IEC TS 62600-101

Edition 2.0 2024-12

TECHNICAL SPECIFICATION

colour inside

Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization

IEC TS 62600-101:2024-12(en)

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CONTENTS

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

Part 101: Wave energy resource assessment and characterization

FOREWORD

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IEC TS 62600-101 has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters. It is a Technical Specification.

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

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

a) Incorporation of annual energy production (AEP), formerly detailed in IEC TS 62600-102, as Annex A in this document and in IEC TS 62600-100.
b) Modification to the list of terms and abbreviations

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

Draft	Report on voting
114/539/DTS	114/555/RVDTS

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

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

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

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

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

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This document provides a uniform methodology that will ensure consistency, accuracy and reproducibility in the estimation, measurement, and analysis of the wave energy resource at sites that could be suitable for the installation of Wave Energy Converters (WECs), together with defining a standardised methodology with which this resource can be described. This document, when used in conjunction with other Technical Specifications in this series (IEC TS 62600), is intended for several types of users, including but not limited to the following:

- Project developers and investors to accurately and fairly estimate resource availability and mean annual energy production at a potential project site for income or return on investment calculations.
- Device developers striving to accurately estimate and report potential device performance, or recommend a particular device design to a project developer, given specific site conditions.
- Utilities and owners or operators in calculating reliability and predictability of power supply, as well as return on investment.
- Policy-makers, planners, and regulators who are concerned with accurately planning usage of seascape among stakeholders, optimisation of resources, and power supply issues.
- Consultants involved in producing resource data and conducting due diligence studies, who require a standard, compatible, and readable data format.

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

The wave energy resource is primarily defined using hydrodynamic models that are successfully validated against measured data. This document deals directly with the theoretical resource and the main focus of the defined methodology is to generate the resource information required to estimate annual energy production. The capture width of a WEC is estimated using the methodology presented in IEC TS 62600-100. Then, using the capture width information, in conjunction with the resource information generated with the methodology described in this document, the methodology in Annex A is used to calculate annual energy production. A framework for estimating the uncertainty of the wave energy resource estimates is also provided in Annex B.

The development of the wave power industry is at an early stage and the significance of particular wave energy resource characteristics is poorly understood. Because of this, the present document is designated as a Technical Specification and will be subject to change as more data is collected and experience with wave energy conversion develops.

An essential element for any published Technical Specification or International Standard is to allow an opportunity to provide feedback on its contents to the appropriate TC 114 Working Group. TC 114 utilizes a standard methodology to allow this. To submit feedback such as proposed changes, corrections and/or improvements to this document, please send an email to the TC 114 Chair using the Contact TC 114 Officers feature on the IEC TC 114 Dashboard, accessible at www.iec.ch/tc114. On the right side of the Dashboard under Further information select the link to contact the TC 114 Officers. On the subsequent page find and select the Send Email link for the Chair to access the email tool.

Complete all the required elements within the email pop-up. For the Subject field please include the document title and edition you are providing feedback for (ex: Feedback for TS 62600-1 ED2). In the Message field, include text which summarizes your feedback and note if further information can be made available (note attachments are not allowed). The Chair may request added information as needed before forwarding the submission to the remaining TC 114 Officers for review and then to the appropriate Working Group for their consideration.

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

Part 101: Wave energy resource assessment and characterization

1 Scope

This part of IEC 62600 establishes a system for estimating, analysing and reporting the wave energy resource at sites potentially suitable for the installation of Wave Energy Converters (WECs). This document is to be applied at all stages of site assessment, from initial investigations to detailed project design. This document is to be applied in conjunction with the IEC Technical Specification on WEC performance (IEC TS 62600-100) to estimate the mean annual energy production of a WEC or WEC array as described in the methodology in Annex A. This document is not intended for estimation of extreme wave conditions.

The wave energy resource is primarily defined using hydrodynamic models that are successfully validated against measurements. The framework and methodologies prescribed in this document are intended to ensure that only adequate models are used, and that they are applied in an appropriate manner to ensure confidence and consistency in the reported results. Moreover, the document prescribes methods for analysing metocean data (including the data generated by modelling) in order to properly quantify and characterize the temporal and spatial attributes of the wave energy resource, and for reporting the results of a resource assessment in a comprehensive and consistent manner.

2 Normative references

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

IEC TS 62600-100:—, *Marine energy – Wave, tidal and other water current converters – Part 100: Electricity producing wave energy converters – Power performance assessment*[1]

IEC/ISO Guide 98-3:2008, *Guide to the expression of uncertainty of measurement*

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

3 Terms and definitions

No terms and definitions are listed in this document.

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

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

1 Under preparation. Stage at the time of publication: IEC/DTS 62600-100:2024.

4 Symbols and abbreviated terms

For the purposes of this document, the following symbols and units apply.

The results of the resource assessment shall be presented in accordance with the SI system of units. Results can also be presented in terms of an alternative system of units if desired.

Symbol	Definition	Units
$c_{g,i}$	group velocity of the i^{th} discrete frequency	[m/s]
C_W	capture width	[m]
$C_{W,i}$	discrete capture width	[m]
d	directionality coefficient	
f_i	i^{th} discrete frequency	[Hz]
f_p	peak frequency	[Hz]
g	acceleration due to gravity	[m/s^2]
h	water depth	[m]
H_{m0}	spectrally estimated significant wave height	[m]
J	omni-directional wave power	[W/m]
J_θ	wave power resolved along the direction θ	[W/m]
$J_{\theta Jmax}$	maximum directionally resolved wave power	[W/m]
k_i	wave number associated with the i^{th} discrete frequency	[m^{-1}]
m_n	spectral moment of n^{th} order	[m^{2}s^{-n}]
n	number of sea states	-
$MV(p)$	monthly variability statistic of parameter, p	
s	directional spreading parameter	
S_i	variance density over the i^{th} discrete frequency	[m^2/Hz]
S_{ij}	variance density over the i^{th} discrete frequency and j^{th} discrete direction	[m^2/Hz/rad]
T_{02}	spectrally estimated average zero-crossing wave period.	[s]
T_e	spectrally defined energy period (also written as T_{-10})	[s]
T_p	peak wave period	[s]
T_z	average zero-crossing wave period	[s]
δ	factor insuring that only positive components are summed	
Δf_i	frequency width of the variance density of the i^{th} discrete frequency	[Hz]

Symbol	Definition	Units
$\Delta\theta_j$	angular width of the variance density of the j^{th} discrete direction	[rad]
$\grave{o}_0$	spectral width	
ρ	reference sea water density	[kg/m^3]
θ	direction of wave propagation	[deg]
$\theta_{J\max}$	direction of maximum directionally resolved wave power	[deg]
φ	geographical latitude	[rad]

5 Classes of resource assessment

5.1 General

This document is intended to be applied across a range of resource assessment study types, from reconnaissance studies spanning a large region to detailed design studies focused on a specific site. The procedure to be followed when undertaking an assessment of the wave energy resource depends on the stage of the study and the study objectives.

Three distinct classes of resource assessments are indicated in Table 1. A Reconnaissance (Class 1) resource assessment is most suitable for application over large areas of seascape and would typically be the first resource assessment conducted in an area. A Feasibility (Class 2) resource assessment is most suitable for refinement of a Reconnaissance resource assessment prior to undertaking a design resource assessment. A design (Class 3) resource assessment is most suitable for application over small areas of seascape and is typically the final and most detailed assessment conducted for a particular project.

The user shall declare the class of resource assessment being undertaken and shall follow the appropriate procedures prescribed herein.

Table 1 – Classes of resource assessment

Class	Description	Uncertainty of wave energy resource parameter estimation	Typical long-shore extent
Class 1	Reconnaissance	High	Greater than 300 km
Class 2	Feasibility	Medium	20 km to 500 km
Class 3	Design	Low	Less than 25 km

NOTE Information on typical extent is provided for guidance only. The class of resource assessment depends on the degree of certainty required, not on the extent or size of the study area.

The results and outputs from previous resource assessment studies can be considered for use as boundary conditions in more detailed studies. As the project progresses through a number of development stages, the wave energy propagation model and its application should be refined such that the uncertainty of the resource estimation decreases. The following factors can reduce uncertainty:

- use of more capable models that include more accurate representation of the physical processes, as outlined in Table 5 in 7.2;
- finer discretization in frequency, direction, space and time;

- use of more realistic boundary conditions and system forcing (winds, currents, etc.);
- availability of additional measurements for model validation; and
- modelling longer durations.

