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Wave and Tidal Energy Yield Uncertainty

Literature Review

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Frazer-Nash Consultancy provides independent technical advice to customers across a wide range of industries. In marine renewables, they support device developers, project developers and investors to design more effective systems, mitigate risk and reduce costs. Their track-record in this field includes resource assessment, array layout optimisation and energy yield uncertainty estimation on several of the leading marine energy projects.

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Executive Summary

As part of its aim of accelerating the commercial exploitation of marine energy, the Marine Farm Accelerator (MFA) seeks to understand the uncertainty in energy yield, and hence revenue, from wave and tidal energy projects. Its first step in this process has been to develop a taxonomy document, listing the categories of losses and uncertainties that should be considered in an Energy Production Estimate (EPE). Frazer-Nash Consultancy has identified and assessed methods of quantifying these uncertainties and this report is one of the deliverables from that work. It contains a review of the relevant literature in this area and hence provides an overview of the state-of-the-art in uncertainty assessment for wave and tidal energy.

The taxonomy document identifies four main aspects to the uncertainty assessment (plus a general "Other Uncertainties" category) and a number of sub-categories under each. The available literature pertinent to each sub-category has been identified and the key themes for each have been summarised. This review encompasses:

- Major academic journals and relevant books (e.g. Renewable Energy, International Journal of Marine Energy);
- Proceedings of the major conferences (e.g. EWTEC, ICOE);
- Key industry publications on marine energy (e.g. IEC standards and technical specifications) and from associated industries (e.g. onshore and offshore wind); and,
- Additional references identified through the stakeholder engagement, which has been undertaken in parallel with this literature review and will be reported separately.

Although the wave and tidal uncertainty categories are the same, the ways in which they should be addressed and the current levels of understanding differ significantly. As a result, the wave and tidal aspects of this review have been largely separated.

The findings of the review can be summarised as follows:

- Measurement uncertainties inherent to the instruments themselves are reasonably small and well-understood in both wave and tidal. There are various ways in which these uncertainties can grow when deployed in non-ideal conditions, and the magnitudes of these increased uncertainties are not always quantifiable. However, there is sufficient understanding of best practice in using the instruments that these increased uncertainties should be avoidable.
- Temporal extrapolation procedures are fundamentally different in wave and tidal projects: tidal flows are largely deterministic (driven by the positions of the sun and moon relative to the earth) whereas waves are stochastic (driven by the weather). Procedures for performing temporal extrapolation are well-developed in tidal and fairly well-developed in wave. In tidal, the key challenges are dealing with sites with substantially asymmetric flow

regimes and addressing wave-current interaction, both in processing measured data from ADCP deployments and in predicting the future resource. In wave, it is tempting to apply methods from the wind industry directly, but there is evidence that this could lead to significant errors because of the influence of long-term trends in features such as the North Atlantic Oscillation. Approaches for overcoming these issues to quantify bias and uncertainty have been proposed in the literature. The effect of anthropogenic climate change has also been addressed, and is expected to be small compared to the “natural” inter-annual variability through the lifetime of projects being conceived now.

- Spatial extrapolation procedures are also well-developed for wave and tidal projects. In general, uncertainties in these modelling techniques need to be assessed via validation against in-situ measurements, although there are a growing number of such validation studies published in the literature (at least for wave) so a suitable meta-study might be able to extract some more generally-applicable values.
- Plant performance uncertainties include a number of sub-categories which need to be addressed separately, most notably:
    - Power performance. Guidance on assessing the uncertainties in power performance tests is available from the wind industry and is considered to be applicable here.
    - Device availability. For the earliest arrays, this will be a substantial source of uncertainty which is hard to quantify. However, in many cases, project developers will push this risk onto device developers via the turbine supply contracts. Monte-Carlo methods exist to predict the variability of availability given a certain set of failure rates, vessel capabilities and metocean conditions. The failure rates themselves are harder to quantify without significant operational experience, although data from other industries (e.g. the OREDA database), combined with analysis and judgement on the effect of the way components are being used, can provide indicative values.
    - Device interactions. A range of models exist for wake and blockage effects (in tidal) and wave interactions (between wave energy convertors). A number of validation studies exist demonstrating the predictive power of these tools on scaled tests in wave tanks, towing tanks and flumes. Full-scale validation is, however, generally lacking and there are a number of reasons to believe that the physics of full scale wake interactions in tidal projects might differ from what is seen on small scales. This therefore constitutes a significant uncertainty. Sensitivity studies, rather than existing knowledge, appear to be the best way of quantifying the potential impact of these uncertainties at present.

A review of the active research programmes currently under way has also been carried out and is summarised in this report. This will inform a gap analysis, which will be the subject of a subsequent report.

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1 Introduction

The Marine Farm Accelerator (MFA) Yield Technical Working Group (TWG) has the aim of quantifying and reducing the uncertainties associated with energy yield predictions of marine energy projects.

Currently there is no standardised method for determining this uncertainty although the MFA has taken an important first step with the development of a taxonomy document which they have refined through consultation with relevant industry practitioners. To assist the MFA in working towards a standardised framework, this literature review provides a summary of:

- The available technical literature on marine energy yield uncertainty, distilled into a concise state-of-the-art;
- The major research activities in the marine energy sector which are addressing either uncertainty directly, or related topics which are potentially useful in its quantification.

Ultimately, this literature review will assist the MFA in highlighting appropriate methods for assessing uncertainties and highlight potential gaps in research which would merit further consideration. The proposed research gaps will be documented in a subsequent report "Marine Energy Uncertainty Gap Analysis".

1.1 Approach

The MFA taxonomy document is used as the basis for this study, and for each category in the document, the study seeks to determine the extent to which uncertainty is considered in the literature. This involves identifying the origins of the key uncertainties and the physical processes or rules from which they derive.

For each category in the taxonomy document, the review determines whether:

- There are specific industry standards, or academic methods presented in the literature which could be used to quantify the uncertainty; or if,
- There is an appreciation that there are issues associated with the uncertainty, but that there is currently insufficient knowledge or confidence to quantify it confidently; or else,
- Uncertainty is not considered at all.

Additionally the review considers:

- Which uncertainty categories are considered in current research programmes and how these programmes will better characterise, or reduce the uncertainties;

- The likely impact of each category on the overall assessment of a project uncertainty calculation. There may be some categories which dominate the overall uncertainty and it is important that these are recognised, so that they can be prioritised if necessary.

1.1.1 Literature Review

A wealth of academic and industry literature exists to support the assessment of uncertainty in wave and tidal energy predictions. Some of this literature has arisen from research specifically focussed on marine energy, whilst other stems from fields such as physical oceanography and off-shore marine operations. The review uses a number of sources as follows:

- Major academic journals and relevant books (e.g. Renewable Energy, International Journal of Marine Energy);
- Proceedings of the major conferences (e.g. EWTEC, ICOE);
- Key industry publications on marine energy (e.g. IEC standards and technical specifications) and from associated industries (e.g. onshore and offshore wind);
- Additional areas identified through the stakeholder engagement. This literature review has been undertaken concurrently with the stakeholder engagement with project developers, device developers, consultants and academics. In particular, this engagement has proved extremely useful in highlighting useful publications in less obvious sources.

1.1.2 Research Project Landscape Map

The literature review reflects the current state of knowledge in the industry, but it is also important to understand what research programmes are underway as this highlights which uncertainty categories are being investigated and also where potential gaps in research lie.

The major research activities and projects within marine energy are presented and any opportunities to extend or build upon the work in extensions or related projects will be identified as appropriate. This study has used the following sources:

- Funding mechanisms (both in the UK and overseas);
- Research activities in related fields (e.g. oceanography);
- Other Offshore Renewable Energy (ORE) Catapult projects.

1.2 Structure of Report

There are a very large number of references published which are relevant to this study. Careful consideration has therefore been given to the way the review is presented to make it useful and concise.

The overall findings of the literature review are summarised in Table 1 (tidal energy) and

- Table 2 (wave energy) in Section 2. These tables describe the extent to which the uncertainty categories are covered in the literature and also which areas are being considered as part of current research programmes. The relative size of each uncertainty is also highlighted to illustrate its importance in the assessment of an overall project uncertainty;
- A more detailed discussion of the literature pertaining to each uncertainty category is then given in Section 3 (tidal) and Section 4 (wave). These sections provide a thorough review of uncertainty methodologies from industry and academia, including examples of case studies and uncertainty assessments where available;
- The research landscape map is given in Section 5. This summarises the major research projects within marine energy that are relevant to uncertainty in energy yield predictions. These projects are referenced within the literature review as appropriate;
- Conclusions from the study are provided in Section 6. These will be used to inform the other aspects of the MFA uncertainty study and in particular highlight potential gaps in research appropriate to uncertainty;
- References are provided at the end of the document in a list format. The uncertainty categories considered by each reference are provided in brackets, with T and W indicating tidal and wave categories respectively. For example (T1a) corresponds to tidal uncertainty category 1a – Measurement.

2 Summary of Literature Review

Table 1 and Table 2 summarise the high-level outcomes of the literature review for tidal and wave energy projects respectively. The conclusions listed here are based on the more detailed reviews presented in Sections 3 and 4.

It is impossible to precisely quantify the impact of each category on an overall project uncertainty as this will depend on the measurement and modelling methodologies used, the technology deployed and the site conditions. However, to provide an indication each category has been rated as Low, Medium or High where Low is likely to make only a minimal impact to overall uncertainty and High is a dominant factor. It is envisaged that these categories will be appropriate for the majority of potential projects.

Table 1: Tidal Energy Uncertainties by Taxonomy Category

Uncertainty Category	Extent to which Uncertainty is addressed in the literature	Inclusion within Research Programmes	Impact on overall uncertainty
1.a Instrument Accuracy	Site measurements are required to determine the speed, direction and turbulence levels of the tidal flows. Each of these has an associated uncertainty. **Current Speed and Direction:** Uncertainty levels on current speed and direction are provided by equipment (ADCP) manufacturers. The ways in which these are demonstrated are understood. **Turbulence:** There are some studies into using ADCPs for turbulence measurements but as yet no definitive methodologies to quantify the uncertainty. The accuracy of turbulence data is expected to vary substantially between device types.	**Current Speed:** N/A - Improvements are made by manufacturers as they upgrade products. **Turbulence:** This is the primary focus of the TIME project. It is also addressed by SuperGen and ReDAPT.	**Current Speed:** **Low** Uncertainty of current speed is typically 1%. **Turbulence:** Measurement uncertainty of turbulence characteristics is variable, but this is likely to be a second-order effect on energy yield so the resulting yield uncertainty is **Low.**
1.b Measurement Interference	Known causes of interference are provided by industry documents on equipment. These can be used to mitigate errors in measurements.	Unlikely to be of direct research interest but may be determined indirectly as part of other studies e.g. SuperGen, ReDAPT, TIME.	**Low** if best practice guidelines are followed and data are quality-controlled appropriately.
1.c Short-term Site Data Synthesis	Not explicitly quantified in literature but effect could be determined through sensitivity studies.	Unlikely to be of direct research interest but may be determined indirectly as part of other studies e.g. SuperGen, PeraWatt, ReDAPT.	**Low** If either no synthesis used or sensitivity studies are used to determine impact.
1.d Data Quality and Metadata	Uncertainty not explicitly quantified in literature but there are good practice guidelines to ensure it is minimised.	Unlikely to be of direct research interest but may be determined indirectly as part of other studies e.g. SuperGen, PeraWatt, ReDAPT.	**Low** If good practice guidelines are followed.

