;
- measures of accuracy provided by the current profiler measurement unit (e.g. signal to noise ratio, error velocity);
- maximum currents observed;
- depth averaged current velocity and tidal height time-series throughout the period of deployment;
- time and bin-averaged current profile through the water column:
  - Data averaged and separated out into hourly flood and ebb tide records, for all data where velocity is greater than 0,5 m/s;
  - Data separated into vertical bins as internally recorded by the instrument (depth cell resolution) or manually averaged by post-processing into larger bin sizes if necessary (nominal bin size/depth ratio of maximum 5 %);
- details of any problems or issues arising during the deployment. Any manipulation of current profiler output data (e.g. to correct or reject data due to pitch and roll of the device) shall be reported and justified;
- the compass calibration procedure and results should be recorded;
- an assessment of the overall quality of data collected should be conducted. The percentage of data that has been found to be good quality should be calculated. Data that is believed to be erroneous shall be highlighted, and for purposes of further data manipulation, can be removed from the record. All Quality Assurance / Quality Control practices applied to the data sets shall be noted, especially any data filtering/removal carried out, particularly in order to derive the depth averaged velocity and the higher and lower vertical bins if they have been extrapolated.

The depth averaged current velocity should be obtained by assuming a constant velocity above the uppermost bin and a linear interpolation to zero between the bottommost bin and the sea bed.

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6.4 Meteorological data

6.4.1 General

Meteorological data to be used for determining the importance of the wind and atmospheric pressure, as described in 7.4.3, shall be identified and reviewed. The locations, period of record and an assessment of the quality of the data shall be reported. In the absence of sufficient measurement data, an alternative is to obtain data from combined numerical models with processed satellite derived wind data.

6.4.2 Wind data

Subclause 7.4.3 identifies whether or not a wind measurement survey is required for the modelling. Measurements should be undertaken following the methodology described in IEC 61400-12-1.

6.4.3 Atmospheric pressure

The variation of atmospheric pressure should be recorded during any field data collection using appropriate means (e.g., a barometric pressure sensor and data-logger). This information may be necessary to account for meteorological atmospheric pressure variations impacting on the resource (e.g., in extreme cases, storm surge).

6.5 Wave climate

Existing wave data at the location of interest shall be reviewed. If sufficient information is already available at a specific location, there may not be a need for further measurements. If the area of interest is not exposed to swell waves, or if it is considered that the wave climate can be modelled using appropriate long term wind datasets, there might be no requirement for a wave monitoring survey, but the decision shall be explained and an assessment of the wave characteristics detailed. For the purpose of resource assessment, the potential for substantial wave-current interaction to have a material impact on the development of flow conditions shall be considered.

The recommended approach for gathering wave related data is to use a waves-enabled current profiler unit (see Note 2). The validity and source of all wave data shall be verified and provided.

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NOTE 1 The local wave characteristics will directly impact the design of TEC devices. The wave characteristics may also potentially impact the long-term tidal energy resource. However, these issues are not covered in this Technical Specification.

NOTE 2 Waves are typically measured in coastal environments using floating wave measurement buoys, which are typically accelerometers or GPS units mounted on an elastic mooring. This approach will not work effectively in combination with extreme tidal conditions as the buoy will be dragged to the maximum extension and its response will be highly biased. It is also important to note that wave-enabled current profilers have a maximum deployment depth for accurate wave measurement. This maximum depth depends of the wavelength of the waves and the profiler operating frequency. Many current profilers cannot monitor waves and currents concurrently which would problematically produce significant gaps in the current profile data.

6.6 Turbulence

6.6.1 General

It is not currently known what scale, frequency and magnitude of current variability (resulting from eddies/turbulence) are important, nor are the limits of hydrodynamic (tidal) and CFD modelling used for turbine design known. This is a subject of ongoing research.

6.6.2 Flow structure / Eddies

Tidal flows past obstructions (e.g., headlands, islands, and in-stream structures) can result in separation, vortex (eddy) formation and shedding that may significantly alter inflow characteristics to TECs positioned leeward of these bathymetric anomalies.

Navigation charts should be consulted to identify obstructions that may lead to significant vortex formation and shedding. For the Stage 2 resource assessments, detailed hydrodynamic modelling should be validated with remote sensing techniques, or stationary/mobile current profiler data collected leeward of the obstruction to verify estimates of the shedding frequency and eddy sizes.

NOTE 1 Predominant features of vertically oriented eddies include:

a) periodic, organised and asymmetric oscillatory motions of the mean flow field at shedding frequencies characterized by the predominant length scale of the obstruction and the speed of the tidal current; and

b) increased turbulence production and intensity. Turbulence characteristics may be quite different between flood and ebb tides.

NOTE 2 The effects of turbulence on TEC performance and annual energy production (AEP) are complex and continue to be an important area of research.

NOTE 3 Alternative remote sensing techniques such as Synthetic Aperture Radar (SAR) have shown some promise in estimating surface current velocities and turbulence features that can be used to better simulate the turbulence characteristics of the site. SAR or other appropriate techniques may help identify eddies and may allow verification of detailed modelling studies.

6.7 Stratification, seawater density and sediment measurement

CTD (conductivity, temperature, density) data near the project site, which can assist with determining the relative importance of stratification and horizontal density driven currents, as described in 7.4.7, shall be identified and reviewed. The location, period of record and an assessment of the quality of the data shall be reported. If sufficient information is already available at a specific location, further measurements may not be required.

The variation of seawater density can have a minor impact on the available energy resource in the water column. In addition, it should be noted that seawater salinity, temperature and density also impact the speed of sound in water which shall be taken into account when calibrating current profiler instruments.

NOTE It is likely that in most situations the water column in strong tidal flows is well mixed due to the inherently energetic nature of the flow in the region of interest. However, in some situations density (salinity and/or temperature) stratification at the TEC site or distant from the site may generate complex behaviour even in the presence of substantial tidal flows. The contribution of stratification to measured currents can be assessed by low-pass filtering stationary current measurements. See Polagye and Thomson (2013) for an example.

High-speed tidal flows may carry a heavy load of sediment in suspension. Such heavy sediment loads, especially sand and gravel near the seabed, may significantly affect the fluid density, turbulence and friction in the flow, which may impact the set-up of hydrodynamic numerical models and also the placement and performance of current profilers. If high sediment loads are suspected, further investigations are recommended, for example using sediment traps on the same platforms as the deployed current profilers.

7 Model development and outputs

7.1 General

For projects larger than c. 10 MW or 2 % of the theoretical undisturbed resource, AEP shall be assessed by hydrodynamic modelling, with appropriate verification by measurements using hindcasting. Hindcasting is used to test or validate a numerical model, by running it for a past time period and comparing results with observations. The application of hydrodynamic models for such projects, rather than in-situ measurements, is required for several reasons, including the greater spatial coverage provided by a model, the ability to use a model to forecast future system behaviour (e.g., response to changes in the existing system such as energy extraction and long term adaptations), and the avoidance of unnecessarily onerous and expensive field data collection requirements.