5.2 Resource assessment and characterization flow chart

The flowchart in Figure 1 depicts the general methodology outlined in this document. Different procedures are to be followed depending on the class of the resource assessment. For Class 1 studies, the resource assessment can be based either on:

a) analysis of existing archived sea state parameters, provided they were generated using a methodology consistent with the requirements for Class 1 studies set forth herein, or

b) analysis of directional spectra generated through the application of a numerical wave propagation model in a manner consistent with the requirements for Class 1 studies set forth herein, or

c) application of Measure-Correlate-Predict (MCP) methods as specified in Clause 8.

For Class 2 and Class 3 studies, the assessment shall be based on either:

d) analysis of directional wave spectra generated through the application of a numerical wave propagation model in a manner consistent with the requirements for Class 2 or Class 3 studies set forth herein, or

e) application of MCP methods as specified in Clause 8.

Regardless of assessment class, the numerical model used to generate the directional wave spectra spanning space and time shall be appropriate for the task, configured in an appropriate manner, and successfully validated against measured oceanographic data. The boundary conditions and source terms (i.e. wind, wave or tidal fields) used to force the numerical model shall also be suitable and verified.

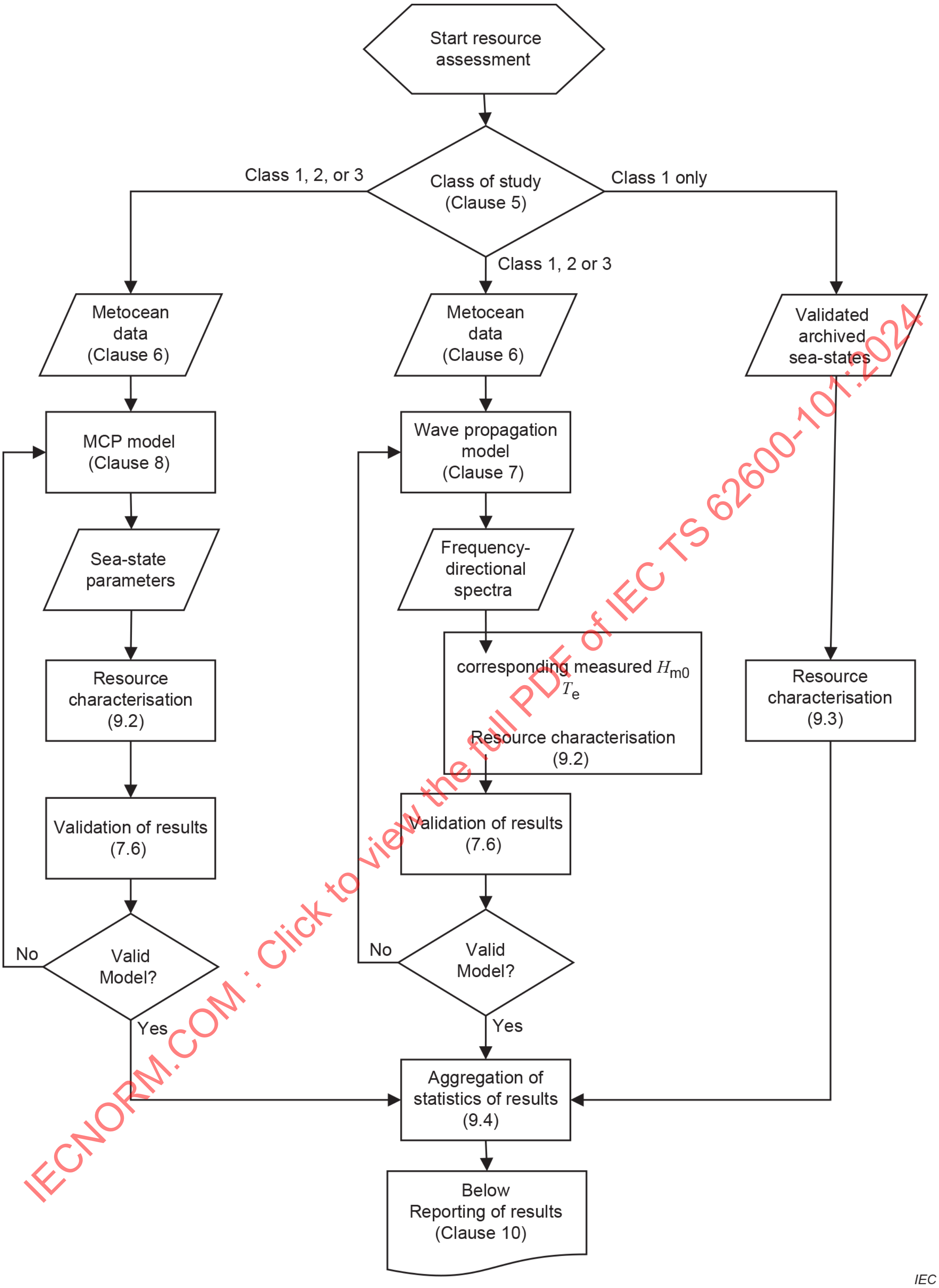

Figure 1 – Wave resource assessment and characterization flow chart

6 Study planning and data collection

6.1 General

To obtain an overview of the factors affecting the wave energy resource across the study area, and to identify the data that will be required to conduct the resource assessment, a site description shall be prepared. The site description shall include, but need not be limited to, a description of the elements in the following subclauses.

6.2 Study area

The study area is the area in which the wave resource is of interest and is to be assessed and characterized. The extent of the study area shall be declared. The main physiographic and oceanographic features of the study area shall be reviewed, especially those features that influence wave propagation and wave climate. When wave modelling is used to assess the resource, the model domain is the area across which the wave conditions are modelled. The model domain can extend beyond the study area. In this case, the extent of the model domain shall also be declared. When MCP methods are used to assess the resource, the study area is restricted to a single location or a finite number of discrete locations.

NOTE It is possible that the model domain is larger than the study area because it extends to the known boundary conditions. In the offshore direction that will typically be for water depths of at least 100 m to 200 m to avoid shallow water influences. In the long-shore direction this will generally be greater than the distance from the offshore boundary to the area of interest. In case the model domain does not extend beyond, or only partially covers, the study area, ensure other means of assessment, appropriate for the chosen class, are used as well.

6.3 Bathymetry

The bathymetry of the model domain shall be described, and a bathymetric contour map shall be prepared. Where existing data sets are used, their source shall be provided. Existing bathymetric data sets will normally be employed in a Class 1 assessment. Depending on the quality of the bathymetric data that is available, new high-resolution bathymetric surveys can be required for higher class assessments. All bathymetric surveys used, whether existing or new, should comply with IHO S44 (2008). A Survey Order 2 or better, as specified in IHO S44, should be used for water depths of less than 200 m, and a Survey Order 3 or better should be used for water depths greater than 200 m.

The bathymetric data shall be used to construct a digital elevation model for use in the wave propagation modelling. In general, the bathymetry shall be defined with sufficient horizontal and vertical resolution to adequately describe the bathymetric features influencing wave propagation. Better resolution is generally required in shallower water (where the waves are more strongly affected by the seabed) and in areas with steep bottom slopes. The spatial resolution of the bathymetric data should meet the minimum requirements shown in Table 2.

Table 2 – Resolution of bathymetric data

Class of assessment:	1	2	3
Recommended maximum horizontal spacing of bathymetric data in water depths greater than 200 m.	5 km	2 km	1 km
Recommended maximum percentage difference in water depth between adjacent bathymetric points in water depths less than 200 m.	10 %	5 %	2 %
Recommended maximum horizontal spacing of bathymetric data in water depths less than 200 m.	500 m	100 m	25 m
Recommended maximum horizontal spacing of bathymetric data in water depths less than 20 m.	100 m	50 m	10 m

6.4 Existing wave data

Existing data and study reports characterising wave conditions across the study area shall be collected, reviewed and described. Existing data can come from previous numerical simulations, physical measurements, earlier resource assessment studies or previous wave climate studies. The existing data and information can help guide the user in setting up the resource assessment, as it can describe key aspects of the wave resource including but not limited to seasonal variability, interannual variability, frequency of storms, prevalence of multimodal wave systems, expected spectral shape and the variability of dominant wave direction. Furthermore, this data can be used to define boundary conditions for numerical modelling provided it conforms to the requirements of 7.3. In the case of Class 1 assessments, the archived data can serve as the primary data source, provided it conforms to the requirements detailed in 6.5. Measured wave data within a numerical model domain can be used for validation, provided it satisfies the requirements of 6.5. If the existing wave data is characterised using parameters that differ from those used in this document, then the data shall be converted to match the parameters consistent with this document. The methods used to convert the data shall be detailed and justified. The uncertainty associated with the existing data shall also be calculated and presented as detailed in 9.5.

