



BSI Standards Publication

Marine energy — Wave, tidal and other water current converters

Part 201: Tidal energy resource assessment and characterization

National foreword

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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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CONTENTS

FOREWORD	6
Introduction	8
1 Scope	9
2 Normative references	9
3 Terms and definitions	9
4 Symbols and abbreviated terms	9
4.1 Symbols and units	9
4.2 Abbreviations	11
5 Methodology overview	12
5.1 Project definition	12
5.1.1 General	12
5.1.2 Stage 1: Feasibility study	12
5.1.3 Stage 2: Layout design study	12
5.2 Methodology	12
6 Data collection	15
6.1 General	15
6.2 Bathymetry	15
6.2.1 General	15
6.2.2 Results presentation	16
6.3 Tidal height	16
6.3.1 General	16
6.3.2 Results presentation	16
6.4 Tidal currents	17
6.4.1 General	17
6.4.2 Tidal current mobile survey	17
6.4.3 Tidal current stationary survey	21
6.4.4 Measurement uncertainty	25
6.5 Meteorological data	26
6.5.1 General	26
6.5.2 Wind data	26
6.5.3 Atmospheric pressure	26
6.5.4 Results presentation	26
6.6 Wave climate	27
6.6.1 General	27
6.6.2 Results presentation	27
6.7 River discharge	28
6.7.1 General	28
6.7.2 Results presentation	28
6.8 Turbulence	28
6.8.1 General	28
6.8.2 Results presentation	29
6.9 Large scale flow structure	29
6.10 Stratification, seawater density and sediment measurement	30
6.10.1 General	30
6.10.2 Results presentation	30
6.11 Generation of annual velocity time series (harmonic analysis)	30

6.11.1	General.....	30
6.11.2	Velocity prediction.....	31
6.11.3	Results presentation	32
7	Model development and outputs.....	32
7.1	General	32
7.2	Choice of model	33
7.2.1	General considerations.....	33
7.2.2	Model selection.....	33
7.3	Model characteristics	34
7.3.1	Model coverage and boundary conditions	34
7.3.2	Model resolution	35
7.3.3	Duration of the model calculations	36
7.4	Analysing data to provide model inputs, calibration and validation	36
7.4.1	General.....	36
7.4.2	Bathymetry interpolation	36
7.4.3	Currents.....	36
7.4.4	Meteorological analysis	37
7.4.5	Waves	38
7.4.6	Turbulence.....	38
7.4.7	Seawater density, salinity and temperature.....	39
7.4.8	Sediment	39
7.4.9	River discharge.....	39
7.5	Model calibration or validation.....	39
7.5.1	General.....	39
7.5.2	Model calibration	40
7.5.3	Model validation.....	41
7.6	Incorporating energy extraction.....	42
7.6.1	General.....	42
7.6.2	Guidance for incorporating energy extraction	43
7.7	General model uncertainty	43
7.7.1	General.....	43
7.7.2	Modelled spatial variation uncertainty	44
7.8	Generation of annual velocity time series	44
7.8.1	General.....	44
7.8.2	Long-term model current predictions (harmonic analysis).....	44
7.8.3	Temporal modelling uncertainty.....	45
7.8.4	Results presentation	45
7.9	General model result presentation.....	46
8	Data analysis	46
8.1	Velocity distribution curves – joint probability distribution.....	46
8.2	Power-weighted velocity calculation.....	47
8.3	Uncertainty in transferring from time to frequency domain.....	49
8.4	Results presentation	49
9	Reporting of results	51
9.1	Purpose of reporting	51
9.2	Contents of the report	51
Annex A (informative)	Calculation of TEC annual energy production	52
A.1	General	52

A.2	Individual TEC annual energy production (AEP).....	52
A.3	Array AEP.....	53
A.4	Loss categories	53
A.4.1	General.....	53
A.4.2	Plant performance and losses uncertainty	53
A.5	AEP uncertainty.....	54
A.6	Results presentation	54
Annex B (informative)	Uncertainty	55
B.1	Uncertainty categories	55
B.2	Combining uncertainties	55
Annex C (informative)	Guidelines for current profiler measurements	56
C.1	General	56
C.2	Instrument configuration.....	56
C.3	Instrument calibration.....	57
C.4	Correcting for clock drift	57
C.5	Depth quality control	57
C.6	Velocity quality control	58
C.7	Estimating turbulence quantities.....	58
C.8	Mobile and hybrid mobile-stationary survey	59
C.8.1	General.....	59
C.8.2	Navigation and vessel-handling	59
Annex D (informative)	Case Studies	61
D.1	General	61
D.2	Site evaluation	61
D.2.1	General.....	61
D.2.2	Stationary survey - design	61
D.2.3	Stationary survey - results presentation.....	64
D.2.4	Generation of annual velocity time series (harmonic analysis)	68
D.2.5	Calculation of TEC annual energy prediction.....	72
D.3	Model case study.....	76
D.3.1	General.....	76
D.3.2	Study location.....	76
D.3.3	Model description.....	77
D.3.4	Model calibration	78
D.3.5	Model validation.....	80
D.3.6	General model output.....	84
D.3.7	Energy extraction.....	86
Annex E (informative)	Tidal resource classification system	92
E.1	Introduction.....	92
E.2	Classification parameters	92
E.3	Classification example	93
Bibliography		96
Figure 1 – The vertical variation of tidal current across an example projected capture area for a horizontal-axis TEC		48
Figure 2 – Joint velocity and direction probability density distribution, a location in Cook Inlet, Alaska		50
Figure 3 – Example velocity magnitude probability histogram		50

Figure 4 – Example exceedance curve for velocity magnitude	51
Figure C.1 – Hybrid mobile-stationary vessel waypoints and tolerance range rings	60
Figure D.1 – Site selection - the Strangford Narrows	61
Figure D.2 – Strangford Lough bathymetry	62
Figure D.3 – ADP seabed frame prior to deployment	63
Figure D.4 – Raw data time-series of heading, pitch, and roll	64
Figure D.5 – Hovmöller diagram showing the current data over the water column over deployment time	65
Figure D.6 – Instantaneous height above mean sea level time series	66
Figure D.7 – Instantaneous current velocity	67
Figure D.8 – Instantaneous power-weighted speed and 10 min averaged power-weighted speed	67
Figure D.9 – Velocity-bin averaged current profiles through the water column	68
Figure D.10 – A 1-year forecast of height above mean sea level and current-speed	72
Figure D.11 – Schottel SIT deployment configuration at QML tidal test site, Strangford Lough, Northern Ireland	73
Figure D.12 – Theoretical, data derived and actual power output performance, cyan data points are taken from (Starzmann et al., 2015 [97])	74
Figure D.13 – Velocity probability distribution at TEC location	74
Figure D.14 – Velocity exceedance curve at TEC location	75
Figure D.15 – Forecast tidal flow magnitude and electrical power output for location 1	75
Figure D.16 – The study area in Tacoma Narrows, WA	77
Figure D.17 – Distribution of tide gauges in the Salish Sea	79
Figure D.18 – Six NOAA - C.MIST CP locations in Tacoma Narrows area used for FVCOM model validation	81
Figure D.19 – Hodographs from the model and field data at all six locations and a scatter comparison of the different matrices computed to quantify the model performance	82
Figure D.20 – Comparisons of modelled and observed vertical velocity profiles at gauge PUG1528 during two spring and neap cycles in 2015	83
Figure D.21 – Velocity exceedance curves from the model and current profiler at gauge PUG1528	83
Figure D.22 – The variation of tidal current speed, V , and power density, P_w , at different tide cycles in the Tacoma Narrows	84
Figure D.23 – Tidal ellipse map of the largest tidal current constituents, M_2 and K_1 , in the Tacoma Narrows (represented by blue lines)	85
Figure D.24 – Joint velocity direction distribution at PUG1528	86
Figure D.25 – Energy extraction at the project location	88
Figure D.26 – The effect of the proposed TEC array in Tacoma Narrows	89
Figure D.27 – Representative TEC locations	90
Figure D.28 – Velocity probability histograms for the three representative TEC locations	91
Figure E.1 – Scatter plot of maximum theoretical power available vs cross-sectional area for all the hotspot locations around the US coast (Kilcher et al. [33])	94
Figure E.2 – Primary parameter classification scheme based on mean velocity	94