For projects where the total power output is expected to be less than c. 10 MW, or those where the proposed energy extraction is less than 2 % of the theoretical undisturbed tidal energy resource, AEP may be estimated from direct resource measurements using static current profiler measurements and harmonic analysis as defined in 8.2.3. In order to use this method, measurements shall be made at each individual turbine location.

7.2 Model coverage, resolution and boundary conditions

7.2.1 Bathymetric data

The quality and resolution of available bathymetric data directly influences the ability of a numerical model to replicate the flow dynamics. Accordingly, best practice in terms of sourcing and quality checking bathymetry data needs to be followed. Processes to ensure that the numerical domains appropriately replicate the actual bathymetry should be adopted and justified.

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The resolution of the model across the domain shall be justified and reported. Guidance is presented in Table 2 relating to minimum grid resolution in the area of interest for project development, and further information is provided in 6.3.5.2. The specification of a maximum of 50 m grid resolution at Stage 2 is an upper bound to the resolution required to capture the spatial variability of the tidal resource in the area of interest at a resolution appropriate to inform micro-siting consideration and overall array AEP assessment.

7.2.2 Model coverage

The model coverage area shall be determined by:

a) the Stage of the resource evaluation (see Table 1);

b) the availability and location of appropriate data for developing model boundary condition specifications;

c) boundaries being sufficiently distant from the proposed TEC site to ensure that they do not artificially influence model results.

NOTE 1 Model coverage beyond the continental shelf break is considered best modelling practice (e.g. Kawase and Gedney, 2013). The benefit of doing so is that accurate boundary-condition specification of tidal constituents can be derived from satellite altimeter sea-surface elevations (globally available). The reliability of such data is increased in deep water, and because tidal constituents are less significant in deep water, the accuracy is increased. The major advantage of using a boundary located beyond the continental shelf break is that shallow water effects that accumulate as tidal waves propagate onshore will naturally develop within a well constructed numerical model. These shallow-water effects are spatially variable and difficult to prescribe accurately if arbitrarily imposing a boundary location within the shelf region. An additional advantage of extending the model simulation region beyond the continental shelf break is that processes within the model domain, such as the energy extraction associated with a proposed TEC array, do not significantly feedback on the boundary specification.

The offshore model boundary should extend beyond the continental shelf break unless detailed boundary conditions are available from another model that does extend beyond the continental shelf. If the model does not extend to the continental shelf break, local shallow-water, topographic and bathymetric effects may be inadequately represented depending on the scale of the tidal array and its effects on the tidal system.

NOTE 2 Requirements for environmental impact assessments at locations distant from the tidal array may also be an important determinant of model coverage.

NOTE 3 Model coverage may be constrained by practical issues such as computational limitations. However, to appropriately identify potentially non-intuitive hydrodynamic interactions, sufficient investment in model development and validation is a crucial aspect of project development for TEC arrays.

7.2.3 Model boundary conditions

Model boundary-condition location and specification are critical to ensuring model accuracy (particularly when modelling energy extraction). The location and accurate representation of these boundaries should be carefully considered at the earliest stage of model development. Boundary data should be constructed from individual constituents for harmonic tidal models, or time series simulated from the available tidal constituents for time stepping models (see 7.3.1).

Sources of boundary information include measured tidal height data from tidal stations, regional-scale tidal hydrodynamic models, and satellite-derived data (see 6.3). In the absence of appropriate boundary data for the desired domain, it may be necessary to extend the model domain until reliable boundaries can be included. Unstructured grid models often ensure a balance of large area coverage and fine-scale detail in sensitive areas of interest. If a structured grid modelling approach is adopted, and nesting becomes necessary, dynamic two-way nesting is recommended.

Although model dependent, both tidal height and velocity data may be necessary for boundary specification; however, tidal velocity data alone is not sufficient. If the model domain does not extend to deep ocean waters, it is typically necessary to include current velocity, as well as the primary tidal height in specification of the boundary condition. In these circumstances it is particularly important not to “over specify” the boundary condition especially for a combination of current and tidal height.

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The extent of the domain needs to be sufficient to ensure the region of interest is not unduly influenced by the model boundary. For Stage 2, when modelling the effects of energy extraction, it is necessary to demonstrate that the model boundaries are beyond the area of impact of energy extraction by comparing to the baseline case.

NOTE 1 If the model boundary does not extend beyond the continental shelf break, it is likely that multiple tidal-station data will be necessary to specify boundary conditions. In such cases, it would be beneficial to incorporate data assimilation techniques (in conjunction with standard methods of prescribing model boundary conditions).

NOTE 2 Literature providing an introduction to data assimilation techniques in numerical models includes Robinson and Lermusiaux (2000), and Zhang et al. (2003).

7.2.4 Model resolution

7.2.4.1 General

The recommended grid resolution for each Stage of a resource assessment is provided in Table 2. The model may be refined as the assessment progresses through the different Stages. Also, model refinement may occur as more data becomes available, such as improved bathymetric resolution, seabed characterization or validation data.

7.2.4.2 Stage 1: Feasibility study

For feasibility, the resolution should be finer than 500 m in the region of interest, and refined to 200 m in regions of bathymetric complexity. Note that resolution finer than 200 m may be necessary in localized areas and narrow channels (see Table 2) including in the vicinity of the proposed TEC array. The limitations of using a coarse-scale model should be recognized and quantified where possible. To demonstrate the validity of the resolution, simulated velocities should be validated against mobile or static field survey data, as described in 7.5.2.

7.2.4.3 Stage 2: Layout design study

Resolution for layout design shall be as fine as reasonably practical, determined by the area to be covered, data density of the bathymetry, and the computational expense. The maximum recommended cell size in the region of interest is 50 m. In order to demonstrate the validity of the resolution, simulated velocities should be validated against mobile and static field survey data, as described in 7.5.2 and it is recommended that a time series simulation spanning at least one month be used for validation.

NOTE Non-hydrostatic pressure may become important at grid spacing below 20 m, therefore it may not be practical to use grid spacing smaller than this for hydrostatic models.

7.3 Choice of model (including characteristics)

7.3.1 General considerations

Hydrodynamic models suitable for tidal resource assessment can be categorized by two general characteristics:

a) time-domain treatment – frequency (harmonic) models or time-stepping models;
b) space domain treatment – structured computational grid (rectangular/curvilinear) or un-structured computational grid (variable size triangular or quadrilateral).

Harmonic tidal models are computationally efficient because they do not require time-stepping. However, harmonic models do not resolve detailed information on flow (current) structure in strongly advective local flows usually present at sites with strong currents. The use of harmonic models is only appropriate for scoping studies or to provide model boundary conditions for more detailed time-stepping models.

Structured-grid models use finite difference or finite volume formulations and have a long history of successful development and application. The grids may have only a single cell size and may require “nesting” or expanding/telescoping within the larger area model to resolve

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flow detail in the local area of interest. Modern structured grid models can be used for all stages of project resource evaluation, as long as the model formulation can accurately define flow structure (e.g., tidal eddies) in the strongly advective regions.