6.5 Wave measurement

6.5.1 Purpose

Measured wave data is required to validate the numerical wave model used to estimate the wave resource over the study area, and to support application of the MCP method. If suitable physical measurements of wave conditions are not available, then new measurements shall be acquired for these purposes. Measured wave data can also be used to develop suitable boundary conditions for wave modelling (see 7.3), but data used for such purposes shall be independent of data used for model validation.

The measurements used for model validation shall satisfy the requirements of 7.6. In particular, the measurements shall provide an accurate and unbiased description of the wave climate at the validation locations(s). This implies that, for Class 1 assessments, analysis of the measurements shall provide reliable estimates of significant wave height, energy period and omni-directional wave power over a sufficient range of wave conditions. Data from a single, accurate, non-directional measuring instrument is sufficient for validation of Class 1 assessments. For Class 2 and Class 3 assessments, in addition to the three parameters required in a Class 1 assessment, it shall be possible to reliably estimate, for all wave conditions, the spectral width and the directional spreading index. Hence, data from an accurate directional wave measuring instrument is required for validation of Class 2 and Class 3 assessments.

NOTE Although data from a single location is sufficient for validation, data from multiple locations is preferred.

6.5.2 Selection of measuring instrument and analysis methodology

The instrument used to collect wave data for model validation shall be capable of measuring quantities that can be analysed to provide accurate and unbiased estimates of the parameters listed in Table 3. The number of independent sea state measurements required to satisfy the requirements for model validation will depend on the wave climate and the class of the resource assessment, as specified in Table 6. In all cases, care shall be taken to ensure that the measurements capture a sufficient range of wave conditions, as specified in 7.6.

To be considered fit for purpose, scientifically defensible evidence shall be provided demonstrating that the measurement instrument and associated analysis methods meet or exceed the performance requirements set forth in Table 3.

NOTE 1 A sufficient number of sea state measurements can be obtained in many ways. For example, by employing a relatively low sampling rate (e.g. daily) over a relatively long period (i.e. several years), or by employing a higher sampling rate (i.e. hourly) over a shorter period (typically one year or less).

NOTE 2 Many different sensors and sensor arrays can successfully be used for estimating non-directional and directional spectra. Non-directional spectra are often derived from measurements of free surface elevation or the heave motion of surface-following buoys. Pressure measurements from a fixed point a short distance below the surface can also provide data necessary for estimating the wave frequency spectrum. Directional spectra are typically estimated from analysis of three simultaneous measurements, such as the heave, pitch and roll of a surface following buoy, or surface elevation combined with orthogonal components of horizontal orbital velocity.

Table 3 – Minimum requirements for wave measuring instruments and associated analysis

Class of resource assessment	**1**	**2**	**3**
Requirement	Value ***xx***		
Precision in H_{m0} greater than ***xx***, 95 % of the time	0,9 m	0,6 m	0,3 m
Overall bias in H_{m0} less than ***xx***	0,3 m	0,2 m	0,1 m
Precision in T_e greater than ***xx***, 95 % of the time	3,0 s	2,0 s	1,0 s
Overall bias in T_e less than ***xx***	1,5 s	1,0 s	0,5 s
Precision in ε_0 greater than ***xx***, 95 % of the time	–	0,10	0,05
Overall bias in ε_0 less than ***xx***	–	0,05	0,02
Precision in directional spreading greater than ***xx***, 95 % of the time	–	15°	10°
Overall bias in directional spreading less than ***xx***	–	6°	4°
Precision in mean direction greater than ***xx***, 95 % of the time	–	15°	10°
Overall bias in mean direction less than ***xx***	–	6°	4°

Refer to Clause 8 for definitions of characteristic parameters.

Measurements spanning the frequency range from 0,04 Hz to 0,5 Hz are recommended in order to achieve the performance requirements set forth in Table 3. For measurements based on recorded time-histories, a minimum record length of 1 200 s per sampling period is recommended, but longer record lengths (up to 3 600 s) can be required in order to increase the resolution and precision of the (directional) wave spectrum that can be derived from the measurements.

NOTE 3 In the absence of extensive industry experience, it is difficult to establish appropriate and reasonable minimum limits on the performance of wave measuring instruments and associated analysis. The limits specified in Table 3 are considered reasonable but can be revised in the future as industry experience increases.

6.5.3 Instrument calibration

Whenever possible, the measurement instrument(s) shall have third party certification. Measuring instrumentation, such as a WMI, that cannot have third party certification, shall be certified by the vendor. The certification shall include at a minimum the requirements listed in 8.2 of IEC 62600-100:—. The instrument shall be successfully calibrated prior to deployment. If the calibration results do not fall within normal operating ranges the instrument should not be used. The calibration shall be repeated immediately following recovery to confirm that the calibration did not change over the deployment period in any way that might contribute to increased measurement error or bias. If the disparity in the pre- and post-deployment calibrations exceeds normal tolerances (provisionally 5 %) then the measurements shall be marked as provisional and should not be used for model validation unless the errors and biases associated with this disparity are shown to be less than the values specified in Table 3.

6.5.4 Instrument deployment

Whenever possible, measured wave data should be obtained in one or more locations close to where wave energy converters are likely to be deployed. If this is not possible, wave data should be obtained from locations where the wave resource is representative of typical conditions throughout the study area and the average water depth is similar to that where wave energy converter deployments are anticipated. It is advisable to avoid locations where the spatial gradients of wave energy are steep such as near islands, prominent bathymetric features, or within the surf zone.

The measuring instrument(s) shall be deployed in accordance with the supplier's specifications and recommendations to maximize precision and minimize bias as much as possible.

For floating instruments, care shall be taken to minimize the error and bias introduced by the mooring system as much as possible. For instruments that rely on sensing dynamic pressures or orbital velocities below the free surface, the sensor(s) shall be located close enough to the free surface to accurately measure wave components with frequencies up to 0,5 Hz. For instruments that rely on sensing wave properties at multiple locations, the locations shall be optimised to minimize error and bias as much as possible.

NOTE It is advisable to deploy more than one wave measuring instrument whenever possible to provide redundancy in the event of instrument malfunction or loss. This approach also has the benefit of providing multiple validation points in the event that malfunction or loss does not occur. Multiple data points are extremely valuable for validation vs. calibration, in addition to obtaining a more accurate assessment of the resource and its spatial variability.

6.5.5 Analysis of measurements

Nearly all measured data sets will contain erroneous or invalid data points. To improve the quality of the data set, screening methods recommended by the instrument manufacturer shall be applied to exclude spurious data as much as possible. Procedures recommended by either the instrument manufacturer or industry-standard best practices, or both, shall be used to obtain the best possible estimate of the wave spectrum and directional wave spectrum (if appropriate) for each sampling period. The methods presented in Clause 9 shall then be used to derive characteristic parameters for use in model validation. The methods used to screen and analyse the measured data shall be fully consistent with the methods for which scientifically defensible evidence demonstrating acceptable measurement performance is available.

In most cases, non-directional wave spectra will typically be obtained from Fourier analysis of the water surface elevation time series. An established method of time-domain or frequency-domain averaging will typically be employed to smooth the raw wave spectrum. Directional wave spectra will typically be obtained by multiplying the non-directional wave spectrum by a frequency-dependent spreading function that describes how the energy in each frequency band is distributed over direction. Many methods can be used to estimate the spreading function, including Fourier series decomposition, Fitting of parametric models, Bayesian methods, maximum likelihood methods (MLM), and Maximum Entropy Methods (MEM). Most methods assume a parametric model for the spreading function at each frequency band. All these methods involve computing the auto-, co- and quad-spectra from at least three distinct measured time series but differ widely thereafter. The last two methods (MLM and MEM) are recommended as they tend to provide superior performance. Further information on directional wave analysis is provided in Benoit et al., 1997. Analysing multidirectional wave spectra: a tentative classification of available methods. Proc IAHR seminar on multidirectional waves and their interaction with structures, 27th IAHR Congress, San Francisco, USA.