Figure E.3 – Scatter plot of mean velocity vs cross-section for all the hotspot locations around the US coast from national tidal resource assessment report (Haas et al., 2011[67]).....	95
Figure E.4 – Tidal stream mean currents across Cook Inlet (60.79 N, 151.26 W), colour-coded by their classes	95
Table 1 – Resource assessment stages	12
Table 2 – Model and field survey recommendations (overview)	14
Table 3 – Differences in measurement requirements at Stage 1 and Stage 2	23
Table A.1 – Recommended loss categories and definitions	53
Table B.1 – Recommended uncertainty categories and definitions	55
Table D.1 – ADP deployment location.....	62
Table D.2 – Sentinel V sampling configuration.....	64
Table D.3 – Sea-level at Location 1: Tidal constituents, amplitudes and phases.....	69
Table D.4 – Depth-averaged current velocity at Location 1 ellipse parameters (major axis, minor axis, inclination and phase).....	70
Table D.5 – Year-to-year variability of AEP	76
Table D.6 – Comparison of modelled and observed tidal constituent amplitude (a) (in meters) and phase lag (Φ) (in degrees) at 10 tide gauge stations in the Salish Sea.....	79
Table D.7 – AEP estimated at gauge PUG1528 using principal component velocity (PCU, in m/s) and different channel vertical positions.....	83
Table D.8 – TEC array configuration used for energy extraction	89
Table D.9 – AEP for each representative TEC and total for the project.....	91
Table E.1 – Proposed tidal resource classification system	93

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This second edition cancels and replaces the first edition published in 2015. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) Includes clauses on assessing wave and current interaction;
- b) Expands turbulence data collection;
- c) Expands the measurement only method to include a combination of static and mobile surveys;
- d) Includes a method for combined tidal and river flow;
- e) Adds more description for treating uncertainty;
- f) Includes two case study examples.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
114/573/DTS	114/590/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

Introduction

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 document 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. However, within this document, guidance regarding the assessment of uncertainty within tidal resource assessment is given. Additionally, [Annex C](#) provides an overview of proposed loss and uncertainty categories, to help users better understand the key areas to be included in an energy yield assessment.

The purpose of this document 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 individual or arrays 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 document will ensure that resource assessment is undertaken in a consistent and accurate manner. This document presents techniques that are expected to provide fair and suitably accurate results that can be replicated by others.

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 TS 62600–200.

In this document, the theoretical tidal energy resource (undisturbed or disturbed by power extraction) is defined by the velocity probability distribution that is used to compute the AEP. For projects where the proposed AEP (converted to average power production) is less than 2 % of the theoretical undisturbed tidal energy resource (or in the case of headlands less than 10 MW installed capacity), AEP can be estimated from direct resource measurements, without requiring hydrodynamic modelling. In all other cases, the velocity probability distribution is assessed by hydrodynamic modelling that includes the effects of energy extraction, with appropriate verification of the baseline model by measurements. The methodology for measuring the required data is also defined. The direct resource measurement approach may use measured data at each TEC location, using either data from a stationary survey or hybrid mobile-stationary surveys, or both.

This document describes only the aspects of the resource required to calculate AEP and assess its uncertainty; e.g. it does not describe aspects of the resource required to evaluate design loads or to satisfy environmental regulations. Furthermore, this document is not intended to cover every eventuality that can be relevant for any particular project. Therefore, this document 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.

Further background reading can be found here: [IEC TS 62600-101:2015](#) [1], Coles and Blunden (2017) [2], Kreyszig (1983) [3], Batten et al., (2013) [4], Burton et al., (2011) [5], Roache (1994) [6].

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 can be suitable for the installation of one or more TECs.

It is intended to be applied at various stages of project life cycle 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 TS 62600–200.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-417, *International Electrotechnical Vocabulary (IEV) - Part 417: Marine energy - Wave, tidal and other water current converters*

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

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-417 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

4 Symbols and abbreviated terms

4.1 Symbols and units

a_0	amplitude difference between the two ends of the tidal channel or largest tidal constituent amplitude in the channel (m)
a_i	additional constituent amplitudes (m)
A	projected capture area of TEC (m ²)
A_b, A_p, A_f	total flow-facing swept area of the blades, supporting poles and device foundation (m ²)
A_k	area of current profiler bin k across the projected capture area (m ²)
B	bias
C_{ext}	extraction coefficient

C_T	TEC thrust coefficient
C_b, C_p, C_f	drag coefficients due to the physical TEC blades, supporting poles, and the foundation
C_p	turbine power coefficient
D_E	equivalent diameter (m)
$f(U_i)$	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 (%)
$\vec{F}^m$	flow retarding force
g	acceleration due to gravity (m / s^2)
I_U	turbulence intensity of the horizontal velocity
i	index for velocity magnitude bin numbers
j	index for number of time intervals
k	index for direction bin numbers or index for current profiler bin across projected capture area
K	turbulent kinetic energy (m^2/s^2)
L	number of samples in the defined averaging period which produces data point n
M_n	model result
n	index number defining an individual data point in a velocity bin
N	number of time intervals
N_B	number of velocity bins
N_h	number of hours in the simulated year
O_n	observed data
O	mean of observed data
P	available annual mean power density (kW/m^2)
$P_i(U_i)$	power generated by the i velocity bin of the TEC power curve (kW)
u, v, w	total measured velocity (m/s)
u', v', w'	turbulent velocity fluctuations (m/s)
$\underline{u}, \underline{v}, \underline{w}$	turbulent-averaged mean velocity (m/s)
$\underline{U}$	horizontal component of the turbulent-averaged mean velocity (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)
U'	root mean squared value of the horizontal turbulent velocity fluctuations (m/s)
$\dot{U}_{i,j,n}$	instantaneous power weighted current velocity across A (m/s)
$U_{i,j,k,n}$	magnitude of the instantaneous tidal current velocity, time j , at current profiler bin k , in velocity bin i , for data point n (m/s)
$\overline{U}_{i,n}$	mean power-weighted tidal current velocity in velocity bin i for data point n (m/s)
V	tidal current speed (m/s)
P	maximum average available power in tidal channel (W)
$\vec{v}$	tidal current velocity (m/s)
P_W	power density (W/m^2)
P_{max}	available theoretical maximum annual average power (W)