Unstructured-grid models were developed to remove the constraints imposed by a fixed grid size in structured grid models. Resolution in unstructured models can range from kilometre scale at the model boundaries to metre scale in the area of interest. Finite element and/or finite volume mathematical formulation methods are typical. Unstructured-grid models are particularly suitable for large regions of ocean where the grid size can be large while allowing very detailed discretisation of areas of interest for tidal device installation. Modern unstructured grid models can be used for all stages of project resource evaluation, as long as the model formulation can accurately define flow structure (e.g., tidal eddies) in the strongly advective regions.

7.3.2 Model selection

Existing hydrodynamic models covering the area of interest may provide the necessary data without the need to develop a purpose-built solution. Alternatively, existing models can be adapted and/or appropriately extended to meet requirements. These are deemed legitimate approaches to meeting the requirements of this Technical Specification. In the absence of existing solutions, purpose-built model simulations will be required.

The following criteria shall be considered, documented and justified during the model selection process:

a) Model and modellers provenance:
   - qualified and skilled numerical modellers;
   - development cycle of the code to be utilised, i.e. stable release vs. development;
   - past successful applications of the code to similar projects with appropriate references;
   - acceptance of the code in the commercial domain; i.e. that the results will be acceptable for project financing decisions.

b) Basic model features and parameterisation:
   - complexity of the computational domain and parameterisation of the governing equations;
   - refinement processes in the computational domain with regards to unstructured meshing or nested regular grids and the implications these choices may have on model accuracy and computational time;
   - complexity and options with regards to boundary-condition specifications (e.g., open, closed, spatially/temporally varying, head, discharge, flux or Flather based);
   - application of Coriolis forces and the reasoning behind inclusion or exclusion;
   - wetting and drying of cells in the intertidal domain, options to reduce oscillation;
   - treatment of turbulence, or its influence, within the model and substantiation of parameter choices;
   - inclusion of shear stress (friction) and rationale for the selection (e.g., global or spatially varying parameter based on field data or free parameter used in calibration);
   - techniques used to represent energy extraction and its parameterisation.

c) Specific model features and parameterisation (where shown to be important):
   - application of wind fields and use of spatially varying vs. global variables;
   - inclusion of wave effects;
   - ability to model eddy formation;
   - treatment of density structures, i.e. barotropic vs. baroclinic, and level of configurability in equation setup;

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- input of fresh water inflows as point source or boundary conditions;
- inclusion of ice coverage;
- implementation of precipitation and evaporation;
- treatment of mobile bedforms;
- hydrodynamic parameters such as horizontal momentum diffusion, turbulence diffusivity, eddy viscosity, and rationale for selection.

7.3.3 Model characteristics

7.3.3.1 Duration of the model calculations

After allowing for appropriate initialisation (which shall be documented and justified), the model is to be run for a minimum of 35 days of simulated time for Stage 1 and Stage 2, such that errors associated with the velocity probability distributions are minimised.

7.3.3.2 2D versus 3D

For Stage 1 studies the model may be either 2D (depth-averaged) or 3D, which resolves vertical velocity variations. At Stage 2, the vertical dimension shall be resolved. Each vertical bin should be sufficiently fine to resolve boundary layers and to include several vertical bins in the cross-sectional area of expected TEC deployments.

Depth-averaged velocity output from 2D models will need to be converted to the velocity at the depth of the TECs for AEP calculations as described in 7.5.2.2.

7.4 Analysing data to provide model inputs, calibration and validation

7.4.1 Bathymetry interpolation

The bathymetric data should be interpolated at a scale appropriate to the entire model domain and computational resources available, with the procedures being reported and justified. If the existing bathymetric data available is not found suitable to meet the needs of the particular Stage of the project, a bathymetric survey (see 6.2) shall be commissioned to provide the necessary resolution.

Modelling practice suggests that bathymetric data should be at least as well resolved as the minimum model cell size throughout the model domain.

7.4.2 Currents

If mobile surveys are available, then an analysis of the current magnitude, variability, and current ellipses over the route of the survey is required.

For static surveys, an analysis of the harmonic constituents of the current for depth averaged velocity is required in Stage 1, and for appropriate vertical bins in Stage 2 (see 7.5.2.2). The depth averaged velocity is to be determined by appropriately averaging across the available vertical bins (it is acknowledged that this analysis is constrained by the availability of data in the bottom boundary layer due to the method of data collection). The validity of the use of harmonic analysis shall be determined by demonstrating the computed constituents capture at least 95 % of the variance of the measured time series.

7.4.3 Meteorological analysis

7.4.3.1 General

Meteorological phenomena such as wind and atmospheric pressure can impact coastal flow development. These phenomena can be persistent (although variable) or may be episodic. Analysis of in-situ data shall assess these potential impacts on overall flow characteristics by comparing observed and modelled system dynamics. If meteorological factors are found to

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significantly impact flow dynamics at the project site – for example, a 5 % change in the current velocity across the area of interest between measured and simulated velocities – these phenomena shall be included in the numerical hydrodynamic simulations.

7.4.3.2 Available wind data at location

The details of measured wind data across the model simulation domain shall be listed with reference to the location of the monitoring station and the period of measurements, and the quality of the data available shall be assessed.

In the absence of measured wind data, a combination of numerical model wind simulation outputs and processed satellite derived wind data may be used. If this approach is used, details of the simulated wind data, its characteristics, and an assessment of accuracy of the predictions shall be reported.

NOTE In general, model outputs of satellite re-analysis data (i.e., satellite and modelled data) are accessible from the web or various national providers (typically government agencies).

7.4.3.3 Assessing the impact of wind on numerical simulations

The influence of local wind conditions on hydrodynamic modelling simulations of periods coincident with the field data should be assessed by including a generic representative set of wind velocities (e.g. using satellite re-analysis wind data coincident with the model simulation time period). Simulation results with and without wind forcing should be compared.

NOTE The wind data record may assist in assessing the source of unresolved variability or persistent residual errors observed in numerical model simulations when compared with field data.

7.4.3.4 Atmospheric pressure

Atmospheric pressure data coincident with the field data period shall be obtained from an appropriate source (e.g., a national weather forecasting service). The atmospheric data shall be analysed to assess the potential for a significant impact on the results of the validation testing between numerical model simulations and field data (or data derived from field data). If potential for significant specific events (e.g., storm surge) is identified, then atmospheric pressure forcing shall be incorporated in the appropriate validation test cases. The process for assessing whether incorporating atmospheric pressure data in the validation is required shall be documented and justified. If atmospheric pressure forcing is imposed in numerical model simulations, the procedures and input data shall also be reported and justified.

NOTE The impact of atmospheric pressure variability on tidal hydrodynamics varies. Specific events, which include storm wind stress and atmospheric pressure, can lead to important phenomena (e.g., storm surge) that will not be reflected in the model results if they are not included in the model development.

7.4.4 Waves

For the purposes of tidal resource characterization, an assessment of the importance of waves in substantially altering the flow conditions at the development site shall be conducted during Stage 1 of the resource analysis. If waves are deemed important, then output from wave analysis software may be used to inform any justifications for (storm-related) periods when the hydrodynamic model outputs do not match the measured data, in contrast to other (non-storm-related) periods where there is a good correlation. If wave measurements have been conducted, then the data should be used to validate the wave analysis. Wave data analysis and application to tidal resource characterization shall be reported and justified.