6.6 Wind data

Existing data on wind speed and direction over the entire model domain shall be reviewed and described, including the source and details of validation. Acceptable data sources include physical measurements and wind fields predicted by numerical models (i.e. from pressure indices), provided the model results have been validated against measured data. The spatial and temporal resolution of the wind data shall be commensurate with the class of the assessment and the sensitivity of the wave model to this parameter. The height of the wind data shall be reported and be consistent with the wave model. Recommended spatial and temporal resolutions for wind data are given in Table 4. If the available wind data is of a coarser resolution than that which is recommended below, it can be interpolated, extrapolated or transformed for use in wave modelling; the methods and procedures used shall be described and justified.

Table 4 – Resolution of wind data

	Reconnaissance	Feasibility	Design
Recommended temporal resolution	3 h	3 h	1 h
Recommended spatial resolution	100 km	50 km	25 km
It is possible that the height of the wind data does not match the height required for the wave resource assessment (typically 10 m), and it can be necessary to adjust wind data to an equivalent height of 10 m using appropriate scaling methods which shall be reported.			

6.7 Tidal and non-tidal current data

Existing information and data on the tidal and non-tidal currents over the model domain shall be reviewed and described, including the source and details of validation. The speed and direction of the currents shall be presented, at a resolution appropriate to their spatial and temporal variability. Acceptable data sources include physical measurement and models that have been validated using measured data. The possible influence of these fluctuations on wave propagation shall be assessed and reported. A sensitivity study (see Annex C), or scientific reasoning, shall be used to assess the importance of these currents. If the influence is likely to be significant over any part of the study area, then the time-varying currents shall be included in the wave propagation model.

6.8 Water level fluctuation

Existing information and data on the water level fluctuations over the model domain shall be reviewed and described, including the source and details of validation. The possible influence of these fluctuations on wave propagation shall be assessed and reported. A sensitivity study (see Annex C), or scientific reasoning, shall be used to assess the importance of water level fluctuations. If the influence is likely to be significant over any part of the study area, then the time-varying water level shall be included in the wave propagation model. If either additional water level measurement or tide modelling, or both, are necessary, the methodology and expected uncertainty shall be described.

NOTE In most circumstances it will be sufficient to prescribe a single water level across the entire model domain at each time step.

6.9 Ice coverage and exceptional environmental conditions

In some locations, wave conditions will be seasonally affected by the presence of either sea ice or exceptional environmental conditions, or both. If applicable, existing data and information on sea ice within and around the model domain shall be collected and reviewed, and the potential influence on the wave conditions throughout the study area shall be assessed and reported. A sensitivity study (see Annex C), or scientific reasoning, shall be used to assess the importance of either sea ice or exceptional environmental conditions, or both. If the influence of either sea ice or exceptional environmental conditions, or both, is likely to be significant over any part of the study area, then the effects shall be included in the wave modelling. The methods and procedures used to include either the effects of sea ice or exceptional environmental conditions, or both, in the wave modelling shall be described and justified.

6.10 Water density

The near surface water density in the study area shall be determined. It can be measured directly, or estimated from measurements of temperature and salinity, or by reference to previous studies. Where appropriate, seasonal variations in water density shall be considered. Alternatively, a water density of 1 025 kg/m^3 can be assumed.

6.11 Gravitational acceleration

Gravitational acceleration shall be defined and reported using one of two methods:

- Standard gravity, which was defined by the 3rd General Conference on Weights and Measures (1901) as 9,806 65 m/s^2; or
- the latitude, φ, corrected value of gravitational acceleration, which is defined as

$$9{,}806\ 12 - 0{,}0258\ 65 \cdot \cos(2 \cdot \varphi) + 0{,}000\ 058 \cdot \cos^2(2 \cdot \varphi)$$

7 Numerical modelling

7.1 General

The raw sea state data required for estimation of the wave energy resource shall be generated using suitable numerical models. The analysis of this data to provide a parametric representation of the sea states and wave climate is specified in Clause 9. The numerical models shall be validated, and where necessary calibrated, using physical measurements. The boundary conditions and wind forcing for the numerical models shall be derived either from a more extensive validated numerical model or from metocean measurements when suitable data is available.

7.2 Suitable numerical models

Table 5 specifies the numerical model features that are required to be considered, recommended, acceptable and not permitted for the three resource assessment classes identified in Clause 5.

If a modelling feature is required to be considered then it shall be included in the numerical model unless it can be shown using sensitivity analysis, or by scientific reasoning, to not significantly affect the wave energy resource (see Annex C). The sensitivity analysis or scientific reasoning justifying exclusion shall be included in the final report. If a modelling feature is recommended, then it is considered best practice and should be included in the numerical model. If a modelling feature is *acceptable* then it can be used in the numerical model. If a modelling feature is not permitted, then it shall not be used in the numerical model.

Table 5 – Elements of suitable numerical models

● Required to be considered ◉ Recommended ○ Acceptable × Not permitted

Component: Description	Reconnaisance	Feasibility	Design
Boundary conditions			
Parametric boundary: Boundary conditions defined by parameters such as H_{m0}, T_e, DWD, s [a]	○	×	×
Hybrid boundary; Boundary conditions defined by wave spectrum with parametric directional parameters [a]	○	○	×
Spectral boundary: Boundary conditions defined by directional wave spectrum	◉	◉	◉
Physical processes			
Wind-wave growth: Transfer of energy from the wind to the waves [b]	●	●	●
Whitecapping: Dissipation due to whitecapping included in model	●	●	●
Quadruplet interactions: Energy transfer due to quadruplet interactions included in model [b]	●	●	●
Wave breaking: Dissipation due to depth-induced wave breaking included in model	◉	●	●
Bottom friction: Dissipation due to bed friction included in model	○	●	●
Triad interactions: Energy transfer due to triad interactions included in model [c]	○	●	●
Diffraction: Diffraction included in model [d, j]	●	●	●
Refraction: Refraction included in model	●	●	●
Effects of sea ice included in model	●	●	●
Water level variations (tides)	●	●	●
Wave reflections	●	●	●
Wave-current interactions	●	●	●
Wave set-up	○	○	○
Numerics			
2nd generation spectral wave model [e]	○	○	×
3rd generation spectral wave model [f]	◉	◉	◉
Mild-slope/parabolic/elliptical wave model [g]	○	○	○
Spherical coordinates [h]	●	○	○
Non-stationary solution	○	○	○
Minimum spatial resolution [i]	5 km	500 m	50 m
Minimum temporal resolution [i]	3 h	3 h	1 h
Minimum number of wave component frequencies in numerical model	25	25	25
Minimum number of azimuthal directions in numerical model [k]	24	36	48

[a] An appropriate spectral shape and directional spreading function should be used.

[b] Importance of wind-wave growth and quadruplet interactions will depend on the geographical extent and their inclusion can be unnecessary for areas with small geographical extents.

[c] Importance of triad interactions will depend on water depth and their inclusion can be unnecessary for areas without shallow water.

[d] Importance of diffraction will depend on the presence of islands, headlands or other obstructions and the inclusion of diffraction can be unnecessary for areas where these do not exist.

[e] Wave model using a phase-averaged spectral representation of the sea-state and simplified parametric representations of non-linear interactions to calculate the propagation and transformation of waves.

[f] Wave model using a phase-averaged spectral representation of the sea-state and explicit representation of the physical processes to calculate the propagation and transformation of waves.

[g] Wave model using the associated phase-resolving formula to calculate the propagation and transformation of waves; recommended for shoreline wave energy converters.

[h] The requirement for spherical coordinates will depend on the geographical extent and directional resolution; their use can be unnecessary for areas with small geographical extents.

[i] Boundary conditions, wind fields, bathymetry and model computational grid/time steps should be defined to correctly reproduce the scale of variation of wave energy conditions in the study area with, at least, this resolution.

[j] Diffraction in spectral wave models is based on a phase-averaged approximation, and possibly does not accurately model the effect of diffraction.

[k] Additional azimuthal directions can be needed to mitigate numerical errors associated with swell propagation and refraction in spectral wave models.

A minimum of 25 wave frequency components and 24 to 48 directional components (depending on the assessment class) shall be used in the numerical model. Finer discretization in frequency and direction is recommended in order to improve the accuracy of the model output. It is recommended that the frequency range of the model output should cover at least 0,04 Hz to 0,5 Hz.