Uncertainty Category	Extent to which Uncertainty is addressed in the literature	Inclusion within Research Programmes	Impact on overall uncertainty
2.a Historic Resource Estimation	This is the uncertainty associated with the validation of models – deterministic and non-deterministic effects: Deterministic methods which fit harmonics to measurement data are generally well developed and considered to be fairly accurate. Uncertainties arise due to the short duration of the measurements relative to the periods of some of the harmonics and the impact of non-astronomical effects during the measurement period. Harmonic analysis is also harder for sites with substantially asymmetric flowfields in flood and ebb. Statistical methods have also been explored and may be used to complement deterministic methods.	This should be considered within the TAM and PeraWatt projects. The TAM project seeks to validate resource models for the current flow prediction at tidal energy sites.	This is somewhat site-specific. For a sheltered site with a long measurement record (>90 days), deterministic methods have a **Low** uncertainty. This can rise to **Medium** for shorter measurement records and/or sites where the measurement period is strongly affected by non-astronomical effects. Statistical methods are not commonly used so would be considered to have **High** uncertainty if used in isolation, although they could usefully complement a deterministic method.
2.b Future Resource Variability	This concerns the use of a model to predict future tidal resource and comprises two main issues: the timing of the project relative to the 18.6-year tidal cycle, and the influence of non-astronomical effects. The uncertainty associated with project timing can be calculated and is low. The impact of non-astronomical effects is harder to predict as it depends on the weather. Wave-current interaction modelling is not well-developed, and even if it were, it relies on having accurate wave and weather data. These involve significant uncertainties.	Wave-current interaction is an area of active research, e.g. SuperGen.	The uncertainty associated with project timing is **Low.** The magnitude of non-astronomical effects is site-specific. For a sheltered site, it is likely to be **Low**; for a more exposed site, it may be **Medium** or even **High.**
2.c Climate Change	There are various studies exploring the effect of climate change on sea-level and wave climates. There is no evidence of a significant effect on tidal energy.	Climate change impacts are considered as part of the SuperGen programme.	The impact of climate change on tidal sites is considered to be **Low.**
3.a Model Inputs	Guidelines for bathymetry and boundary conditions are given in IEC standards, but the choice of bed-roughness data is still under debate. There are various studies which discuss the choice of boundary conditions at potential sites but it is difficult to draw universal conclusions from these studies.	This is considered as part of SuperGen, PeraWatt and TAM projects.	**Medium** The choice of inappropriate boundary conditions has the potential to cause significant uncertainty, although a sensitivity analysis can be used to quantify the impact.
3.b Horizontal and Vertical Extrapolation	There have been various studies on the ability of models to predict the spatial variability of models across a resource. However, these are generally site specific and there are few general rules or methodologies. Vertical extrapolation is required because many tidal current models are 2D depth averaged. There is a potential uncertainty associated with inaccurate vertical velocity profiles but this can be mitigated using sensitivity studies.	Spatial variability is being particularly addressed in TAM but also as part of SuperGen and PeraWatt.	Horizontal extrapolation uncertainties would be developed based on site-specific data, but are likely to be **Medium** to **High** in many cases. Vertical extrapolation uncertainties depend on the complexity of the flow at the site in question, and are likely to be **Low** to **Medium** in most cases.

Uncertainty Category	Extent to which Uncertainty is addressed in the literature	Inclusion within Research Programmes	Impact on overall uncertainty
4.a Availability	There are a number of published studies which offer methods for quantifying the availability – typically applying Monte-Carlo and sensitivity studies to standard industry component data. Ultimately, it will be difficult to quantify uncertainty of tidal devices until more devices are deployed, there is an increase in operational data, and there is a convergence to a few principal designs.	Considered as part of SuperGen, TEC and WSI projects.	From the point of view of the overall project energy yield, the uncertainty is likely to be **Medium** to **High** for the early arrays, until operational experience is gained. Project developers may, however, be able to pass some of this risk onto turbine suppliers, reducing their exposure to this uncertainty.
4.b Resource-Array Interactions	This includes wake effects and blockage on tidal resource. Wake effects are reasonably well understood in wind industry but there are technical limitations in applying these to tidal devices. There is also an absence of full scale tests for validation. Blockage effects are harder to validate and models tend not to be able to capture the key physics. However, the IEC standards state that small arrays (<10MW or 2% of the theoretical resource) blockage is not likely to be significant.	Considered as part of ReDAPT and TAM projects.	The uncertainty could be a **High** proportion of the predicted wake loss, however for the early arrays involving a small number of turbines, this is likely to translate into only a **Low** to **Medium** uncertainty on energy yield.
4.c Marine Energy Convertor Power Performance	IEC standards prescribe methods and conditions for power performance testing. Project uncertainties arise from two sources: the uncertainty of the power curve derived from the power performance tests, and the application of this power curve in other locations with different water depths, turbulence characteristics and wave climates. The wind industry is moving to rotor-averaged power curves which capture these effects, but their applicability to tidal turbines is unproven.	Considered as part of SuperGen and in the development of the IEC Technical Specifications. Also considered in the wind industry through the Power Curve Working Group and other IEC initiatives.	**Medium**
4.d Electrical Losses	The uncertainty associated with power losses in the subsea cables, any distribution hubs and also the power monitoring devices should be bounded by the uncertainty limits of the components used, as given by the relevant IEC standards.	Should be considered (if only indirectly) as part of the ReDAPT project and the TEC demonstrator.	**Low**
4.e Performance Degradation	Similar to availability, this is not an area where uncertainty is well quantified. It is envisaged that this uncertainty will be better understood as more devices are deployed. There is evidence from the literature that marine growth characteristics are likely to vary between sites, depending on native species and water temperature. There is also evidence from the wind and aerospace industries that the susceptibility of aerofoil profiles to added roughness varies significantly.	Anti-fouling paints are being assessed as part of the ReDAPT project. Also considered as part of SuperGen. There may also be some read-across from the ORE Catapult's Blade Leading Edge Erosion Programme (BLEEP) if it looks at quantifying the effect of leading edge erosion on turbine performance.	Currently the impact of this is largely unknown. For early arrays, it should be mitigated through inspection and maintenance. In the interim, it is judged to be **Medium**.
4.f Curtailment	This is not addressed specifically in the industry guidelines or academic literature, but there is experience from the wind industry. The effect on any site depends on the terms of the Power Purchase Agreement.	Not covered in current research programmes on marine energy.	**Low** Depending on the terms of the PPA.

Table 2: Wave Energy Uncertainty by Taxonomy Category

Uncertainty Category	Extent to which Uncertainty is addressed in the literature	Inclusion within Research Programmes	Impact on overall uncertainty
1.a Instrument Accuracy	Uncertainties on wave height and period are provided by equipment (ADCP) manufacturers. The process by which these are established is understood.	N/A - Improvements are made by manufacturers as they upgrade products.	Uncertainty of wave height is typically **Low** (1%). However, the algorithms used to calculate the wave statistics introduce additional uncertainties, the magnitude of which depends on the averaging period and sample rate.
1.b Measurement Interference	Known causes of interference are provided by industry documents on equipment. These can be used to mitigate errors in measurements.	Unlikely to be of direct research interest but may be determined indirectly as part of other studies e.g. SuperGen, ReDAPT	**Low** If data correctly monitored and fault checked.
1.c Short-term Site Data Synthesis	This is considered to be similar to tidal energy uncertainty (see Table 1, Category 1c).		
1.d Data Quality and Metadata	This is considered to be similar to tidal energy uncertainty (see Table 1, Category 1d).		
2.a Historic Resource Estimation	The IEC Technical Specification identifies two methods of characterising the historic long-term resource: long-term runs of a validated model, or a Measure-Correlate-Predict (MCP) approach similar to that used in the wind industry. In either case the long-term record will be of finite length so there will be uncertainty from inter-annual variability (see category 2a). If MCP is used, additional uncertainties will also arise from the quality of the correlation and the consistency of the long-term reference data. These can be assessed using techniques from the wind industry.	This is considered by SuperGen and PeraWatt projects.	**Low** for long-term modelling, potentially **Medium** for MCP.
2.b Future Resource Variability	This is the uncertainty associated with the inter-annual variability of the wave resource over the project duration. Wave climate variability is known to be site specific, which means that unlike wind, it is not possible to prescribe a single value for the variability. This variability (and hence the associated uncertainty) can be derived from long-term modelling. In addition, inter-annual variability is generally correlated to global climatic indices (North Atlantic Oscillation in UK waters). The NAO cannot be forecast accurately from one year to the next, so this variation cannot be predicted deterministically for the lifetime of a project. The uncertainty associated with it can, however, be estimated from statistical models of these indices.	Inter-annual variability of wave resources is being considered as part of the SuperGen project.	**Medium**

Uncertainty Category	Extent to which Uncertainty is addressed in the literature	Inclusion within Research Programmes	Impact on overall uncertainty
2.c Climate Change	The uncertainty here is on the impact of climate change on long-term trends in global climate indices. Various studies have suggested a weak sensitivity with large error bands. Application of these results in wave energy suggests that any associated uncertainty in wave climate is small compared to the inter-annual variability for projects being conceived now.	Considered as part of SuperGen	**Low**
3.a Model Inputs	**Bathymetry:** Standards mandate the reporting of the uncertainty of surveys. The resulting impact on wave speed can be determined to be small but not negligible. **Wave Data at Model Boundaries:** These are generally derived from larger-scale reanalysis datasets. They are known to have certain biases but this will be manifested as uncertainty in the model predictions. **Meteorological Data**: Several datasets are available for use in resource assessments. Since wind is a second order effect on wave resource, the sensitivity to wind speed is low.	Considered as part of SuperGen	**Low**
3.b Horizontal and Vertical Extrapolation	The focus here is horizontal propagation of waves from model boundary conditions to WEC locations. Third generation models (e.g. SWAN) capture all the physical effects relevant to this propagation. There have been several validation studies comparing these models to buoy data, which demonstrate good agreement. These studies also illustrate how the associated uncertainty can be calculated on a site-specific basis.	Considered as part of SuperGen	This is site-specific but likely to be **Medium** for many sites.
4.a Availability	This is considered to be similar to tidal energy uncertainty (see Table 1, Category 4a).		
4.b Resource-Array Interactions	Wave interaction models have been validated against tank tests on small scale, and shown to give good agreement. For early projects involving small numbers of devices, these interactions are expected to have a small impact on energy yield in any case.	Considered as part of SuperGen	The uncertainty could be a **High** proportion of the predicted interaction effect, however for the early arrays involving a small number of devices, this is likely to translate into only a **Low** uncertainty on energy yield..
4.c Marine Energy Convertor Power Performance	The same issues raised for tidal energy apply here, namely the uncertainty in the power matrix and applicability of that power matrix in other wave climates. The actual uncertainties here are likely to be higher for two reasons. Firstly, the power matrix is two-dimensional so contains many more “bins” than a tidal turbine power curve. This means that the number of points occurring in each bin during a test is likely to be smaller. Secondly, the impact of tertiary variables such as spectral shape and wind direction is expected to be stronger than the equivalent factors in tidal.	Considered as part of SuperGen and in the development of the IEC Technical Specifications.	**Medium** for early arrays, reducing to **Low** as the industry gains operational experience.
4.d Electrical Losses	This is considered to be similar to tidal energy uncertainty (see Table 1, Category 4a).		

Uncertainty Category	Extent to which Uncertainty is addressed in the literature	Inclusion within Research Programmes	Impact on overall uncertainty
4.e Performance Degradation	This is considered to be similar to tidal energy uncertainty (see Table 1, Category 4e).		
4.f Curtailment	This is considered to be similar to tidal energy uncertainty (see Table 1, Category 4f).		

3 Literature Review – Tidal Energy

Best practice in the resource assessment and power performance prediction of tidal energy systems is being prepared by the IEC. In particular, the IEC Draft Technical Specification 62600-201 (Reference 1), currently at Committee Draft stage, is likely to be very influential in determining how tidal resource assessments are carried out and hence how Energy Performance Estimates (EPEs) are performed in future. This document prescribes two levels of assessment:

- Stage 1 – "Feasibility" – Investigates the scale and attributes of the energy resource within a particular study area. The results assess the feasibility of constructing tidal energy arrays at sites within the study area by estimating the 'undisturbed site resource';
- Stage 2 – "Layout Design" – Focused on generating detailed and accurate information on the tidal energy resource in a specific area to determine AEP, through supporting the layout design of a tidal array, and may incorporate energy extraction impacts upon the project scale. Stage 2 studies should consider the technology to be installed and locations of tidal energy converter (TEC) deployments in order to estimate AEP with lower uncertainty.