7.4.5 Turbulence

Simple assessment of the gross properties of the mean and fluctuating flow properties may be reported if available using standard techniques (see Note 1). Further analysis of the mean and fluctuating flow properties at various stages of the tidal cycle may also prove to be informative. As a minimum, time-varying turbulence intensity and vertical distribution of the

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horizontal velocity should be analysed and reported from the available field data. Turbulence intensity (I) is a measure of the generic properties of the flow variability.

$$I = \frac{u'}{\overline{U}} \quad (1)$$

Where u' is the root-mean-square of the turbulent velocity (or standard deviation) and $\overline{U}$ is the mean velocity. However, these assessments may be limited by current profiler set-up, as the calculation requires high frequency data (see Note 2). It may also be beneficial to consider the inherent noise in the data due to the set-up of the current profiler (see Note 1). If the turbulence intensity, I, is reliable when compared to background noise levels, then the turbulent kinetic energy (K) can additionally be estimated.

$$K = \frac{3}{2}(\overline{U}I)^2 \quad (2)$$

Alternatively, turbulent kinetic energy dissipation (ε) may be estimated from the velocity shear measurements using:

$$\varepsilon = \frac{15}{2}\upsilon\overline{\left(\frac{\partial U}{\partial z}\right)^2} \quad (3)$$

Where υ is the kinematic viscosity and $\overline{\left(\frac{\partial U}{\partial z}\right)^2}$ is the time average of the square of the vertical gradient of the horizontal velocity.

NOTE 1 Gooch et al. (2009), Gunawan et al. (2011), Stevens et al. (2012) and Thomson et al. (2012) are examples of useful reference papers.

NOTE 2 See 6.3.5.3, the current profiler set-up most appropriate for assessment of tidal characteristics across lunar cycles may not be also well suited to turbulence analysis.

Vertical distribution of the horizontal velocity should be reported graphically and for flood and ebb tides separately.

The turbulence data could be used for the numerical modelling (e.g., to best match bottom friction estimates) and AEP estimates.

NOTE 3 The evolution of turbulence intensity (I) and turbulent kinetic energy (K) in highly energetic tidal regimes is an area of ongoing research, especially with respect to how this evolution is impacted in the near-field by TEC operation. Measurements of turbulence intensity at potential tidal energy development sites and in the wake of individual (and arrays of) full-scale operational TECs are necessary to inform whether additional prescription is required.

7.4.6 Flow Structures / Eddies

Mobile current profiler measurements should be analysed to characterize the spatio-temporal variation of the inflow velocity field acting on the TEC. Vortex shedding effects on the inflow can be characterized using methods described (see 6.6.2) and eddy length scales obtained from the field measurement data. If these are identified in the region of the intended development site, the model, validated with additional mobile surveys as required, should be used to quantify the extent, strength and temporal variability of the flow separation and wake zones. Methodologies used to assess flow structure and eddies should be reported alongside interpretation of the analysis (e.g. see Note). If significant off-axis flow, or flow asymmetry, is found in Stage 2, it shall be documented at the deployment site(s) via field measurements at a resolution relevant to TEC deployment.

During numerical model selection for Stage 2 it is important to select a hydrodynamic model that can accurately model eddy formation (harmonic models cannot normally model eddies).

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NOTE Gonella, 1972 is an example of a useful reference text.

7.4.7 Seawater density, salinity and temperature

The international thermodynamic equation of seawater – 2010 (known as TEOS-10) (IOC, SCOR and IAPSO, 2010) should be utilised to determine density profiles from CTD data, and the results obtained reported and interpreted. Field data will be specific to the measurement location. Additional analysis of potential density structure and density driven flow both in the region of interest for development, and the wider area to be simulated in the numerical model can be achieved to some extent by analysis of historic databases. Historic databases (see note) can be useful sources of ocean salinity and temperature throughout the intended model domain. The decision as whether or not to include modelling of temperature and salinity transport during Stage 2 shall be reported and justified.

NOTE One such database is NODC (Levitus) World Ocean Atlas 1998:

http://www.esrl.noaa.gov/psd/data/gridded/data.nodc.woa98.html

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7.4.8 Sediment

If a significant suspended sediment load is found to be present at the project site, then the impact on the fluid density/viscosity used in the model should be considered, including the resulting changes in depth averaged model bottom friction (for 2D models) or bottom friction and turbulence definition (for 3D models). The procedures used to include suspended sediment in the numerical model, where appropriate, shall be reported and justified.

7.5 Model calibration / Validation

7.5.1 Model calibration

Model calibration should include the adjustment of bottom friction/turbulence parameters and in some cases model grid refinements, so that model results provide the most accurate numerical match to measured data.

At all project stages the numerical model shall be calibrated against tidal height measurements recorded within the model domain. The tidal height stations, see 6.3, used for calibration should provide good spatial coverage of the model domain. They should be selected to provide the best overall description of the tidal dynamics in the model area. By comparing time series of tidal height calculated from tidal constituents obtained from the measurements and actual measured tidal height, it can be established whether non-tidal factors play an important part in determining water level and current conditions in the modelled domain (e.g., if the constituents capture 95 % of the variance). Modelling strategies can then be identified to investigate the magnitude and significance of non-tidal factors and estimate the impact on tidal energy resource.

Model and measured tidal height data shall be compared on the basis of harmonic constituents of amplitude and phase for all constituents determined to be important in the measurements, or compared to the time series directly if harmonic analysis was deemed insufficient.

Many archived tidal height records are of short duration. The record duration determines the number of constituents that can be differentiated during the tidal harmonic analysis and the accuracy of the analysed constituents. In addition short duration records may contain short-term or medium-term non-periodic contributions to water level, such as storm surge or atmospheric pressure, which are not accurately filtered out during the harmonic analysis. These factors may contaminate the constituent data sets used for model calibration and it is recommended, where possible, that primary model calibration be done on a small set of longer term tidal height records (>35 days) supplemented by shorter records where necessary.

The model should also be calibrated against tidal height data measured at the site during the mobile surveys (Stage 1) and any static surveys which include water level measurements (Stage 2). Model calibration to tidal height data measured at the site is likely to be challenging because of the rapid changes in harmonic constituent phase in areas of high tidal current velocity. However, calibration to the site data may identify an area of the model where the numerical resolution is inadequately refined to define the tidal dynamics accurately. It is therefore strongly recommended that model calibration, to measured tidal height data at the site, should be attempted at an early stage of model development, so that the appropriate model grid resolution for tidal height simulation can be determined.

The accuracy of the model simulations of tidal height and phase shall be reported in the form of tabular and graphical comparisons between model and measurements for all the major modelled harmonic constituents. The report shall include an estimate of the overall accuracy of the model (percent error in amplitude and degrees of phase), an identification of any local anomalies in model performance/accuracy, a description of any systematic differences between modelled and measured results, and a justification for the selection of the calibrated model simulation.