NOTE 1 It can be necessary to include in the wave model computations at frequencies up to 2,0 Hz in order to adequately resolve important physical processes, such as wind-wave growth and whitecapping.

The flexibility and complexity of typical wave propagation models means that acceptable results are not guaranteed, and care shall be taken to ensure that the numerical model that is used includes the necessary features to correctly reproduce all of the important wave transformations over the study area, and that the model is applied in a manner sufficient to deliver outputs having the desired resolution and accuracy.

NOTE 2 Wave energy conforming to what is commonly described as a stable sea state has a wide range of both spatial and temporal variability. Spatial variability is related mainly to sea bed morphology (and in some cases currents) while temporal variability is more related with the characteristics of the generation mechanisms. Spatial variability increases inshore as a direct result of wave bottom interaction and contour shadows but, depending on coastal morphology, it can be very stable alongshore for kilometres, or create incredible differences on the order of metres (breaking, focusing and defocusing, etc.). In the case of temporal variations, wave conditions can be very stable for hours or even days (in the case of long travelling groundswells arriving in local calm weather) or change extremely fast (wind waves associated with local perturbations). Because of this, it is not possible to give recommendations appropriate for all cases.

The numerical model should produce a minimum of 10 years of sea state data. Sea state data shall be generated with a minimum frequency of 1 data set every 3 h. Less than 10 years of sea state data can be produced if necessary. However, in any case (10 years or less) an estimate of the uncertainty of the wave resource assessment shall also be produced and provided with the sea state data (see 9.5).

Archived wave data (e.g. hindcast) can be used for the wave resource assessment provided that the methods used to generate the data are consistent with the requirements of this document. When using archived model wave data, all changes in model configuration shall be noted and adequate validation shall have been performed (as defined in 7.6) for each model configuration.

Climate change, anthropogenic or otherwise, can cause the wave resource to change over a period of longer than 10 years. Climate change is complex, and predictions of its effects are extremely unreliable. Therefore, it is recommended that the wave resource is assumed to be stationary unless there is clear evidence to the contrary. Any assumptions made and steps taken to include the possible effects of climate change in the resource assessment shall be clearly stated and justified.

7.3 Definition of boundary conditions

Boundary conditions for the numerical modelling shall be defined using either:

a) physically recorded metocean data;

b) historical data predicted by a more extensive numerical model; or

c) a combination of the above.

Where physically recorded metocean data is used, the data set should span a period of at least 10 years with a data return rate greater than 70 %. Methods recommended by the supplier of the measuring instrument used to acquire the data, or the agency responsible for either collecting or supplying the data, or both, shall be applied to exclude erroneous or invalid observations before use. Any known bias shall also be removed prior to use.

The metocean data should be collected and analysed following a consistent methodology. This is of particular importance when two or more data sets or instrument deployments are used.

Where wave data produced by previous modelling is used to define the boundary conditions for new numerical modelling, the data set should span a period of at least 10 years. The previously modelled wave data shall have been successfully validated against physically recorded metocean data. It is recommended that the same validation requirements as specified in 7.6 are used; however, it is recognised that other validation procedures can have been used. In this case the procedures and results shall be fully reported. Where possible, any bias shall be removed from the previously modelled wave data before it is used to develop boundary conditions for new modelling.

Suitable boundary conditions can also be developed by combining physically recorded metocean data with numerical predictions. For example, wave data produced by previous numerical modelling can be used to fill in gaps in the physically recorded data set. Where the physically recorded data is non-directional, modelled wave data can be used to add directional information. The methods used to develop the hybrid boundary conditions shall be described and justified.

For boundary conditions specified in parametric form, any missing data can be estimated using MCP techniques as described in Clause 8. Missing parametric data can be estimated from available measurements for other locations, or from the outputs of previous wave modelling. The secondary data sources shall be assessed to ensure they are fit for purpose. The methods used to estimate the missing data shall be described and justified.

If necessary, data sets with duration less than 10 years can be used to define boundary conditions; however, the use of shorter data sets is discouraged as the uncertainty of the estimated wave resource parameters will increase.

The homogeneity of the wave conditions along the full extent of the offshore model boundaries shall be assessed, and spatially varying boundary conditions shall be developed to represent any spatially variable wave conditions. A sensitivity study (see Annex C), or scientific reasoning, shall be used to assess the importance of spatially varying boundary conditions. If the influence is likely to be significant over any part of the study area, then the spatially varying boundary conditions shall be included in the wave propagation model. When measured or modelled data is available at discrete points, a linear interpolation can be used to approximate the spatial variation in wave conditions along the model boundaries.

To simplify the specification of boundary conditions for wave modelling, it is recommended that, to the extent possible, offshore model boundaries be located in areas where wave conditions are reasonably homogeneous, beyond shallow water influences, and where suitable data is available. Ideally, reliable wave data sets will be available at multiple locations along the offshore model boundaries so that spatially varying boundary conditions can be prescribed.

For Class 2 and Class 3 assessments, modelled wave data produced by previous lower-class assessments may be used to establish suitable spatially varying boundary conditions. In particular, it is recommended that a Class 3 resource assessment for a design study use results from a Class 2 resource assessment; however, this is not a requirement and other appropriate verified boundary conditions can be used.

NOTE The use of information from a lower-class assessment to establish boundary conditions for a higher class assessment can result in the transmission of errors that result in unsuitable levels of uncertainty.

For a typical Class 3 assessment of an exposed nearshore site, the spatial variability in wave conditions across a small-scale offshore boundary located in deep water should be minimal but should still be checked since the accuracy required for the predictions is increased.

7.4 Modelling the nearshore resource

The wave energy resource in very shallow water is strongly influenced by the effects of depth-limited wave breaking, a natural process that typically produces steep spatial gradients in wave height. The depth-limited wave breaking process is sensitive to the prevailing wave conditions in addition to fluctuations in water level, nearshore currents and potentially even temporal changes in the bathymetry. When it is desirable to attempt to extend the resource assessment into shallower water depths where depth-limited breaking occurs frequently, a wave model that includes a reasonable simulation of wave non-linearities and depth-limited wave breaking processes shall be employed to predict the spatial and temporal variation in wave conditions across the nearshore area. Consideration of depth-limited breaking is required for shallow water modelling. The ability of the model to simulate the decay in wave heights across the surf zone with reasonable precision shall be verified and confirmed by a scientifically defensible method. The modelling shall take into consideration the effects of water level fluctuations, currents and bathymetry changes, unless it can be shown that these effects are negligible. Further guidance on modelling the nearshore resource is given in Annex E.

In situations where information on the shallow water wave resource is not required, an acceptable alternative is to restrict the resource assessment to deeper water depths where depth-limited breaking occurs infrequently. In this case, the location of the limiting depth contour shall be clearly specified and justified, and the exclusion of regions with shallower depths shall be duly noted. In general the resource estimate should be made to the outer limit of the breaking zone for the most energetic annual wave condition.

7.5 Effect of WEC array on wave energy resource

It is recognized that the presence of a WEC array can have a considerable effect upon the local wave energy resource, such that the wave energy incident upon a given WEC can differ from the case in which there were no other WECs in the region. As such there can be a loss of accuracy for an energy production estimation that relies upon a resource assessment that does not consider array effects. In cases where an energy production estimation for a particular WEC array is required, where appropriate the effects of the WEC array on wave propagation should be included in the numerical model. Any modifications made to the numerical model to account for the effects of a WEC array shall be documented and justified. If the WECs in the region have frequency-dependent power takeoff characteristics, the corresponding WEC implementation in the numerical model should also be frequency dependent.

In the case that the WEC array is not present when the wave data to be used for validation of the numerical model is measured (see 7.6), then the effects of the WEC array shall not be included in the validation of the wave propagation model.

7.6 Validation of numerical models

7.6.1 General

All numerical modelling shall be validated using measured wave data. The ability of the wave model to accurately predict the wave resource shall be assessed and confirmed. Whenever possible the numerical model output should be validated using data from one or more locations close to where wave energy converters might realistically be deployed. If this is not possible, because deployment locations are unknown or otherwise, the validation data should be from location(s) where the average water depth is close to the expected depths of future wave farm deployments, and where the wave climate is typical of conditions throughout the study area. It is advisable to avoid locations where the spatial gradients of wave energy are steep, such as near islands and prominent bathymetric features. The location of the validation sites, the source of the validation data, and the properties of each data set shall be described in the technical report (see 10.3).