In this work, it is assumed that if an uncertainty assessment is being carried out, it is on the basis of a Stage 2 resource assessment, and that the recommendations made in the current draft of IEC DTS 62600-201 for Stage 2 will be followed. If a specific project requires a different approach to be taken for the resource assessment, a different approach may also then be required to assess the energy yield uncertainty.

3.1 Site Measurement (Category 1)

3.1.1 Instrument Accuracy (Category 1a)

Measurements for prospective tidal sites are generally undertaken using Acoustic Doppler Current Profilers (ADCPs). These are used to measure three parameters: current speed, current direction and turbulence characteristics. All three are measured as a function of time. Bottom-mounted ADCPs are used to provide flow data which can be used as the basis of an EPE, although vessel-mounted systems may be used at earlier stages to indicate the spatial variability of the resource.

3.1.1.1 Instrument Accuracy (Category 1a)

Measurement uncertainty in current velocities is caused by a combination of random error and bias. Random errors result from Doppler noise and turbulence fluctuations which are reduced by averaging over a number of readings "pings". Over a large number of measurements, the average effect of these random errors tends to zero. The bias errors are intrinsic to the device and do not tend to zero with increasing numbers of data points. These mainly arise from uncertainties in the beam direction due to manufacturing tolerances. Bias errors are difficult to detect and generally cannot be removed (Reference 2).

Manufacturers generally provide uncertainties and examples of these are given as follows (bias and single ping error respectively). It is assumed that these represent standard uncertainties, although this is not explicitly stated in the specifications.

- Nortek Signature 500 (Reference 3): Speed: 1% +/- 0.5cm/s, Direction: 2°
- Teledyne Workhorse Sentinel (Reference 4): Speed: 0.5% +/- 0.5cm/s, Direction: 2°

Reference 5 states that generally single ping random error can vary from a few mm/s to as much as 0.5m/s. The random error is reduced with increased data points as ~ $N^{-1/2}$ where N is the number of data points. Even for a large random error then as long as there are sufficient number of data points the random error will generally be smaller than the bias. Consequently, further averaging will not change the mean current speed.

An independent estimate of ADCP bias is provided in Reference 6. This states that bias is typically less than 10mm/s. For a current speed of 1m/s this equates to an uncertainty of 1%, which is in broad agreement with the manufacturers' specifications.

Reference 7 presents a method for directly estimating the Doppler noise levels (and hence random errors in mean velocity data) from the measured signal. The values found were generally higher than suggested by manufacturers, but still of the same order of magnitude. Importantly, this work does, however, recognise that waves can have a strong impact of the robustness of the method (see side-lobe measurement interference in Category 1b).

ADCPs also have a real time clock which can be used to monitor the periods of tidal stream harmonics. Their accuracy is generally good and as an example Reference 3 states +/-1min per year. Reference 1 provides guidance for dealing with clock drift. Accurate information on the times of peak currents is useful in validating flow models.

Measurement monitoring systems are being developed as part of the Integrated Marine Energy Measurement Platform project at EMEC.

3.1.1.2 Turbulence

Turbulence affects energy yield in three ways:

- It affects the kinetic energy flux through the turbine, and hence can alter the apparent power curve of the turbine (see category 4c);
- It accelerates wake recovery (see category 4b); and,
- It is usually the primary driver of device fatigue loads, so influences the cost and/or availability of tidal energy devices (see category 4a).

ADCPs can provide reasonable estimates of many turbulence parameters such as turbulence intensity and kinetic energy (Reference 8), although there have been few published results of measurements from high-energy sites (Reference 2). To measure turbulence using an ADCP the raw data from individual “pings” must be retained, since averaging would obscure the velocity variance and Doppler noise must be removed from the velocity variance statistically. The accuracy is often poor in comparison to other measurement techniques (e.g. Acoustic Doppler Velocimetry) due principally to:

- Inaccuracy of velocity measurements (due to Doppler noise and nonhomogeneous flow between beams – see category 1b);
- Poor temporal and spatial resolution of the instruments due to pinging frequency and bin sizes and widths respectively.

Turbulence measurements would be improved by faster sampling rates and less spatial averaging. There is also a need for the correlation of turbulence measurements to statistically, if not directly, correlate with blade load data from the turbine blades (Reference 9).

Reference 10 states that turbulent statistics calculated from ADCP data will not capture the whole spectrum. The filtering process used in ADCPs means that some frequencies are attenuated completely while others will be amplified. Ultimately, this means that a turbulence spectrum will be skewed by an ADCP. This also highlights that other measurement techniques (e.g. hot-wire anemometer) should be used to calibrate the ADCP data.

Measurement and evaluation of turbulence effects is being investigated specifically as part of the TIME (Turbulence in Marine Environments) project.

3.1.2 Measurement Interference (Category 1b)

There are various potential causes of interference which can increase the uncertainty in measurement. These are summarised in Sections 3.1.2.1- 3.1.2.6.

3.1.2.1 Side-lobe interference

In addition to transmitting sound pulses through the main beam, ADCPs transmit sound through side lobes. Reflections at the water surface from the side lobes interfere with reflections from water particles from the main beam, causing part of the measurement height to be contaminated. For side lobes at 20° to the main beam, the contaminated region is the top 6% of the water column and for 30° this increases to 15%. Consequently, measurements from this contaminated region should not generally be used. Side-lobe interference may be mitigated by the use of bistatic profilers (Reference 8) but this is not common practice.

In rougher sea conditions, the contaminated regions are likely to be lower (Reference 6). The impact of side-lobe interference is usually apparent in the data, so appropriate quality control procedures can be put in place to identify and remove the affected data points.

3.1.2.2 Transducer Ringing

ADCPs transducers continue to vibrate after transmitting sound pulses, and during this time the returned echoes are contaminated by the vibration (ringing). For an ADCP operating at 300kHz (e.g. Teledyne Sentinel), the result is that the data measured 2m from the ADCP is contaminated and is not generally used (Reference 5).

3.1.2.3 Non-Homogeneous Flow

The uncertainty stated by manufacturers for ADCPs is based on the assumption of homogeneous flow across layers of constant depth. However, in practice there may be spatial variations across a site due to shear, and instrument uncertainty does not account for the error caused when separate beams detect spatially varying flows (Reference 1). ADCPs report “error velocity” which can be used to evaluate whether the assumption of non-homogenous flow is reasonable, and this is an important built-in functionality to evaluate data quality.

Similar issues are encountered in the wind industry when using LIDARs in complex terrain. These measurements are sometimes corrected by combining with Computational Fluid Dynamics (CFD) flow modelling (e.g. Reference 11). This process could be applied to tidal currents but there is currently limited evidence of this being undertaken.

3.1.2.4 Proximity to Ferrous Materials

Proximity to ferrous materials affects the magnetic compasses inside ADCPs and can therefore introduce biases in flow directional measurements (Reference 12). This can be mitigated by calibrating the unit prior to the survey whilst it is mounted within the deployment frame (Reference 1), and also checking the compass calibration on return from the survey.

3.1.2.5 Pitch and Roll

Non-zero tilt angles cause the acoustic beams to measure at different depths such that the resulting bins (determined by time delay of the returned signal) are no longer in the same horizontal plane. This is normally adjusted by “bin mapping” which uses the beam velocity nearest the nominal bin centre, although it can result in omitting or duplicating data and does not correct for the fact that the beam velocities averaged over different depth ranges are combined to calculate the flow field. Reference 13 reports that typical errors for the standard method are approximately 0.01m/s, although these can be reduced by a factor of 10 or so by linearly interpolating the beam velocities from the measured values.

3.1.2.6 Positional Uncertainty

If as ADCPs are lowered into water they are pulled by currents, the sea-bed location could be different from the sea surface location. This does not cause measurement uncertainty directly, but may affect the interpretation of the results and would be manifested as a spatial extrapolation uncertainty (see Category 3).

3.1.2.7 Vessel Mounted ADCPs

ADCPs may be vessel mounted to provide an initial assessment of spatial variation at a site, although they are unlikely to be used for the primary measurement of the resource. Vessel mounting can lead to additional uncertainties arising from temporal and spatial resolution and ambiguities between the boat and current speeds (Reference 14). This latter issue is generally mitigated through bottom-tracking (Reference 5, 15) although this can be adversely affected by large amounts of material, such as clay, sand or vegetation moving near the sea bed (Reference 6).

Reference 5 states that bottom tracking has a typical single-ping accuracy of a few mm/s.

A framework for estimating uncertainty of vessel mounted ADCPs has been produced (Reference 14) which illustrates that some of the vessel-mounted uncertainties may be evaluated using available information. Good practice guidelines for conducting vessel mounted studies are given in IEC standards for Tidal Energy Resource Assessment and Characterisation (Reference 1).

3.1.3 Short Term Site Data Synthesis (Category 1c)

There are various reasons why there may be short terms gaps in data including datapoints removed in quality control, device memory failure and transmission drop-outs.

Ultimately, it is good practice to only compare actual measurement results with model predictions as any gaps in data will automatically be manifested as greater uncertainty. However, if it is necessary to synthesis data then a sensitivity analysis should be conducted to quantify its uncertainty.

3.1.4 Data Quality and Metadata (Category 1d)

To provide a comprehensive assessment of the quality of survey data it is necessary to record or document certain information. This allows exploitation of the survey data by a variety of users with different requirements. Guidelines on the metadata which should be included as part of a measurement study are given in the IHO Standards for Hydrographic Surveys (Reference 16).

Any uncertainties arising from poor data quality and/or contradictory metadata would need to be handled on a case-by-case basis.

3.2 Temporal Variation (Category 2)

3.2.1 Historic Resource Estimation (Category 2a)

Long-term predictions of tidal currents for resource assessments are generally provided by models which are calibrated using a time series of current speed measurement data. Tidal currents are largely deterministic although they may be affected to a lesser or greater extent by stochastic meteorological events (waves, storm surge) and turbulence (References 17 and 18).

The uncertainties associated with fitting measurement data to models therefore comprise those associated with:

- The quality of the fitting of the harmonic constituents to measurement data;
- The duration of the measurements, and hence the number of constituents that can be fitted with confidence; and,
- Non-astronomical effects (e.g. meteorological events) which occurred during the measurement campaign and which are not (necessarily) representative of future events.

3.2.1.1 Fitting Harmonics to Measurement Data

The astronomical effects are predicted by harmonic analysis. The number of constituents that are included in the analysis depends on the length of time series of data available for fitting; the longer the time series the greater number of tidal constituents that can be included and hence the more accurate the resulting predictions (Reference 19). The draft IEC Technical Specification (Reference 1) provides guidance on modelling tidal constituents.

Models operate with a finite number of tidal constituents and the importance of the tidal constituents not included must be assessed. If these missing constituents have a significant impact on calculated current speed then a methodology to include their effect shall be developed, justified and reported. Typical methods include:

- Data assimilation of measured tidal height constituents and extrapolation to the model driving boundary;
- Examination of measured and modelled tidal constituents at the project site to identify the amplitude and phase of missing constituents. The “missing” constituents can then be added to the modelled constituent database at a specific location or, where justified, to all modelled current constituents in the project area.

In addition to conducting harmonic analysis a direct extrapolation of measurements informed by harmonic periodicities may be carried out and the results compared to those of the harmonic analysis. Whilst this method does carry some uncertainty, it may overcome some of the limits of harmonic predictions with respect to ebb/flow asymmetries and certain topographical/ bathymetric influences that are likely to be reproduced by harmonic constituents (Reference 17).

Additional relevant studies published in the literature on harmonic analysis reports that:

- Reasonable accuracy (standard error of 5%) is obtained from 30-day observations (Reference 17);
- Using more than one month’s data does not hugely increase the accuracy of the predictions (Reference 20).

