Deliverable T3.1.2

Data Collection & Survey Best Practice Report

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Abstract

Data collection, modelling and resource assessment are key stages in the planning of any tidal energy project. This report forms part of the Tidal Stream Industry Energiser (TIGER) project, seeking to support the development of the tidal energy industry. It provides a summary of relevant international standards and other industry guidelines, reviewing a range of methodologies for conducting site assessments. The best practice for data collection as baseline for tidal resource assessment and engineering design are presented with a focus towards comprehensive site surveys, rather than early-stage initial scoping studies. The report will be a guide to data collection for industry practitioners and researchers, as well as involved stakeholders, investors and decision-makers.

The report emphasises that the requirements and conditions for every tidal energy project are different. The data collection, modelling and assessment processes should be carefully planned, considering site and project specific factors. Expert knowledge is essential to ensure that high-quality data is collected and that the resource assessment is suitable for the project. The cost of data collection campaigns, both financially and in terms of project time, can be significant and a balance needs to be struck when deciding on the scope of marine operations and data measurement campaigns. Data sharing between institutions and projects can have significant benefits to projects, helping to keep costs down and improving output. The mutual sharing of resources offers improvements that may be beyond the investment potential of a single project. It can be equally beneficial to the industry for pilot projects to provide ‘lessons learnt’ reports following completion.

Numerical simulation is essential for all but the smallest projects and the methodologies employed in site assessment are discussed. All modelled and measured data will contain uncertainties, which should be understood to assign appropriate confidence to key performance indicators, such as Annual Energy Production (AEP) and Levelised cost of electricity (LCOE).

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1 Introduction

This deliverable is prepared as part of the EU Interreg Channel funded 'Tidal Stream Industry Energiser (TIGER) project. The aim of the TIGER project is to accelerate the growth of Tidal Stream Energy (TSE) in the France (Channel) England (FCE) region, to realise economic benefits for coastal communities.

The project seeks to build cross-border partnerships to develop new technologies, test and demonstrate them at several locations in and around the Channel region. The project brings together sector specialist organisations, SMEs & technology developers, with academic experts, to build cross-border teams to collectively accelerate the development of the sector. Project partner turbine developers, supported by academia & research organisations, work together, creating one new UK/FR supply chain network that will deliver new designs for improved performing/ lower cost turbines.

In order to foster that dynamic, some challenges must be tackled. Among them, guiding the developers to help them in their project development, streamlining the consenting process, increasing knowledge by sharing available data and expertise and raising public awareness are important.

To facilitate knowledge sharing in the area of data collection site survey, the project has established the so-called Data Survey Network Group, which consists of expert representatives from all partners and external stakeholders. The group has been established on the 30th April 2020 and has since met regularly every 3 months, with further specialist meetings where required. The terms of references are provided as Annex A. This deliverable is based on the discussions, expertise and lessons learnt from this forum.

1.1 Scope of Report

The aim of this report is to describe the results of best practice, models and identify standardised data collection equipment identified through the Survey Network Group. The report has been endorsed by the project steering group (PSG) and Strategic Advisory Group (SAG) [pending approval from the SAG]. This report discusses characterisation of the resource at a tidal energy site, as such, the focus is on;

- Resource assessment for a particular site/tidal array, rather than regional or national scale.
- Obtaining pre-deployment resource data (currents, water levels, waves, bathymetry) for the purpose of energy yield prediction and engineering design (loading). This is distinct from performance assessment of deployed tidal turbines. The latter is subject of project Deliverable T1.7.3 "Accredited turbine performance test procedures".
- Whilst the flow data obtained will be suitable for other analyses, this report does not consider
    - Input to turbine or array-scale modelling. The only flow-device interaction considered here is on the scale of modelling turbine influence on resource (through additional blockage and drag)
    - Device-specific energy yield prediction, as this requires further information such as power performance, availability, and wake interaction.
    - Environmental or ecological data to assess wider impacts of an array.

Note that there remain various unknowns about characterising the resource at a tidal energy site. Attempting to answer these questions is something that would fall outside the scope of a resource assessment for a commercial deployment and may be more properly addressed as part of a research project. However, as the current deployments are all pre-commercial, there may be scope for combining resource assessment with fundamental research. In this document, the focus is on industrial best practice rather than scientific state-of-the art review. However, this work does seek to highlight areas where further research is required, too.

1.2 Target audience:

This best practice report seeks to provide concise information for industry stakeholders that require an overview to data collection and site survey methods for tidal energy projects. This could be institutional stakeholders, including investors, insurance companies, local authorities, and governmental bodies, as well as policymakers and the wider supply chain. It also gives an opportunity for researchers and practitioners in the sector to compare their methods and processes with the practices and methods presented here.

1.3 Aims & objectives:

This report aims to use a combination of reviewing existing resources, analysis of the engineering requirements for site characterisation and analysis of data collection practices to consider resource assessment procedures for tidal energy projects. To achieve this, it has the following objectives.

- Review existing standards and best-practice guidelines for setting up a tidal energy resource assessment
- Define the parameters required for site characterisation and engineering design
- Specify site and design parameters necessary for use in simulations of tidal turbine performance and loading.
- Describe data collection practices, necessary to gather these data sets

2 Overview of standards and guidelines

2.1 International standards

2.1.1 IEC TS 62600-201: Tidal energy resource assessment and characterization (2015)

IEC TS 62600-201 is the most used standard for resource assessment related to marine energy. The 2015 standard builds on the previous EMEC report (Assessment of Tidal Energy Resource, 2009).

Two resource assessment stages are defined at the outset, as show in Table 1.

Table 1– Reproduction of IEC TS 62600-201 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 standard highlights the focus at stage 1 on *investigating the scale and attributes of the energy resource within a particular area*, and at stage 2 on *generating detailed and accurate information on the tidal energy resource at a specific area to determine AEP*.

An overview of recommendations for modelling and physical data capture at each of the two stages is given. Physical measurement recommendations are defined in the standard with reference to later sections, however key modelling recommendations given at the outset are:

- Minimum number of harmonic constituents for modelling driving boundary (4-8 at stage 1 and 8-12 at stage 2)
- Grid resolution (<500m or >10 cells across channel section at stage 1 and <50m at stage 2)
- Period of model run (>35 days in both cases).

Harmonic analysis on available current data is also highlighted and recommended to include at least 20 constituents at both stage 1 and stage 2.

A series of recommendations are made on data collection (section 6), within sub-sections on Bathymetry, Tidal data quality, tidal height, tidal current surveys (mobile and stationary), instruments and layouts, and output data and result presentation. These are summarised below:

Bathymetry:

Data must be captured with sufficient resolution to support hydrodynamic modelling, which should have a maximum grid size of 50m. If existing data is used, caution should be taken, and the data checked against modern methods. If a survey is undertaken, it should be conducted in accordance with *IHO Standards for Hydrographic Surveys: 2008* and reporting of bathymetric survey activities should be to the standard of the ICES *Guidelines for Multibeam Echosounder Data: 2006*.

Data to be provided with any survey undertaken should include:

- Date of 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

Tidal data quality:
As a minimum, data should include graphs of typical daily, monthly, and annual tidal height, current speed, and direction, generated either from measured data or calculated from tidal harmonic constituents derived from measured data using harmonic analysis software. Capturing a typical day, month or year may require the capture of data for longer than one day, one month or one year, and should be presented in the context of the 18.6 lunar-solar cycle. IEC TS 62600-201 recommends the use of the *ISO/IEC Guide 98-3:2008* standard approach for calculating data quality but does highlight that the application of this method to turbulent flow is subject to debate. The use of standard deviation of velocity measurements over averaging period is therefore recommended as a quantitative assessment of uncertainty due to inhomogeneous flow.

Tidal height:
When used for model calibration or validation, the number of locations required for tidal boundary conditions depends on model complexity, boundary length, and model specifics. Data to be provided at each location should include:

- Location (shown on geo-referenced map with bathymetric data and shoreline, in consistent coordinate system with bathymetric data)
- Date and length of measurement
- Methods used
- Calibration reports
- Tidal range and vertical datum (standard definitions used in the project country)
- Analysed tidal constituent data
    - Amplitude and phase of all constituents, such that >95% of total variance is captured
- Assessment of data quality

Tidal current surveys (mobile):
Mobile surveys are recommended for use at stage 1. It is noted that a mobile current survey is not in itself sufficient to specify annual velocity distribution, though in combination with a model may be able to provide useful information about spatial variability.
Data collected using current profilers should be collected by competent operators with experience of such devices to mitigate poor mounting or configuration errors. Surveys should be designed to account for size, bathymetry, and volume of the site in question, and should use appropriate scales to capture local variability. Data should be collected during a typical Spring cycle, noting as above that this may require a longer capture period. Data collection at a Neap cycle is also recommended to understand the difference in characteristics between Spring and Neap conditions. Mobile velocity data should be processed into suitable vertical and horizontal bins. Suggested sizes are 1 m vertical bins and 25m 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. Deep sites will require low frequency equipment (300Hz is suggested) and hence larger depth bin and horizontal bin sizes.

The standard notes that large sites are likely to require the distribution of survey work over multiple tidal cycles, and therefore notes that bottom-tracking derived vessel speeds are essential.

Data to be provided for each timestep should include:

- Time (UTC) with year, month, day, hour, minute, seconds
- Location (given in a coordinate system consistent with the bathymetry data)
- 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 other tidal height measurements)
- Quality indicators and uncertainty levels for the horizontal positioning of the vessel

Results should be presented including the above, as well as maps and images presented with consistence reference abscissa.

Tidal current surveys (stationary):

If to be used for calculating AEP directly, stationary surveys are recommended to be undertaken over a minimum of 90 days. If not being used for direct AEP calculation, the required 20 harmonic constituents can be achieved with a minimum of 35 days' capture, though it is noted that longer datasets will often improve accuracy. Layout design 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*"

The number of instruments deployed will depend on the proposed array size, with instruments deployed at the centre of the array or key representative locations in a smaller array and informed by hydrodynamic modelling in a larger array.

The standard requires an averaging period of 10 minutes or less, but greater than or equal to 2 minutes. A suitable integer divisor of 600s should be used for consistency with AEP calculation. Sampling frequency should be maximised within the constraints of device battery and memory but should be no more than 20 seconds.

Data should be processed into vertical bins with resolution dependent on the instrument and water depth with u, v, w and z (depth) in each bin for each time interval. The bin averaging method should be noted. 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. The movement of the device should be monitored and recorded, and the frame used designed to minimise magnetic deflection by using non-ferrous metals.

Output data to be provided is as in the mobile case with the following additions:

- All applied data calibrations
- 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

Data to be presented is again as in the mobile case with the following additions:

- 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
- Compass calibration procedure and results should be recorded
- 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.

IEC TS 62600-201 states that meteorological data to be used for determining the importance of wind and atmospheric pressure shall be identified and reviewed. Locations, period of recording and quality should be reported. Wind data, if deemed necessary, should be undertaken using the methodology described in standard IEC 61400-12-1. Atmospheric pressure should be recorded during field data collection using appropriate means, such as a barometric pressure sensor, since this data may be necessary to account for pressure variations which impact the resource.

Existing wave data should be reviewed and if deemed sufficient, or the site is not exposed to swell waves, there may be no need for a wave monitoring survey. If a survey is deemed necessary, the standard recommends the use of a waves-enabled current profiler. Floating wave measurement buoys are deemed unsuitable due to the extreme tidal conditions which will drag the wave buoy to the maximum extension and result in highly biased results. It is further noted 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.*"

The standard includes a very small section on Turbulence, stating that it is an area of ongoing research and that it is not currently know what scale, frequency and magnitude of current variability are important. Seawater stratification, density and sediment are also acknowledged as having potential small impacts, and the standard notes that they should be considered.

The standard offers guidance for modelling, calculation of energy extraction and data analysis and presentation. Annex B also offers specific guidelines for current profiler measurements. Recommendations in five areas are summarised below:

General:

- Current profilers are not, in general, sufficient for turbulence characterisation.
- Current profilers should include heading, pitch and roll sensors in order to convert measurements into earth coordinates. Time series of data from these sensors should be used to verify any platform movements and by noting deployment and recovery locations. Movement of more than 50m suggests suspect data.

Instrument configuration:

- Instruments should be configured to obtain vertical resolution of 1m or finer.
- Vertical range of the measurements should be over the full turbine area, not just up to hub height.
- Sampling rate should be selected to ensure horizontal uncertainty in averaged velocity of less than 5cm/s.
- It should be noted that instrument-reported horizontal uncertainty may overestimate certainty, particularly close to the profiler and at low (<1m/s) velocity.
- The potential for "cross talk" (mutual interference) between two or more active acoustic devices should be borne in mind. This can occur when the same frequency or multiples of a common frequency are used.

Clock drift:

- Assuming clock drift is linear if it occurs, correction is suggested by ensuring the accuracy of the device clock on deployment and adjusting to compensate for any difference at retrieval. It may also be possible to neglect without ill effect any drift which is small compared to the phenomena of interest.

Depth quality control:

- Depth quality correction is used to control for abrupt changes in depth which may cause misleading pressure sensor results. If change in depth between consecutive measurements is above a certain threshold (which should be justified and documented), a value of the mean of previous and next measurements should be used instead.