All measured wave data used for validation shall be acquired and analysed as specified in 6.5. For buoy measurements, automated quality control procedures should include as a minimum those defined by the NDBC Handbook of Automated Quality Control 2009 and shall be supplemented by manual checking to maximize data validity. Industry-standard quality control methods used for any other measurement system shall be implemented where appropriate and details recorded.

7.6.2 Validation data specification

A validation data point is a single sea state measured at a particular location and time, and a validation data set consists of all validation data points associated with a particular location. To facilitate validation, the validation data set shall be used to construct an omni-directional H_{m0}-T_e scatter table showing the proportional frequency of occurrence of different sea states. The scatter table will comprise many cells or bins, each corresponding to a particular and unique small range of H_{m0} and T_e (see 10.6). Model error shall be evaluated by considering the data in each scatter table cell, and overall. To minimize the potential for correlation of error within a cell, validation data points within a single cell of the scatter table shall be derived from measurements separated by a minimum time period. A minimum separation period of 6 h is recommended. To minimize the potential influence of seasonal bias for locations where the wave energy resource features significant seasonal variations in any relevant characteristic quantity (see Clause 9), the validation data set shall include data from throughout the year. The monthly return rate on measured data shall be documented and a mean return rate of less than 70 % over any three month period shall be highlighted. Where feasible, such deficiencies in the validation data set should be mitigated with additional measurements during the months with low return rates.

NOTE 1 The suggested 6 h separation period is based in expert opinion. However, if it can be shown that there is no correlation between data points separated by a period of less than 6 h then this shorter separation period can be used.

The validation data set shall be gathered over a sufficiently long time to include a full range of wave conditions at the site. The required temporal extent of the validation data set shall be based on achieving sufficient coverage of the omni-directional H_{m0}-T_e scatter table showing proportional frequency of occurrence of sea states over the duration of the resource assessment (see 10.6). Coverage shall be defined as the sum of the proportional frequency of occurrence of the represented scatter table cells (obtained over the duration of the resource assessment). A cell in the scatter table can be considered to be represented when it contains a minimum number of validation data points. Coverage requirements for all classes of assessments are given in Table 6. For each validation data set, a scatter table indicating the number of validation data points in each cell, highlighting satisfaction of the representation criterion, shall be prepared and presented in the final report.

NOTE 2 A minimum coverage of e.g. 95 % does not indicate that 95 % of all sea state cells shall be represented in the validation data set, but rather that the sum of the proportional frequency of occurrence of the represented cells is at least 95 %.

7.6.3 Procedure

Model validation shall be based on the model's skill in predicting the key resource parameters describing the energy resource listed in Table 6 and defined in 9.2. The data point value for parameter p derived from the wave measurements is denoted p_D and the corresponding value derived from the wave modelling is denoted p_M . For each represented cell the normalized error between measured and modelled values of parameter p shall be calculated as:

$$\mathbf{e}_p = \begin{bmatrix} \left(p_{\mathrm{M}_1} - p_{\mathrm{D}_1}\right) / \, p_{\mathrm{D}_1} \\ \vdots \\ \left(p_{\mathrm{M}_k} - p_{\mathrm{D}_k}\right) / \, p_{\mathrm{D}_k} \end{bmatrix} \quad (1)$$

where p_{M_k} and p_{D_k} are values at coincident time-steps t_k for $k = 1 \ldots n$, where n here is the number of measured/modelled parameter value pairs in the cell. In the case of the characteristic direction (see 9.2.6) no normalization will be applied. The error for each cell shall be separated into a systematic error, $\mu_{ij}\left(e_p\right)$, and a random error, $\sigma_{ij}\left(e_p\right)$. The systematic error, or bias, shall be defined as the mean (see 9.4.2) of the errors in cell i, j , whilst the random error shall be defined as the standard deviation (see 9.4.3) of the errors in cell i, j . It is considered good practice that p_{D} and p_{M} are calculated by integrating the spectrum over the same frequency range.

NOTE 1 The characteristic parameters are denoted as $p \in [J, H_{m0}, T_e, \ldots]$ where the ellipsis indicates that more parameters can be considered beyond these minimum set.

NOTE 2 The calculation of error specified here includes error in the measured parameters due to a number of influences, which include instrument precision, calibration error and sampling variability. Further detail on this topic can be found in [10].

From the viewpoint of wave energy resource characterization, the significance of the systematic and random errors within any given cell can be related to their influence on the estimation of energy availability or production. For each cell i, j , the product of the proportional frequency of occurrence f_{ij} and mean incident wave power J_{ij} (where f_{ij} and J_{ij} are obtained over the duration of the resource assessment, not from the validation data set) gives a strong indication of the significance of any error and shall form the basis for computing the weighting factor, w_{ij} , as:

$$w_{ij} = J_{ij} f_{ij} \quad (2)$$

For those scatter table cells i, j where the requirements for a minimum number of validation data points is unmet (see Table 6), f_{ij} shall be set to zero. If a specific WEC technology is being considered, then the weighting factors can be scaled by the capture width $C_{W,ij}$ associated with each cell (see IEC TS 62600-100), as:

$$w_{ij} = C_{W,ij} J_{ij} f_{ij} \quad (3)$$

In any case, the weighting matrix shall be normalized such that its sum is unity, as:

$$\hat{w}_{ij} = \frac{w_{ij}}{\sum_{i,j} w_{ij}} \qquad (4)$$

The weighted mean systematic error $b(e_p)$ shall be calculated as the sum of the element-wise product of the normalized weighting matrix and the systematic error matrix, as:

$$b(e_p) = \sum_{i,j} \hat{w}_{ij} \mu_{ij} \qquad (5)$$

Similarly, the weighted mean random error $\sigma(e_p)$ shall be calculated as the element-wise product of the normalized weighting matrix and the random error matrix, as:

$$\sigma(e_p) = \sum_{i,j} \hat{w}_{ij} \sigma_{ij} \qquad (6)$$

NOTE 3 The use of the weighted mean error is intended as a metric for validating model results over the represented H_{m0}-T_e domain of the validation site data set.

Table 6 specifies the maximum acceptable weighted mean systematic and random errors for each key parameter and class of resource assessment. The coverage requirements for validation data are also given in Table 6, and are also dependent on the class of the resource assessment being performed as defined in Clause 5. The numerical modelling output shall be considered to be successfully validated for a specific location and class of resource assessment when the criteria in Table 6 are satisfied. If necessary or desired, various refinements or changes in methodology (see 5.1) can be adopted in an attempt to reduce the overall error and successfully validate the model.

The process used to validate the numerical model output and the results of the validation shall be documented in the technical report (10.3). If the numerical modelling output could not be successfully validated, due to a lack of suitable wave data or any other reason, then the results of the resource assessment shall be clearly labelled as "provisional". In this case, the reasons for the provisional status shall be clearly described in the technical report. The provisional label can be removed once any outstanding validation issues have been addressed.

The validation procedure described above is summarized in Figure 2. The procedure shall be repeated for each validation location.

Table 6 – Minimum validation requirements

	Class 1: Reconnaissance	**Class 2: Feasibility**	**Class 3: Design**
Validation data coverage requirements			
Minimum number of validation data points to represent cell	3	5	5
Minimum coverage by validation data	90 %	90 %	95 %
Max acceptable weighted mean systematic error, $b(e_p)$			
Significant wave height, H_{m0}	10 %	5%	2 %
Energy period, T_e	10 %	5 %	2 %
Omni-directional wave power, J	25 %	12 %	5 %
Direction of max. directionally resolved wave power $\theta_{J\max}$	-	10°	5°
Spectral width, ε_0	-	12 %	5 %
Directionality coefficient, d	-	12 %	5 %
Max acceptable weighted mean random error, $\sigma(e_p)$			
Significant wave height, H_{m0}	15%	10 %	7 %
Energy period, T_e	15 %	10 %	7 %
Omni-directional wave power, J	35 %	25 %	20 %
Direction of max. directionally resolved wave power $\theta_{J\max}$	-	15°	10°
Spectral width, ε_0	-	25 %	15 %
Directionality coefficient, d	-	25 %	15 %

In the absence of extensive use, it remains unclear what values should be adopted as reasonable minimum validation requirements. The validation requirements defined in Table 6 are based on what is currently considered achievable and the likely requirements of resource assessment. The requirements defined in Table 6 will be revisited and revised as additional experience is gained in the industry.