$Q_{\max}$	maximum volume flux through the tidal channel (m ³ /s)
R	linear correlation coefficient
S	total number of current profiler bins across the projected capture area normal to the principal axis of energy capture
Sk	skill
TECA	expected TEC availability (%)
TECAEP	expected annual power production for the TEC (kWh)
z	depth (m)
ε	turbulent kinetic energy dissipation (J/kg)
σ_n	standard deviation of the uncertainty in the horizontal current speed (m/s)
θ_p	principal direction of flow (deg)
θ	direction of the depth-averaged or hub height velocity (deg)
θ_k	direction for the k^{th} bin (deg)
γ	coefficient within Garrett and Cummins equation
ρ	water density (kg/m ³)

4.2 Abbreviations

AEP	annual energy production
ADV	acoustic doppler velocimeter
CP	current profiler
CTD	conductivity, temperature, depth
CFD	computational fluid dynamics
DGPS	differential GPS
EEP	energy extraction plane
FDC	flow duration curve
FVCOM	finite volume community ocean model
GPS	Global Positioning System
HAB	height above bed
IEC	International Electrotechnical Commission
IHO	International Hydrographic Organization
ISO	International Organization for Standardization
MW	megawatt
NOAA	National Oceanic and Atmospheric Administration
NTP	network time protocol
PAS	publicly available specifications
PCA	projected capture area
PST	phase-space thresholding
QA	quality assurance
RMS	root-mean-squared
SAR	synthetic aperture radar
SD	standard deviation
SJDF	Strait of Juan de Fuca
SMS	surface-water modelling system

TI	turbulence intensity
TEC	tidal energy converter
TS	technical specification
USGS	United States Geological Survey
UTC	Coordinated Universal Time
VDC	velocity duration curve

5 Methodology overview

5.1 Project definition

5.1.1 General

This document 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 document 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, channel, etc. with a medium level of uncertainty and is used to identify potential project locations. The layout design study is expected to focus on the particular sites chosen through the feasibility studies and is used to predict project AEP with a lower level of uncertainty. A classification system is described in [Annex E](#) to assist with site identification.

Table 1 – Resource assessment stages

Stage	Aim	Area
Stage 1	Feasibility	Whole estuary, channel, etc.
Stage 2	Layout design	Development site

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 layout design). The AEP (calculated using the method outlined in [Annex A](#)) can be assessed based on data from either direct measurements or from hydrodynamic modelling. In addition to defining the methodologies throughout this document, case studies for both approaches are provided in [Annex D](#).

The relative scale of the project impacts the allowable methodology that can be employed. To determine the relative scale of the project, the expected AEP of the project is compared with the maximum theoretical (undisturbed) tidal energy resource available within the project site.

The method for computing the theoretical tidal energy resource available shall be justified. Note that this method can only be employed for tidal channels or estuaries. In the case of headland sites, there is currently no accepted method to quantify level of energy extraction, and hence the direct measurement approach for AEP calculation can be employed if the project has less than 10 Megawatt (MW) installed capacity.

The theoretical tidal energy resource describes the upper bound of available power from a tidal stream in a channel. As turbines are added to a channel, the turbine drag causes an increase in the pressure head between the two ends of the channel, and a reduction in the volume flux through the channel. The total power extracted by the turbines is the product of the head loss across the turbines and the volume flux through the channel. Adding too many turbines to the channel blocks the flow, resulting in a reduction in the available power. A general formula gives the maximum average available power as between 16 % to 24 % of the peak undisturbed tidal pressure head, from one end of the channel to the other, multiplied by the peak of the undisturbed mass flux through the channel, as described in [Formula \(1\)](#) as taken from Garrett and Cummins (2005) [7].

$$P = \gamma \rho g a_o Q_{\max} \quad (1)$$

where

- P is the maximum average available power
- γ is the coefficient ranging between 0,16 to 0,24 depending on the hydrodynamic mechanism(s) driving the flow
- g is acceleration due to gravity
- a_o is the amplitude difference between the two ends of the channel
- $Q_{\max}$ is the maximum volume flux through the channel in the undisturbed case

The exact level of energy extraction is dependent on the hydrodynamic mechanism(s) driving the flow, which are typically characterised as either tidal streaming (the physical response to maintenance of the continuity equation where flow acceleration occurs when flow is forced through a constriction); hydraulic current (flow arising from the pressure gradient created by a difference in water level between two bodies of water) and resonant systems (constructive interference between an incoming tidal wave and a reflected tidal wave, causing a standing wave). The hydrodynamic mechanism can be specific to the selected location.

For projects where the proposed AEP (converted to average power production) is less than 2 % of the theoretical (undisturbed) tidal energy resource (expressed as maximum average power available), AEP can be estimated from direct resource measurements, without requiring hydrodynamic modelling. Current profiler measurements and harmonic analysis (see [6.11](#)) are considered sufficient for these projects because there is expected to only be limited, if any, impact on the underlying hydrodynamics of the site due to the project. In order to use this method, static (bed-mounted) measurements shall be made at each individual turbine location, or a combination of static (bed-mounted) measurements within the proposed array area can be combined with mobile survey data using a hybrid mobile-stationary survey method as described in [6.4.2](#) and [6.4.3](#). Such projects can also use the hydrodynamic modelling required for larger projects. If the data collection indicates that the TECs should be deployed in different locations to where static current profiler data has been collected, then it is necessary for the hybrid mobile-stationary survey to have covered the location of the proposed TECs and the methodology for extrapolating to those other locations using the hybrid mobile-stationary survey should be explained in detail and justified. It is also recommended that the hybrid mobile-stationary survey approach with 'stop-overs' is used in preference to a hybrid mobile-stationary survey approach without 'stop-overs', except in cases where it can be demonstrated that a hybrid mobile-stationary survey approach without 'stop-overs' produces sufficiently accurate data.

In all other cases, where the AEP (converted to average power production) is more than 2 % of the theoretical tidal energy resource (expressed as maximum average power available), or in the case of headland sites an installed capacity of 10 MW or more, AEP shall be assessed by hydrodynamic modelling that includes the effects of energy extraction, with appropriate verification of the baseline model by measurements. The first step in this process is to define the required model inputs, as described in 7.2 which also discusses 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 can then be assessed as per 7.5. For feasibility studies, the model output can 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 can 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 document. However, the modelling methodologies described within this document can be used to assess some of the impacts of TEC deployments, including changes in tidal regime, tidal currents and bottom sediment movements, and can also provide data required for environmental studies. External constraints to be considered in determining the tidal resource can apply.

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 subclause in this document where the detailed information related to that activity is contained. These recommendations consider the practicalities of gathering the data to satisfy these requirements.