Velocity quality control:

- Velocity spikes should be removed or replaced with representative values. Again, a justified and documented threshold value, here for the difference in consecutive velocity measurements, should be used to correct the data. Methods suggested include the Phase-Space Thresholding (PST) technique (Goring and Nikora 2002), the modified PST method (Parshehet al. 2010) and spectral noise filtering (Goring and Nikora 1998, Garcia et al. 2005, Thomson et al. 2010 for turbulence intensity).

2.1.2 DNVGL-ST-0164 – Tidal Turbine Standard (2015)

Standard DNVGL-ST-0164 includes sections on design principles, manuals, site conditions, loads and load effects, materials and design of foundations, blades, general machinery and electrical equipment, and testing, operation and maintenance. Data collection and survey practice is

included in Section 4 (Site Conditions and Characterisation) and Section 5 (Loads and Load Effects).
In Section 4, the report also discusses currents, waves, water level and wind. Current is represented by a 10-minute mean streamwise current speed and standard deviation, which are assumed to remain constant over the period. Current speed at hub height is used as the reference current speed in the DNVGL standard. Turbulence intensity is defined as the ratio of standard deviation of velocity fluctuations in the three directions to the mean streamwise velocity. If harmonic analysis is used, a series of requirements are highlighted, including analysis period, constituents, analysis software, prediction period and weather. Section 4.2.2 (Parameters for normal current conditions) suggests the representation of current by a 10-minute mean streamwise speed. Current measurement using ADCP is discussed in Section 4.2.4, where the requirements of IEC 62600-200 Sec 7.2 are adopted, with the following additions:

- *Measurement duration shall be as a minimum long enough to ensure capturing the turbine's cut-in and cut-out current speed,*
- *When harmonic analysis is used to predict tidal elevations and currents a minimum of 30 days length of site measurements is required to distinguish enough harmonic components*
- *Quality assurance parameters of the measurement records shall be reported.*

Section 4.3.2 discusses wave measurements, but does not male specific recommendations, instead directing the reader to *ISO 19901-1, DNV-RP-C205, IEC 62600-200* and *EquiMar Project Deliverables 2.2* and *2.7.*

Table 2 – Reproduction of DNVGL-ST-0164 Table 5-8: Proposed load combinations for load calculation.

		Environmental load and return period to define characteristic value of corresponding load effect.				
Limit State	*Load combination*	*Wind*	*Waves*	*Current*	*Ice*	*Water level*
ULS	1	50 years	50 years	5 years		50 years
	2	5 years	5 years	50 years		50 years
	3	50 years		5 years	50 years	MWL

Section 5 includes a table of proposed load cases (Table 5-5 in the original report) combing environmental variables for 8 design situations (power production, power production with fault, start-up, normal shutdown, emergency shutdown, parked, parked with fault, transport, assembly maintenance and repair). These cases inform selection of resource parameters. Additional cases for floating turbines are also included in Table 5-7. Basic load cases are also provided for cases where information is not available to produce the required characteristic combined load effect directly (Table 1).

The report proposes different load factors for ULS depending on the level of confidence in the resource parameter characterisation (1 for *statistically derived with several years data from the location*, 1.05 for *1-month complete measurements at site*, 1.25 for *Incomplete measurements).* This highlights the value of extensive data collection.

The report suggests that wind can be represented by a steady model, using extreme case return periods of 1 year, 5 years and 50 years. A power law shear speed profile is suggested. Further relevant site conditions are also discussed, including Ice, salinity, temperature, density, etc. Some guidance on seabed and geotechnical investigations is also given, with the reader directed to, *DNV Classification Notes No 30.3, ISO 19901-8* or *Eurocode 7* for further information.

2.1.3 BV NI603 R01 – Current and tidal turbines (2015)

Bureau Veritas Guidance Note NI 603 DT R01E is largely related to the certification of turbines and does not include specific guidance on resource assessment. Section 2.3 of the standard discusses Environmental data, highlighting areas which must be included:

- *Data for the extreme condition*
- *Data for the limiting environmental (threshold) conditions considered for each normal operational condition or any other specific design condition*
- *Long term distribution of environmental data on which the design of the structure for fatigue is based*
- *Data for any other particular design condition*

The standard advises that relevant standards are to be applied, and highlights American Petroleum Institute, IEC (specifically 62600 series), ISO (specifically 29400) or "other relevant standards".

It is notable that the API and ISO standards apply generally to offshore structures. The IEC standard is specific to tidal energy. It may be beneficial to combine standards, for example by using API or ISO standards in areas such as wind loading, and IEC standards for met-ocean conditions.

2.2 Other guidelines and relevant documents

2.2.1 EPRI – Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion Devices (2006)

This document is an output of the EPRI (Electric Power Research Institute) TISEC (Tidal in Stream Energy Conversion) project, and aims to "*provide a methodology […] to estimate the power and energy production of different TISEC devices at various sites with their native tidal stream flow climate.*"

Various sections of the document refer to the fundamentals of tidal stream energy, tidal data sources (with particular focus on available data in the United States and Canada at the time of writing), and some information on resource assessment in Chapter 3.

Here the method used to calculate the total annual mean tidal stream energy resource at a series of project sites is described. The report describes simple metrics such as shear profiles, velocity distributions and discusses the methods used to estimate potential power production at the project sites. Data was sourced from software packages *WebTide* and *Tides & Currents,* but the report does not describe any methods used to measure or undertake surveying.

2.2.2 IEA OES - Guidance on Assessing Tidal Current Energy Resources (2008)

The IEA Ocean Energy Systems (OES) report is a basic report prepared by the NRC Canadian Hydraulics Centre in 2008 and published in 2009. The report includes a large section on the fundamental nature of tides and description of tidal constituents. Subsequent sections discuss kinetic power in tides and mathematical methods for calculation of potential generated power. Case studies describe the use of ADCP and ADV. A 28-day recording period was used in the Minas Passage case study undertaken by the Bedford Institute of Oceanography, and a 14-day period was used at the Quebec City location. However, the report does not include assessment of the suitability of this period or discussion of methods.

2.2.3 EMEC - Assessment of Tidal Energy Resource (2009)

The EMEC Assessment of Tidal Energy Resource represents the first detailed guidance document on the assessment of tidal stream resources. This document ultimately forms the basis of the IEC 2015 guidelines. The EMEC document covers four key stages of resource assessment:

- Stage 1: Regional assessment – Site screening
- Stage 2a: Site assessment - Pre-feasibility
- Stage 2b: Site assessment - Full-feasibility
- Stage 3: Site assessment - Design development

Bathymetric study recommendations are given in relation to the four stages of resource assessment. The report recommends that for a pre-feasibility assessment (Stage 2a), bathymetry data should be from a data set with soundings of spacing approximately 100 m. For the full-feasibility assessment (Stage 2b), the bathymetry data should be from a data set with soundings of spacing approximately 20m, and for the development stage (Stage 3), the bathymetry data should be from a data set with soundings of spacing approximately 5 m. Where required, bathymetric surveys should be undertaken to IHO Standards for Hydrographic Surveys (2008). Multi-beam echo sounder (MBES) systems are recommended over single-beam echo sounder (SBES) or side scan sonar (SSS).

Section 5 of the report includes discussion of existing data, such as that gathered from existing regional oceanographic centres, and recommendations for the estimation of current speeds. This is related to the stages of assessment given above and is summarised in a table in the original report (Table 2).

Table 3 - Reproduction of Table 2 from EMEC Assessment of Tidal Energy Resource: Methods to estimate current speed

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

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

Subsequent report sections focus on tidal harmonic analysis. The number of harmonic constituents included in an assessment is a key value. The report suggests that simple harmonic analysis with up to four components may be sufficient for Stage 1 but highlights that velocity errors of 50–100 % might remain. At Stage 2 or 3 it is recommended to use Fourier analysis to extract more tidal constituents, using software which follows a method recognized by the industry. A time series of velocity at 10-minute intervals is recommended, over a period of one month or one year. Modelling is discussed in Section 5.3, with recommendations on software, resolution, and dimensions. A list of software, dimensions and grid structure is given in the report.

Section 5.4 (Field Study) gives recommendations for Transect study, stating that a transect study should be undertaken during stage 2. It is recommended to undertake the study around the areas in which turbines will be deployed, during a typical spring cycle, during the two days with strongest currents. If time constraints or boat availability do not allow this, the transect survey may be carried out at any peak flood or ebb cycle and data extrapolated to the mean spring peak cycle. The report states that the transect study should be undertaken by towing an acoustic instrument below a boat. The following specific recommendations are given:

- Transect velocity data shall be processed into suitable vertical and horizontal bins; these may be for instance 1 m vertical bins and 25–50 m horizontal bins.
- The sampling frequency should be 2 Hz, and the depth of the first bin should be less than 5 m below the surface level.
- In order to overcome bias in the direction of vessel motion, transects should be measured in both directions, back and forth, and data processing should average the two opposing transects to help remove this bias.
- Each transect should therefore consist of a traverse in both directions over a short time interval (< 10 min).
- Each transect should not last for more than 10 minutes, otherwise the velocity at the start of the transect might have changed significantly by the time the boat returns to the start position.

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

On the deployment of static devices, installation is recommended at locations highlighted by modelling as suitable for tidal energy device installation. The deployment of two devices is strongly recommended. At stage 2b, data should be recorded for at least 15 days for a single turbine installation, or one month (minimum) to three months (recommended) for an array. At stage 3, a single turbine installation requires 30 days' data, and an array 3 months (minimum) to one year (recommended).

Recommendations suggest the data collection interval should be between 2 and 10 minutes, velocity data should be processed into 1 m or 50 cm vertical bins with u, v, w and z in each bin for each time interval. Sampling frequency should normally be 2 Hz. The standard deviation in velocity measurement should be less than 5 cm/s and the current direction measurement shall be better than ±5 °. Vertical bins should start as close to the seabed as possible and extend close to the sea surface. Data to be recorded is as in the transect case, with the addition of turbulence data and exclusion of quality indicators.

Recommendations for velocity distribution data analysis are described in Section 7. 10-minute standard interval and 0.1m/s bin size are recommended. The term V_{msp} is used to define maximum velocity. V_{msp} is described as the peak tidal velocity observed at a mean spring tide. Where static survey, model or harmonic analysis results are available over a month, maximum velocity is defined as the peak velocity that has been reached for 10 minutes over the month. Where transect surveys have been undertaken during the two strongest days of representative spring tide, V_{msp} is the 10-minute average maximum velocity. In other cases, extrapolation should be used.

Sections 7 also describes tidal range (to be compared to previous or related work), tidal ellipse (generated using a model or static field data and generated specifically for ebb and flood if the flow direction differs from the major axis by more than 10% for more than 5% of time), and the calculation of power density. Average power density for number of bins N_B and bin number i is calculated as:

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

Where:
ρ = density of water (kg/m^3)
U_i = Central velocity magnitude in the ith bin (m/s)
$f(U_i)$ = Time occurrence likelihood of a velocity in each 0.1m/s bin (%)
V_{rmc} = Cube root of the mean of the cubed velocities

Extrapolation of data recommendations are based on the comparison of monthly and annual data. If a difference in power density of more than 5% is calculated, further calculations should be undertaken to determine the reason. Comparison of model and field data is discussed in Section 7.7, giving key recommendations for depth profile (plotted at different critical locations and compared using power laws), maximum velocities (V_{msp} compared between modelled and measured and explained if a difference of more than 10% is found), time series (assessed using a cross-correlation procedure with mean, phase shift, amplitude, and scatter statistics).

The impact of external effects is discussed in Section 7.10. The report recommends the calculation of 1-year, 10-year and 50-year currents considering storm, wind, wave and atmospheric effects. No guidance is given on how to calculate extreme waves, though consideration of 50-year and 100-year storm waves is recommended. If no wave data is available, measurements are recommended. Recording frequency of 5Hz is recommended, but in practice may be unfeasible (for example, a typical Nortek DWR4 buoy is able to output wave data at 2.56Hz) The report recommends the consideration of wind data, and if no wind data is available, suggests the methodology described in IEC 61400-12-1 should be used. Though turbulence is mentioned, it is highlighted as an area of ongoing research and no guidance is given.

Following measurement or calculation of a velocity profile, calculation of electrical power is described. If no specific turbine has been identified, general characteristics are given (rotor efficiency between 38% and 45% at cut-in and rated velocities respectively, rated velocity at 71%

of V_{msp} at hub height, powertrain efficiency of 90%). Mean annual electrical power and annual energy production calculations are described in Sections 8.4 and 8.5.

2.2.4 EquiMar (2011)

The EquiMar (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact) project produced a series of deliverable reports.

Deliverable D2.2 (Wave and Tidal Resource Characterisation)
This report *describes and discusses techniques for wave and tidal measurement and analysis for the purposes of resource assessment.*

In common with other guidance documents, a series of measurement levels are defined, in this case as follows:

- Early Stage: Baseline data to confirm potential
- Project Development: Specific measurements to reduce uncertainty and allow energy production estimates
- Marine Operations for the farm: Specific measurements to compare to energy production data, correlate between resource and output, and to allow design improvement.