NOTE Inclusion of phase error separate from amplitude error is important, as phase error will directly lead to amplitude error and it may be useful to also analyse the amplitude error after correcting for phase error.

Measured tidal data, usually archived by national hydrographic departments in the form of harmonic constituents, may contain occasional systematic errors such as unit conversions (e.g., feet to metres) or timing errors (recorder clock errors or daylight savings time). These types of error can often be identified during model calibration. However, if no clear error can be found or explained, then the problem data set should be eliminated from the model calibration procedure.

Model calibration to tidal height ensures that the numerical model is able to accurately simulate flow continuity in the numerical domain. However, this procedure does not determine whether the model can simulate momentum/advection processes important to accurately model currents. Two issues determine whether the currents are modelled correctly:

a) model ability to simulate strongly advective flows, specifically with respect to major eddies, and
b) model grid discretisation.

Therefore it is recommended that simulated model currents are compared in detail to measured current data to determine whether the model selected is capable of simulating measured currents at the project site and that the grid discretisation (refinement) is adequate to replicate observed current conditions. If either of these criteria cannot be met, then either a more advanced numerical model should be considered and/or the computational grid refined until currents are modelled more accurately.

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7.5.2 Model validation

7.5.2.1 General

Validation of the model simulations is achieved with quantitative comparisons between the AEP results computed from the stationary surveys of the measured current and from the model simulations. The AEP shall in each case be calculated based on the method outlined in Annex A using time series computed from constituents of the modelled or measured currents, or the time series may be used directly if harmonic analysis is deemed insufficient.

Measured long period tidal data (> 35 day) includes many more tidal constituents than can usually be simulated in a numerical model. These “missing” tidal constituents (found in the measurement record) may be used to supplement the modelled constituents where very long term (> 1 year) tidal height and current predictions are required.

It may be necessary to apply a low pass filter to the measured current data, to remove instrument noise and turbulent motions. In this instance, the correct phase shall be preserved. If necessary, the data for each horizontal component shall be filtered first forward and then backward in time through the same filter to avoid introducing a phase shift. The filtered and unfiltered data shall then be compared, particularly with respect to its resultant power density.

The percentage difference between the model and the measured data shall be summarized. The reasons for substantial differences between the model and the measured data should be investigated and substantiated wherever possible.

NOTE 1 A suitably constructed and implemented model at Stage 2, when compared to correctly measured currents at a suitable location, may typically have c. 5 % errors in the relevant current velocities, which corresponds to uncertainty in AEP of c. 15 %.

NOTE 2 Reasons for substantial differences between the model and measured AEP may include: measured currents being in locations of significant eddies; errors in measured currents; and other modelling errors such as lack of sufficient resolution in time or space.

NOTE 3 Appropriate statistical techniques include assessment of mean and absolute relative error (e.g., Brière, et al. 2006) and model skill analysis testing (e.g., Warner et al. 2005). Hess et al. (2003) provides additional methodologies for analysing model data agreement.

An assessment of the overall accuracy of the modelling at the site and an explanation of how the model accuracy will impact the magnitude of estimates of the tidal resource shall be undertaken.

7.5.2.2 Current depth profiles

If the model is only operating in 2D for Stage 1 studies, the approach used to extrapolate the velocity from the average depth to the hub height shall be reported and justified. A recommended approach in these cases would utilise velocity profile data from the static survey to assist in defining characteristic depth profiles across the region of interest. However, extrapolation from 2D results is a significant assumption and this shall be taken into account when defining uncertainty of the final results.

For 3D studies, the measured current depth profiles should be plotted at different critical locations and times to compare to the modelled current profiles where the model is operating in 3D. As a minimum, consideration of instantaneous profiles during the flood and ebb cycles across the record length shall be compared.

NOTE 1 Modelled and measured current profiles can be directly compared by animating both data sets over time and observing any systematic differences. Small differences in phase make this comparison difficult and the modelled data may have to be “corrected” for phase to allow a direct comparison of the measured and modelled current profiles.

NOTE 2 In Stage 2, at the final model calibration phase, 3D measured current profiles can be used to improve the modelled current profiles by estimating and then testing out revised bottom friction, drag and turbulence parameters.

The quality of fit between the predicted numerical model current profile results and the observed data from tidal velocity time series data shall be assessed, interpreted, and reported. The methods used to conduct this assessment shall be reported and justified.

7.6 Incorporating energy extraction

7.6.1 General

The preceding subclauses have considered the undisturbed tidal energy resource. However, the act of harvesting energy from this resource will disturb the underlying tidal hydrodynamics. This will have implications locally in terms of altered flow fields in the immediate vicinity of the TEC (e.g., the downstream wake generated by device TEC, changes in eddy patterns), and potential far field impacts (e.g., reduced tidal prism, tidal flow diversion from the project site, changes in tidal phasing). When assessing the available tidal energy resource, it is therefore necessary to consider the impact of various levels of energy

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harvesting and subsequently assess the proposed development with an understanding of the energy extraction impacts.

NOTE 1 Understanding of the potential impact of energy extraction from TEC arrays is evolving; existing useful references include: Black & Veatch/Carbon Trust (2011); Garrett et al. (2004); Garrett et al. (2005); Sutherland et al. (2007); Polagye et al. (2008); Karsten et al. (2008); Draper et al. (2009); Vennell (2010); Vennell (2011); Polagye et al. (2011), Defne et al. (2011), Walters et al (2013).

NOTE 2 In the case of a series of downstream TECs, it is important to characterize and quantify the extent of the wake of the device, e.g., see Stevens et al. (2012).

Further developments in understanding the impact of TEC operation and energy extraction are likely to arise. Solutions proposed in the latest peer-reviewed literature should be carefully considered as scientific understanding evolves. In particular, enhanced understanding of TEC to TEC interactions, informed by observations of operational arrays of TECs and high resolution CFD modelling, may enable improved parameterisation of these processes within hydrodynamic models.

NOTE 3 These impacts are important from a physical environmental perspective (e.g., altered tidal range, alteration to sediment transport patterns), from a biological environmental context (e.g., alteration of the position of tidal fronts impacting feeding patterns across the trophic levels), and from an economic perspective (e.g., reduced flow velocity available to the TEC and hence a potential shortfall in estimated revenue generation).

7.6.2 Methodology for incorporating energy extraction

7.6.2.1 General

Incorporating energy extraction in the numerical model is required to enable assessment of future scenarios incorporating the proposed array development. A parametric equation (often additional) is required, embedded in the numerical model, which captures the essential operational characteristics of the proposed technology and acts as an appropriate energy sink.

Energy extraction modelling shall be included in the resource characterization activity wherever the intended installed capacity is greater than 10 MW or the proposed energy extraction is greater than 2 % of the theoretical undisturbed tidal energy resource (see note 1 in 7.6.1).

NOTE Energy extraction assessment for an array of TECs prior to project development can only realistically be assessed using a numerical modelling framework. Methods for assessing energy extraction impacts, by embedding an additional parametric based term or terms in a tidal hydrodynamic model, have been proposed in the academic literature. It is possible to apply these techniques using the numerical model already developed for the resource characterization. The existing methodologies are a ‘work in progress’ and require validation against appropriate field data when relevant large-scale arrays are commissioned. These formulations allow consideration of potential gross impacts on far field flows. They do not provide accurate solutions appropriate for assessing intra-array effects between TECs.