Table 2 – Model and field survey recommendations (overview)

		Stage 1 (feasibility)		Stage 2 (layout design)	
Project size	Tidal channel or estuary: less or greater than 2 % of undisturbed resource Tidal headland: less or greater than 10 MW installed capacity	Less	Greater	Less	Greater
Modelling	Modelling requirements overview	Measurement only option, or modelling	Modelling Required (7.2 and 7.3)	Measurement only option, or modelling	Energy extraction required (7.6)
	Minimum number of harmonic constituents for modelling driving boundary (tidal amplitude)	8 constituents		8 constituents	
	Grid resolution at the area(s) of interest	500 m or 10 grid cells across a channel section; 2D		No more than twice D_E without energy extraction; odd number of grid points per D_E with energy extraction; 3D, minimum 3 layers across TEC device	
	Period of run	> 35 days		> 35 days for validation, 1 year for analysis	
Physical data requirement	Bathymetry	6.2	6.2	6.2	6.2
	Tidal height	6.3	6.3	6.3	6.3
	Wave characteristics	6.6	6.6	6.6	6.6

		Stage 1 (feasibility)		Stage 2 (layout design)	
	Meteorological data	6.5	6.5	6.5	6.5
	Turbulence	6.8recommended	6.8recommended	6.8required	6.8required
	Stratification, seawater density and sediment measurement	6.10	6.10	6.10	6.10
	Tidal currents – mobile survey	6.4.2 spring-tide survey at a minimum	6.4.2 spring-tide survey at a minimum	6.4.2 spring- and neap-tide survey	6.4.2 spring- and neap-tide survey
	Tidal currents – stationary survey	6.4.3 1 lunar month duration for model-based approach 2 lunar month duration for direct measurement approach	6.4.3 1 lunar month duration at a minimum	6.4.3 1 lunar month duration for model-based approach 2 lunar month duration for direct measurement approach	6.4.3 1 lunar month at a minimum
	River discharge	6.7	6.7	6.7	6.7
Data analysis	Harmonic analysis on available current data (6.11 and 7.8.2) (minimum no. of constituents)	20 constituents	20 constituents	20 constituents	20 constituents

6 Data collection

6.1 General

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 currents. This includes measurements of bathymetry, harmonic tidal currents, as well as non-tidal low frequency processes that can impact tidal resource assessment such as storm surge, residual flows and buoyancy-driven flows, and high frequency processes such as waves and turbulence. For projects with AEP less than 2 % of the theoretical tidal energy resource (or in the case of headland sites with less than 10 MW installed capacity), the field measurements can be used to provide the velocity distributions to directly calculate AEP for individual turbines. Guidelines for current profiler measurements - including distinctions for small vs. large projects - are provided in 6.4.2, 6.4.3, and Annex C.

6.2 Bathymetry

6.2.1 General

The required resolution of the bathymetry data to feed into a hydrodynamic model is described in 7.4.2.

The bathymetric data already available shall be reviewed, e.g. contact with the oceanographic centres responsible for the region concerned is recommended. It is possible that local fishing vessels have instrumentation that meet the here mentioned requirements and also have available bathymetric data that could be of use. If existing data are 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 shall be conducted in accordance with the IHO

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

6.2.2 Results presentation

A map should be provided for all undertaken surveys for which data are 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 or 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 or 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 nautical 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 nautical charts is not a fixed datum but may change from chart to chart and should be defined.

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

6.3 Tidal height

6.3.1 General

Tidal height data are 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 either the extent of the model domain, the number of interconnected channels, or the size of any enclosed embayments and channels connecting to the open ocean within the modelled domain.

6.3.2 Results presentation

The data at each location shall include:

- location, both in latitude and longitude as well as the coordinate system used for the bathymetric data;
- date and length of measurement;
- measurement methods and vertical datum;
- calibration reports or calibrations applied to the data;
- tidal range;
- analysed tidal constituent data, including the amplitude and phase of all constituents identified as important; the data record for harmonic analysis (see 6.11.1) should ideally be

one year or longer, but should be a minimum of a full lunar month and consist of integer multiples of the spring or neap cycle;

- should a significant harmonic residual exist, the cause of this, such as atmospheric pressure differences or, in estuarine areas, changes in freshwater flow, is to be investigated and commented upon;
- 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 or 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. The tidal datum should be consistent with that used for the bathymetric data.

6.4 Tidal currents

6.4.1 General

Tidal current measurements are a centrepiece of tidal energy resource assessment. Whether they are used to validate numerical models, or if they are used to calculate AEP directly, it is clear that measurements of the currents are indispensable to resource assessment. Selecting a suitable current profiler for a project will depend on several factors, including: water depth, deployment duration, spatial and temporal resolution requirements (especially when measuring turbulence), and mounting requirements. Water depth is an especially important consideration because there is a trade-off between resolution (higher frequency current profilers typically have higher spatial and temporal resolution) and the range over which these instrument provides accurate measurements (lower frequency instruments have longer range).

The current profiler shall be calibrated in accordance with the manufacturers recommendations. All tidal currents will be presented in reference to a coordinate system relative to true north.

NOTE Current profiler calibration is a challenging and complex topic. While most manufacturers of these instruments do include setup (sometimes called 'calibration') procedures, those procedures are typically limited to calibrating individual sensors within the instrument (e.g. the compass) and performing various functionality checks. This is not the same quality of calibration as is often expected or required of test laboratories in the application of standards. Not only are there no third-party organizations that certify the accuracy of current profilers, there is no clear process for how to certify them. This is because these certifications typically involve comparison of the instrument's measurements to an independent and highly reliable reference measurement. Considering that current profilers measure water velocity throughout a water column from ten to several hundred meters deep, it is a huge practical challenge to design a system that would be capable of providing an independent and reliable reference measurement. This being the case, this is why this document does not require a calibration certificate for current profiler instruments.

6.4.2 Tidal current mobile survey

6.4.2.1 General

A mobile or hybrid mobile-stationary current survey is one of the options to provide valuable information about the spatial variability in tidal currents at a proposed TEC site. The information from either a mobile or hybrid mobile-stationary current survey, or both, is particularly useful for model validation, to plan the deployment of further stationary current profiler measurements described in 6.4.3, or for spatial extrapolation when used in combination with stationary surveys. When using the hybrid mobile-stationary or mobile current survey for computing the AEP, it is necessary to explain in detail and justify the methodology for doing so. However, mobile current survey data are not an adequate data source to specify an annual velocity distribution.

NOTE There are alternative methods of measuring spatial variability of the flow such as drifters, aerial imagery and shore-based radar. While all of these can provide additional information on spatial variability and data that could potentially be used for model validation, they each have intrinsic limitations, making them more suited for the reconnaissance stage of projects which precedes Stage 1 and is not covered within this document. Drifters, for example, do not provide the temporal resolution required for harmonic analysis and might not provide the necessary spatial coverage as the user has no control over drifter trajectory. Radar and aerial imagery can provide excellent spatial coverage under certain conditions, but both yield only surface currents.

For Stage 1, it is recommended that mobile surveys be conducted during spring tides at a minimum. An additional neap tide survey can be useful. For Stage 2, it is recommended that mobile surveys be conducted during both spring and neap tides.

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 either a poorly mounted or configured system, or both. Additionally, accurate and high-resolution vessel positioning, both in the horizontal and vertical directions, is a critical factor in undertaking a successful mobile current survey and it is therefore necessary to have an accuracy equal to or better than differential Global Positioning System (GPS).

6.4.2.2 Mobile and hybrid mobile-stationary survey design

A (standard) mobile vessel-mounted current profiler survey continually traverses a single line, or undertakes a ladder survey or box-circuit, for at least one full flood and ebb tidal cycle. The objective is to revisit each part of the circuit with sufficient frequency to resolve variations in the tidal current amplitude and phase. This condition typically restricts circuit times to 1 h to 1,5 h or less. Therefore, mobile survey design involves consideration of the trade-offs between spatial and temporal coverage and resolution related to the practical limitations of vessel speed and instrument operational limits in terms of vessel speed.