Section 2.2 (Wave Measurement) and 2.3 (Tidal Measurement) provide guidance on measurement methods and practice. Section 2.2 (Wave Measurement) begins with an introduction to time series, suggesting common recording periods of between 20 minutes to 1 hour. Continuous data sampling with sample rates of 2Hz is suggested as typical. Fixed and sub-surface measurement devices are discussed, followed by surface buoys and Acoustic Doppler Profilers (ADPs). Risks to ADP use (e.g. trawling or burial) are highlighted, and the challenges of data recovery discussed. HF radar is offered as a potential alternative to ADP systems, with advantages including spatial coverage and the avoidance of instrumentation in the water. Section 2.3 (Tidal Measurement) again highlights ADPs and HF radar as potential capture methods. Example measurement frequencies for ADPs and HF radar are given, with the former suggested at around 1MHz in shallow water and 600kHz in deeper water, and the latter between 5 and 50MHz.

The report provides further details on parameterisation of both wave and tidal data for resource assessment, giving a flow diagram for each (shown below in figure 1 and 2).

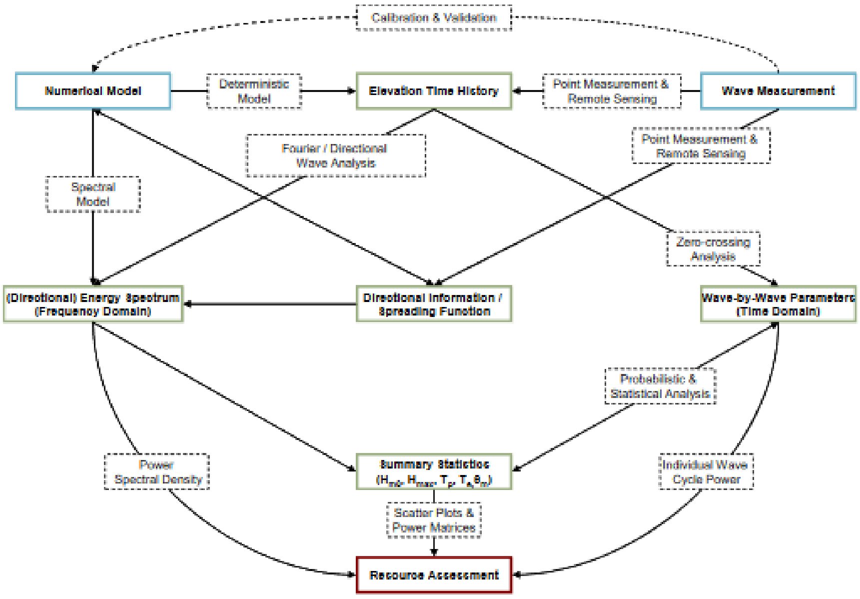


Figure 1: Reproduction of Figure 7: Data sources and analysis methods for wave resource assessment from Equimar D2.2 report

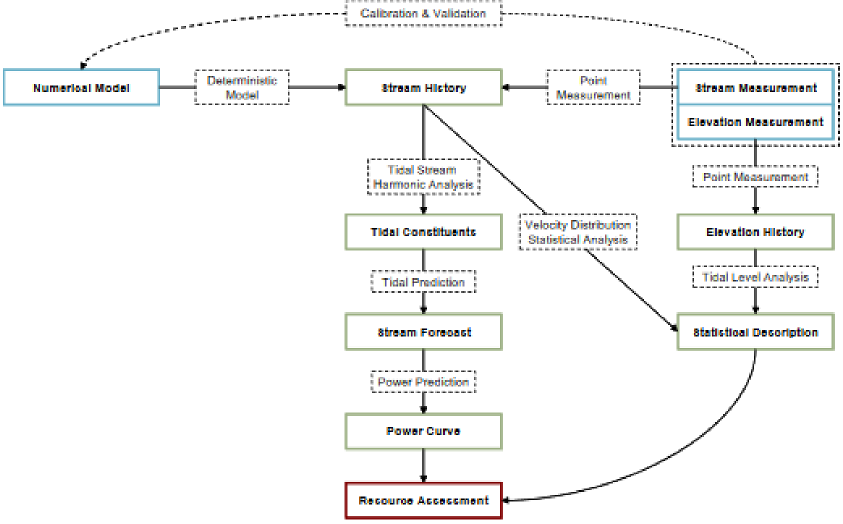


Figure 14 Data sources and analysis methods for tidal resource assessment

Figure 2 - Reproduction of Figure 14: Data sources and analysis methods for tidal resource assessment from Equimar D2.2 report

Quality control is discussed for both wave and tidal data. The report highlights that data quality control of wave records is more problematic due to the devices and broad-band data form. Potential errors such as spikes, extended constant values, noise and distortion are highlighted. Various analysis and parameterisation methods are discussed for wave and tidal data, including harmonic analysis, Fourier analysis and statistical analysis. Recommendations for harmonic analysis are that a minimum of 14 days' analysis is required to resolve M2 and S2 tides, and that 30 days is required to distinguish enough components for tidal turbine power estimation.

Deliverable D2.3 (Application of Numerical Models)
This report aims to discuss *key aspects of the application of numerical models to marine energy resource assessment*. Three key sections are included: Wave resource modelling, tidal resource modelling, and calibration of numerical models.

The wave resource modelling section begins by acknowledging challenges in wave measurements which modelling can help mitigate, including the scarcity of reliable data, the cost of measurement programmes, and the fact that measurement methods such as bouys and ADCP provide only point measurements.
Wave models are divided into two categories: Spectral and Deterministic, with the following broad characteristics:

Table 4: Reproduction of Table 1 from Equimar D2.3 report: Basic characteristics of deterministic and spectral models.

	Deterministic	**Spectral**
Output	Surface Profile	Spectral energy
Equations	Fundamental equations	Integrated equations.
Range of application	Typically used in shallow water over limited areas.	Global or local applications, deep and shallow water conditions
Modelled Physics	Most wave advection and non-linear interactions.	All the physical processes (but diffraction not explicitly considered and nonlinear interactions handled in an approximate way)
Computational requirements	Computationally intensive.	Limited, potentially short
Modelled Area	Very limited in space	Both large and small scales
Useability	Not user friendly.	User friendly (at different levels)

A series of specific models (WAM, WAVEWATCH III, SWAN, MIKE21, TOMAWAC) are described and their relative advantages discussed. A comprehensive description of model inputs, setup and limitations is given.

In the tidal modelling section, model types are again introduced, this time focussing no Navier-Stokes based models. A similar list of specific models is given and a comparison between MARS 2D and TELEMA2C2D is provided, including limitations and trade-offs.

The calibration and validation section discusses model tuning. Some possible data sources for validation are highlighted. In the wave modelling section, mathematical calculations of five statistical parameters (Bias, RMS error, Scatter, Model Performance Index and Operational Performance Index) are given. For validation of tidal models, the importance of reliable bathymetry and the influence of open boundary conditions is highlighted, and it is noted that meteorological effects will also influence the any data used. The potential for harmonic analysis or filtering to remove surge from data is briefly discussed. Section 4.3.2.2. suggests that bottom friction is a key parameter in the tuning of tidal models, suggesting an assimilation method if sufficient data points are available. Limitations on tidal modelling highlight the potential limitations of 2D and 3D models due to the impact of other phenomena, such as storm surges created by strong atmospheric forcing or river discharge, seasonal stratification or fronts.

Deliverable D2.4 (Wave Model intercomparison)

The stated aim of this Equimar report is to examine *the practicalities of applying a numerical model to transform a wave climate from one location to another.* Three wave models were considered in the report: SWAN, MIKE 21 and TOMAWAC. The general procedure for numerical wave modelling is illustrated schematically in the report and shown below (figure 3):

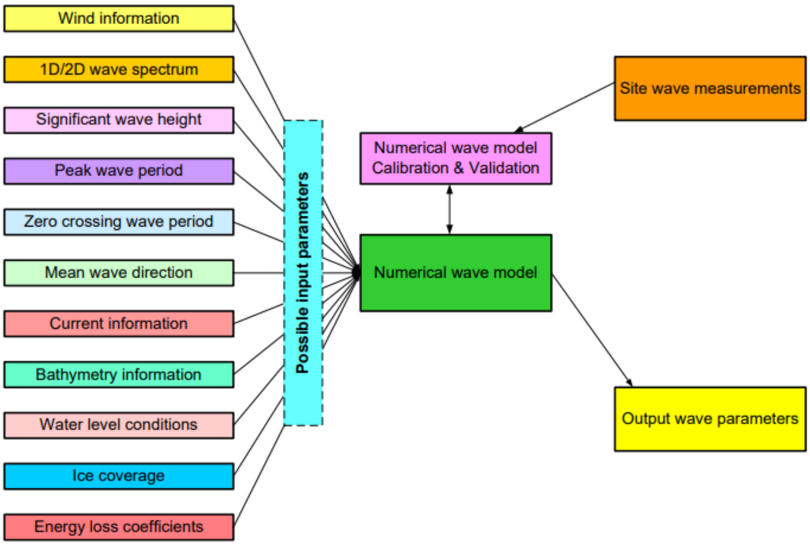


Figure 1 Reproduction of Figure 1 from Equimar D2.4 report: Schematic representation of numerical wave modelling process.

The importance of bathymetry is again emphasised, as is mesh resolution. The report states that the most common source of errors in third generation wave models is input data, and one of the most frequent sources therein is wind data. The report then compares the three models for a sample location. Results indicate that under the influence of the parameters selected, the unstructured SWAN model produced the highest correlation coefficients with eight wave parameters from recorded data. All reported correlation values exceeded 0.8. The report states that *it is apparent from the correlation plots that there are few differences between [the] three model's outputs which could be attributed to their individual formulations and input model parameters (coefficients) selected for the simulations.*

Deliverable D2.6 (Extremes and Long-Term Extrapolation)

This short deliverable report focusses on *methods that may be applied to assessment of extreme sea states for the purposes of marine energy resource assessment.*
Three main considerations are introduced: Available observations, timescale, and environmental parameters. Challenges in gathering observation data from in situ and satellite measurements are highlighted (short duration in the former and coarse sampling in the latter), and in general, numerical models are recommended as a suitable data source for extrapolation, with measurements used as validation. Validation or correction is important due to the potential bias in model data due to simplification or approximation. Two common timescales in wave cases (individual wave and sea-state) and wind cases (gust and mean wind speed) are highlighted.

Induced loading and response are said to depend on one or more parameters, based on one or more met-ocean phenomena.

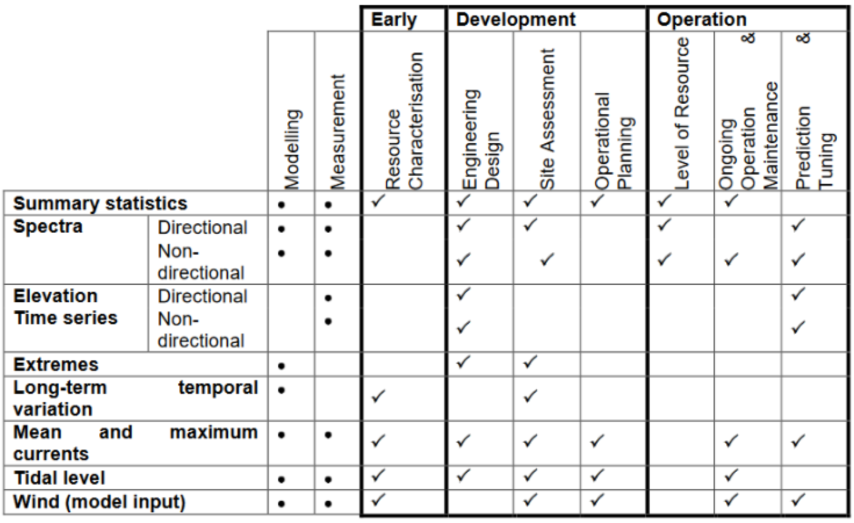
In Section 3, a series of extrapolation methods are described, namely:

- Mono-parameter:
  - Block maxima
  - Storm maxima
- Multi-parameter:
  - Response Based Design methods
  - I-FORM environmental contours
  - Joint distribution for extrapolation

Deliverable D2.7 (Resource Assessment Protocol)

This deliverable report gives an overarching view of methods for wave and tidal resource assessment and is informed by the specific Equimar reports discussed above. Wave and tidal resource assessment over three project stages are discussed: *Early Stage*, *Project Development*, and *Operation.* Across these stages, resource assessment is important in defining available energy resource, in designing the engineered structure to be installed, and in informing marine operations.

Early stage assessment for wave energy is suggested to use 10 years' data from wave atlases, global models, or previous measurement programs, 10 years' modelling including global and local models with estimates of H_{m0} and T_e. At the project development stage, wave modelling should be expanded to include a recommended 500m bathymetry resolution, wind speed and direction, current speed and direction, and tidal levels. Models should be validated with site measurements. Site measurements should include a minimum recording period of 1 year and should be recorded using a directional wave buoy and ADP. Extremes, in terms of 10-, 25- and 50-year return period H_{m0} should be considered following modelling and measurement. In the operation phase, modelling should be short term for prediction and planning, and measurements should be taken in the device vicinity concurrently with performance measurements. These are summarised in Section 2.1.4 (Table 5, a reproduction of Figure 2.4 from the original report), as copied below.