3.2.1.2 Non-Deterministic Methods

Statistical methods (e.g. probability distribution function), similar to those used in the wind industry, can be used to predict the temporal variation in tidal resource instead of harmonic analysis. Here the probability distribution function is obtained from finite-duration measurements and is assumed to be representative of the long-term distribution (Reference 21). This method captures all components of the tidal currents (deterministic and non-deterministic) but cannot account for any longer-term variability than the length of the data set. Comparing the two methods, Reference 21 suggests that statistical methods might be more accurate than deterministic methods. Furthermore, this work highlights that uncertainty in tidal predictions could be reduced in the future by combining statistical methods developed in the wind industry with traditional deterministic methods. This would involve the use of long-term data sets at a variety of locations.

3.2.1.3 Non-Astronomical Effects during Measurement Period

There may have been non-astronomical effects during the measurement period which deviate the measured tidal currents from the harmonic oscillations. Guidance on how to mitigate this uncertainty is given in the IEC standard (Reference 1):

Analysis of in-situ data shall assess the potential impacts on overall flow characteristics by comparing observed and modelled system dynamics. If meteorological factors are found to significantly impact the flow dynamics (e.g. a 5% change in current velocity) across the area of interest between measured and simulated velocities then these phenomena shall be included in the numerical hydrodynamic simulations. This includes consideration of wind, atmospheric pressure, waves, turbulence, eddies, water density and sediment.

The influence of these factors should be excluded from a harmonic analysis. To allow for this, hydrodynamic models can be run with these terms included (for comparison with measurements) and without them. The harmonic analysis can then be conducted using the model data without meteorological forcing, or by using the difference between the two models used to modify the measurements.

3.2.2 Future Resource Variability (Category 2b)

The key uncertainties here are those associated with applying a given model to predict future tidal currents. It is assumed that the model has been validated and the astronomical constituents have been accurately captured.

In this category, there are three uncertainties:

- How a project with an as yet unfixed commissioning date may be affected by future (known) astronomical variations in tidal current;
- The impact of non-astronomical effects which may occur during the project. In particular this is the impact of meteorological effects, i.e. wave-current interaction on future tidal currents;

- Changes in water density during the project life-cycle.

3.2.2.1 Project lifespan vs Long-term Astronomical Variations

There are long-term astronomical variations in tidal currents which operate at time scales similar to, or greater than the likely duration of tidal energy projects. Consequently, the total energy realised from a project depends on the how the project falls within these astronomical variations. If the start date of a project is not fixed at the point where energy predictions need to be finalised for funding, this provides an uncertainty in the ultimate energy yield.

Astronomical effects on tidal currents are generally predicted by harmonic analysis which relates the periodic motions of the earth, moon and sun into a series of harmonic constituents. There are some dominant harmonics, the largest of which, at least for semi-diurnal tidal systems such as those around the UK (Reference 19), is the rotation of the earth with respect to the moon (M_2) which has a period of 12.42hrs. There are other constituents with periods ranging from a few hours up to a year, as well as some important longer term constituents at 8.85years and 18.6years. These two longer-term constituents can cause M_2 to vary by up to +/-3.7% over the 18.6 year period (References 19, 22, 23). (Note that this is a peak value, not a standard uncertainty). Consequently, the uncertainty associated with how a project 'falls' in the long-term astronomical variation will have a maximum variation of 3.7%, although for a project of any reasonable length (e.g.10-15 years) this is likely to be lower, and will be mitigated entirely if the project start date is known. The maximum uncertainty for a project of given duration can be determined by simple analysis. A sensitivity study can be performed to look at various feasible start dates and project durations and the uncertainty determined from the results.

The effect of temporal variations of tidal current on energy yield has been considered in Reference 22. In particular, this investigated the effect of the variability of M_2 on the available power at the Pentland Firth. For this location, the 3.7% variation in M_2 due to the longer-term constituents varies the available power (i.e. kinetic energy flux) by approximately 10%. The variation in energy yield is, however, lower because there is no sensitivity to flow speed above rated power.

3.2.2.2 Future Non-Astronomical Effects

Non-astronomical effects provide uncertainty in tidal energy yield prediction through:

- Changes to the flow speeds and hence the power produced by the turbines;
- Changes to the kinetic energy flux through the turbine for the same mean flow speed (due to wave orbital velocities); and,
- Increased loading on support structures and hence maintenance and downtime of devices.

Reference 24 describes some observations which show that in 12.5m water depth, the depth averaged speed of the principal semi-diurnal lunar constituent (M_2) decreased by 5% with each 1m increase in wave height. Whilst this is only an isolated study, it demonstrates that large wave heights have the potential to cause significant uncertainty in current conditions. Understanding this uncertainty will require knowledge of:

- The degree to which future wave climates can be predicted. This is dealt with in the Wave Energy literature review (Category 2a);
- The impact of waves on current, “wave-current interactions”. This is an area of current research (e.g. see Table 3, SuperGen project). Wave-current interactions have been investigated since the 1960’s, although until recently there has not been significant research on the specific effects of waves on tidal streams energy devices (Reference 25). More research is needed to understand the impact of realistic oceanographic conditions at renewable energy sites in both shallow and deep water conditions. This could involve combining a number of ADCPs to map currents over a fairly large area.

Relevant studies on wave-current interaction include the following:

- Reference 25 reports a study where a significant proportion of the wave climate (between 49% and 93% of the time) including extreme wave events, was found to be propagating in a direction which was oblique to the major axis of tidal flow. A common assumption within studies of wave loading upon tidal stream turbines is that wave propagation is aligned with the tidal flow – either following or opposing the current. This work highlights that wave angle should be considered in studies which examine the interaction of turbines with their environment;
- Reference 24 showed that the impact of waves on current is dependent on the depth of the site with shallower sites being particularly affected.

3.2.2.3 Density changes

A constant water density is often assumed in analysis. If significant temperature and/or salinity variation are expected, the impact of these can be quantified via standard relationships (Reference 26).

3.2.3 Climate Change (Category 2c)

There has been significant research on the effect of climate change on sea-level rises and the occurrences of storm surges as part of studies on coastal flood defences. For example, the UK Climate Impacts Programme 2009, UKCP09 predicts absolute sea-levels could rise by between 100 and 300mm by 2030 and that there is likely to be a significant increase in extreme high sea-levels suggesting increased storms (Reference 27). This could well have an effect on the energy yield of tidal devices through decreased availability, although it is anticipated that changes in wave climate will mainly affect wave energy converters (see wave energy literature review Category 2c). The impact of climate change on tidal currents appears less well understood, and there is no evidence at present to suggest that climate change will cause a significant change in the tidal resource.

3.3 Spatial Variation (Category 3)

3.3.1 Modelling Inputs (Category 3a)

For tidal energy projects involving a small number of turbines, the uncertainty associated with spatially extrapolating measurement data from fixed locations can be eliminated by installing ADCPs at all proposed tidal turbine locations. Clearly this is not appropriate for larger projects with many turbines and in this case it will be necessary to model spatial variations.

There are three main inputs for modelling tidal sites; bathymetry, bed roughness and boundary conditions.

3.3.1.1 Bathymetry

The available bathymetry, its density and quality determines the resolution to which a model can be constructed for the areas of interest and in the far field the ability of the model to generate over-tides from forcing conditions (Reference 28). The IEC Technical Specification on tidal energy resource assessment does not explicitly define specifications for bathymetry although this is covered in the equivalent specification for wave energy (Reference 29). Here, specifications for bathymetry data are given and from these standard uncertainties can be calculated. More details on this are given in the Wave Energy Literature Review (Category 3a).

3.3.1.2 Bed-Roughness

Bed-roughness provides friction to the flow and is one of the least well understood aspects of tidal modelling. There is considerable debate about the physicality of the values used (e.g. Reference 30) and in practice, rather than prescribing a known value, bed-roughness is generally used to tune the model results. Without designated research on this topic involving extensive site surveying, modelling and potentially experimental testing, there may be some debate on the use of bed roughness for some time. However, although an isolated study Reference 31 considers the modelling sensitivity to bed friction at the Pentland Firth and reports that the effect of variations in values used is, in fact not significant.

3.3.1.3 Boundary Conditions

The main boundary condition is typically the tidal elevation which is derived from global models, but the current velocity at the boundary (Reference 1) may also be included. The accuracy of the models depends on the proximity of the required location to available sites used to calibrate the model. Current best practice is to set the boundaries at a considerable distance from the area of interest (e.g. off the continental shelf) (Reference 28). This is corroborated by the following studies:

- Reference 28 compares the global tidal model DTU10 to a set of reference data points from the UK Hydrographic Office (UKHO) software TotalTide. Three stations were chosen for the comparison; (i) NW continental shelf, (ii) North Sea and (iii) the location of Kirkwall. The standard uncertainty (in deviation of DTU10 from UKHO) reduced with the distance offshore with values of 0.06m to 0.2m determined for locations (i) and (iii) respectively.

- Reference 32 reports that in the deep ocean, all tidal models agree within 2-3cm.

Overall, any uncertainty in the model inputs will be propagated through the model and will be present in the output parameters. However, there is scope for the potential cancellation of errors which hides uncertainty. For example, a strong forcing of boundary conditions may be balanced out by a high bed-roughness. This may provide realistic flow speeds but would fail to accurately capture blockage effects.

Where necessary sensitivity analysis may be used to quantify the impact of any input uncertainties.

3.3.2 Horizontal and Vertical Extrapolation (Category 3b)

This uncertainty is concerned with the use of a model to extrapolate resource information spatially and vertically from the measurement location.

Once the model has been set up with the appropriate inputs, it is firstly calibrated and then validated using measurement data. Good practice dictates that these should be different data sets although there appears to be no specific guidance on how much of the (often limited) data should be used for calibration and how much for validation.

Various types of model can be employed for characterising the spatial variation of the resource. In order of increasing complexity (and hence computational cost), the main types are:

- 2D depth-averaged models solving the shallow-water (Saint Venant) equations by finite volume or finite element methods;
- 3D models solving the shallow-water equations on a series of planes between the seabed and sea surface, again using finite volume or finite element methods; and,
- Full 3D CFD models, which solve the Reynolds-Averaged Navier Stokes (RANS) equations using a finite volume method, usually run with the sea surface elevation specified from a shallow water equation model.

The degree of complexity required to capture the behaviour of the flow at a particular site depends on the complexity of the flow through that site. 2D depth-averaged models are almost always used as a first step, and continue to be useful as they allow feedback effects such as blockage to be modelled (see Category 4b). However, they give no information on the vertical profile of the flow, so without further information, they entail substantial uncertainties in vertical extrapolation (see Section 3.3.2.2). The other models can be used to extract the flow velocity at hub height and/or the rotor-averaged velocity approaching the turbine, so with these, the uncertainty in shear profile does not need to be addressed separately. Even so, differences in shear profile between models and measurements can help to identify the root causes of modelling errors.

3.3.2.1 Spatial Variation

If no modelling is carried out to predict the spatial variation of the resource, the uncertainty is defined by how much the flow may be expected to change across the distance between the measurement location and the turbine position. Reference 21 addresses this question, and for a specific site, determines the spatial variation in energy predictions relative to a reference location and reports uncertainties for an ideal turbine of 10% at 50m (90th percentile level), 15% at 150m and 20% at 250m.

Ideally, one would like to have a comprehensive validation dataset for models to demonstrate how much this uncertainty can be reduced by using each type of model. Unfortunately no such study appears to exist at present. The general trends in flow models can be sense-checked using vessel-mounted ADCP data or X-band RADAR data (Reference 1) but these are rarely accurate enough to enable quantitative uncertainty analysis.

Reference 33 summarises the results of the validation of a 3D hydrodynamic model of the Falls of Warness using three ADPs as part of the ReDAPT project. Time-domain and spectral analysis were used and in both cases the model provided an excellent fit to the ADP data. The maximum absolute bias between the model and measurements was 0.13m/s (speed) and 8.1° (direction).

The PerAWaT project (Table 3) has developed a planning tool for tidal arrays; TidalFarmer, which aims to provide a methodology to predict the extractable power, including the uncertainty, from an array of tidal stream devices. It is not clear at present how this uncertainty will be calculated.