A hybrid mobile-stationary survey uses a vessel-mounted current profiler to collect data at multiple locations (e.g. anticipated TEC locations or locations for either calibration or validation of hydrodynamic models, or both), which is recommended to be for discrete time intervals (e.g. between 5 min to 10 min, termed a 'stop-over') over at least one full flood and ebb tidal cycle, revisiting each location with sufficient frequency to resolve variations in the tidal current amplitude and phase as described above (e.g. hourly). Such a survey is concurrent with, and takes measurements over, a bed-mounted current profiler, so as to allow later correlation between the vessel-mounted data and the bed-mounted data (generally expected to be of higher quality, resolution and accuracy) and thus potentially allow a long-term analysis of the currents at the multiple stop-over locations. Particularly in cases requiring significant spatial coverage or extrapolation, concurrent data from a second bed-mounted current profiler should be used as additional validation of the method. The advantage of a hybrid mobile-stationary survey over a standard mobile survey is that it allows a correlation of the mobile survey data with bed-mounted survey data, and when using stop-overs means that approximately an order of magnitude more data are captured at the exact locations of interest, and the impact of short-term turbulence or eddies on the currents measured at these locations is minimised. Field trials of this method have shown an extremely good correlation between hybrid mobile-stationary survey data and bed-mounted survey data (Johnson, F. 2023 [8]; Perez et al., 2023 [9]). Theoretical modelling of this method has also highlighted its potential for estimating AEP (Xu et al. 2022 [10]). The hybrid mobile-stationary survey approach and measurements can be used:

- for supporting AEP calculations (instead of deploying long-term stationary surveys at each TEC location, or using modelling) for projects with AEP less than 2 % of the theoretical (undisturbed) tidal energy resource (as energy extraction impacts, which can only be modelled, are then expected to be minimal), if concurrent with a long-term stationary survey, or equally for the same purpose for headland sites with less than 10 MW installed capacity,
- to supplement either the likely limited stationary survey data or less accurate (standard) mobile survey data, or both, for the calibration and validation of hydrodynamic models (with or without a concurrent long-term stationary survey).

If it can be demonstrated that a hybrid mobile-stationary survey approach without stop-overs can sufficiently accurately measure the tidal current variation at locations of interest, then this

approach can be used in a similar manner to the hybrid mobile-stationary surveys with stop-overs.

If hybrid mobile-stationary surveys are used to extrapolate measurements from a stationary survey, the methodology for extrapolating to other TEC locations should be explained in detail and justified. It is recommended that the hybrid mobile-stationary survey approach with stop-overs is used in preference to the hybrid mobile-stationary survey approach without stop-overs except in cases where it can be demonstrated that a hybrid mobile-stationary survey approach without stop-overs produces sufficiently accurate data.

Although hybrid mobile-stationary surveys can be used for projects with AEP less than 2 % of the theoretical (undisturbed) tidal energy resource (or headland sites with less than 10 MW installed capacity), it is important to recognize that there can be additional impacts on AEP that are not captured without modelling, such as the direct wake impacts from a turbine to other turbines and local blockage effects.

Comprehensive coverage by mobile surveys in space and time can be possible for sites with a characteristic size in the order of several hundred metres but can be more difficult to achieve for larger sites (Palodichuk et al., 2013 [11]). A larger area can be covered through the use of multiple vessels simultaneously or further surveys by the same vessel over additional tidal cycles, although special considerations will be necessary in terms of how to consider or combine data sets from different tidal cycles that differ in amplitude.

NOTE It can be possible to conduct harmonic analysis of the mobile current profiler data. See Simpson et al. (1990) [12], Vennell (1994) [13], Vennell and Beatson (2006) [14], and Vennell and Beatson (2009) [15] for details of how to conduct such an analysis.

The design of the mobile survey in terms of spatial coverage and the exact transect or hybrid mobile-stationary locations should consider:

- the practical limitations related to vessel speed and instrumentation limits related to vessel speed, the number of vessels available, and the requirement to sufficiently resolve the tidal cycle;
- the intended use of the data (model validation vs. direct measurement of spatial variability);
- the stage of the project (e.g. larger area for Stage 1 vs. smaller area for Stage 2);
- the spatial variability at the proposed site (e.g. to resolve headland eddy shedding, or if there are significant changes in depth across the project site);
- mobile current profiler transects (looking down) should cross a static deployment (looking up) on several occasions to aid uncertainty definition or when the mobile survey data will be used to extrapolate time series spatially. On hybrid mobile-stationary surveys this would preferably be manifested as a stop-over above the static deployment location (field experience suggests that any acoustic interference between the current profiler instruments can be dealt with in post-processing quality assurance (QA) assuming the current profilers are configured for measurements at sufficiently different frequencies).

Mobile velocity data shall be processed into suitable vertical and horizontal bins; these can be for instance 1 m vertical bins and 25 m to 50 m horizontal bins. Current profiler averaging times should be set to aim for a resolution of at least 1 ping per 2 m horizontal track. The horizontal bin size shall be selected to resolve the significant flow features within the survey area. A 25 m to 50 m spatial resolution means that accurate bottom-tracking or GPS derived vessel speeds are essential. Deep locations will typically require low frequency current profilers (perhaps 300 kHz) and hence larger depth bin and horizontal bin sizes. The profiler should be configured to sample as rapidly as possible within the practical limitations of the instrument and water depth (e.g. 1 Hz or more is preferable), and the profiler should be configured to save every ping - rather than doing internal averaging - in order to support accurate grouping of data into spatial bins.

Hybrid mobile-stationary data shall be processed into suitable vertical and horizontal bins; these can be for instance 1 m vertical bins within a 10 m to 20 m horizontal radius around the stop-over location, depending on the station-keeping capability of the vessel.

The data collection should preferably be conducted during a typical spring tidal cycle as a minimum (see 6.11.1). If a full data set cannot be obtained on a spring tide, results can be interpolated from other data that can be available. The methodology should be justified and fully reported. When possible, mobile surveys of neap tidal cycles should be conducted to resolve differences between spring and neap tides.

When using the mobile survey data to identify characteristic flow scales for comparing to the model, it is important to consider the length scale limitations of both the measurements and the models. All discussions of spatial scales for flow features measured in the field versus the model shall be put in the context of the minimum resolvable scales for each.

6.4.2.3 Output data

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

- time (UTC) with year, month, day, hour, minute, seconds;
- location (given in a coordinate system consistent with the bathymetry data in 6.2);
- velocities for each vertical bin in the three directions (Easting, Northing and vertical with positive upward) corrected for declination and deviation;
- measures of accuracy for each vertical bin 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);
- water depth if the instrument configuration allows;
- vessel velocity (either from current profiler bottom-track, or a high-precision ship GPS);
- quality indicators and uncertainty levels for the horizontal position and velocity of the vessel;
- tidal height from a nearby tide gauge (reported in a reference frame consistent with that in 6.3.1).

6.4.2.4 Results presentation

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

- map figures: location of the survey (given in a coordinate system consistent with the bathymetry data in 6.2), with coordinates of track lines, and the date and period of survey, with time along each track;
- time series figures: tidal elevation observed during survey(s). The maximum and minimum annual (or 18,6 year) tidal elevation in relation to a predefined vertical datum (such as the lowest astronomical tide, or mean lower low-water), should also be indicated for reference;
- if the mobile survey data are used in conjunction with stationary current profiler data to extrapolate spatially to arrive at time series data for other locations, a time series at these other locations should be plotted alongside the measurements from the mobile survey that occur at that location. As previously stated, it is necessary to suitably explain and justify the extrapolation method;
- velocity transect or hybrid mobile-stationary figures: currents at specific depths and different stages of the tide, along either the survey track or interpolated between adjacent transect lines in the case of a ladder survey, or both, or at the specified stop-over location in the case of a hybrid mobile-stationary survey. The direction of the transect should be indicated here for reference (e.g. an arrow pointing in the direction of vessel travel);
- bathymetry comparison figures: a comparison of the water depth measured during the mobile survey to the previously determined bathymetry (see 6.2).