		Modelling	Measurement	Early	Development			Operation		
				Resource Characterisation	Engineering Design	Site Assessment	Operational Planning	Level of Resource	Ongoing Operation & Maintenance	Prediction & Tuning
Summary statistics		•	•	✓	✓	✓	✓	✓	✓	
Spectra	Directional	•	•		✓	✓		✓		✓
	Non-directional	•	•		✓	✓		✓	✓	✓
Elevation Time series	Directional		•		✓					✓
	Non-directional		•		✓					✓
Extremes		•			✓	✓				
Long-term temporal variation		•		✓		✓				
Mean and maximum currents		•	•	✓	✓	✓	✓		✓	✓
Tidal level		•	•	✓	✓	✓	✓		✓	
Wind (model input)		•	•	✓		✓	✓		✓	✓

Figure 2.4 Summary of methods used and data required for resource assessment at each stage of a wave energy development.

Table 5 - Reproduction of Figure 2.4 from Equimar D2.7 report: Summary of methods used and data required for resource assessment at each stage of a wave energy development.

Key parameters are as referred to in the deliverable D2.2 report and shown above. Key parameters are also summarised in Table 2.2 in report D2.7, which provides a good indication of parameters which should be included in modelling and measurement. The discussion of measurement methods in report D2.2 is reiterated, and the requirement for ISO 8601 compliant timestamps is highlighted. Processing and spectrum calculation is discussed in Section 2.3.2 with recommendations for cut-offs, resolution and key terms.

Wave modelling is discussed in Section 2.4. As discussed in report D2.3, third-generation spectral models are recommended, ranging from global models for early-stage assessment to dedicated nearshore models for project development and operational modelling. Boundary condition requirements are summarised below:

- *Early-stage resource assessment shall result in a minimum of ten years of data.*
- *Primary output should be* H_{m0}*,* T_e *and* Θ_m*)*
- *Parametric data will be sufficient for input at the offshore boundaries, obtained from one of three sources:*
    - *Archived global model output*
    - *Results from running a global model using wind data as input*
    - *Long-term offshore measurements. This option is not recommended because of the lack of spatial coverage of most measurement programmes.*

At project development and operation stages, these simple parameter results should be replaced with spectral output, with inputs at the offshore boundary in the form of 2D spectral data, including a separate description of wind, waves, and swell (each with its own H_{m0}, T_e and Θ_m) from archived spectral global models or offshore measurements.

Met-ocean data is not deemed necessary for early-stage studies but should be included later. Wind data should always be included at later stages and where possible variable wind conditions should be applied in favour of constant wind. The report recommends tidal data only when the site requires it (recommended in shallow water where $d<\lambda/2$ where tidal excursion may modify

water depth by more than 5%). Similarly, it is recommended to include currents if their velocity is greater than 2-3% of the local group velocity of dominant waves.
Extreme value recommendations for sea states are that the 10-, 25- and 50-year return period values of H_{m0} with 90% and 95% confidence intervals should be calculated. Individual wave extremes are not mandatory but the same return periods are recommended.

Recommendations for Tidal resource assessment follow a similar pattern, with coarse grid (<5km resolution) or area (<500m resolution) models suggested at the early stage, followed by modelling with bathymetry resolution <50m, calibrated and validated with site measurements. Measurement is also recommended at the project feasibility stage, with minimum 1 month duration using ADP. At the project development and operation stages, 3 months ADP data is recommended. Key parameters are as shown in the flowchart above.

Key site characteristics to be recorded at the start of a project are given in Section 3.2:

1. Bathymetry at the site shall be established through a bathymetric survey.
2. Tidal range at the site shall be established by measurement.
3. Tidal constituents at the site shall be established by combined modelling and survey.
4. Wind at the site shall be established using ongoing measurement. Meteorological model output and/or offshore wind measurement stations may be needed for operational forecasting.

Section 3.3 deals with Tidal measurement, suggesting that a single turbine deployment would require a single measurement device, located near to the planned location of the turbine and on the minor axis of the tidal ellipse centred on the turbine. Array deployments would require numerous measurement devices, though no specific numbers are given. Data to be recoded should include peak ebb and flow at each spring and neap, wave height and period, and tidal components. Time series data should be recorded, including acoustic quality data. ADPs are suggested, and wave buoys are indicated as not suitable. Remote sensing is highlighted as being potentially useful for model calibration, but not suitable for tidal measurements. As in the wave case and in report D2.2, metadata should be recorded with a correct timestamp and description.

Extremes in tidal data (including extreme high sea levels and extreme currents) should be included in analysis. Extreme sea levels often typically occur from high water on a spring tide and a storm surge. Hence the use of a joint probability method (JPM) is recommended. The JPM ideally requires four years' data (though one year can be used). For the calculation of extreme currents, it is highlighted that finding sufficiently long datasets may be a challenge. Further details on the calculation of survivability and extremes is given in Section 4 of the report.

2.2.5 Marinet - Tidal Measurement Best Practice Manual (2013)

This report includes best practice guidelines for flow assessment at a range of scales, including towing tanks, basins, small scale field testing and full-scale field testing, with the final section being the most relevant to this summary. The Marinet report is largely based on the EMEC *Assessment of Tidal Energy Resource* report, which is also a major contributor to IEC TS 62600.
As in other reports, a number of stages are defined (here site screening, pre-feasibility study, full feasibility study, design development). It is suggested that current speed estimation is

undertaken using daily, monthly and annual tide height, speed and direction, based on measured or calculated data depending on the stage of development.

A series of recommendations on harmonic analysis are provided. Firstly, it is observed that aliasing may occur if ebb and flood tides are asymmetric in intensity. It is also observed that "*Analysis can be conducted independently for the two components of horizontal velocity (i.e., north and east components), jointly using complex analysis, or jointly using horizontal velocity (i.e., ebb and flood velocity magnitude signed negative and positive). The accuracy with which these options represent the tidal currents may be site specific and no peer-reviewed analysis has yet been conducted to identify a preferred approach.*". The report notes that these uncertainties do not preclude the usefulness of harmonic analysis but do lead to some ambiguity in the interpretation of the results, highlighting that it is important to quantify and report the accuracy with which the harmonic constituents represent the underlying measurements.

Direct extrapolation is also highlighted as an alternative to harmonic analysis, and it is noted that the uncertainty associated with this method may not be any greater than that of harmonic analysis. However, direct extrapolation does not allow the representation of longer variations in flow than the time period recorded. Observations should be at least 30 days in length, and ideally longer to minimise this effect.

Modelling is also discussed. Resolution of 50m or better is recommended in areas where error in peak and average velocities is expected to be below 10%. Models should be run for at least 30 days, ideally 3 months to allow the extraction of annual datasets. 2D models are acceptable at stage 2 (pre-feasibility), beyond which 3D models with bin size of 1m are recommended.

A series of recommendations on the use of measurement equipment are given, specifically on Divergent-beam Acoustic Doppler Profilers (DADP) and Acoustic Doppler Velocimetry (ADV). The differing advantages of the two methods are discussed, generally highlighting the high temporal resolution and ability to monitor turbulence as advantages of ADV, versus the general averaged data available or velocity profile from DADP equipment.

General advice is given on the use of equipment, including:

- Care must be taken to correctly set the magnetic compass in a DADP
- Magnetic variations must be considered
- Roll and tilt sensors should be used to correctly level a device
- Positioning is key as a variation of just 10m can have a major impact on results. GPS can be used but knowing the position of a vessel at deployment can be difficult.

Field surveys of 1 month are suggested as a minimum, with 3 months preferred. Unless a point measurement is sufficient a transect using acoustic equipment is suggested. Calibration to ISO/IEC 17025:2005 should be undertaken. Transect surveys are recommended to be undertaken during a typical spring tidal cycle and processed into vertical and horizontal bins (1m vertical and 25-50m horizontal are recommended). Sampling frequency of at least 1Hz and the location of the first bins within 5m of the water surface are also recommended. To limit the impact of vessel motion, two surveys in opposite directions should be undertaken within a short period of time. Static surveys are generally preferable to transect surveys, and should use measurement bins of 0.5m to 2m at 1m intervals, with data collection for between 2 and 10 minutes. Data to be included is as recommended in the EMEC report above. Further recommendations in section 6.2 describe the potential impact of side lobe interference near acoustically solid boundaries, and consideration of tidal range, meteorological and met-ocean conditions (with recommendations to follow IEC 61400-12-1 for wind data measurement if necessary).

2.2.6 Nova Scotia DOE – Statement of Best Practices (2014)

The Nova Scotia Department of Energy and Marine Renewables Statement of Best Practices for In-stream Tidal Energy Development & Operation report includes sections on background (with subsections on regulatory considerations, resource and environmental evaluation, community and first nations engagement and application), a statement of best practices and a series of specific best practice recommendations. The relevant section to resource assessment is section 4 (Tidal Energy Resource Assessments).

The report highlights the importance of accurate assessment of the power resource but does not make its own specific technical recommendations. Four general best practices are suggested, which include the use of ADCPs at current locations throughout a proposed site, a monitoring duration of at least 35 days, methods appropriate to allow spatial analysis of currents throughout the site, and the suggested integration of resource assessments with baseline ecosystem assessment.

Beyond this, no specific guidance is given, but reference is made to a series of other standards and reports. Two of these are specific to the Minas Passage and Bay of Fundy, and three are generic standards included elsewhere in this report (IEA OES - Guidance on Assessing Tidal Current Energy Resources (2008), EPRI – Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion Devices (2006), and IEC TS 62600-201: Tidal energy resource assessment and characterization (2015))

2.2.7 ORJIP Ocean Energy - Supporting good practice in consenting for tidal stream and wave technologies in Wales (2019)

The report by ORJIP (Offshore Renewables Joint Industry Programme) was produced for the Welsh Government by two consultancies, Aquatera Ltd and MarineSpace Ltd., with a focus on consenting. The report includes Wales-specific and some European policy background, and discusses policy, targets and environmental impact assessment in this context. The report does not include any specific guidance on resource assessment.

2.2.8 Meygen - Lessons Learnt from MeyGen Phase 1A (2020)

Following the completion of the initial phase of the MeyGen project (Phase 1A), a lessons learnt report was produced and issued in both full and summary report formats. These reports do not offer specific guidance for resource assessment but do offer insight and learning on the methods used in the MeyGen project.

Many of the relevant points raised relate to the application of data recorded, rather than the method of capture or resource assessment:

- “Having real-time met-ocean data feeds on site can be invaluable as it allows detailed operational planning.” Maintaining long-term on-site measurements could be considered as part of project planning phase.
- “Turbulence variations across the site can significantly influence performance of individual turbines if they have a narrow design envelope. Having a machine that can be remotely adapted to different environmental conditions would negate the need to decide between

operating a turbine at suboptimal parameters or choosing to mobilise an unplanned intervention."

- "There were some design changes which occurred after financial close and impacted the manufacturing stage. This created challenges and was difficult to manage given the number of contract interfaces"
- "MeyGen's knowledge of the influence of turbulence improved during the detailed design phase. These influences include the loads on the turbines and support structures and the dynamic interactions between them. This improved understanding helped the detailed design phase, which consequently took longer than anticipated. Designing turbine blades for turbines of this scale at a site this energetic (with respect to wave and turbulence loads as well as non-turbulent tidal loads) was also more challenging than anticipated."

One key point raised does relate specifically to resource assessment:

- "MeyGen recommends that, as part of the initial resource assessment, an ADCP is placed at the exact location of the proposed turbines, rather than in the vicinity, as this will provide certainty with regard to the environmental conditions the turbine will face. MeyGen also recommends designing the turbine and blades for a range of environmental conditions (for example turbulence intensity or flow speed) and not just for a particular small envelope. This will provide greater adaptability should the conditions be different to those expected."

The report also comments on the feasibility of IEC performance assessment, noting that:

> "*MeyGen attempted to conduct the power performance assessment according to IEC TS-62600-200, but in practice found that the required bed-slope conditions for ADCP placement could only be met on one side of each turbine. This, in conjunction with the excessive costs of deploying two bed-mounted ADCPs per turbine (i.e. 8 in total) led to the decision to place only a single ADCP on either the incident flood or ebb side of the turbine (whichever met the required seabed slope conditions).*" and "*Going forward, MeyGen is considering still using only a single ADCP per turbine for future power performance assessments. This would be placed perpendicular to the main flow direction, in line with the turbine, to allow it to measure both the ebb and flood flows, albeit slightly offset spatially. MeyGen is in communication with the IEC TS-62600-200 Maintenance Team to feedback on their usage of the technical specification.*"

It has been suggested during the TIGER project that a well-calibrated model may also offer a route to lower ADCP costs by filling some data gaps.

2.2.9 FLOWBEC project

The FLOWBEC (FLOW and Benthic ECology 4D) project ran between October 2012 and August 2016. A key aim of the project was to *"improve understanding of the fine scale details of the flow regime in areas of high tidal and wave energy and the effects of Marine Renewable Energy Devices (MREDs) on flow conditions"*. During the project, two deployments of the FLOWBEC platform, which included sonar, acoustic Doppler velocimeter and flourometer equipment, were undertaken using a new mooring methodology without trailing mooring lines. This method used an underwater Remotely Operated Vehicle to attach the recovery line, and deployment and recovery was reported as highly successful.

3 Site and design parameters

This section discusses the information and parameters required from a resource assessment campaign, for input to energy yield predictions and the structural design process. The focus is on the analysis of the site data, collected using the practices described in Section 5. The problem of defining site and design parameters can be considered in two ways. One way is to start by asking what information is needed for design and energy yield analysis, then to go on to consider how do to go about measuring and modelling the site conditions to derive this information. Alternatively, we could start by asking how we can measure and model the resource as accurately as possible, then go on to consider how we summarise the spatially and temporally varying flow field information for use in design and energy yield studies. This is somewhat of a "chicken-and-egg" problem, in that without knowing the detailed features of the flow field and how they impact the design, it is difficult to specify how to summarise and parameterise the information. We require both an understanding of the flow conditions and the sensitivity of the design to various features of the flow conditions. In this report, we have opted to start by discussing the required outputs from the resource assessment, informed by the current understanding from industry and academia.