3.3.2.2 Shear Profile

Vertical extrapolation is required in two contexts: to interpolate between ADCP measurement locations if no one location is sufficiently close to hub height; and, to convert depth-averaged velocities from 2D depth-averaged models into hub-height velocities.

It is rare for ADCP measurements to be so coarse that they require significant interpolation. However, if this is required, a logarithmic or power law is typically used to provide a continuous velocity profile through the water column. Reference 34 reports that these profiles do not always accurately predict the flow; for example, where the maximum velocity is not at the water surface. It proposes using a hybrid mechanistic-empirical shear profile.

When calculating hub-height flow speeds from 2D depth-averaged velocities, it is necessary to assume a shear profile. Typically, the nearest ADCP location will be used to characterise the shear profile. However, shear profiles are known to vary significantly across relatively short distances, so this method entails significant uncertainty. In the absence of any other data, sensitivity studies can be performed to assess the impact of plausible shear profiles in energy yield. This allows the associated uncertainty to be estimated.

3.4 Plant Performance and Losses (Category 4)

3.4.1 Availability (Category 4a)

From a project developer's point of view, the risks associated with uncertainties in availability may be mitigated through performance guarantees between developers and device providers. However, the uncertainty is still significant for two reasons. Firstly, device developers are likely to warrant a lower availability than they believe they can achieve in practice, so even if this warranted availability is achieved, there is some uncertainty as to the availability level that will be reached. Secondly, device developers may be unwilling or unable to take on the entire liability for this risk for the early arrays (and financially unable to stand behind such a guarantee even if it is made), so it is questionable how practical it is for project developers to pass on this risk entirely.

The availability of tidal turbines is very difficult to quantify for two main reasons:

- There is uncertainty in the failure rates themselves because there is insufficient operational data from the turbines to quantify these directly. Reference 35 states that this may lead to substantial underestimates of the failure rate.
- There is random variability in the availability that would be obtained with known failure rates.

These issues should be addressed to an extent in the next few years as more devices are deployed, operational information is obtained, and there is a convergence to a few principal designs. However, it is likely that a significant aspect of availability is site-specific, as accessibility for planned and un-planned maintenance will vary between sites due to metocean and/or transportation limitations. In the meantime, failure rates of components and systems can be predicted for generic devices using industry standard data (e.g. the OREDA database, Reference 36). These can then be used to predict mean availability, and the variability of that availability, using methodologies from other industries (particularly the wind industry) such as Monte-Carlo analysis and sensitivity studies (Reference 37, 38, 39).

3.4.2 Resource Array Interactions (Category 4b)

This uncertainty category is intended to capture the various ways in which a tidal array influences the resource. There are two primary mechanisms that are thought to be most significant:

- Wake effects. This relates to the velocity deficit behind a tidal turbine. If another turbine is placed in this downstream region, it will experience a reduced inflow speed and therefore generate less power than it would in the free-stream.
- Blockage. This relates to the influence of the turbine's thrust causing the tidal flow to be re-directed from where it would otherwise have gone.

These effects are clearly closely linked. Moreover, there are effects which blur the boundary between the two. For example, the flow immediately outside the wake region just downstream of a turbine may be accelerated by the presence of the turbine, and some array layouts feature staggered grids to attempt to take advantage of this effect. Some would classify this as a local-scale blockage effect, whilst others would include it under wake effects.

Wake modelling is fairly well-developed in the wind industry, and this knowledge can inform wake losses in the tidal sector. Onshore, measurements of wake losses can be hard to disentangle from the influence of terrain, so some of the purest validation cases come from the offshore wind sector. A variety of tools and methods are used to predict wake losses in offshore wind. Semi-empirical models are still common, with the Ainslie model (Reference 40), sometimes referred to as the Eddy Viscosity model) and Jensen Park model (Reference 41) still widely used. Other models are more firmly rooted in the real flow physics: full CFD models (e.g. WindModeller, Reference 42) have shown promising results (Reference 43), but they are computationally expensive. Simplified CFD modelling approaches have also been used successfully, including parabolised Navier-Stokes solvers (which neglect any upstream influence of the turbines and hence greatly reduce computational cost, e.g. Reference 44) and at least one linearised CFD model, Fuga (Reference 45).

Until recently, there was a dearth of validation data for offshore wake effects. The best-known measured dataset, from Horns Rev, was so commonly used in developing and tuning models that it became problematic to use in validation. As a result, large uncertainties tended to be applied – typically 50% of the predicted wake loss. Recently, a number of validation studies have been performed, including by the Offshore Wind Accelerator programme (References 46 and 47) which demonstrate the predictive power of the models. On the basis of the results, the OWA has argued for a reduction in the typical wake loss uncertainty from 50% to 25% of the predicted wake loss, with potential for further reductions once further validation studies have been completed. This performance was achieved by models of all types, demonstrating that semi-empirical models can be set up in a way that gives reliable wake loss predictions for a range of wind farms, and that physics-based models capture those physics accurately enough to give good estimates of wake loss.

Of course, this increasing confidence in offshore wind wake models has come about through validation against production data from large wind farms. No tidal arrays exist yet, so equivalent validation is not possible here, and it would be dangerous to assume that the models will retain their predictive power. Indeed, there are reasons to believe that they may exhibit poorer performance for tidal flows than wind. Most significantly:

- Tidal flows are constrained by the free surface, whereas wind farms can draw down momentum from the geostrophic wind above the farm. This influences the flow around the device, accentuating the acceleration around the wake and fundamentally changing the mechanism that limits array efficiency for large farms. Large wind farms' array efficiencies are limited by the rate at which they can draw down this energy and momentum from the geostrophic wind (Reference 48, 49) whereas tidal arrays are expected to be limited by the driving head acting on the flow (e.g. Reference 50). This also has more local effects, influencing the actuator disk solution for an individual turbine and hence its power and thrust coefficients (Reference 51).

- Tidal flows tend to have one dominant direction in flood and one in ebb, whereas wind resource is more smoothly distributed over the full 360°. This is particularly significant because many wind wake effects models perform well when averaged over large direction sectors (e.g. 30°) but poorly over narrow sectors (e.g. 5°). See Reference 45 for more information on this effect. Tidal resource assessments will be much more susceptible to the uncertainty associated with narrow direction sectors.

In the absence of full-scale array data for validation, models tend to be validated against data from towing tanks and/or flumes (Reference 52, 53 and 54). Some good agreement between models and measurements has been noted (e.g. Reference 55 and 56). This is much better than nothing, but does have its limitations. Specifically, it is impossible to match all of the pertinent parameters between models and full-scale tests. These pertinent parameters include:

- Reynolds number, which quantifies the effect of viscosity in the flow relative to inertial effects and is know to be significant in wake recovery;
- Froude number, which quantifies the relationship between the tidal flow speed and the surface wave speed and hence affects the free-surface effects;
- Tip speed ratio, which governs the hydrodynamic performance of a rotor in isolation; and,
- The intensity, length- and time-scales and anisotropy of the turbulence in the inflow to the turbine, which are known to strongly affect wake recovery (Reference 57).

The effect of tip speed ratio is often eliminated by using a perforated disk rather than a rotor blade, and matching the porosity of that disk to the thrust coefficient of the real turbine. This has precedents in wind power (e.g. Reference 58). The effects of Reynolds number and inflow turbulence are much harder to account for experimentally. Also, the sensitivity to detailed characteristics of inflow turbulence is captured relatively poorly by most models: in semi-empirical models, these influences are parameterised in coarse ways; in CFD models, the turbulence is generally assumed to be isotropic and separated in scale from the bulk flow.

Larger-scale blockage effects are even harder to validate, and realistically, only long-term monitoring of the sites of the first large arrays will provide full validation of the methods used. However, some challenges can be foreseen in integrating this effect into hydrodynamic models.

The IEC specification states that if the array is extracting less than about 10MW or 2% of the theoretical resource, large-scale blockage effects are not significant. Many early arrays (or early phases of arrays which will eventually be larger) will fall into this category. However, this also means that early arrays will not provide any validation of the ability to model this effect.

Large-scale resource modelling is generally carried out using 2D depth-averaged models such as Mike21, Telemac and Delft3D. These can apply additional momentum sink terms in the equations to capture the effect of tidal turbines. However, there are challenges in specifying these momentum sink terms:

- Relating inflow speed to the flow speed at the turbine location (i.e. accounting for the induction factor) has been solved in the wind industry using look-up tables for axial induction factor, and similar methods have been applied in tidal (Reference 59);
- 2D depth-averaged models cannot accurately capture wake interactions between turbines. Using turbines' local inflow speeds and thrust curves will therefore give erroneous results in wake-affected regions;
- 2D depth-averaged models also lack sufficiently sophisticated turbulence modelling capabilities to adequately resolve wake dissipation;
- Turbines also influence the shear profile and turbulence level in the wake region, which alters the bed friction (Reference 60). This interaction is not well understood at present.

For these reasons, different types of models need to be combined to capture all of the relevant flow physics, for example Reference 61 and 62. The process of coupling 1D, 2D and/or 3D models is complex. The specific approach taken in any study would need to be reviewed to understand whether all of the relevant physical processes were being captured by an appropriate model, and whether this influence could be transmitted through the modelling chain so that feedback mechanisms were captured.

3.4.3 Marine Energy Converter Power Performance (Category 4c)

There are two main uncertainties here:

- Uncertainty within the results of full-scale performance testing (at EMEC or similar) which are used to define a rated power performance curve for the device;
- Additional uncertainty when the device is deployed at the project location. This is due to site specific effects such as current shear, waves and turbulence.

3.4.3.1 Performance Testing

The methodology for full-scale testing is given in the Power Performance Assessment IEC standards (Reference 63). This also provides a list of uncertainty parameters which should be included in the assessment as a minimum (e.g. electric power, current speed and data acquisition). The standard does not specify a methodology for quantifying the overall uncertainty on the measured power curve, but is included in the equivalent wind standard (IEC 61400-12, Reference 64). The approach specified in that standard is equally applicable in tidal energy.

3.4.3.2 Site Specific Power Performance Uncertainty

IEC standard (Reference 63) states that "*quantification of the uncertainty associated with applying a power curve from one location to another is difficult, and depending on the site and sea conditions may amount to several percent*". However, whilst it states that there is a potentially significant influence on the Tidal Energy Converter (TEC) power performance due to turbulence and wave, the standard has not been developed sufficiently to be able to capture these effects.

To begin to characterise the uncertainty, it is important to understand the conditions in which the device has been tested, as these will need to be compared to predictions of the conditions at the proposed project site.

The transferability of power curves from one site to another has been a hot topic in the wind industry for some time. The current committee draft of the next edition of the wind turbine power performance testing standard (Reference 64) provides a method of normalising the power curve to a reference turbulence intensity (defined in this case as a function of the wind speed). This approach is based on quantifying the kinetic energy flux through the rotor, and assuming that the turbine can capture a fixed proportion of that kinetic energy flux. This approach could be applied to characterise the effect of turbulence on a tidal turbine and, in principle, could also be extended to capture the effect of waves. In practice, however, the response of the turbine to this temporally and spatially varying flow depends on its dynamics and control strategy, so there is no guarantee that such approaches will work.

Turbine performance models such as TidalBladed allow predictions to be made of the sensitivity of turbine performance to turbulence and wave conditions. Such tools could be used as a starting point in assessing the associated uncertainty. This issue is being addressed by the PeraWatt project which is aimed at producing validated tools for predicting energy yields at tidal sites and ReDAPT which provides test data from a full-scale turbine.

3.4.4 Electrical Losses (Category 4d)

It is assumed that the uncertainty associated with electrical generation in the device has been quantified at the full-scale testing (Category 4c). Consequently, this category is concerned with the uncertainties in electrical losses at the project site, namely those associated with:

- Submarine cables between the devices and distribution point;
- Subsea hubs or underwater termination units which are used to integrate power from one or several devices; and,
- Measurement of the power produced.

These same uncertainties are considered in the offshore wind industry. The properties of the cables and other electrical components used can be specified accurately by suppliers.