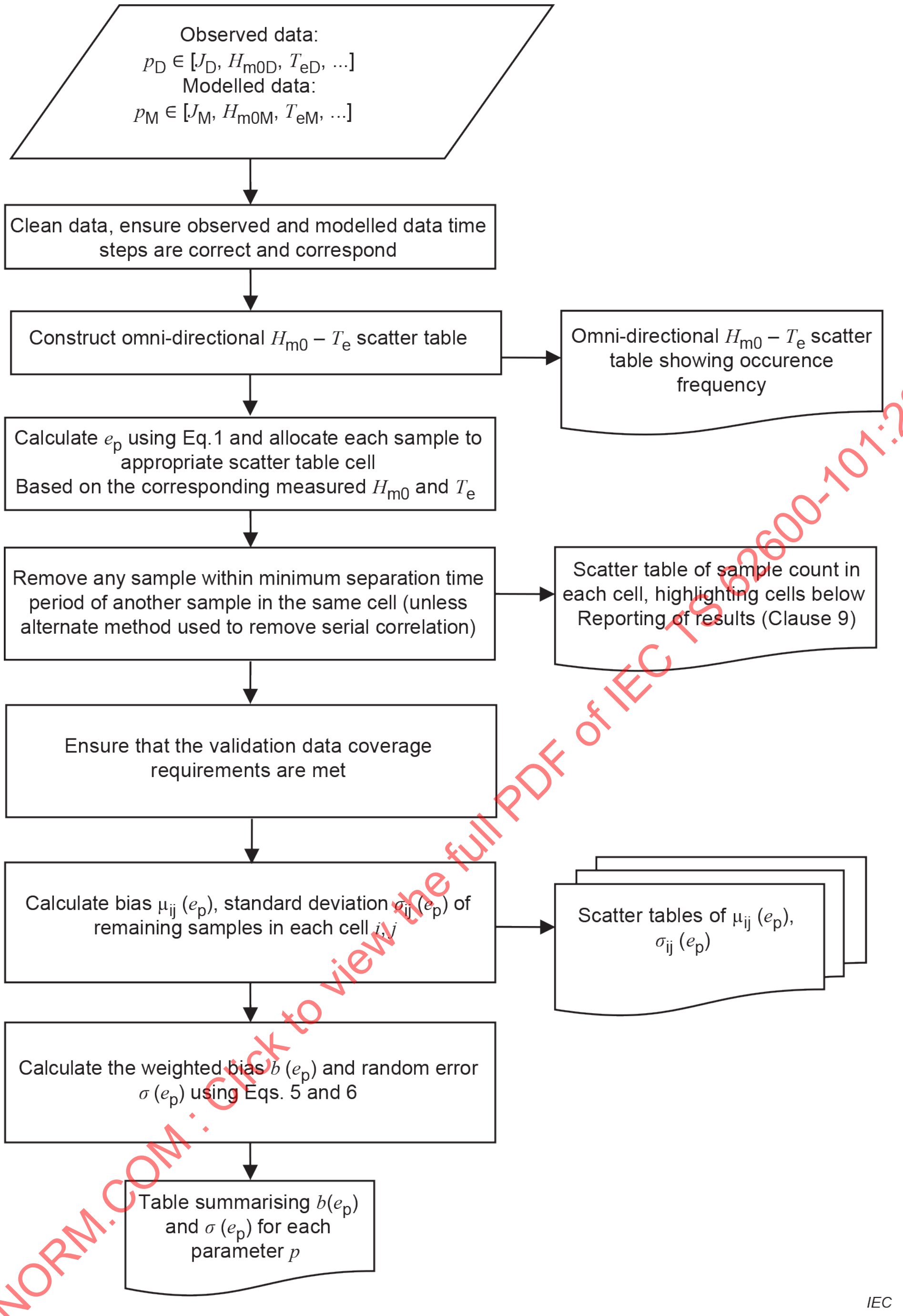

Figure 2 – Validation flow chart

7.6.4 Extent of validation

The geographical extent of validation of the wave energy resource shall be determined and reported. The extent of validation is defined as the areas surrounding the successful validation points where the uncertainty in the mean annual wave power is less than specified in Table 6. It is recommended the area surrounding a successful validation point is defined by uncertainty propagation using the numerical model; however, other methods for defining the extent of validation can be used, provided they are justified scientifically.

Determining the extent of validation is not an exact process and it is necessary to make a number of approximations and assumptions to produce an estimate. The procedure outlined using uncertainty propagation is expected to produce a reasonable estimate; however, if better methods of generating estimates are identified in the future they should be used where appropriate.

If the extent of validation is defined using uncertainty propagation, the methods defined in [10][2] can be used. To reduce the computational effort the uncertainty propagation can be completed using a weighted representative set of sea-states; however, the choice of representative sea-states and weightings shall be justified and reported. Parameters that should be considered in the uncertainty propagation include the bathymetry, marine currents and process parameters such as the bottom friction coefficient. Parameter uncertainties can be estimated using experience or derived from measurements; whatever method is used it shall be justified and reported, together with the value of the parameter uncertainty used. The complexity of the numerical model means that it is recommended to use Monte Carlo methods for propagation of uncertainty from these parameters to the mean annual wave power. The percentage uncertainty in mean annual wave power shall be defined as the variation in the mean annual wave power normalised by the mean annual wave power at the validation point. The uncertainty is normalised so that parameter variations outside the extent of validation do not affect the calculation of the extent of validation.

The choice of the method of uncertainty propagation should be justified. If a method other than that in [10] is used, then it should be detailed.

NOTE 1 It is important that the numerical model used to determine the extent of validation includes all relevant sources of wave transformation - even if these sources are not required for model validation. For example, this would occur where the validation point is in the open ocean, but it is desired that the extent of validation includes a region where diffraction can have a significant impact on the wave resource.

NOTE 2 The estimation of the extent of validation using uncertainty propagation assumes that the model formulation used to represent the wave propagation processes is correct. It is not possible to use the numerical model to estimate the resultant uncertainty and if included it would have to be estimated using experience and reference to other data. However, it is considered that because the numerical model has been validated at the validation point then it is reasonable to assume that the model is adequate and the uncertainty due to the model formulation can be assumed to be negligible.

Where validation has been achieved using MCP methods (Clause 8), the extent of validation is limited to the validation point because there is no data available for extrapolation. Where model calibration (7.7) has been used, then the effect of calibration shall be included in the estimation of the uncertainty in the mean annual wave power. In general, model calibration will increase uncertainty and reduce the extent of validation because the calibration function is likely to vary with location in an unknown manner. The increase in uncertainty due to calibration can be estimated as the difference between the raw and calibrated mean annual wave power densities at the validation point; however, other methods can also be used.

In all cases the full method used to determine the extent of validation shall be justified and documented in the technical report (10.3).

NOTE 3 It is important to note that the numerical model output for locations outside these validation areas potentially could be equally or even more accurate than for locations within the validation areas; however, the accuracy cannot be assessed or verified without validation against reliable measured wave data. The portion of the study area over which validation is achieved can be increased by considering additional validation sites. Indeed, the use of multiple validation points is encouraged due to the increased confidence it provides of the skill of the numerical model.

[2] Numbers in square brackets refer to the Bibliography.

7.7 Model tuning and calibration

Model tuning refers to adjusting model parameters or settings (e.g. wave growth or dissipation terms such as bottom friction). Model calibration refers to adjusting model outputs to improve agreement with measurements.

Tuning of the model can involve adjusting model parameters to improve the accuracy of the model's predictions; however, the parameters shall not be assigned unreasonable values chosen solely to improve model accuracy. The magnitude of the chosen coefficients in the final version of the model shall be justified and, if possible, cross referenced with previous studies.

Measured data can also be used for calibration of the numerical model to improve the accuracy of the model's predictions. Calibration of the model involves modification of the model output based on a function derived from the difference between the raw model output and a sub-set of the measured data. If model calibration is used this shall be reported, together with details of the calibration functions used and the changes in model uncertainties obtained. Measured data that is used for model calibration shall originate from time periods that are distinct from and non-overlapping with the time periods from which the validation data sets are drawn.

8 Measure-Correlate-Predict (MCP) methods

8.1 General

MCP methods can be used for Class 1, Class 2 and Class 3 assessments, when assessment at discrete points is sufficient and provided the key resource parameters can be predicted with suitable accuracy to satisfy the validation requirements of 7.6. It is important to note that MCP methods provide no information regarding the wave field surrounding the measurement point and so the extent of validation shall be restricted to the location(s) of interest at which wave conditions are measured and the wave resource is subsequently estimated, which will henceforth be identified as MCP measurement location(s).