We start by presenting some general considerations in Section 4.1, followed by specific recommendations for currents, water levels, waves and other environmental variables in Sections 4.2-4.5.

3.1 General considerations

3.1.1 Spatial and temporal variability

The flow field at tidal energy sites is complex. It is varying in both space and time, at multiple scales. A key aspect of the resource assessment is to quantify the spatial and temporal variability for all environmental variables. This requires a combination of measurements and modelling. Measurements can provide high resolution temporal coverage (of the order of seconds), but are limited in spatial coverage and duration (typically of the order of a few months). Conversely, models provide spatial information over time, but there is typically a trade-off between the resolution and extent of the models, with some models providing low resolution information over large areas and time periods and others providing high resolution information for smaller spatial areas and shorter time periods. Combining the information from measurements and various types of models is important for properly quantifying the spatial and temporal variability in the resource. This is discussed further in Section 5.

We distinguish between descriptions of the following:

1. Flow conditions over short space- and time-scales, over which flow and wave conditions are considered approximately stationary in a statistical sense. It is assumed that these conditions can be adequately summarised in terms of a finite set of parameters.
2. The longer-term variability of flow and wave parameters, usually specified in terms of probability distributions or histograms.
3. The spatial variation of distributions of summary parameters over a deployment site.

For turbulent tidal flows without waves, simulations of device response are typically conducted over a period of 10 minutes (Greenwood et al (2019)). For design of offshore structures where tidal currents are less significant, wave conditions are usually assumed stationary over periods between 30 minutes to 3 hours. However, in tidal energy sites, where there can be significant wave-current interaction, shorter timescales are appropriate. There is no specific guidance in the standards, but time periods between 20 and 40 minutes are likely to be more appropriate for characterising wave conditions at tidal sites.

For spatial variability, relevant scales would be of the order of the spacing of individual turbines. In simulations of turbine response, flow and wave conditions are usually considered stationary over the volume containing the turbine. Some CFD models with domains covering multiple turbines, may explicitly resolve the variation in flow conditions over a site, and not require assumptions about spatial variation. However, due to computational constraints, these models will be limited in the number of load cases which can be considered and are likely to be run in parallel with simpler engineering models, which do require assumptions about spatial stationarity. For these types of models, understanding the spatial variation in flow and wave conditions is important.

3.1.2 Predictability and probabilistic description

Astronomical tides, driven by gravitational forces from the earth, moon and sun, are variable, but, in theory, completely predictable. In practice, however, there is some uncertainty associated with estimates of harmonic constituents of water levels and current speeds, when estimated from limited-duration records containing 'noise' from both measurement uncertainty, turbulence, waves and other meteorological influences. For tidal energy sites, the meteorological influence on the currents and water levels is typically small in comparison to the astronomical component. However, this component is stochastic in nature, requiring a probabilistic description. Moreover, the short-term, small-scale fluctuations in the flow, due to turbulence and waves, are also stochastic in nature.

The predictable components of the tides can be described both in a deterministic sense, in terms of either harmonic constituents or forecasted time series, or in a probabilistic sense, in terms of histograms of flow speeds. For the slowly-varying stochastic components, such as sea state parameters or meteorologically-driven currents, these are described in terms of probability distributions and statistics of these distributions (e.g. mean values, standard deviations, return levels, etc.). The short-term variability of waves and turbulence is described in terms of spectra. Spectra can be interpreted as a probability distribution of fluctuation intensity with frequency, with the random aspect given by the phases at each frequency.

3.1.2.1 Statistical modelling

Due to the required probabilistic description of the resource, it is worth making some remarks on statistical modelling. There are various motivations for fitting statistical models to observations, which may be relevant to resource assessment, such as:

1. Summarising complex information in terms of a small number of parameters
2. Compensating for incomplete information (having a limited number of observations)
3. Extrapolating outside the range of observations

Point 1 above, is relevant when describing short-term random fluctuations, such as turbulence of waves, in terms of spectra. Typically, the second-to-second variations are not used directly as inputs to performance or loading simulations. Instead, the stochastic variation is described in terms of a standard spectral shape, which is specified in terms of a small number of parameters (e.g. a von Karman spectrum for turbulence, or a JONSWAP spectrum for waves). Vertical profiles of flow speed and turbulence intensity can be described in terms of either assumed standard models (e.g. a power law) or mean measured profiles.

For summary variables such as depth-averaged current speed or significant wave height, it may not be necessary to fit a statistical model to observations, as there may be sufficient observations to form empirical histograms of occurrences. Fitting a statistical model to observations could increase uncertainties in energy yield or loading, since observed distributions may not be well-described by standard probability distributions (e.g. Rayleigh, Weibull, log-normal, etc.), and there is no *a priori* reason to suppose that observations will follow one distribution or another. Therefore, when there are sufficient observations such that an empirical histogram of observations appears relatively smooth, this is likely to give a better description of the data than a fitted probability distribution.

For estimates of extreme values of stochastic variables, statistical modelling is necessary, and provides a rationale for extrapolating outside the range of observations. Tidal turbines need to be designed to withstand environmental conditions with return periods of 50 years (that is, conditions which have an exceedance probability of 1 in 50, for any given year). Empirical estimates of return values direct from time series of observations are subject to very high uncertainty due to random sampling effects. For example, even if a 50-year dataset was available, a 95% confidence bound for the return period of the largest observation in the 50-year dataset, would be approximately (13.5, 1975) (Mackay et al. (2019)). To compensate for this, statistical models are usually fitted to smooth the sampling variability and extrapolate outside the range of observations. This is discussed further in the subsections below.

3.1.2.2 Joint distributions

As well as providing probabilistic descriptions of individual variables, there is a need to characterise the joint occurrence of multiple variables, in terms of joint distributions. For some combinations of variables there may be strong relationships, with a relatively small range of values of one variable for a given value of the other. For example, at many sites, water levels are strongly related to the current speed at a given stage of the tide. Similarly, turbulence intensity can also be strongly related to current speed, especially at higher current speeds, where there is often a relatively narrow range of values of turbulence intensity observed for a given current speed. However, for other combinations of variables, there can be a much larger range of observed values of one variable for a given value of another. For example, a large range of wave heights, periods and directions may be observed for a given value of current speed and direction, requiring a probabilistic description of their joint occurrence.

As with univariate distributions, it is preferable to use an empirical description of the joint occurrence when there is sufficient data, since finding joint probability models that provide an adequate description of the observations can be challenging. However, as the number of variables (dimensions) increases, the amount of data required to form an empirical estimate of the joint distribution increases exponentially, the so-called 'curse of dimensionality'. This may necessitate fitting of a statistical model in order to compensate for the lack of observations.

Whilst statistical modelling of univariate extremes is a relatively well-developed field (Coles (2001), Jonathan & Ewans (2013)), there is less consensus on methodologies for statistical modelling of multivariate extremes. The most common approach used in offshore design, is to quantify multivariate extremes in terms of environmental contours. For example, the use of environmental contours are recommended in the design standards for offshore wind turbines (IEC 61400 & DNVGL-ST-0119). Environmental contours are a way of describing combinations of variables which have an equal joint probability of exceedance in some sense. There are various ways to estimate environmental contours, which can lead to large differences in the contours derived. Recent reviews and guidance on estimating environmental contours are presented in Ross et al (2020), Haselsteiner et al (2021), Mackay et al (2021), and Hauteclocque et al (2022).

3.1.2.3 Aleatoric and epistemic uncertainties

Uncertainties are sometimes classified as either aleatoric or epistemic. Aleatoric uncertainty relates to the random, unpredictable nature of the physical processes under study. It represents unknowns which change each time an experiment is repeated. Aleatoric uncertainty cannot be reduced, only identified and quantified.

Epistemic uncertainty is related to our lack of knowledge of the physical processes under study. It is referring to information which could be known in principle but is not known in practice. Epistemic uncertainties can be reduced by gathering more information. For example, this could be by gathering data for longer periods, more locations, or using more precise models.

In terms of the probabilistic description of the resource, discussed above, epistemic uncertainties refer to how well we know the distribution of resource parameters, and aleatoric uncertainties refer to being uncertain as to what random sample of observations will be observed in a given time period (e.g. over the lifetime of the tidal turbine).

The goal of the resource assessment will be to reduce epistemic uncertainties in our knowledge of the resource, as far as practically possible, and quantify aleatory uncertainties.

3.1.3 Parameterisation

As mentioned above, the flow field at tidal energy sites is complex, with spatial and temporal variation on multiple scales. Hypothetically, if high resolution models were run for long time periods, we could have a long time series of spatially- and temporally-dense 3D flow fields, incorporating the effects of turbulent tidal currents (including meteorological effects) and waves, covering the entire deployment site, potentially covering many years. Note that an ADCP dataset represents a subset of this hypothetical information, for a single vertical profile at a point, and for a limited time period (and subject to the caveats on the instrumental limitations, discussed in Section 5).

The question then arises, as to how to use this information about the flow field. Currently, it is computationally prohibitive to run detailed simulations of turbine response (performance and loading), for such a multi-year time series. The flow field information therefore needs to be summarised somehow, usually in terms of a number of representative models (e.g. shear profiles, wave and turbulence spectral shapes), which can be represented by a small set of parameters, so that a smaller number of simulations can be conducted for a subset of parameter combinations. This subset of simulations can then be used to estimate the long-term energy yield and loading.

There is a trade-off between the fidelity of the representation of the resource (and hence the derived turbine response), and the number of parameters used in the description. Clearly, the more parameters that are used to describe the flow field, the greater the number of turbine response simulations are required to cover the parameter space. This is another instance of the "curse of dimensionality" mentioned above. For example, if we consider basic parameters for water level, current (depth-averaged speed, direction, turbulence intensity) and waves (height, period, direction) and assume fixed shear profiles and wave and current spectral shapes, then this gives seven variables. If 10 values of each parameter are considered, then 10^7 simulations are required to cover the parameter space. If 10-minute time-domain simulations are conducted for all combinations of variables, then this equates to 190 years of simulations! So clearly, some kind of sensitivity analysis is required to determine which resource parameters have the greatest impact on response.

This emphasises that it is difficult to draw a bright line between the job of the resource analyst and that of the structural designer. It is not always clear which combinations of environmental variables will lead to the worst loading, or significantly impact power performance. Therefore, as well as providing information about joint distributions of parameters, it is also recommended that the resource analyst provides the raw time series of data from measurements and models, so that further analysis can be conducted during the design process.

3.2 Currents

3.2.1 Short-term / short-scale characteristics

The short-term variations of the flow field are usually characterised for a vertical line through the water column, with characteristics considered over 10-minute periods. The mean characteristics of the flow are assumed to be approximately stationary over short horizontal scales, the width of a rotor diameter, say, whereas the coherence in fluctuations relative to the mean are assumed to be related by eddy structures in the turbulence.

For a given 10-minute period, the variation of the flow field over the water column is usually represented by the following parameters and models:

- A depth-averaged or rotor-averaged current speed and direction
- A depth-averaged turbulence intensity (TI) in three directions: streamwise (in-line with the principal flow direction), transverse, vertical. Where TI is defined as the ratio of the standard deviation of the flow speed to the mean flow speed.
- A vertical profile for flow speed, direction and TI (i.e. the values of these parameters at given heights above the sea bed).
- A turbulence spectrum, this can pose a challenging problem with regards to separating the turbulent flow from the wave action. Accurate measurement of turbulence cannot be acquired from ADCP data (see section 4.2) and usually require separate measurement campaigns. There are currently no theoretical models for water particle motions under combined turbulence and waves, hence separating these effects is problematic. Most simulation software assumes of linear superposition of waves and turbulent currents.

The vertical profile is a function of vertical position, and turbulence spectra are functions of frequency, as such it is helpful to find models which can represent these functions in a small number of parameters. For the vertical profiles, a common assumption is that the flow speed varies as a power law:

$$U(z) = U_{DA}\left(\frac{\alpha+1}{h}\right)\left(\frac{z}{h}\right)^{\alpha}$$

Where U_{DA} is the depth-averaged current speed, h is the water depth, z is the elevation above the seabed, and α is the exponent. The DNV standard recommends using a value of if site-specific data are not available. At some sites, measured profiles have been observed to differ from the power law model. In this case, a mean measured profile can be used, where the mean is taken for a specific range of flow conditions. For example, the mean profile could be calculated binned by flow speeds, and separated into separate ebb and flood conditions), possibly even sub-divided further into accelerating and decelerating phases of the tide. In this case, the depth profile is parameterised by the flow speed and the phase of the tide. Figure 4, shows an example for the EMEC test site, presented in Sellar et al (2018). The depth-profile differs from the 1/7 power law and differs with flow speed and phase of the tide.