In the case of power measurement uncertainty, a maximum value is prescribed for each of the components used to measure the power (e.g. current transformers, voltage transformers, power transformers and data acquisition system). The limits on the uncertainties of these components (which depend on their class) are prescribed by the IEC standards. For example, in the case of a current transformer the limit on uncertainty is +/-0.5% of the current at 100% load and +/-0.75% and +/-1.5% at 20% and 5% load respectively.

The other components have similar limits of uncertainty and when combined the total is approximately 1% or less. Consequently, the uncertainty in power measurement is likely to be low compared to other categories.

3.4.5 Performance Degradation (category 4e)

Performance degradation of tidal devices, like availability, will be quantified as more devices are deployed and there is more operational data. However, this is also an active area of research and should be considered as part of the Tidal Energy Converter (TEC) demonstrator.

Marine growth on blades has the potential to cause substantial performance degradation. The extent of marine growth depends on a number of different factors such as geographical location, season of the year, water chemistry, temperature, substratum type, sunlight, distance from the shore and turbulence. The effect of this added roughness on the hydrodynamic performance of the blades will depend on the aerofoil sections used, as some are much more susceptible to roughness than others (Reference 65). Reference 66 investigates the effect of blade roughness and biofouling on the performance of a marine current turbine. Blade roughness was found to reduce the power coefficient by almost 20%. This is consistent with experience of blade erosion on wind turbines.

Another potential concern is the biofouling of a heat exchanger, where there may be a supply of warm exit water. This has been noted as a problem in desalination plants although mitigation methods including intake chlorination appear to be effective (Reference 67).

3.4.6 Curtailment

This category deals with the uncertainty in the transferral of power from the device or array to the electricity network. Curtailment can arise from either local constraints made by the distribution or local transmission network, or system-wide constraints from the National Grid. System-wide constraints are difficult to predict as they are a result of balances between demand and supply at national level. Local scale curtailment can be predicted to some extent by comparing the generator output profile with the local electricity demand profile using statistical methods.

Curtailment uncertainty has been considered in the wind industry (Reference 68) and could be readily applied to marine energy. However, it is very much project-specific, as the project developer’s exposure to this risk depends on the terms of the Power Purchase Agreement (PPA) they have in place.

4 Literature Review – Wave Energy

Wave resource assessment is a complex, immature and rapidly-developing area. As such, the literature is developing at a rapid pace, and new studies are likely to be published which complement or supersede the review shown here in the near future.

However, attempts are being made to develop best practice in this area, most notably by the IEC. The IEC Draft Technical Specification 62600-101 (Reference 29), currently at Committee Draft stage, is likely to be very influential in determining how wave resource assessments and hence EPEs are performed in future. This document prescribes three levels of assessment:

- Class 1 – "Reconnaissance" – an initial assessment with high uncertainties, suitable for identifying potential sites only;
- Class 2 – "Feasibility" – a more detailed assessment with moderate uncertainties, suitable for assessing the feasibility of potential sites; and,
- Class 3 – "Design" – a higher level of detail again, with the intention of bringing uncertainties down to a level where investment decisions can be made.

It is assumed that if an uncertainty assessment is being carried out, it is on the basis of a Class 2 or (more likely) Class 3 resource assessment. It is therefore assumed that the recommendations made in the current draft of IEC DTS 62600-101 for Class 2 and 3 resource assessments will be followed. If a specific project requires a different approach to be taken to resource assessment, a different approach may also be required to assessing the energy yield uncertainty. This should be highlighted in the documentation accompanying this uncertainty assessment.

4.1 Site Measurement (Category 1)

4.1.1 Instrument Accuracy (Category 1a)

In-situ measurements for prospective wave energy sites are generally made using either wave buoys (most commonly the Waverider) or bottom mounted Acoustic Wave And Current profiler (AWAC). Satellite altimeters can also be used to obtain near-instantaneous average of waves over a large area by measuring the distortion in transmitted radio pulse when reflected back from wave crest/trough.

As with tidal measurements, the manufacturers of these devices provide specifications for their uncertainty:

- Waverider MkIII: 0.5% of measured wave height immediately after calibration, deteriorating to 1% of measured value after 3 years (Reference 69);
- Nortek AWAC: <1% of measured value (Reference 70);

- Satellite altimeters: +/-10% (Reference 71).

Regardless of the measurement method used, the calculation of wave statistics involves additional uncertainty. This arises from the fact that these complex parameters are being estimated from a finite number of measurements, and they constitute random scatter in the resulting estimates of significant wave height and period. This is discussed in more detail in Reference 72. For a typical Waverider configuration of 30 minutes averaging period at 1.28 Hz data acquisition, the algorithm used to calculate the significant wave height within the buoy, H_s, has an uncertainty of 4% (based on H_s = 4 x zeroth spectral moment).

Reference 73 makes a comparison of wave buoys, ADCP, satellite measurements and HF radar. This study recommends the use of wave buoys as the most accurate and well-proven, although notes they are susceptible to accidental and malicious accidental damage which will potentially affect data quality (Category 1c). In other work, wave radars have been reported to have equal accuracy to wave buoys (Reference 12).

4.1.2 Measurement Interference (Category 1b)

4.1.2.1 AWAC

AWACs can suffer from attenuation of surface signal which limits their useable depth to around 20m (Reference 74). Acoustic Surface Tracking (AST) developed by Nortek claims to allow AWAC to measure more accurately in deeper waters and that in a limited test case (32m depth) the AWAC performs with similar accuracy to a waverider buoy.

Generally bottom mounted AWAC are better suited than wave buoys for measuring at near-shore waves as they are more protected from breaking waves (Reference 74).

In rough conditions, spray or air bubbles in the water can cause problems with devices that measure waves from below the surface (Reference 75).

4.1.2.2 Wave Buoys

Wave buoy data uncertainty may increase due to sudden impacts (slamming), as internal accelerators are rated at a given limit (Reference 73). These appear as realistically shaped but unrealistically large waves in the displacement time series. Faults of this kind can be identified by testing for cross-correlation of the displacement signal with the filter pattern (Reference 75).

Moorings can affect the response of the buoy by restricting its range of motion. If the mooring does not have sufficient flexibility it is possible for the buoy to be dragged through or around wave crests. For a Datawell standard mooring, horizontal motion is adequately followed up to a period of 20s (Reference 76). Therefore if manufacturers' instructions are closely followed, uncertainties associated with mooring can be assumed to be minimal.

4.1.2.3 Satellite Altimeters

Altimeters are capable of making accurate measurements of wave height, but existing algorithms are not suitable for estimating WEC power, since they do not correctly reproduce the joint distribution of wave height and period. This has been the subject of recent research (Reference 75).

Rain has a significant effect on radar signals. However, because of the difficulties in obtaining rain-rate profiles from satellite data, no attempt is generally made to correct for rain attenuation on back scatter. Instead, rain-contaminated altimeter observations are generally flagged and excluded (Reference 75).

4.1.3 Short Term Site Data Synthesis (Category 1c)

This is considered to be similar to the uncertainty of tidal systems. See Section 3.1.3.

4.1.4 Data Quality and Metadata (Category 1d)

This is considered to be similar to the uncertainty of tidal systems. See Section 3.1.4.

4.2 Temporal Variation (Category 2)

4.2.1 Historic Resource Estimation (2a)

The current draft of IEC 62600-101 identifies two ways in which the historic long-term resource variability can be characterised:

- Long-term runs of a validated wave model; or,
- A Measure-Correlate-Predict (MCP) approach as used in the wind industry.

In either case, the “long-term” historical record will still be of finite length, so there will be some uncertainty arising from inter-annual variability. This can be captured using the same approaches discussed under Category 2b.

If long-term runs of a validated wave model are used to provide the long-term reference, the uncertainty of the model is characterised using the approaches outlined under Category 3. In that case, no additional uncertainties apply.

If an MCP approach is used, additional uncertainties apply to capture the quality of the correlation and the quality and consistency of the long-term reference.

Uncertainties associated with the consistency of the long-term reference data need to be addressed on a case-by-case basis. Indications of potential inconsistency could include changes in instrumentation or movement of the measurement equipment, lack of regular recalibration or construction of any structures near the reference measurement location.

Uncertainties associated with the MCP process itself are easier to characterise in a repeatable manner. MCP is commonly used in the wind industry, and a large number of different methodologies have been developed (e.g. References 77, 78 and 79). Some studies have compared the predictive power of these methods, including Reference 80 and Reference 81. The use of MCP in wave energy is relatively immature, although it has been undertaken and the current draft of IEC 62600-101 states that it is impossible to conclude at present which method is preferable in this application.

One standard approach for evaluating the uncertainty in MCP predictions is to assess the uncertainty in the parameters fitted in the correlation (Reference 77). However, as pointed out by Rogers, this can underestimate the true uncertainty in the result. The reason for this is that each time-series is itself serially correlated. So, the data tend to have clusters of points related to specific weather events. Rogers et al. demonstrate that assessing the uncertainty using the jack-knife method gives a more robust estimate of the true uncertainty. This approach has been used in some subsequent studies (e.g. Reference 82 and Reference 83).

4.2.2 Future Resource Variability (Category 2b)

The key uncertainty to be addressed here is the inter-annual variability of the resource during the period covered by the EPE. Even if the developer could perfectly characterise how the project would perform in an average year, the actual energy yield over the period of the EPE is uncertain. No amount of additional analysis or measurement could reduce this uncertainty – the weather far in the future is “un-knowable”. The only control that the developer has is over the period covered by the EPE – in the long-term, inter-annual variabilities tend to balance out towards the mean, so the associated uncertainty reduces.

The key challenge then is to quantify the inter-annual variability associated with wave energy. In the offshore wind sector, it has become standard practice to use an inter-annual variability characterised by a standard deviation of 6% of the mean (Ref 84, 85). Because there is assumed to be no correlation from year to year, the uncertainty applied in an EPE is generally 6% divided by the square root of the number of years covered by the EPE.

Inter-annual variability in waves has been addressed by a number of authors, most notably:

- Mackay *et al*., Reference 86 and Reference 75. These deal specifically with a location 150km north of Cape Wrath, but addresses the question from a fundamental level, and seeks to give generally-applicable guidance. This is also referenced in Annex C of the IEC TS.
- Neill *et al.*(Reference 87). This addresses the NW Europe Continental Shelf as a whole.
- Neill *et al.* 2014 (Reference 88). This addresses wave resource variability in the seas around Orkney.
- Van Nieuwkoop *et al.* (Reference 89). This shows and comments upon the inter-annual variability at the WaveHub site in Cornwall but does not analyse the inter-annual variability in any detail.
- Phillips *et al.* (Reference 90). This is an earlier study on the WaveHub wave resource, which quantifies inter-annual variability.

- Vidal *et al.* (Reference 91). This addresses a number of Spanish sites based on modelled data.
- Liberti *et al.* (Reference 92) This focuses on the wave resource in the Mediterranean sea, and maps the inter-annual variability of wave resource around the Italian coast.
- Woolf *et al.* (Reference 93). This characterises the open-sea conditions in the North Atlantic based on satellite observations.
- Reguero *et al.* (Reference 94). This evaluates the global wave resource using reanalysis data, assesses inter-annual variability and links that variability to global various climate indices.

A number of common themes emerge from these papers. In particular:

- The inter-annual variability of the wave resource is shown to be highly site-specific. Significant variations in inter-annual variability are noted between the west and east sides of Orkney (Reference 88), and around the Italian coastline in Reference 92. This means that it is not possible to prescribe a single value for inter-annual variability as is commonly undertaken for wind. The inter-annual variability also varies between seasons.
- The inter-annual variability is generally correlated to global climatic indices. In UK waters, the relevant index is the North Atlantic Oscillation, i.e. the pressure difference between the Icelandic Low and the Azores High. This correlation was first noted by Bacon and Carter in 1993 (Reference 95). Similar correlations have been noted between the Southern Annual Mode and the wave climates in Tuvalu (Reference 96) and north-eastern Australia (Reference 97). The NAO and other global climatic indices exhibit long-term trends, meaning that their values are correlated from year to year.