7.6.2.2 Guidance on formulation of the (additional) term in the model

Time-stepping tidal hydrodynamic models all utilise some form of continuity and momentum equations as the key mechanisms for describing flow development. The terms in the equations are numerical expressions used to describe various aspects of key flow phenomena (e.g., advection, wind stress, bed stress, sub-grid scale processes). In order to successfully model energy extraction an additional term is needed that is related to the energy extraction through the introduction of a user-defined time-varying parameter (see 7.6.2.3). In 2D applications using the shallow-water equations, this may be achieved by increasing the value of the bed friction parameter. As the bed stress term on which the bed friction parameter operates acts as a momentum sink, this is a valid mode of operation if the increase in the bed friction parameter is directly related to the amount of energy lost to the system. However, this approach is not appropriate in 3D applications. Models based on the double averaged Navier Stokes equations may include a form-drag term that requires closure which may be used to represent a parameterized turbine. A universal solution can be achieved by the introduction of an additional term in the momentum equations and the inclusion of an additional source of TKE. The momentum term should introduce an additional (friction-like) retarding force in the

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momentum equations. It is important to ensure that the units of this new term are consistent with the other terms in the existing equation set, as this may vary depending upon the form of the governing equations adopted (e.g., conservative and non-conservative forms of the shallow-water equations). The derivation of the additional term applied in the model shall be reported and justified in sufficient detail to enable an independent assessment of the approach adopted.

7.6.2.3 Guidance on specification of the energy extraction

The introduction of an additional term in the model equations enables the prescription of the total energy dissipation related to the operation of TECs. It is recommended that at least the following factors are considered, when prescribing the level of energy dissipation related to the local flow velocity, in the numerical cell(s) of interest:

- the electrical energy harvested by the TECs;
- the 'water to wire' conversion efficiency of the TECs (hydrodynamic losses: blade hub and tip losses, blade profile drag, wake vorticity, etc., mechanical system losses, electrical system losses);
- the spacing of the TECs relative to the plan area of the numerical model cell(s);
- the form drag associated with the TECs' support structure;
- energy losses associated with the downstream mixing of the TECs' wakes and the free-stream velocity.

Combining these factors will enable the construction of a 'hydrodynamic energy extraction curve' similar to a TEC power curve, where particular inflow velocities can be related to a particular level of energy extraction from the hydrodynamic system. This can then be applied in the tidal hydrodynamic model as a look-up table or analytical expression of the variation of energy extraction for a given velocity condition. The energy extraction values associated with each of the factors listed above, and additional factors identified, shall be reported and justified along with the finalised look-up table or analytical expression to be applied.

7.6.3 Practical incorporation of energy extraction in modelling

The basis of the resource assessment is the calibrated, validated, and verified numerical modelling simulation without the TEC array (i.e. the 'base case' or existing natural tidal hydrodynamic system). Repeating the base case numerical model run with the addition of the energy extraction components as detailed in 7.6.2, in conjunction with the specification of TEC characteristics and layout, creates a 'future case' scenario. This allows the quantification and reporting of:

- The amount of energy extracted (or removed) from the tidal system, estimated through the use of the energy extraction terms in the model.
- The amount of energy harvested (to useful energy, i.e. electricity) from the tidal system using the power curves from IEC TS 62600-200 and the method outlined in Annex A of this specification.
- Alterations to the local and far field response of the tidal system, including changes to local and far field tidal velocities and tidal height (by direct comparison between the 'base' and 'future' cases from the model).

NOTE Alterations to the far field response of the tidal system will have various levels of importance depending upon the legislative and regulatory requirements imposed on the project. Presenting this data may need various different methods of parsing the far field response data comparisons. From an operational perspective, all projects will benefit from consideration of the alteration to local current velocities, both spatially (2D and 3D) and temporally. Alteration to the local tidal range and tidal prism characteristics are also of generic interest.

If the alterations to the far field response are deemed to be physically realistic, then the 'future case' numerical model output of velocity time series shall be used as the basis for the extrapolation of model data to a longer time period as defined in 8.2. This will then allow the computation of energy extracted and/or harvested from the system when this Technical Specification is used in conjunction with IEC TS 62600-200.

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8 Data analysis and results presentation

8.1 General model result presentation

The results of the numerical model analyses shall be presented in a format that best illustrates the general characteristics of the tidal height and current variability over the proposed project site. The detail of the results presented should reflect the assessment Stage, with increasing detail from Stage 1 to Stage 2.

Model output data should be presented in the following graphical formats (see also Note 1 below):

a) Contour charts of current magnitude and associated vector, power density, and tidal height over the project area for a single typical spring and single typical neap tide cycle, averaged over an appropriate time interval, e.g. 30 min. However, identification of smaller eddies may need a shorter time interval than 30 min. For Stage 1, the current data should be depth averaged. For Stage 2, 3D model data is available and the current data should be presented at several different depths below the water surface relevant to the specific TEC deployment. It may be beneficial to provide these charts as an animation (e.g. video file), as this may assist with understanding flow development within the model, e.g. the nature of eddies, etc. (see also Note 2).

b) Contour charts of current and tidal height constituent amplitude and phase data over the project area, including current ellipse data. For Stage 1, data should only be presented for the dominant tidal constituents at the project site (which should be justified, see Note 3).

c) Contour charts of the difference between the 'base case' and 'future case' resource scenarios (see 7.6.3) for current magnitude and associated vector, power density and tidal height over the project area for a typical spring and neap tide cycle, as defined in clause (a) above.

NOTE 1 The objective of these graphical presentations is to illustrate and document the overall variability of the tidal current and tidal height over the project site. This data can then be used, where appropriate, to select specific locations for TEC deployments.

NOTE 2 Animations of tidal currents are particularly useful in identifying the importance of tidal eddies at the specific project site.

The dominant tidal constituents are specific to the tidal dynamics at the project site and are likely to include constituents M2 and K1 plus residuals Z0. For project Stage 2, additional constituents should also be presented including S2 and shallow water constituents such as M4.

NOTE 3 It is important to note that the residual current constituent Z0 is known to be very important in strong tidal flows with large eddies or non-tidal flows.

NOTE 4 The selection of a typical (or mean) spring and neap tidal cycle is useful as then, if appropriately selected, the outputs will be close to the annual average outputs.

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8.2 Generation of annual velocity distribution

8.2.1 General

Modern modelling methodologies and computational speeds mean that model simulations should generally be undertaken for time periods of a year although, if necessary, extrapolation of model data may be undertaken by harmonic analysis, unless meteorological factors are found to significantly impact flow dynamics at the project site (see 7.4.3). If meteorological factors unduly impact on the extrapolation, it is necessary to model for an average year (within the 18,6 year tidal cycle).