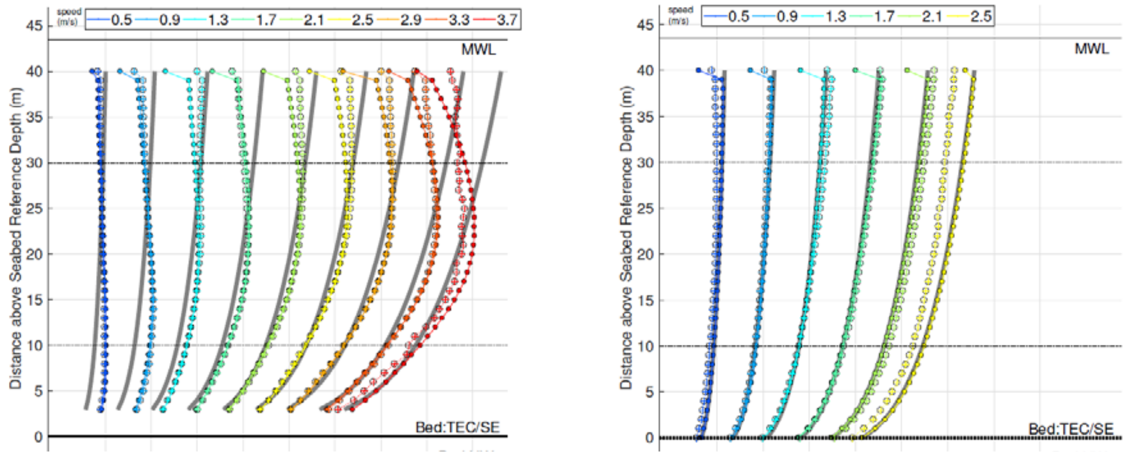


Figure 4. From Sellar et al (2018). "Depth profiles of streamwise velocity for (a) ebb and (b) flood tide. Solid grey lines show power-law fit (a = 7). Small filled circles and large open circles with a centred cross show flows in the absence and presence of waves, respectively. Data is binned by speed as per the top horizontal legend. MWL shows mean water level. SE and NW indicate depths at southeast and northwest positions. (a) Ebb tide streamwise velocity depth profiles. (b) Flood tide streamwise velocity depth profiles"

If a mean measured profile is used, the variation of the measured profiles about the mean profile should be quantified for each bin. Some variation about the mean profile would be expected due to random sampling effects (e.g. from turbulence and instrumental noise). However, if the variation is larger than would be expected from sampling alone, then this should be examined further.

A similar approach can be used to estimate mean turbulence spectra, binned by flow speed (or other variables). Alternatively, standard models for turbulence spectra exist (e.g. von Karman or Kaimal). However, most were developed for turbulent winds, so may be less appropriate for tidal flows. Milne et al (2013) compare measured turbulence spectra from the Sound of Islay to the von Karman model and found good agreement. However, appropriate models may be site specific, so it is recommended that comparisons are made for the specific site of interest. If standard models for turbulence spectra are used, then these are normally parameterised in terms of three components of TI and integral length scales.

3.2.2 Long-term characteristics

When analysing the long-term characteristics of the flow, it is common to separate the astronomical component of the currents from the meteorological components. This is normally achieved using harmonic analysis. The astronomical component is deterministic in nature and can be used to forecast flow conditions at future times. The meteorological component of the flow is driven by local winds, pressure fields (storm surges) and wave breaking. The meteorological component is stochastic in nature and therefore requires a probabilistic description.

3.2.2.1 Harmonic analysis

Harmonic analysis is the process of representing measured water levels or current speeds in terms of harmonic (sinusoidal) components with pre-determined frequencies, corresponding to the relative motions of the Earth, moon and sun. Various open source software packages are available for harmonic analysis, such as the T_TIDE package (Pawlowicz et al, 2002) or UTide (Codiga, 2011), which are commonly used in tidal energy studies.

Some studies have noted potential problems when using harmonic analysis to analyse currents (as opposed to water levels). The Marinet Tidal Measurement Best Practice Manual (2013) notes that asymmetries in flood and ebb tides can result in energy being aliased into integer multiples of the underlying constituent. It notes that the effect can be partially mitigated by conducted harmonic analysis separately for the two horizontal flow components (east-north or streamwise-transverse) or jointly using complex analysis.

Various metrics for identifying harmonic constituents can be calculated, such as the signal to noise ratio, percentage of total energy and Rayleigh criterion to guide which harmonics can be identified in a record of a given length (see Codiga, 2011, for details). The uncertainty in the estimated constituents should be specified (see Thiebot et al 2020 for an example of the effect of the uncertainty in constituents estimated from disjoint 36-day periods from the same site)

A further aspect to consider is long-term lunar nodal corrections. The inclination of the moon's orbital path relative to the plane of the Earth's equator varies over a period of 18.6 years, known as the lunar nodal cycle. This modifies the amplitude of the tides. For longer records, in excess of 18.6 years, this modulation can, in theory, be estimated directly from the time series. However, in practice, normally only a short record of onsite measurements is available. In this case, a lunar nodal or “satellite” correction can be applied, which modulates the amplitudes of the constituents to replicate this longer-term variation. The lunar nodal cycle has been shown to affect the available tidal energy at a site in a given year (see Thiebot et al 2020, 2022), and should be accounted for in the analysis.

3.2.2.2 Statistical analysis

Ideally, we would like to know the joint distribution of all short-term flow parameters. However, due to the limitations mentioned in Section 4.1.2.2, this is not possible in practice. Moreover, it is difficult to visualise a joint distribution in more than two variables. In terms of energy yield and loads analysis, the key distributions to estimate are:

- Histograms of flow speed (either depth-averaged or rotor-averaged)
- Joint distribution of flow speed and direction (sometimes referred to as a tidal ellipse, when plotted on polar axes)

- Joint distribution of flow speed and TI (note that this may differ between ebb and flood tides due to bathymetric features)

For all these metrics, it is important to specify the time period over which distribution was estimated, as the distribution will change depending on the phase of the lunar nodal cycle. For the meteorological component of the flow speed, there is likely to be a seasonal variation, due to seasonality in the winds and waves which generate these currents. It may be difficult to estimate long-term characteristics of meteorological-driven currents from relatively short in-situ records (of the order of one to three months). Care should be taken when making general conclusions about the importance of meteorological effects from short records.

3.2.3 Extreme conditions

The extreme value of the astronomical component of the current can be estimated relatively straightforwardly from harmonic analysis, by calculating the maximum current speed over the 18.6-year lunar nodal cycle.

However, there is less information available about estimating the relative importance of the meteorological component of the currents. This generally requires numerical modelling, to generate longer records than are available from in-situ measurements. For example, Davies and Flather (1987) considered extreme meteorologically induced currents over the northwest European continental shelf and found currents exceeding 1 m/s in some areas. Bruserud and Haver (2018, 2019) considered current conditions in the North Sea, based on five years of measurement. In this region, they noted that wind-driven currents set up inertial oscillations (varying currents with periods depending on the Coriolis parameter), with amplitudes up to 0.7 m/s. They note that current measurements for considerably more than one year are required for reliable estimates of extreme current conditions. For tidal energy sites, where meteorological components of the current are likely to be small in comparison to the tidal component, further research is required to determine the importance of meteorological effects on extreme current speeds.

3.3 Water levels

There are various parameters and terminology used to describe water levels. Short-term fluctuations (waves) are considered separately. The term still water level (SWL) is used to refer to values of the sea surface elevation above the seabed, averaged over periods of 10 minutes or longer. The mean water level (MWL) is defined as the arithmetic mean SWL over the 18.6-year lunar nodal cycle. As measurements durations will be much shorter than this, harmonic predictions can be used to calculate the MWL. The tidal range is the difference between the highest astronomic tide (HAT) and lowest astronomic tide (LAT). Estimates of HAT and LAT can also be calculated from harmonic analysis of shorter records.

The total still water level (TSWL) is the combination of the astronomic tide and storm surge. When estimating extreme TSWL, the tide and surge components are generally assumed to be independent (Pugh & Vassie, 1978), and their distributions are estimated separately, then recombined to get TSWL. Due to its importance for coastal protection, there is a large literature on estimation of extreme TSWL, see e.g. Haigh et al (2010), Idier et al (2012), Batstone et al (2013) Ross et al (2018) for relatively recent work on this topic.

3.4 Waves

3.4.1 Short-term characteristics

The short-term characteristics of wave conditions are described in terms of directional surface elevation spectra, which specify the distribution of the wave energy with frequency and direction. Wave spectra are normally summarised in terms of spectral parameters, defined in terms of moments of the spectrum. The non-directional characteristics are usually described in terms of significant wave height, and various wave period parameters (peak period, zero-upcrossing period, mean period, energy period), while directional characteristics are summarised in terms of spectrally averaged mean direction and spread (the standard deviation of the energy about the mean). These are defined in standard texts on ocean waves (e.g. Tucker and Pitt, 2001, Holthuijsen, 2007). Sometimes, the spectrum is partitioned into swell components (waves that are generated by winds elsewhere and propagate to the site) and wind sea components (waves generated by local winds. Spectral parameters can be calculated for each partition.

When running simulations of the turbine response to wave loading, a model is required for the wave spectrum. There are various standard models for the shape of the frequency spectrum (the directional spectrum integrated over direction) and directional distribution (see e.g. Tucker & Pitt, 2001). In offshore engineering, the most common model is the JONSWAP spectrum (Hasselman et al, 1973). As with turbulence spectra, the appropriateness of the assumed model should be verified for the particular site of interest.

A further important distinction to be made is between relative and absolute wave period parameters. Absolute periods or frequencies are those measured at a fixed location, as would be measured by an ADCP. Relative periods or frequencies (sometimes called intrinsic frequencies) are those which would be measured in a frame of reference moving with the current. Understanding the relative wave periods is important, as the sub-surface wave-induced velocities are determined by the relative period, not the absolute period. Estimating the relative period from fixed measurements requires complex inversion algorithms (Draycott et al, 2019, Pillai et al, 2021). However, wave models can output both relative and absolute wave periods.

3.4.2 Long-term characteristics

There is little guidance in the tidal standards for information required on wave conditions. However, general guidance from offshore design can be used for reference. The importance of wave information will depend on the exposure of the site and the technology being used (devices with structures on or near the free surface will be more exposed to wave action). From the perspective of performance and loading, the key wave variables are likely to be the significant wave height, peak period and wave direction relative to the current. Considering the joint distribution of these wave variables as well as current variables is challenging. Especially for fatigue loading, which requires estimating the total number of load cycles that a component will undergo in its lifetime. It may be possible to simplify the situation, by making assumptions about relations between variables (i.e. assuming that one variables value is determined completely by the other variables, e.g. assuming collinear waves and currents), but this may not always be conservative and sensitivity studies would need to be conducted for the structure of interest.

Assessment of extreme loading is somewhat simpler, if the environmental contour method is used, since only combinations of variable with specified return periods need to be considered. A method for estimating 3D environmental contours of current speed, significant wave height and relative wave direction was proposed in Mackay and Hardwick (2022). Due to the stochastic nature of waves, with high seasonal and inter-annual variability, long-time series of waves are required to estimate joint extremes of waves and currents. Moreover, due to the interaction between waves and currents in fast tidal flows, coupled wave current models are required to capture the modulation of wave characteristics by flow conditions. It was shown that the largest wave conditions occurred in opposing currents.

3.5 Other environmental variables

The IEC and DNV standards recommend obtaining data for other environmental conditions, such as ice, seawater density, salinity and temperature, and suspended sediments. Reference is made to these documents for specific recommendations.

Whilst wind and atmospheric pressure may not directly influence loads on submerged structures, they may be important for loading on any part of the structure above the water level, and also for loads during installation and operation. Obtaining wind and atmospheric measurements can also be used for validating boundary conditions for numerical models.

4 Tidal Resource Assessment

This section discusses the best practice for the process of completing a Tidal Resource Assessment as part of a tidal stream energy project based upon technical standards, published literature and 'lessons learnt'. Resource assessment studies are typically divided into one of two or three categories. Stage 1 refers to early-stage scoping studies and stage 2/3 refer to more advanced commercial investigations. This document discusses the best practise methods for resource assessments at project site scale with a focus on commercial deployments, unless otherwise stated this refers to a stage 2 study as defined by the IEC standard.
This section discusses data measurement campaigns and numerical simulation of met-ocean data. Where modelled data is used to inform the development of a project the scope of input data is discussed as are the data required for calibration and validation.

By following the best practice methodologies discussed in this section, the objective is for projects to undertake high-quality resource assessment work to reduce the project risk. Part of following the best practice is to understand the limitations of the data. High quality data is important to reduce risk and give financeable levels of confidence within a project. A distinction should be made between inherently predictable quantities (for example harmonically driven tidal flows) which can be extrapolated from relatively short data sets and stochastic processes (for example wave heights). The latter quantities may require long-term data sets to be collected or simulated in order to have an adequate understanding of the conditions.
Quantifying and understanding the uncertainties in the data are important facets of a resource assessment. As the resource data are used to inform many key project quantities, including the predicted energy production and LCOE failure to properly understand the limitations of the resource data could impact project viability or success. The approach to managing uncertainty is discussed in the following.