These factors are acknowledged in the IEC TS. The use of site-specific inter-annual variability data is discussed based on hindcast model data. It suggests that 10 years of hindcast data is sufficient to determine a stochastic inter-annual variability (which can be treated in a similar fashion to that in the wind industry). However, a much longer-term dataset is required to adequately characterise the effect of sensitivity to factors such as the NAO (which they term "climatic variability". They cite Mackay's claim that for a farm at the Cape Wrath location built in 1980 with a 20-year lifespan, the energy yield would have been 9% greater than would have been estimated based on the wave climate during the preceding 20 years. This clearly represents a large uncertainty which is challenging to characterise.

The NAO cannot be forecast accurately from one year to the next (Reference 98), so this variability cannot be characterised over the lifetime of the wave energy project.

Various NAO indices have been defined, which quantify its value in slightly different ways. Sources for some of these indices are reported in Reference 99 but Mackay et al. note that these indices actually correlate well, so the sensitivity of the results to the choice of index should be small. Some of these datasets contain estimates of NAO values back to the early 19th century (e.g. the data in Reference 100 based on Reference 101 and Reference 102). These datasets allow the long-term variability of the NAO to be assessed.

There is still some debate over the choice of statistical model to fit to the long-term behaviour of the NAO. Stephenson (Reference 103) tests various model forms, and finds that a FAR(1) model is the most appropriate. Stephenson, Barbosa (Reference 104) and Mackay have all fitted FAR(1) models and obtained similar results. Mackay's values have then been used to assess inter-annual variability in wave energy yield by synthesising long-term time-series based on this statistical model and extracting the inter-annual variability directly from the results.

There is conflicting evidence over whether the long-term behaviour of these indices is changing due to climate change. This is discussed under Category 2c.

4.2.3 Climate Change (Category 2c)

As discussed under Category 2a, there are long-term trends in global climate indices affecting wave climate (e.g. the NAO). These natural variations are captured by the literature referred to in that section. The question to be addressed in this section is: are any additional long-term trends in these indices being caused by anthropogenic climate change?

There has been some discussion of this question in the literature, both directly concerned with wave energy resource and wider oceanographic questions (see for example Reference 86). The most comprehensive and relevant treatments are given in Stephenson et al (Reference 103) and Mackay et al (Reference 86). Stephenson et al use the results from 18 global climate models run for an 80-year period to infer the influence on atmospheric CO_2 concentration on the NAO. This shows a weak sensitivity with substantial uncertainty, so a sensitivity of zero is still within the error bars of the results. From this work alone, one cannot demonstrate that climate change has an impact on wave climate. Mackay puts this result in the context of the inter-annual variability of the wave climate, and demonstrates that over a 20-year project life, any impact due to climate change would be much smaller than the natural variability of the wave climate. They therefore conclude that climate change does not need to be considered in wave resource assessments. Reference 105 comes to a similar conclusion using different source data.

4.3 Spatial Variation (Category 3)

4.3.1 Modelling Inputs

The key inputs to wave models are:

- Bathymetry data;
- Wave data at model boundaries;
- Meteorological data inside the model domain, i.e. wind speed, wind direction and air pressure;

- Tide height and/or tidal current data (if required);
- Water density.

Each of these inputs has an associated uncertainty.

4.3.1.1 Bathymetry

The draft IEC TS recommends use of Survey Order 2 data or better for water depths below 200m, and Survey Order 3 or better in deeper water, as defined in IHO S44 – Standards for Hydrographic Surveys (Reference 16). IHO S44 mandates reporting of the bathymetry uncertainty in the survey results. The maximum vertical depth uncertainty associated with Survey Order 2 is expressed as a 95% confidence interval (i.e. approximately 2 standard deviations) of:

$$\sqrt{(1m)^2 + (0.023 \cdot Depth)^2}$$

So in 50m water depth, this corresponds to a standard uncertainty of 0.78m. For long waves, the wave speed is proportional to the square root of water depth, so this would imply a standard uncertainty in wave speed of less than 0.77%. This uncertainty is small but potentially not negligible.

The EquiMar Wave Model Intercomparison (Reference 106) shows a comparison between two publicly-available bathymetry datasets: GEBCO_08 (Reference 107) and NOAA ETOPO1 (Reference 108). Differences of around 3m to 5m were noted for the specific intercomparison location on the west coast of Portugal. The impact of these differences on the predicted wave resource was not quantified, but a sensitivity study could be carried out for a short duration to quantify the potential impact.

4.3.1.2 Wave Data at Model Boundaries

Wave boundary conditions for resource models are generally derived from larger-scale reanalysis datasets such as those from the European Centre for Medium-Range Weather Forecasting (ECMWF). These datasets are known to have certain biases which can influence the results from the model. For example, Reference 109 and 110 note a general bias in the ECMWF data to over-estimate wave height with small wave heights, under-estimate wave height for large wave heights and under-estimate wave periods throughout.

Some parties have developed independent wave hindcast datasets to provide improved boundary conditions, most notably the ANEMOC and ANEMOC-2 datasets developed by EDF Energy and partners in France (Reference 111).

Any uncertainty and/or bias in the boundary condition data will manifest itself as uncertainty and/or bias in the predictions of the model. If these uncertainties are judged to be consistent over the period of the simulation, boundary condition uncertainties would not necessarily need to be accounted for separately – the overall uncertainties in the results produced would already capture the influence of uncertainties in the boundary conditions.

4.3.1.3 Meteorological Data

Several global reanalysis datasets and local hindcast datasets are available for use in resource assessments including the ERA-Interim (Reference 112), NCEP-NCAR (Reference 113) and NASA MERRA (Reference 114). These combine model predictions with assimilation of satellite data, ground observations, radiosonde data and/or other sources. Data are typically available from 1979 (when the first weather satellites were launched) to the present day. More local hindcast data are available from various governments and agencies, e.g. the UK Met Office (Reference 115).

Validation studies have been carried out on these global datasets (e.g. Reference 116) and local hindcasts (e.g. Reference 117). The results vary, but predictive power is generally good. This validation is often performed with a view to wind resource assessment. Because the wind kinetic energy flux scales with wind speed cubed, accurate wind speed estimates are very important. In the context of local wave modelling, the sensitivity to the wind speed is much smaller.

4.3.1.4 Tide Height and/or Current Data

The draft IEC TS 62600-101 includes an annex specifying how to assess whether tide height and/or current variations are significant in quantifying the wave resource for a particular site. If these factors do need to be considered, the uncertainty in them can be quantified using the method discussed for tidal energy (Section 4.3.1). The uncertainty implied in the wave resource can them be determined via a sensitivity study.

4.3.1.5 Water Density

See Section 3.2.2.3.

4.3.2 Horizontal and vertical extrapolation (Category 3b)

Vertical extrapolation is irrelevant to wave energy. The focus here is propagation of waves from model boundary conditions to WEC locations.

Third-generation models such as SWAN (Reference 118) capture all of the physical effects relevant to this propagation, including:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth;
- Wave generation by wind;
- Three- and four-wave interactions;
- Whitecapping, bottom friction and depth-induced breaking;
- Dissipation due to aquatic vegetation, turbulent flow and viscous fluid mud;
- Wave-induced set-up;

- Propagation from laboratory up to global scales;
- Transmission through and reflection (specular and diffuse) against obstacles;
- Diffraction.

The use of such third-generation models is recommended in the draft IEC specification.

Several validation studies have been performed comparing the results of wave propagation models with buoy data. These include:

- The EquiMar Wave Model Intercomparison (Reference 106);
- Studies at WaveHub in Cornwall (Reference 89).

4.4 Plant Performance and Losses (Category 4)

4.4.1 Availability (Category 4a)

This is considered to be similar to tidal energy uncertainty (see Section 3.4.1).

4.4.2 Resource Array Interactions (Category 4b)

Much of the early research on wave power in the 1970s and 1980s focussed on interactions between wave energy devices (References 119, 120, 121). Any device which captures wave energy must also generate radiated waves, and these early studies highlighted that in monochromatic seas, the interference between these radiated waves and the incident wave field could have a significant effect on energy capture.

Early studies used analytical solutions to the potential flow equations and approximated each wave energy device as a point absorber. More recent work has built on this foundation using finite buoy sizes, solving numerically rather than analytically, and has achieved similar results (Reference 122).

Many of these studies also used monochromatic sea states, which is part of the reason that large interaction effects were noted. These interaction effects are strongly dependent on the ratio of the device spacing to the wavelength. In realistic polychromatic sea states, some of this sensitivity tends to cancel out across the spectrum so the impact of interactions is reduced.

These wave interaction models have been used to optimise array layouts. In one such study (Reference 123), variations in power production of +4.6% to -28.7% relative to the baseline “no interaction” case were predicted based on the layout of an array of 10 point absorbers, even under polychromatic sea conditions. On the basis of this evidence, the sensitivity of energy yield to interaction effects and layout could be significant.

There appears to be little explicit analysis of the uncertainty in wave interaction modelling in the literature, and given that there are no commercial-scale wave farms, no full-scale validation data is available. There are, however, various papers reporting interaction effects from wave tank experiments (Reference 124 being arguably the most comprehensive) and validation of numerical models against these tank test results (e.g. Reference 125, 126, 127, 128, 129). Although a statistical analysis of the results from various studies does not appear to be available, the level of agreement between models and measurements is generally good. This gives confidence that the uncertainty arising from wave interactions will be substantially lower than the range of interaction effects quoted above.

Most wave energy devices are known to scale fairly well as long as viscous effects are small, waves do not break and Froude number scaling is employed, although there are some additional complications with oscillating water columns (Reference 130). It is therefore expected that tank test results should be reasonably representative of full-scale behaviour.

4.4.3 Marine Energy Converter Power Performance (Category 4c)

As with tidal energy, the two key uncertainties are those associated with:

- The results of full-scale performance testing (at EMEC or similar) which are used to define the power performance matrix for the device;
- The deployment of the devices at the project location, which has different site specific characteristics from the performance testing location (e.g. tidal currents, shear and turbulence).

4.4.3.1 Performance Testing

The methodology for full-scale testing is given in the Power Performance Assessment IEC standards. This also provides a list of uncertainty parameters which should be included in the assessment as a minimum (e.g. significant wave height, energy period, wave power density and electrical power).

This standard defines the capture length of the WEC as a function of the significant wave height and energy period (the power matrix). This capture length varies more smoothly with wave parameters than power output so reduces the sensitivity to bias within each bin. The standard specifies that the standard deviation of measurements within each bin should be recorded, and this enables the uncertainty in the power matrix to be quantified.

4.4.3.2 Site Specific Power Performance Uncertainty

There is evidence of WEC power performance being sensitive to spectral shape, directionality and wind direction. None of these factors is included in the power matrix as specified in the IEC standard. These imply that power matrices will differ between sites.

There is no general guidance on how these effects should be accounted for. If sufficient data have been collected from the power performance test, these sensitivities can be identified from the data. However, it is unlikely that this data will be available. In this case, the sensitivities would need to be predicted from an appropriately-validated model, and the uncertainties on these sensitivities assessed based on the model validation.

4.4.4 Electrical Losses (Category 4d)

This is considered to be similar to tidal energy uncertainty (see Section 3.4.4).

4.4.5 Performance Degradation (category 4e)

There are a number of degradation mechanisms which can affect any mechanical system over time, for example those arising from component wear and/or material corrosion. Specifically of interest in wave devices is the potential impact of marine growth. This is mentioned in the equivalent section on tidal energy; however, most tidal turbines rely on fast-moving lifting surfaces whereas most wave energy devices use slow-moving bluff bodies. The speed of movement of tidal turbine blades inhibits marine growth but these lifting surfaces are more susceptible to any growth that does occur. For wave devices, the effect is more similar to that on other marine structures, where marine growth affects the added mass and drag coefficients of members.