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 shall be reported and discussed. 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 or quality control practices applied to the data sets shall be described and justified. The original raw data should be retained for future reference.

6.4.3 Tidal current stationary survey

6.4.3.1 General

The aim of a stationary survey is to provide a temporally evolving dataset at a specific location. The data for this survey is typically collected using bottom-mounted upward-looking current profilers, or either up- or down-looking current profilers mounted on moorings, or both. Stationary current-survey data can be used to provide either primary validation or calibration data, or both, for an accompanying hydrodynamic model (hereafter: "model-based approach"), or to directly calculate AEP for individual turbines through combination with the turbine's power curve, and by deriving harmonic constituents (hereafter: "direct-measurement approach") following the harmonic analysis guidance provided in [6.11](#).

6.4.3.2 Stationary survey design

Selecting the number and placement of velocity measurement instruments is a critical - and often challenging - aspect of stationary survey design. Instrument numbers and locations depend on the stage and scale of the assessment. For the direct-measurement approach, the instruments shall be placed at the location of the proposed TEC (in the case of a floating TEC at the estimated centre of the excursion area) unless the hybrid mobile-stationary survey approach is employed ([6.4.2.2](#)).

For approaches involving modelling, velocity measurement instruments shall be positioned at locations suitable for model calibration and validation. This typically means targeting locations that are representative for the intended TEC array installation. It can be beneficial to deploy current profilers at the exact location of one or several of the proposed turbines both in terms of model calibration or validation, but also because it will provide data that can potentially be used at later stages of the project in terms of power curve tests and assessment of accuracy of wake modelling as more turbines are added, by comparing future flow data to the undisturbed flow at the TEC location. In all cases, the bathymetry data used to select measurement sites 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. This is to avoid data being influenced by sharp changes in bathymetry that are not resolved by the numerical model, and also to avoid the instrument being deployed such that it is tilted with respect to the vertical (a gimbal can reduce this issue, but that comes with risk of the instrument swaying). A bathymetric survey might be required, and the recommendations given in [6.2](#) should be followed.

Selecting the sites that meet these objectives - especially before a validated model exists - is typically non-trivial, and can require consideration of several data-sources, including:

- use of a model to aide in measurement site selection. When the model is unvalidated or the accuracy of the bathymetry is low or unknown, the model results should be interpreted cautiously and in conjunction with the other methods below;
- measurement of either the flow structure or bathymetry, or both, by conducting a mobile survey or hybrid mobile-stationary survey (see [6.4.2](#)) prior to conducting a stationary survey (see [6.4.3](#)). When interpreting this data, however, it is important to remember that - due to short-period fluctuations - the location of the highest velocity in a given mobile survey transect is not necessarily the location of the highest average velocity;

- interpretation of the bathymetry based on a fundamental understanding of the physics of flows through narrow passageways can be helpful. For example:
 - in the cross-channel direction the largest depth-integrated flow typically occurs in the deepest part of a channel. This is due to both the fact that a deeper channel supports more volume-flux, and because bottom friction plays a reduced role (and therefore velocities are often higher);
 - in the along-channel direction the cross-channel averaged velocity is highest where the cross-sectional area of the channel is smallest, and the flow is accelerated by the kinematic constraints of the channel boundaries;
 - tidal eddies can impact the selection of TEC locations at the project site; therefore, it is necessary to consider eddy locations when selecting locations for detailed static current profiler deployments. Eddies can be identified by a number of techniques, including tidal current mobile surveys, aerial imagery, local knowledge, nautical charts, shore-based radar, current drifters, or inspection of the visual or infrared spectrum;
 - when the accuracy of the bathymetry data is low or unknown, it can be useful to refine measurement sites based on local or field-knowledge of the project area in combination with the approaches above.

It can also be necessary to incorporate other factors into measurement siting decisions, such as bottom composition, bottom slope, or other technical or logistical factors of making measurements at a particular site. Whatever the constraints are, they should be documented in the final report, and the rationale behind the measurement sites should be described.

Once measurement sites have been selected, the design of the stationary survey shall consider:

- current profiler (CP) deployments shall span a minimum of one lunar month for the model-based approach, and two lunar months for the direct-measurement approach. 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. However, to reduce bias in the results, it is important to perform analysis on durations that correspond to integer multiples of the spring or neap cycle. 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 can also be important for tidal resource assessment). The pre-requisite of extracting 20 harmonic constituents from a data set can be achieved with a minimum of a lunar month data set; deployments longer than a lunar month will reduce the uncertainty in both harmonic and time-series analysis of the data, provided an integer multiple of the spring or neap cycle is resolved;
- the sampling interval shall be no greater than 10 min and the averaging period shall be justified based on the site characteristics, but will generally be between 2 min and 10 min (to filter the majority of turbulence from observations). This provides consistency with AEP calculation in order to provide flexibility to operate the CP for longer durations within battery and memory constraints. 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 for Stage 1 and at least once every second for Stage 2 type projects, i.e. a sampling frequency of 1 Hz or higher is required for projects aiming to resolve turbulence. Where possible, the raw ping data should also be stored;
- 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 instrument as possible and extend close to the sea surface (or sea bed in the case of moored downward looking instruments), ensuring full coverage at the likely deployment depth excepting the necessary small area immediately above the instrument and below the surface (or close to the bed in the case of moored downward looking instruments) due to the blanking distance and side lobe interference. In sites with a large tidal range or with strong surface effects (e.g. waves), care should be taken when analysing the near-surface bins. For the direct-measurement approach, the bins shall span the projected capture area (PCA) of the TEC;

- 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 pitch and roll of the instrument shall be recorded over the course of the deployment. If a gimbal mount is used, this shall be noted in the report;
- 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 or pod and following manufacturer recommendations;
- if possible, multiple deployments across the project site should also have a sufficient temporal overlap so that they can be cross-correlated so that cross-correlations between different data sets can produce sufficiently strong correlations;
- where feasible, the measurements should be acquired during periods which are subjected to less meteorological forcing (e.g. avoid storm or hurricane seasons).

A summary of the measurement requirements for Stage 1 and Stage 2 projects are listed in [Table 3](#). Additional detailed guidelines for current profiler measurements are provided in [Annex C](#).

Table 3 – Differences in measurement requirements at Stage 1 and Stage 2

	Stage 1 - feasibility	Stage 2 - layout design
Number of deployments	At least one instrument shall be deployed within the intended project site.	Several deployments across the region of the TEC array encompassing 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.
Turbulence intensity (see 6.8 for details)	Recommended	Required
Location (small array) (see 5.2)	The instrument(s) should be deployed at the centre of the array or at key representative locations (model-based approach or the HMS approach) or at proposed TEC locations (direct-measurement approach)	
Location (large array) (see 5.2)	As above	For a 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.

6.4.3.3 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](#)), (local and national regulatory requirements can apply);
- time (UTC) with year, month, day, hour, minute, second;
- all applied data calibrations;
- velocities in the three geo-referenced 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 or reject data during processing;
- measures of current profiler heading;
- cell start depth (bottom cell) and cell stop depth (top cell);

- total water depth and tidal height above the project chart datum;
- instrument sampling scheme such as sample rate, averaging method etc.;
- it is recommended that all current measurement instruments should record water level data simultaneously with currents to provide additional data for either model validation or calibration, or both;
- instrument make and model, as well as instrument configuration files.