4.1 Scope of study

Projects will require in-situ data measurement campaigns as part of the resource assessment as well as the wider project planning work. In all but the smallest projects, in-situ data will be combined with numerical simulation as part of the resource assessment. Collection of high-quality measured data are essential for validation and calibration of models. Data measurement campaigns are expensive and time consuming, so to ensure that resources are used as effectively as possible the scope of offshore activities should be strategically planned. Data collected for the resource assessment for a tidal energy project will include as a minimum:

- Flow speed and direction
- Water level variation

In most projects, the tidal data alone will not be sufficient to properly assess the resource, the following data should also be included in the resource assessment:

- Waves
- Wind
- Turbulence
- Bathymetry
- Seabed geotechnics

4.2 Measurements

Table 2 Summary of data collection

Data Type	Collection Equipment
Currents	ADCP, ADV
Water Level	ADCP, Tide gauge
Waves	ADCP, Wave buoy
Turbulence	ADV, High frequency flow meter
Bathymetry	Single / multibeam sonar, side scan echo
Geotechnics	Sample collection and testing, sonar

Collection of flow velocity data are usually undertaken with Acoustic Doppler Current Profilers (ADCPs), which can be either surface mounted on a vessel or platform, or seabed mounted and left in-situ throughout the campaign. ADCPs are limited by internal battery life (and in the case of some older models, internal memory). The procedures for deployment and retrieval of ADCP units will vary according to the conditions on sites. Seabed mounted instrumentation should be deployed in a low-drag enclosure with enough weight to ensure that it is not moved by the currents. The frame should include a gimble to ensure that the device is correctly orientated throughout the deployment. The inclusion of a surface marker buoy is recommended however where this is not possible then acoustic release systems can be used for device recovery. It is recommended that a secondary method for locating and recovering the ADCPs is planned for, in the event of the primary method failing. Deploying instrumentation in high energy tidal flows is challenging with risks leading of loss of data and/or equipment. Instrument deployment risks involve:

- Failure of the equipment to record data correctly.
- Incorrect positioning, deployed at an angle or inverted.

- Problems recovering the device
- Complete loss of the device.

To maximise the likelihood of a successful measurement campaign ADCP deployments require careful planning to acquire high-quality data.

A measurement campaign of at least 30-35 days (IEC, DNV) is required to sufficiently determine the harmonic flow on site however it should be considered that if the site is subjected to non-astronomical flows (storm surges, river discharges, large wave action etc…) then longer data collection should be considered. If the data are being used to directly determine the site resource (without numerical simulation) then a minimum of 90 days is recommended. ADCPs collect data by measuring the doppler shift from 3-5 diverging 'beams', the distance between the beams increases away from the instrument, as such uncertainty in the data is greater near the surface for seabed mounted ADCPs.

ADCP units report quality control measures in the internal software, these can be used to identify erroneous data points, however further quality control of the data should be undertaken before the data is further used. Multiple flow measurement campaigns should be undertaken to ensure the conditions across the site are captured. The number of campaigns and locations of the devices will depend on the characteristics of the site. Flow data can also be collected with Acoustic Doppler Velocimeters (ADVs), these follow a similar principle to ADCPs but over a much smaller volume effectively providing a point measurement and sample at a much higher frequency (up to 20Hz). ADVs may be useful for quantifying turbulence which cannot accurately be acquired from ADCP deployments.

Water level data will likely also be captured from the on-board pressure sensors of the ADCPs as part of the current measuring campaign. In addition to this data can be collected from tide gauges at the site if available. As with flow data 30-35 days is required to support numerical simulation.

Wave current interaction has a significant impact on both the tidal energy resource and the survivability and reliability of devices. In all but the most sheltered of sites it is important that wave action is considered as part of the tidal resource assessment. Wave data can be collected from ADCPs (extra configuration will be required) but is more commonly available from measurement buoys. It should be noted that wave buoys may not work effectively in strong tidal flows so seabed mounted profilers may be required. With the development of smaller wave measurement devices, the cost of wave measurement campaigns has reduced significantly in recent years (REF: Spotter buoys). As wave action is a stochastic (random) process a longer dataset will be required to capture the site characteristics.

Bathymetry data should be examined prior to any marine operations. Where possible high resolution bathymetric survey data should be used to help site any instrumentation. The process for this collection should follow the international standards (International Hydrographic Office (2008), ICES (2006)).

When planning the data measurement campaign consideration should be made to whether resources can be combined with other data collection. Standards on ecological assessments and seabed geotechnics also should be considered. There may be potential to collect these data at the same time as resource data. This could potentially reduce the overall cost of data collection

4.3 Modelling

Flow models can be broadly categorised as either:

- Finite Element/Volume Models. Deterministic models to calculate the hydrodynamics across a spatial mesh in the time domain using the shallow water approximation of Navier Stokes.
- Computational Fluid dynamics, extremely computationally intensive modelling used to resolve complex structures and high-resolution effects. Not suitable for the site resource assessment but may be used to accurately site turbines, quantify turbulence, investigate device wakes, and assess structural loads in addition to coarser scale flow modelling.

4.3.1 Hydrodynamic modelling

There are a significant number of finite element and finite volume flow modelling codes, both open-source and commercial, which can all simulate hydrodynamics over a defined area. These models simulate the flow (and other hydrodynamic parameters) across a spatial and temporal range specified by the user with a high degree of flexibility. The design of mesh and selection of inputs will all effect the model output and should be carefully chosen to ensure high-quality data and minimise uncertainties. The choice of model code should depend on the availability of software and the experience of personnel. It should be ensured that the model chosen is suitable for the project site. The modeller should refer to technical documentation and published literature to determine that the code is suitable. Equimar Deliverable 2.3 provides a (non-exhaustive) list of popular well validated modelling codes. In determining the suitability of modelling code, the following considerations need to be made:

- Depth averaged or 3D.
- Mesh type: rectangular, curvilinear or unstructured.
- Ease of mesh refinement.
- Treatment of turbulence.
- Treatment of wind and wave action (spatial / temporal).
- Boundary condition options
- Wetting / drying options in inter-tidal cells.

The exact requirements of the model will be highly site and project dependent. The spatial resolution of flow models are recommended in the international standards (IEC and DNVGL) to be no more than 50m at the turbine site. This can be achieved either with nested regular grids or with a variable resolution unstructured mesh. Furthermore, models for site resource assessment (stage 2/3) should include vertical resolution (3D models), with particular focus to be given to bins at the proposed turbine hub height.
The boundary conditions for flow models are usually provided as a set of astronomic constituents (with phase and amplitude defined for the site), the harmonic analysis may be derived either from global (or other lower resolution) models or from measured data. Model boundaries should include both water-level and flow velocity however depending on the distance to the site of interested and site characteristics it may be suitable to provide a water-level only boundary.

Hydrodynamic models accept several physical and numerical inputs. The choice of these will affect the output to varying degrees and it is largely down to the available data and the experience of the modeller to set these values. These inputs may be the result of other simulations (as the outputs of the hydrodynamic models may be used as inputs elsewhere). Figure 3 gives an example of the interconnectivity of different models used throughout a tidal energy project. It is important to note that uncertainties will be present it all data sources and can carry through different models if not correctly accounted for.

There is likely to be a trade-off between the time and resources available for modelling and the level of detail and accuracy of the outputs. Increasing the spatial and temporal resolution increases the computational demand of the simulation and the time required for processing.

Wave current interaction has a significant impact of the flow resource (Hardwick et al (2021)) and unless the site is sheltered from wave action then a spectral wave model should be included as part of the resource assessment.

Consideration should be made regarding the benefits that can be gained by coupling models together. Models can be standalone (no data sharing between models), coupled one-way (one model is run first and then the data provided as inputs to the second model) or two-way (both models are run simultaneously passing data between them at each timestep). Coupling wave and flow models together allows for the effects of wave-current interaction to be visible in the output of both simulations however it is more computationally demanding and will require greater time and resources.

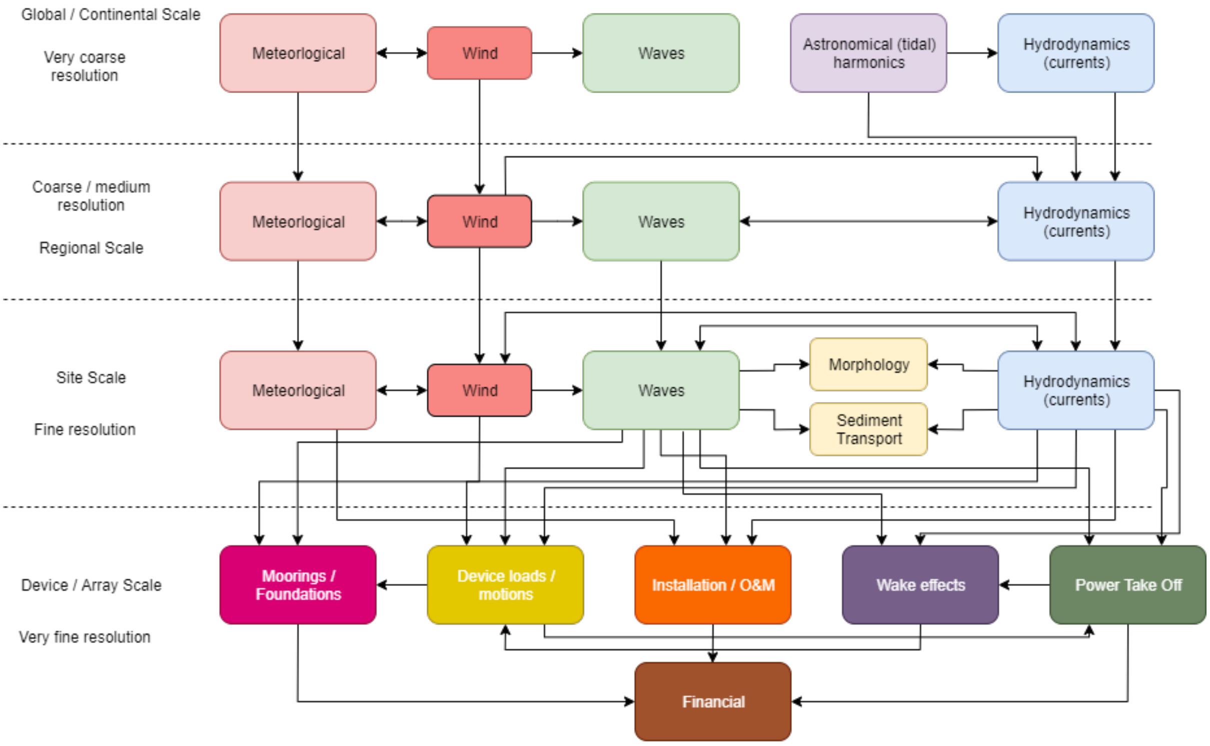


Figure 6 - Interconnectivity of different numerical simulations

4.3.2 Computational Fluid Dynamics

Computational Fluid Dynamics is a numerical method for simulating the free-stream flow of a fluid. There are several different methodologies and assumptions that can be applied depending on the use case and resources available. For tidal energy project planning CFD may be used to determine the localised flow effects, this can be used to determine the siting of individual devices and how the devices impact the flow, and hence how that impacts the energy resource across the site.

CFD is also instrumental in quantifying turbulence, this is important in resource quantification as the turbulence in the flow will impact how much energy can be extracted, as well as for engineering design and other project stages. Turbulence is an extremely complex phenomenon which is challenging to accurately model. Depending on the resources available and required level of detail there are different methods and assumptions applied. The most common CFD codes for resolving turbulence are shown in figure 7. The Reynolds Averaged Navier-Stokes (RANS) approach calculates a time-averaged approximation to the turbulence from the Navier-Stokes equations. The more complex LES approach resolves the flows of larger turbulent structures directly while filtering and averaging the smaller scale turbulence. Direct Navier-Stokes (DNS) is the most complex approach and involves attempting to directly simulate all turbulence. It is extremely computationally expensive and not commonly used.

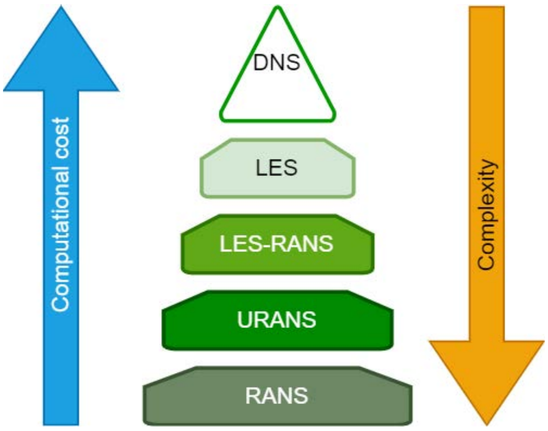


Figure 7 - Different CFD codes

4.4 Model Calibration & Validation

Data from numerical simulations must be rigorously validated against trusted data to understand its accuracy (and limitations). Data should be validated against measured data covering at least 30-35 days and at several locations across the site. The general characteristics of the flow should be examined along with a harmonic analysis. Assessment of uncertainty through model validation is very important – whether calibration is applied or not.

The model output may be improved by calibrating the system to better fit the output. Calibration can be approached by:

- Tuning of model inputs (e.g. bottom roughness, dissipation terms, etc.)
- Correction of model outputs (e.g. apply linear or other correction to flow speed or water level)

Both approaches involve attempting to improve the fit of model output to some trusted (usually measured) dataset. Since the models are large and complex computational simulators involving numerous physical and numerical calculations reducing errors is a challenging process. While manipulating parameters and / or output to better fit validation data may appear to improve output it must be done in a careful and scientific way to ensure that the model output is robust and trusted. Since most models include many empirically derived parameters, tuning of inputs is a reasonable approach, especially for parameters for which we have little information (e.g. bottom roughness). Correction of outputs is widely used, but less physically justifiable. However, it is a pragmatic approach, to reduce systematic bias in model predictions. In both cases it is important that care is taken not to overfit the model to data particularly where the amount of calibration data is limited. Separate calibration and validation datasets must be used to ensure that 'tuning' is appropriate outside the calibration period reducing the possibility of over-fitting to observations. The statistical technique of cross-validation can be used to assess predictive performance (divide the measured datasets into P groups and calibrate with P-1 groups and validate using the excluded group then repeat, leaving out a different group each time) and build up a picture of uncertainties. More sophisticated uncertainty assessments can be conducted using emulators, although this is likely to be computationally prohibitive for commercial studies.