However, it shall be recognised that models operate with a finite number of tidal constituents, mainly dictated by available constituent data on the driving boundary. The importance of the tidal constituents not included in the numerical model shall be assessed, for both current speed and power density magnitudes during project Stage 2. If these "missing" constituents have a significant impact on calculated current speed and power density then a methodology to include their effect shall be developed, justified and reported. The methodology described in 8.2.2 should be considered in order to achieve this.

NOTE All tidal height harmonic constituents contribute directly in amplitude to the observed time series of tidal height. The number of tidal height constituents that are available to drive the numerical model are generally limited to the principal 8 to 12 diurnal and semi-diurnal constituents. However, in general, shorter period tidal constituents such as diurnal, semi-diurnal and shallow water constituents contribute a much larger proportion of the total current speed than for tidal height. This means that semi-monthly, monthly and annual constituents have a much smaller impact on current speed than they do on tidal height. In addition, it is important to note that numerical tidal models actually calculate shallow water tidal constituents (e.g. M4, MS4) from the diurnal and semi-diurnal constituents specified at the model driving boundary. These shallow water constituents or overtides are therefore not “missing” from the modelling analysis. Figure 1 shows the impact of including selected tidal current constituents on the total predicted current for a typical month.

If the model driving boundary is located in shallow water, then the modeller shall carefully analyse what shallow water constituents are actually simulated within the model and assess and document the impact on the accuracy of the model current predictions.

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8.2.2 Potential methodologies for simulating “missing” tidal constituents

The error in modelled tidal currents from using a limited number of tidal driving constituents shall be assessed and reported. The analysis shall estimate the percent error in modelled currents, at the project site, resulting from “missing” constituents, and if necessary then methods shall be developed to reduce/correct these errors. For Stage 1, it may not be necessary to develop a detailed method to correct the errors. However, for Project Stage 2, where accurate current and power density results are required, a detailed method shall be developed, justified and reported.

The following methods should be considered for adding “missing” constituents to the modelled data at the site.

a) Data assimilation of measured tidal height constituents and extrapolation to the model driving boundary. This method is particularly useful for monthly and annual constituents but may also be used for missing diurnal and semi-diurnal constituents. The model should then be run again including the extrapolated constituents although long model runs will be required to adequately describe very long period constituents.
b) Examination of measured and modelled tidal current constituents at the project site to identify the amplitude and phase of missing long period current constituents and minor diurnal and semi-diurnal current constituents. The “missing” constituents can then be added to the modelled constituent data base at a specific location or, where justified, to all modelled current constituents in the project area.

8.2.3 Long-term model current predictions (harmonic analysis)

Once the modelled (or measured) current constituents have been “corrected” for missing constituents, currents can be predicted at the site for periods of a year or more using harmonic analysis. When predicting long term tidal currents each year should be separately predicted, to avoid nodal drift over long time scales which can cause miscalculation of tidal velocities.

For Stage 1, depth averaged currents should be predicted. For Stage 2, where 3D modelling is required, currents at specific depths related to TEC deployment should be predicted. For Stage 2, energy extraction as defined by 7.6 shall be included.

The harmonic analysis should be performed using software that follows a method recognised by the industry (see 6.3.1, Note 1). For Stage 1, time series of current speed and directions at 30 min intervals over the period should be predicted. For Stage 2, the predicted output interval should be reduced to 10 min.

There may be significant uncertainty associated with the harmonic decomposition of strong tidal currents. Therefore, if harmonic analysis is not sufficiently accurate, results may be obtained by using the modelled or measured time series directly to produce the probability distributions for the velocities, as described in the next subclause.

NOTE 1 In addition to conducting a harmonic analysis a direct extrapolation of measurements informed by harmonic periodicities may be carried out and the results contrasted to those of the harmonic analysis. The direct extrapolation results in a probability distribution that is subject to some uncertainty, but for flows with a significant non-linear flow contribution not necessarily worse than the uncertainties associated with direct harmonic analysis. For direct extrapolation of measurements, the procedure for developing a probability distribution described in 8.3 is applied to the measurement time series (either hub height or area-weighted). Because this distribution is based on observations that include an incomplete number of periodic cycles (e.g., neap-spring, apogean-perigean), the resulting distribution may deviate from the distribution that would be obtained by observing currents over the entire 18,6 year epoch. Observations should be at least 90 days in length to avoid high errors, while longer observations would further reduce uncertainty. Note that while this method does carry some uncertainty, it may overcome some of the limits of harmonic predictions with respect to ebb/flood asymmetries and certain topographic/bathymetric influences that are unlikely to be accurately reproduced by harmonic constituents (e.g., Polagye and Thomson, 2013).

NOTE 2 The significance of the error with respect to AEP estimation that is associated with either harmonic prediction or direct extrapolation depends upon the specifics of the TEC. For example, errors associated with velocities significantly below cut-in velocity are immaterial to a performance estimate.

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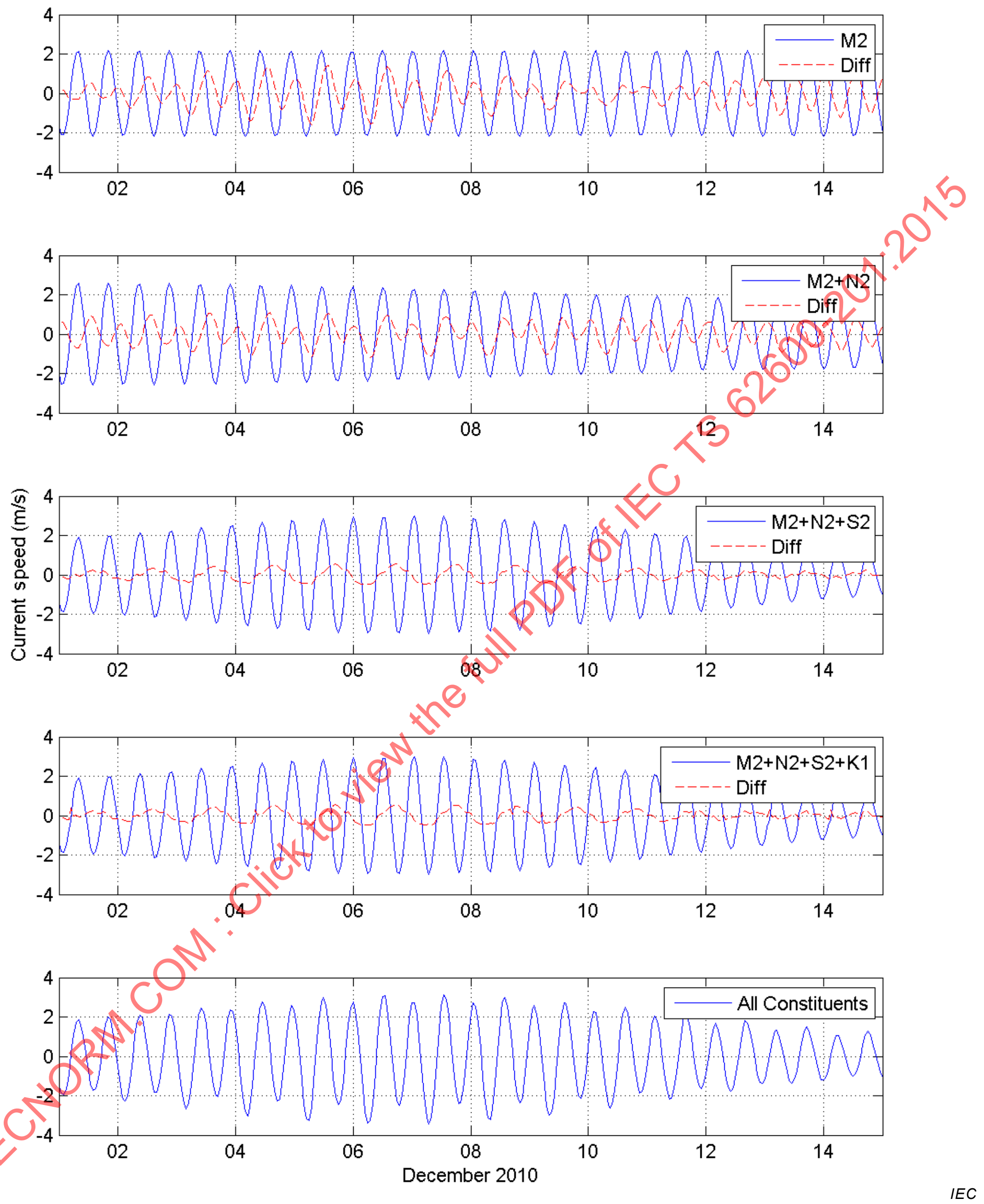