Guidance on how to account for this is given in the DNV Recommended Practice on environmental conditions and loads (Reference 131). It specifies modifying the effective diameter of components to account for this growth, and references the ISO standard on offshore structures for the petroleum industry (Reference 132) and a separate petroleum industry standard (Reference 133) for guidance on how to quantify this thickness. It also specifies a typical density and roughness for marine growth. The impact of these changes could be assessed using wave device performance modelling.

4.4.6 Curtailment

This is considered to be similar to tidal energy uncertainty (see Section 4.4.6).

5 Research Project Landscape Map- Tidal and Wave

Table 3: Research Project Landscape Map

Name of Programme	Research Institution Details	Uncertainty Categories covered	Aims and Work Packages	Opportunities to extend or build upon the work	Published Results
SuperGen Phase I & II Whilst this programme is complete it is mentioned here as it includes many of the key uncertainty categories	Phase(I) Oct 2003-Sept 2007 Universities: Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde Funding: ESPRC Phase (II) Oct 2007-Sept 2011 Universities: Edinburgh, Heriot-Watt, Lancaster, Queen's University Belfast and Strathclyde. Funding: ESPRC	Wave and tidal: 1b 2a 2b 2c 3a 3b 4a 4b 4c 4e	Phase (I) - Increase knowledge and understanding of the extraction of energy from the sea; - Reduce risk and uncertainty for stakeholders; - Enable progression of marine technology and energy into true positions in future energy portfolios. Applicable work packages included: - Appraisal of energy resource and interaction between converters and fluid environment - Methodologies for device evaluation - Full-scale field validation - Testing procedures for tidal current devices Phase (II) Phase II has more emphasis on increasing knowledge and understanding of device-sea interactions of energy converters from model-scale in the laboratory to full size in the open sea. Applicable work packages include: - Combined wave and tidal effects - Arrays, wakes and near field effects - Reliability - Power take-off - Moorings and positioning	During the running of Phase I some developers have moved from concept to prototype development and this has been reflected in the objectives of Phase II.	Significant number of published work – all listed on SuperGen website.
UKCMER (Phase III of SuperGen)	Oct 2011-Sept 2016 Universities: Edinburgh, Strathclyde, Queen's	Wave and tidal: 2a 2b 2c 3a 3b 4a	Key projects: - Effect of tidal flows on performance and structural integrity of tidal stream turbines; - Marine device extreme loading and structural integrity - Designing for Survivability;	This programme is ongoing. Opportunities to extend the work will be identified in due course.	See SuperGen above.

Name of Programme	Research Institution Details	Uncertainty Categories covered	Aims and Work Packages	Opportunities to extend or build upon the work	Published Results
	University Belfast, Exeter plus various other associate Universities. Funding: ESPRC	4b 4c 4e	- Increasing the life of marine turbines - Flow interactions between turbines and sediment; - Large scale interactive coupled modelling of environmental impacts of marine renewable farms; - Assessment of wave and tidal resource and the effects of energy extraction on it, and physical and ecological consequences of wave and tidal energy extraction (Terawatt). - Prediction of extreme loading on marine renewable devices (SMARTY)		
Equimar Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact May 2008-Apr 2011 (complete) Although complete, this is included here as it provided a basis for marine standards development.	Universities: Edinburgh, Strathclyde, Exeter, Manchester, Southampton, other European Universities France, Scandinavia, EMEC Funding: European	Wave and Tidal: 1a 1b 2a 2b 3a 3b 4a 4b 4c	Produced a suite of protocols for the evaluation of marine energy converters. Harmonised testing and evaluation procedures across a wide variety of devices. Assessed devices using the protocols and covered: site selection, device engineering design, the scaling up of designs, the deployment of arrays of devices, environmental impact and economic issues. Importantly, the protocols established a sound base for the development of IEC marine energy standards.	N/A	Significant information in public domain
PerAWaT	DNV GL (lead), E.On, EDF Universities: Queen's University Belfast, Edinburgh, Manchester, Oxford	Wave and tidal: 2b 3a 3b	Producing validated tools capable of significantly reducing the level of uncertainty associated with predicting the energy yield of major wave and tidal arrays. The project aimed to provide an assessment of the likely energy yield from large scale wave and tidal arrays, with known levels of uncertainty. This is designed to reduce the commercial risk faced by developers, utilities and	Potential extension would be comparison with data from ReDAPT for full-scale validation of a single device. Verification with a full-scale array.	Awaiting release of information from ETI.

Name of Programme	Research Institution Details	Uncertainty Categories covered	Aims and Work Packages	Opportunities to extend or build upon the work	Published Results
	Funding: Energy Technologies Institute (ETI) Completion: 2015		investors. Comprehensive modelling plan at a range of scales which should provide a robust tool.		
ReDAPT	Alstom, E.On, EDF, DNV GL, EMEC Universtites: Edinburgh and Plymouth Marine Laboratory, Funding: Energy Technologies Institute, £12.6M	Tidal only: 1b 2a 3a 3b 4b 4c 4e	Demonstration of the performance of a tidal generator in different operational conditions. Aims to increase public and industry confidence in tidal turbine technologies by providing a wide range of environmental impact and performance information. - Validation of power performance models - Validation of hydrodynamic models - Install 1MW tidal generator at EMEC demonstrating buoyant turbine design - Collection of comprehensive machine and marine environment data Timeframe: Due to complete 2015	- Could be compared with data from PerAWaT for full-scale validation	Published reports and papers expected early 2015.
Tidal Array model Real-World Evaluation Project (TAM)	Nova Innovation Ltd, combined with a wide range of project modellers	Tidal only: 2b 3a 3b 4b	- Validation of resource models to predict the flow rates at a tidal energy site, based on local geographic and atmospheric conditions. - Validation of the device models concerned with the interaction of flow with a stand-alone tidal turbine - Assessment of the performance of device models within Nova's tidal array.	Opportunities will be identified as the project is developed.	Recently announced so no information in public domain yet.
Tidal Energy Converter (TEC) Demonstrator	Atlantis Resource Corporation, Black & Veatch, Lockheed Martin. Funding: Energy Technologies Institute, £3.2M	Tidal only: 4a 4d 4e	Identify, develop and prove the best routes and supply-chain options to commercially viable tidal stream technologies when deployed at array scale. Two 1.5MW turbines will be installed on the structure at the Atlantis owned MeyGen tidal stream array in Pentland Firth, Scotland.	Opportunities will be identified as the project is developed.	No information in public domain yet.

Name of Programme	**Research Institution Details**	**Uncertainty Categories covered**	**Aims and Work Packages**	**Opportunities to extend or build upon the work**	**Published Results**
Marine Renewables Infrastructure network (MARINET)	31 Partner organisations including NAREC, EMEC, Universities: Exeter, Strathclyde, Edinburgh, Queen's University Belfast and various Universities in France, Germany and Scandinavia Funding: European 2011 - 2015	Wave and tidal: 4c	Network of research centres and organisations that are working together to accelerate the development and commercial deployment of these technologies. The initiative aims to streamline and facilitate testing by offering periods of free-of-charge access to world-class test facilities and by developing joint approaches to testing standards, research and industry networking and training. Aims to standardise testing methodologies and practices including data analysis, instrumentation, and scalability of prototype modelling.	N/A	N/A
IEC TC114 US Technical Advisory Group 2007 onwards	Various industrial partners		Mission is to prepare international standards for marine energy conversions.	N/A	N/A
Virtual Wave Structure Interaction (WSI) Simulation Environment	Universities: Manchester Metropolitan, Plymouth	Wave: 3a 4a	Aims to develop models to predict hydrodynamic impact on rigid and elastic structures. This is linked to, and part of an integrated programme of numerical modelling and physical experiments at large scale. Plans to develop numerical code to simulate laboratory experiments.	N/A	N/A
Time (Turbulence in Marine Environments) (Project under consideration)	Partrac ABPmer Ocean Array Systems IT Power Managed by The Carbon Trust	Tidal: 1a 4b 4c	Measurement and evaluation of turbulent effects in tidal arrays in Scottish Waters. Aims to present a framework on resource assessment, device design/operation and array yield.	Opportunities will be identified as the project is developed.	N/A

Name of Programme	Research Institution Details	Uncertainty Categories covered	Aims and Work Packages	Opportunities to extend or build upon the work	Published Results
Integrated Marine Energy Measurement Platform	EMEC	Tidal (mainly) but may also be useful for wave 1a	Design of a seabed monitoring system for taking measurements using active sonar, acoustic Doppler profilers, temperature, conductivity. This is designed to create an all-in-one solution for data collection and management requirements in first arrays.	Opportunities will be identified as the project is developed.	N/A

6 Conclusions

This report has provided a review of the available literature on energy yield prediction uncertainty based on the taxonomy document produced by the MFA. The taxonomy document identifies four main categories and a number of sub-categories. The available literature pertinent to each sub-category has been identified from a number of sources including academic and industry publications, conference proceedings and other sources identified through the stakeholder engagement.

The key conclusions of this report are as follows:

- Measurement uncertainties inherent to the instruments themselves are reasonably small and well-understood in both wave and tidal. There are various ways in which these uncertainties can grow when deployed in non-ideal conditions, and the magnitudes of these increased uncertainties are not always quantifiable. However, there is sufficient understanding of best practice in using the instruments that these increased uncertainties should be avoidable.

- Temporal extrapolation procedures are fundamentally different in wave and tidal projects: tidal flows are largely deterministic (driven by the positions of the sun and moon relative to the earth) whereas waves are stochastic (driven by the weather). Procedures for performing temporal extrapolation are well-developed in tidal and fairly well-developed in wave. In tidal, the key challenges are dealing with sites with substantially asymmetric flow regimes and in addressing wave-current interaction; both in processing measured data from ADCP deployments and in predicting the future resource. In wave, it is tempting to apply methods from the wind industry directly, but there is evidence that this could lead to significant errors because of the influence of long-term trends in features such as the North Atlantic Oscillation. Approaches for overcoming these issues to quantify bias and uncertainty have been proposed in the literature. The effect of anthropogenic climate change has also been addressed in the literature, and is expected to be small compared to the "natural" inter-annual variability through the lifetime of projects being conceived now.

- Spatial extrapolation procedures are also well-developed for wave and tidal projects. In general, uncertainties in these modelling techniques need to be assessed via validation against in-situ measurements, although there are a growing number of such validation studies published in the literature so a suitable meta-study might be able to extract some more generally-applicable values.

- Plant performance uncertainties include a number of sub-categories which need to be addressed separately, most notably:

- Power performance. Guidance on assessing the uncertainties in power performance tests is available from the wind industry and is considered to be applicable here.
- Device availability. For the earliest arrays, this will be a substantial source of uncertainty which is hard to quantify until there is more operational information and convergence to a few key designs. In many cases, project developers will push this risk onto device developers via the turbine supply contracts. Monte-Carlo methods exist to predict the variability of availability given a certain set of failure rates, vessel capabilities and metocean conditions. The failure rates themselves are harder to quantify without significant operational experience, although data from other industries (e.g. the OREDA database), combined with analysis and judgement on the effect of the way components are being used, can provide indicative values.
- Device interactions. Wake and blockage effects are unlikely to be a concern for early tidal arrays comprising only a few devices, although this is a potentially important for future larger sites. A range of models exist for wake and blockage effects (in tidal) and wave interactions (between wave energy convertors). A number of validation studies exist demonstrating the predictive power of these tools on scaled tests in wave tanks, towing tanks and flumes. Full-scale validation is, however, generally lacking and there are a number of reasons to believe that the physics of full scale wake interactions in tidal projects might differ from what is seen on small scales. This therefore constitutes a significant uncertainty. Sensitivity studies, rather than existing knowledge, appear to be the best way of quantifying the potential impact of these uncertainties at present.

A comprehensive list of references is included to substantiate the conclusions of the literature review.

This literature review and research landscape map will be combined with the results of the stakeholder engagement and used as the basis of a reference document for the MFA. This will involve a number of uncertainty assessments of example projects, using a new uncertainty calculation tool also developed as part of the project. In addition, the results of the literature review and research landscape map will be used to inform a gap analysis to highlight potential areas which could be explored to improve methods for quantifying and reducing uncertainties.

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