6.4.3.4 Results presentation

The results from any static field survey for either tidal range or tidal velocities, or both, shall include for each deployment:

- location shown on a geo-referenced map with the bathymetric data and shoreline. The map shall indicate the location of measurement points, and the 'principal axes' of the tidal flow (e.g. Thomson and Emery, 2014 [16]) with the positive direction of the principal axes in the direction of flood. The following Formula (2) shall be used to calculate the direction of principal flow:

$$\theta_p = \frac{1}{2} \arctan \left(\frac{\langle \sin(2\theta) \rangle}{\langle \cos(2\theta) \rangle} \right) \quad (2)$$

where

- <> denotes a time-average over the data record,
- p is principal, and
- θ is the direction of the depth-averaged (Stage 1) or hub-height (Stage 2) flow at a measurement location.

- 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 (Stage 1 and 2) or power-weighted across the energy extraction plane as defined in 8.2 (Stage 2) current velocity and tidal height time-series throughout the period of deployment;
- velocity-bin averaged current profiles through the water column. The depth-averaged velocity, or the velocity at hub height shall be used to define a "representative streamwise velocity". Note that in the case of floating turbines, the hub height velocity will be moving up and down in the water column with the water surface. Then velocity profiles shall be grouped by this representative velocity and averaged together to obtain a velocity profile for that representative velocity. The representative velocity shall have both signs, so that distinct profiles for both ebb and flood are presented;
- tidal-phase (relative to peak flood or ebb or low or high tide) can also be presented, but are not required;
- 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 or quality control practices applied to the

data sets shall be noted, especially any data filtering or 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 bottom-most bin and the sea bed.

6.4.4 Measurement uncertainty

Uncertainty associated with the measurements of tidal flow can be calculated by assessing the uncertainty associated with the measurement device. For devices such as current profilers or velocimeters, uncertainty is dominated by potential bias due to manufacturing tolerances or degradation, i.e. doppler noise. The uncertainty in the measurements will vary based on the configuration of the instruments (e.g. the number and size of the bins for a current profiler). Therefore, it is recommended that the device manufacturers are consulted and the device technical specifications are assessed to determine the appropriate uncertainty contribution to use.

NOTE As an example of instrument uncertainty - the technical specification states that the minimum accuracy of the measurements using the device is 0,5 % of the measured value (i.e. $\pm 0,5$ cm/s). It is assumed that these represent standard uncertainties, although this is not explicitly stated.

Several sources of uncertainty affect the quality of the data and their interpretation:

- beam spread footprint: the divergence of current profiler beams means that the horizontal footprint of the processed velocity profile (i.e. in an Eulerian coordinate system) expands as the range from the instrument increases. Therefore, the Eulerian velocities measured by these instruments implicitly include some amount of spatial averaging over the beam-footprint, and vertical bins. This can introduce uncertainty when the velocity changes significantly over scales similar to the beam footprint (e.g. near sharp gradients in bottom bathymetry or bottom roughness, or horizontal eddies); it also complicates the task of estimating turbulence statistics from current profilers;
- spatial position uncertainty: the accuracy of the vessel or instrument position;
- vessel velocity (for mobile surveys): since vessel velocity is used to correct current velocity estimates, the accuracy of the vessel velocity can play a large role in the accuracy of the velocity measurements, especially when vessel speed is large compared to the water velocity.
- instrument pitch and roll: excessive vessel pitch and roll will lead to the instrument angle frequently changing from the vertical and thus measurements averaging across larger horizontal areas, which has the potential to smear vertical resolution;
- temporal uncertainty between model and measurements.

Measurement uncertainty should also include any uncertainty caused by interference as a result of physical instrument support or mooring structure, gross movement, rocking or environmental interference. This uncertainty can be removed by discarding affected data through error-checking. The device manufacturer should be consulted to ensure that the configuration of the measurement device is suitable for the site. If data are deemed to be affected by interference (e.g. side lobe interference, transducer ringing, etc.) this data should be removed and reported during the post-processing analysis. In order to reduce uncertainty, it is recommended that the use of synthesised data to “fill in” missing data should be avoided whenever possible, and only raw measured data should be used within the assessment.

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) [17]. However, application of this method to current profiler non-steady (turbulent) flow data are 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 the data are transformed into a

velocity vector at a single point. The ISO/IEC Guide 98–3 (2008) [17] provides a method for characterising 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 measured as described in 6.4. 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.

For sites where measured data are (mostly) collected remote from the TEC location, it is necessary to evaluate the spatial extrapolation at the site. At the time of the writing of this document, there is no consensus on an approach to quantify spatial extrapolation uncertainty for an arbitrary site, as such, the following recommendations have been made. This can be evaluated through carrying out hybrid mobile surveys, transect surveys across the site (covering the TEC locations) or through the development of a validated numerical model. The uncertainty associated with transect surveys using vessels should consider the factors outlined in 6.4.2.2. The appropriate method to quantify the spatial extrapolation uncertainty should be decided by the user depending on the availability of data and the suitability of the approach should be justified. The method used should comment on the following suggested areas: extrapolation distance, the variability of bathymetry, differences in depth, velocity gradients calculated from the measurements.

For cases where a validated model is used to evaluate the spatial extrapolation uncertainty, see 7.7.2. A general overview of uncertainty and guidance on combining uncertainties is provided in Annex B.

6.5 Meteorological data

6.5.1 General

Meteorological data to be used for determining the importance of the wind and atmospheric pressure, as described in 7.4.4, shall be identified and reviewed. Results from the global numerical models with processed satellite derived wind and atmospheric data (i.e. ERA5) shall be retrieved either during the same period as the model validation or calibration, or both. Any local measured data (e.g. barometric pressure sensor, wind gauge) shall be used to validate the results from the global model.

6.5.2 Wind data

7.4.4 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.

6.5.3 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 can be necessary to account for meteorological atmospheric pressure variations impacting on the resource (e.g. in extreme cases, storm surge).

6.5.4 Results presentation

The extent, variables, time period, time and grid resolutions used to extract results from the global numerical model shall be documented.

The locations, period of record and an assessment of the quality of the data shall be reported for any wind and atmospheric pressure measured data. Measured data shall include the following information:

- time-series figures: observed wind speed and direction, and atmospheric pressure;
- wind rose figures: observed wind rose for wind data during the entire period of record and for periods during storm events;
- measured data comparison figures: a time-series comparison of the measured data with combined numerical models with processed satellite derived wind or atmospheric data. Any discrepancies between both datasets shall be reported and discussed. Any manipulation of model global results data to correct the differences shall be reported and justified.

6.6 Wave climate

6.6.1 General

Waves can significantly affect tidal currents and power through modification of currents and turbulence in the water column. Existing wave data at or near the location of interest shall be reviewed to determine if waves should be accounted for in the tidal energy site assessment - see [IEC TS 62600-2:2019 \[18\]](#), 6.2. For the purpose of resource assessment, the potential for substantial wave-current interaction to have a material impact on flow conditions shall be considered. Generally, coastal wave measurements and modelling software provide sufficient information for an initial (screening) level review. If significant wave heights are greater than 1 m and peak wave periods are greater than approximately 6 s, further information should be reviewed to determine the significance of waves in the tidal resource assessment.