4.5 Uncertainties

Uncertainties in the resource data will arise from imperfect modelling or measurement of the natural phenomena affecting tidal energy generation and operation. However, uncertainty in the calculation of project energy yield will also incorporate how other quantities are calculated. This will include how resource data are applied to the device power curve and into predictions for factors such as; installation, service schedules, faults and decreasing efficiency.

In this report, the focus is on uncertainties related to resource data rather than infrastructure related uncertainties (e.g. performance in given conditions, wake interactions, curtailment, faults, etc.). This will include limited consideration of uncertainties in the extrapolation of measured and modelled data to predict extreme values.

4.5.1 Resource data

Uncertainties in resource data are related to;

a. The accuracy of historic data (measurements and modelling)
b. The time relevance and coverage of the datasets available
c. The spatial relevance and coverage of the datasets available
d. Variability of the resource in relation to the spatial and temporal scale of your data.

Short-term or instantaneous accuracy of a data set is primarily controlled by the instrument capabilities and the methods adopted to operate the instrument. For the majority of instruments used in commercial projects, these are well understood and published by instrument manufacturers. Furthermore, they are commonly stochastic and may not introduce bias into resource assessment analysis.

However, achieving published accuracy will depend on suitable deployment techniques and ongoing efforts are investigating the relevant importance of each process in the accuracy of ADCP deployments for tidal energy. As practice develops and commercial developments use resource data in increasing detail. There remains a strong role for research here to review accuracy of parameters that are critical to resource assessment.

For example, as tidal energy developers consider operational projects, turbulence has gained in importance and uncertainty in measured values is under renewed scrutiny.

Bias in data sets may arise where the data are not accurately capturing the processes affecting a site. For short-term deployments, medium-long term variability may introduce uncertainty to a data set that cannot capture these variabilities. Note that in contrast to wind and waves, tidal resource is primarily deterministic, and the stochastic component can be expected to average out over the long term. As such, shorter deployments can resolve medium-term variability.
When the measurement site is not located precisely at the point of application of any subsequent analysis (e.g. resource assessment), spatial variability in the conditions will introduce uncertainty, with the potential for bias related to consistent differences in the regime between sites. The spatial data set afforded by physical modelling can account for spatial variability, but only within the stated uncertainties of the model output. Research work is ongoing to quantify the potential magnitude of spatial variability. However, without expensive, multi-device deployments, which are beyond the expectation of commercial projects, this analysis is dependent on modelling and the associated uncertainties in that process.

Long term changes in the climate may also affect future resource and may need to be factored into the analysis. Accounting for the 18.6-year nodal cycle will affect project revenue projections but may not be resolved in short-term measurements. Sea level rise is predicted to accelerate over the next 100 years. While this is likely to be a relatively small change compared to typical depths, there is considerable variation in predictions and therefore uncertainty in how much influence it may have on resource assessment. Attempting to model the impact of changing sea level depth through modelling will face the challenge that predicted changes will be small compared to the accuracy of the model itself.

4.5.2 Extreme assessments

Uncertainties in estimates of extremes are more complex. The statistical modelling of extreme quantities is more complex than for mean values (e.g. annual mean power) because fitting a model to extrapolate outside the range of observations results in much larger uncertainty than predicting mean quantities.

- For tidal currents, the main component is deterministic, so uncertainties in extremes are related to uncertainties in harmonics. However, there is less information about how significant the stochastic component is at extreme levels under the influence of extreme water levels and currents due to meteorological effects (e.g. storm surge).
- For subsequent project energy yield calculations, the main uncertainties in extremes are likely to be related to waves, which is stochastic quantity with considerable long-term unpredictability.

There are various guidelines on methods for estimating extremes, but some methods recommended in standards may be inherently biased. This is an ongoing area of research.

Much longer datasets are typically required for estimation of extremes than estimation of annual mean power to estimate 10-, 50- or 100- year maxima (without encountering very large uncertainty) will require a dataset of several years, a minimum of 20-years of hindcast data is typically needed for extreme wave analysis. Assessing all potential combinations is usually infeasible due practical limitations on computational/experimental resources. The environmental contour methods are often used in offshore design to reduce the required number of design conditions. But these introduce various simplifying assumptions which can result in both positive and negative biases (Haselsteiner (2021), Mackay and Hardwick(2022)). This should be considered when assessing uncertainties in design loads.

5 Discussion

The cost and effectiveness of the data collection and survey process are an important consideration for tidal stream energy sites. In general, taking more measurements and investing more measurement resources will improve accuracy as well as temporal and spatial coverage. Similarly, in general, more investment in modelling efforts supported by greater computational resources and alongside suitable measurement campaigns, can increase the level of detail and coverage in the resultant datasets. However, resources available to commercial projects will be finite and investment decisions for site measurements and/or modelling will be strategic based on the level of improvement on offer in the subsequent use of those datasets.

Due to timeframes, cost and availability of established resource monitoring, a conscious balance between data generated, the cost and the time required must be found. The work in TIGER has enabled a joint approach between site owners, technology developers, researchers, and modellers to find this balance in a R&D project, supported through funding. This is a synergistic approach to establish the data and resource modelling for tidal energy sites. It has highlighted how monitoring programs requirements will vary for each tidal stream site. For example, the Gulf of Morbihan is an enclosed basin and behaviour is different to channels or headlands. In practice, this means that all aspects of standards are not appropriate everywhere. As such, it is important to understand the morphology and constraints of the site alongside the proposed development.

In general, higher levels of risk are associated with taking in-situ measurements from ADCPs in tidal energy sites. However, they underpin accurate monitoring programs and are required within all of the published best-practice guides that were reviewed for both tidal flow and wave conditions. Furthermore, in the scientific monitoring programs and research publications that have been reviewed, in-situ measurements consistently emerge as essential in ensuring necessary levels of accuracy.

An efficient route to improving in-situ measurement availability is to share resources. Access to previous measurements provides data directly, without associated risks and costs for a deployment. However, it is noted that there are commercial sensitivities of sharing data, particularly where it may affect investment decisions or competition. Nevertheless, where multiple datasets exist in a region, there is significant mutual benefit from sharing those resources. This review has highlighted that increased data coverage either spatially or temporally (or both) offers improvements in accuracy and validation for subsequent modelling. The mutual sharing of resources offers improvements that may be beyond the investment potential of a single project. Furthermore, projects such as FLOWBEC have highlighted how resource data that is crucial to engineering design and resource assessment can also be highly valuable to other stakeholders conducting environmental analyses or regional assessments.

The synergistic work in TIGER and similar centrally funded initiatives promotes a joint approach that can facilitate data sharing, optimising the benefits from resources across the industry and to stakeholders. This can be highly effective at accelerating development

alongside understanding impacts and developing effective mitigation that can help remove barriers to development.
To date, most funded work makes use of data repositories, designed to provide open access to data sets and promote sharing. However, in many cases non-standard data processing, missing meta-data or refusal of access prevent the re-use of these data sets for subsequent projects. The work reviewed here and establishment of comprehensive best-practice for the industry can support effective data sharing. Whilst funders and licensing agreements can promote adoption of these practices, regional initiatives, such as TIGER could move beyond best-practice to generate best-in-class outputs for a region. This allows the wider support of individual resource campaigns operating in isolation and hence remove some of the risk associated with in-situ measurements, accelerating resource and consenting through the provision of excellent validation data for modelling without requiring long-term campaigns from the developer.

This report covers data collection and survey. As such, it is not focussed on the subsequent analysis of resource data. However, best-practice for data collection is targeted towards achieving the best results from subsequent analysis. Resource data underpins a range of analyses. One such area is linking regional-scale modelling to site and device-scale modelling used for detailed site design and engineering design. In general, the more accurate the regional model, the better the inputs for high-fidelity models. Finer-scale CFD for assessing factors such as spatial variability in flow conditions and turbulence and wake modelling affects both performance estimates and loading. The TIGER project is developing cross-comparison of high-fidelity models (LES) with lower-fidelity models and alignment to create a coherent modelling framework. This will enhance confidence in the longer term that aims to reduce uncertainties in the future and help to develop best-practice methods for the industry.

6 Conclusion and Recommendations

Key findings:

- Every site is different and there is no ‘one size fits all’ approach to site assessment. Expert knowledge of the site and careful planning is needed to ensure that high quality data is collected suitable for the project.
- All measured and simulated data contains uncertainties, these should be considered to ensure that key project parameters (e.g. AEP, LCOE) are reported with appropriate confidence levels.
- Data sharing within the industry can be used to the benefit of future projects.
- Identified and reported ‘lessons learnt’ are very valuable. They should be regularly reviewed, updated and communicated amongst stakeholders.
- The cost of data collection campaigns, both financially and in project time, can be significant and a balance needs to be struck when deciding on the campaigns.

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Annex A – Terms of Reference Data Survey Network Group

Name of group: Survey Network Group

Title: Terms of Reference

Purpose/role of the group:
The Survey Network group has been established in April 2020 by the University of Exeter and Project Partner in the Tidal Stream Industry Energiser Project (TIGER).

The main purpose of the Survey Network Group is to coordinate and/or access the site and turbine performance data available/collected in TIGER. The Survey Network Group will work together to establish best practice for data collection, it will concentrate on site environmental, resource and turbine performance data.

The aims of the group are to agree best practice methodologies and protocols for data collection, storage and dissemination. This includes recommendations to assure the standardisation of modelling tools, equipment, and processes and their respective data requirements and use.

The University of Exeter will publish a report of these findings, describing the results of best practice, models and identifying standardised data collection equipment (WP T3.1.1).

Membership:
The Survey Network Group consists of representatives from the Lead Partner, Offshore Renewable Energy Catapult (OREC), the European Marine Energy Centre (EMEC), site operators and owners, and the Academic partners involved in the TIGER project. The Academic partners specified in the Survey Network Group are as follows:

- Université de Caen Normandie
- University of Exeter
- Université le Havre Normandie
- Université Bretagne Sud
- University of Manchester
- University of Plymouth

The site operators and owners specified in the Survey Network Group are as follows:

- MorbihanHydroEnergies SASU
- Minesto AB
- Orbital Marine Power Limited
- Electricité de France
- Cambrian Offshore SW Ltd
- SEENEOH
- Normandie Hydroliennes
- Bretagne Developpement Innovation
- HYDROQUEST

- QED Naval

Designated individuals nominated by all site operators, data owners and academic partners involved in the data survey will form the membership of this group, formally commencing by the end of April 2020.

The meetings, analysis and resulting report will be completed by March 2022.

Accountability:
Individual responsibilities are as follows:

- The University of Exeter will assemble, organise and chair the Survey Network Group. With the input and contributions of the Survey Network Group partners, it will lead on the draft and production of the deliverable report detailing the group's findings; the results of best practice, models and identify standardised data collection equipment.
- The Academic partners: the Université de Caen Normandie, the University of Exeter, the Université Bretagne Sud and the University of Plymouth will concentrate on site environmental data.
- The Academic partners: the Université de Caen Normandie, the Université le Havre Normandie and the University of Manchester will concentrate on resource and turbine performance data.
- EMEC will establish new accredited testing processes developed in the group's Tidal Resource Modelling work (WP T1.7) that will verify the performance of tidal turbines.
- Following report delivery, it will be endorsed by the PSG and SAG and then all TIGER Project partners will be responsible for disseminating it through websites, networks, conferences and events.

Review:
These Terms of References shall be reviewed annually by all Project partners, and amended as necessary, subject to consent by all other partners and the chair.

Working methods/ways of working:
Our approach to working will be open and collaborative. While works will continue within each partner's organisation, findings will be shared at the Survey Network Group meetings and at the research progress meetings.

The default meeting mode will be online / remote / video conferencing, whilst making use of physical meeting opportunities, where possible.

Meetings will be held quarterly, in the first month of every quarter. Indicative meeting months are as follows:
April 2020
July 2020
October 2020
January 2021
April 2021
July 2021

October 2021
January 2022
April 2022
July 2022
October 2022
January 2023

The University of Exeter will arrange and chair the meetings. The Agenda will be drafted and circulated by the Chair, collecting items from all partners. Minutes from the meeting will be taken and circulated in the week following the meeting.

The format of these meetings will be a targeted sharing of information/processes, as well as group discussions. Administrative support for these meetings will be provided by the University of Exeter.

A meeting will require a minimum of 4 partners to be quorate, with the Chairperson having the casting vote.

Sharing of information and resources (including confidential materials):
Information and resources will be shared through the TIGER sharepoint already set up by the Lead Partner, OREC.

Confidential materials and copyright issues are covered through the Partnership Agreement. For information on Intellectual Property Rights in the project, please refer to Article 12 and 13 in the document ‘Partnership Agreement – TIGER V7 12022020’.