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NOTE Calculated from the US tidal energy database http:\\www.tidalstreampower.gatech.edu, Defne et al. (2012).

Figure 1 – The effect of predicting tides with various constituents from Cook Inlet, Alaska

8.2.4 Results presentation

The results from the harmonic analysis shall include for each site location:

- number of constituents used;
- constituents used, with respective amplitude and phase;

- method by which the constituents were extracted and utilised to generate time series data;
- data source from which constituents were extracted;
- location reference for the data source (WGS 84);
- exact date and period of the analysis;
- time series plots of current speed and direction.

8.3 Velocity distribution curves – Joint probability distribution

This subclause describes how to obtain $f(U_i)$, the velocity distribution, for use in conjunction with IEC TS 62600-200 to estimate an array's projected annual energy production, as described in Annex A.

A histogram analysis for the tidal current speed and direction shall be carried out using the results from the modelled tidal harmonic analysis results (if harmonic analysis is deemed sufficient) or directly from the time series (either modelled or from measurements). At Stage 2, the histogram analysis shall be derived from time-series extracted from a tidal hydrodynamic model simulation spanning one 'typical' year (see 6.3 for guidance on what constitutes a typical year). The hydrodynamic model simulation should include a prescription of the effects of energy extraction appropriate to the intended scale of energy harvesting, as explained in 7.6. The location of the TEC(s) considered in this analysis shall be well correlated to the location of the outputs from the hydrodynamic model (the preferred location within the model may vary depending on the exact model characteristics), or to the location of the measurements.

If the power characteristic of the TEC is known, it may be useful to use a specific velocity bin width and averaging period (see IEC TS 62600-200). In other cases, the use of 10 min as the standard averaging period, and 0,1 m/s as the velocity magnitude bin width, is recommended. The size of the directional bin is recommended to be no larger than 10 degrees.

The percentage of time, $f(U_{i,} \theta_k)$, 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 joint velocity direction distributions as shown in Figure 2. The velocity distribution at the site location(s) is the sum of the probabilities across all directions.

The velocity distribution (or exceedance curve as shown in Figure 3) should be plotted with data from the model and static measurement results and any difference in the shape of the exceedance curve discussed.

The velocity distribution should also be computed separately for the ebb and the flood cycles as the sum of the probabilities across 180 degrees centred on the flood/ebb directions, to be consistent with IEC TS 62600-200. 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 TEC, the $f(U_i)$ shall be estimated over the projected capture area of the TEC, with reference to IEC TS 62600-200. For each bin and each cycle (separately for the flood and ebb cycles), the main direction of the current shall be stated. The current direction will often be different for each velocity bin; the weighted average (over the working velocity range of the TEC) should be considered to be the principal direction of the current, and should be used for both the ebb and flood cycles to determine the TEC optimum orientation.

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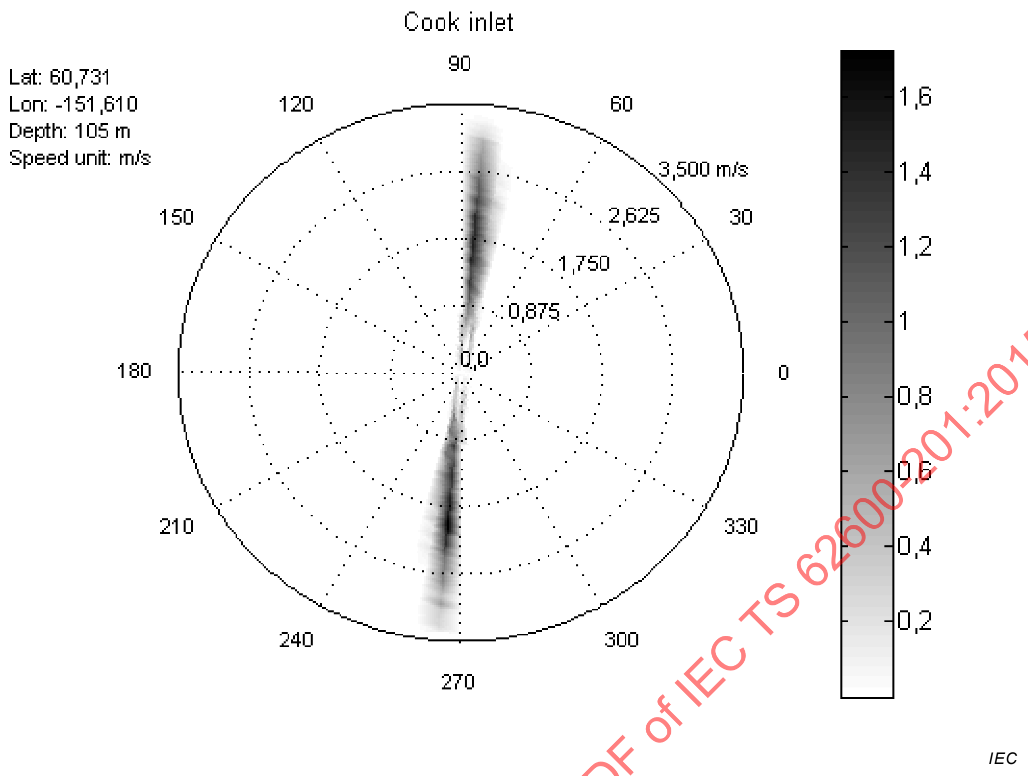

NOTE Calculated from the US tidal energy database http:\\www.tidalstreampower.gatech.edu, Defne et al. (2012).

Figure 2 – Joint velocity and direction probability distribution, a location in Cook Inlet, Alaska

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