If wave measurements or sufficiently validated operational models are available at or near a specific location and wave effects are determined negligible per the above criteria, there is no requirement for further measurements. However, if the waves are determined to be significant and no adequate wave data are available, it can be necessary to conduct wave measurements.

Waves are typically measured in coastal environments using current profilers, bottom mounted pressure transducers, or surface buoys. Other methods such as satellite altimetry and high frequency radar can be available for the site, but should be carefully evaluated for reliability in characterising the site specific wave environment. Surface buoys are generally not effective in tidal conditions suitable for TEC devices due to biased buoy responses in high water velocities. The recommended approach for gathering wave related data at a tidal energy site is to use a waves-enabled current profiler unit - see [IEC TS 62600-2:2019 \[18\]](#), 6.5, for wave measurement specifications. The validity and source of all wave data shall be verified and provided.

Where waves are significant, wave information at the site, whether existing or collected as part of the site characterization, shall be used to develop a seasonal description of the wave environment. The seasonal wave description shall include a monthly compilation of maximum and average significant wave heights and peak periods for the evaluation of time periods when waves are significant.

6.6.2 Results presentation

The extent, variables, time period, time and grid resolutions used to extract results from the numerical model shall be documented.

The locations, period of record and an assessment of the quality of the data shall be reported for any wave measurement data. Measured data shall include the following information:

- time-series figures: observed significant wave height and peak period;
- wave rose figures: observed wave rose for peak wave direction during the entire period of record and for periods during storm events;
- measured data comparison figures: a time-series comparison of the measured data with available numerical models. Any discrepancies between both datasets shall be reported and discussed. Any manipulation of model global results data to correct the differences shall be reported and justified.

NOTE 1 Hashemi et al. (2015b) [\[19\]](#) provide an overview of the impact of waves on the tidal energy resource.

NOTE 2 The local wave characteristics could directly impact the design of TEC devices. See [IEC TS 62600-2:2019 \[18\]](#) for further information.

6.7 River discharge

6.7.1 General

The importance of river discharge should be determined by comparing the upstream annual average river discharge to the average tidal flow rate during ebb tide determined with either transect measurements or a validated numerical model. If the river discharge is more than 10 % of the average ebb tide flow rate, a minimum of one year of data of the upstream discharge shall be collected using the methods outlined in [IEC TS 62600-301:2019 \[20\]](#). This data will be used for developing the flow duration curves (FDC) to be used for performing the resource assessment.

6.7.2 Results presentation

The location, period of record, and an assessment of the quality of the data shall be reported for discharge data. The measured data shall be presented in the following formats:

- time series of the measured flow rate during the period of record;
- the FDC as computed using the method described in [IEC TS 62600-301:2019 \[20\]](#).

6.8 Turbulence

6.8.1 General

Flows at tidal energy sites are inherently turbulent due to the high Reynolds numbers; however, the magnitude of the fluctuations can vary significantly from location to location and between ebb and flood. The fluctuations associated with the turbulent flow are believed to affect both fatigue and extreme loads which impact device design as detailed in [IEC TS 62600-2:2019 \[18\]](#) and can affect the uncertainty in the AEP estimates. An assessment of the turbulence level might also help either inform or validate modelling results, or both. The evolution of the turbulence in highly energetic tidal regimes is an area of ongoing research (see Note 1), especially with respect to how this evolution is impacted in the near-field by TEC operation.

NOTE 1 Stevens et al. (2012) [21], Thomson et al. (2012) [22], Milne et al. (2013) [23], Mycek et al. (2014) [24], Gunawan et al. (2014) [25], McCaffrey et al. (2015) [26], and Guerra and Thomson (2017) [27] are examples of useful reference papers.

The most common turbulence statistic utilised in renewable energy industry is turbulence intensity (TI), which is a ratio of the fluctuations in the horizontal current speed to its mean value (see [Clause C.7](#)). TI can be computed from either acoustic Doppler velocimeters (ADV) or Doppler profilers, provided that the instruments are configured correctly (guidance in [Clause C.7](#) for Doppler profilers). Arguably, the simplest way to obtain TI estimates is to use the same Doppler profilers that are used for tidal current stationary surveys (see [6.4.3](#)).

At the "feasibility study" level (Stage 1), measurements are recommended to include TI, but they are not required by this document. At the "layout design study" level (Stage 2), turbulence intensity measurements are required, and the measurement of more detailed turbulence statistics such as turbulence kinetic energy, turbulence length scales, turbulence spectra, and Reynolds stresses is recommended as these can be required for design or power performance purposes as discussed in [IEC TS 62600-2:2019 \[18\]](#) and [IEC TS 62600-200:2013 \[28\]](#) (see [6.8.1](#), [Note 2](#) for useful references). Measurements in addition to TI would be beneficial to the tidal energy research community, and can also be valuable in either selecting sites or informing the design of robust and efficient devices, or both.

NOTE 2 Useful references for turbulence measurements include: Stacey et al. (1999) [29]; Vermeulen et al. (2011) [30]; Milne et al. (2013) [23]; McCaffrey et al. (2015) [26]; McMillan et al. (2016) [31]; McMillan and Hay (2017) [32]; Kilcher et al. (2017) [33]; Guerra and Thomson (2017) [27]; Horwitz and Hay (2017) [34]; Guerra and Thomson (2019) [35]

6.8.2 Results presentation

The results from turbulence measurements and analysis are similar to those for the tidal current stationary survey (see 6.4.3.4). If the measurements are carried out simultaneously, reference the repeated results. For all turbulence measurements, the results should include:

- instrument make and model, as well as sampling configuration (frequency, resolution) of the instrument;
- 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;
- measures of current profiler orientation (e.g. heading, roll and tilt);
- cell start depth (bottom cell) and cell stop depth (top cell);
- total water depth and tidal height above the project chart datum;
- maximum and minimum tidal range observed during survey, preferably relative to maximum and minimum annual (or 18,6 year) tidal range;
- maximum currents observed;
- estimation of the Doppler noise, either from the manufacturer guidelines or from velocity spectra (see Clause C.7);
- averaging interval used for TI estimation;
 - an averaging period of 5 min is typically used in the tidal energy industry (a 10 min window is more often used at wind-energy sites), but the presence of either nearby headlands or islands, or both, can require longer intervals to capture the larger scale fluctuations.
- precise definition of TI used (i.e. either horizontal or streamwise, see Annex C);
- time series of turbulence intensity at hub height, after the removal of Doppler noise;
- vertical profiles of turbulence intensity during peak-ebb and peak-flood;
- joint probability distribution for TI and velocity (see 6.8.2, Note).

NOTE See Figure 6 of Gunawan et al. (2014) [25].

6.9 Large scale flow structure

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

Navigation charts should be consulted to identify obstructions that can 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 or mobile current profiler data collected leeward of the obstruction to verify estimates of the shedding frequency and flow structure configuration.

NOTE 1 Predominant features of vertically oriented eddies include:

- a) periodic, organized and asymmetric oscillatory motions of the mean flow field at shedding frequencies characterised by the predominant length scale of the obstruction and the speed of the tidal current; and
- b) increased turbulence production and intensity. Turbulence characteristics can be quite different between flood and ebb tides.

NOTE 2 The effects of turbulence on TEC performance and 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 can help identify eddies and can allow verification of detailed modelling studies.