MCP techniques can be employed to estimate the wave energy resource at a MCP measurement location, and to help develop boundary conditions for use in wave modelling. The MCP approach involves measuring wave conditions at the MCP measurement location for a limited time period and then correlating these measurements with data from another location, henceforth called the MCP reference location, where reliable long-term wave data is available. The correlation functions between the wave data from the two locations are then used to estimate wave conditions at the MCP measurement location over a longer period. For Class 2 and Class 3 assessments, directional spectral data shall be obtained at both locations and characteristic parameters calculated as specified in 9.2. For Class 1 assessments, non-directional spectral data is sufficient, although directional data is preferred and recommended. MCP methods can only be used successfully when the wave conditions at the MCP measurement location and the MCP reference location are sufficiently correlated to each other. This implies that the two locations are subject to common wind fields and wave systems, and that the two locations are in reasonable proximity to each other.

NOTE Although MCP methods could theoretically be used to estimate directional wave spectra this has not yet been demonstrated in practice and the potential difficulties are unknown. Thus, MCP is currently limited to the estimation of characteristic parameters such as the omni-directional wave power, J, significant wave height, H_{m0}, and energy period, T_e. Progress towards application of MCP methods to estimate both characteristic parameters and directional spectra will be monitored during the maintenance phase of this document.

8.2 Procedures

The following procedures and reporting requirements shall be followed whenever MCP methods are used.

- The coordinates of the MCP reference location and the MCP measurement location shall be reported, together with the source and validity of the long-term and short-term wave data. The long-term data shall satisfy the same requirements as for the boundary data used for hydrodynamic modelling (see 7.3).
- The methods used to acquire and analyse all measured data shall be fully consistent with the requirements of 6.5. The methods detailed in Clause 9 shall be used to compute characteristic parameters from the measurements.
- Data-pairs of characteristic wave parameters shall be produced using concurrent wave data for the MCP measurement location and the MCP reference location.
- For each data pair type, a correlation function shall be generated using a (generation) sub-set of data-pairs. Any correlation function that maximizes the correlation between the two locations can be used. The correlation function used, together with the methodology for its production (including choice of the generation sub-set) shall be reported and justified.
- An estimate of the set of characteristic parameters describing the wave conditions for the MCP measurement location shall be produced using the correlation functions together with the long-term wave data for the MCP reference location.
- Validation data for the MCP estimate shall be produced using a (validation) sub-set of data-pairs that is independent from the generation sub-set. The validation data set shall satisfy the requirements of 7.6, and in particular shall include elements representing a sufficient range of wave conditions at the site of interest. In most cases, the generation and validation sub-sets can be assumed to be independent when all elements in the validation sub-set are separated by more than 24 h from all elements in the generation sub-set.
- The validity and associated uncertainty of the MCP estimates shall be calculated by comparing the estimated and measured wave data (characteristic parameters) at the MCP measurement location for the validation sub-set using the procedures, data and reporting requirements defined in 7.6 and 10.6.
- The resulting wave energy resource estimate, including its derivation, validity and uncertainty shall be reported as specified in 10.6. If the estimate could not be successfully validated, then the results of the resource assessment shall be clearly labelled as "provisional".

Although MCP methods have been used extensively in wind energy resource assessment, no generally accepted method of defining suitable correlation functions has been identified for wave energy resource assessment. Each correlation function proposed has advantages and disadvantages dependent on the required effort and the particular characteristics of the sites and resource. Furthermore, in many cases the correlation function is specifically tailored for the wind energy resource by filtering of the data-pairs used for correlation. MCP methods have not been used extensively for wave energy resource estimation and it would be inappropriate to try to define the type of correlation functions that should be used. This can change as additional experience is gained in the use of MCP for wave energy resource estimation.

9 Data analysis

9.1 General

The data analysis uses sea state data to produce characteristic parameters that are relevant to the performance of wave energy converters. If directional wave spectra, either measured or generated as specified in Clause 7, are available then the wave energy resource shall be analysed as specified in 9.2. However, for Class 1 assessments when only parameterized sea state data is available, the wave energy resource can be analysed as specified in 9.3. The methods specified in 9.2.1 to 9.2.5 shall also be used to calculate characteristic parameters from non-directional wave spectra. If no directional information is available, then the directionally resolved power and associated parameters can be omitted from the wave resource assessment.

Of primary importance is an estimate of the mean omni-directional energy flux per unit width, or wave power. In addition, the parameters for characterizing an individual sea state shall include:

- characteristic wave height,
- characteristic wave period,
- spectral width,
- direction of maximum directionally resolved wave power, and
- directionality coefficient.

The uncertainty of these estimates shall be quantified. Presentation of the spatial and temporal variability of these characteristic quantities is outlined in Clause 10.

If the resource is being investigated with respect to a particular WEC, sensitivity studies can suggest additional characteristic quantities beyond those recommended below. If this is the case, the appropriate characteristics should be calculated and archived. Conversely, if the WEC is shown to be insensitive to a particular characteristic parameter (e.g. direction of maximum directionally resolved wave power) then that parameter can be excluded from the assessment. However, in general this is not recommended because it can be determined in the future that the WEC is sensitive to a particular parameter and then it is possible that the relevant data is not available, or a different WEC can be considered in future.

9.2 Characterization using two-dimensional wave spectra

9.2.1 Overview

The sea state shall be characterised using the directional wave spectrum obtained at each grid point in time and space. For any given directional wave spectra, the variance density over the i^{th} discrete frequency and j^{th} discrete direction is S_{ij} .

Directionally unresolved characteristic quantities are more conveniently calculated by first transforming the two-dimensional frequency-directional variance densities to one-dimensional frequency variance densities according to the following formula:

$$S_i = \sum_j S_{ij} \Delta\theta_j \quad (7)$$

Spectral moments are used to calculate many characteristic sea state parameters. Spectral moments of the n^{th} order shall be calculated from the frequency variance density according to the formula:

$$m_n = \sum_i f_i^n S_i \Delta f_i \tag{8}$$

The numerical integration used to calculate spectral moments, or other integrated parameters such as the omni-directional or directionally resolved wave power, can influence the calculated parameters. The numerical integration method, range, and resolution shall be reported.

The following parameters shall be calculated at all grid points.

9.2.2 Omni-directional wave power

The omni-directional, or directionally unresolved, wave power is the time averaged energy flux through an envisioned vertical cylinder of unit diameter, integrated from the sea floor to the surface. The omni-directional wave power is calculated as:

$$J = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta \theta_j \tag{9}$$

and

$$c_{g,i} = \frac{\pi f_i}{k_i}\left(1 + \frac{2k_i h}{\sinh 2k_i h}\right) \tag{10}$$

The wave number associated with a given frequency and depth is implicitly defined through the dispersion relation:

$$(2\pi f_i)^2 = g k_i \tanh k_i h \tag{11}$$

9.2.3 Characteristic wave height

A spectrally derived estimate of the significant wave height shall be used to characterize the wave heights of a given sea state. It is calculated using the zeroth spectral moment according to the formula:

$$H_{m0} = 4\sqrt{m_0} \tag{12}$$

NOTE H_{m0} is not generally equal to the significant wave height defined as the mean of the highest third of waves, which is typically identified using the subscript *s* or *1/3*. This relationship is derived assuming waves are Rayleigh distributed.

9.2.4 Characteristic wave period

The preferred characteristic wave period is the energy period. The energy period is the variance-weighted mean period of the one-dimensional period variance density spectrum (i.e. variance spectral density as a function of period). The energy period shall be calculated using moments of the wave spectrum, defined by Formula (8), according to the following formula:

$$T_e \equiv T_{-10} = \frac{m_{-1}}{m_0} \quad (13)$$

Additional characteristic periods can also be calculated. The peak period is the inverse of the frequency associated with the maximum value of the wave spectrum:

$$T_p = 1/f_p \quad (14)$$

NOTE The peak period is very sensitive to spectral shape and it is not recommended that this period is used for defining the wave energy resource.

The average period of zero-crossing waves can be spectrally estimated according to the following formula:

$$T_z \cong T_{02} = \sqrt{\frac{m_0}{m_2}} \quad (15)$$

9.2.5 Spectral width

The spectral width characterizes the relative spreading of energy along the wave spectrum. The spectral width as defined as the standard deviation of the period variance density, normalized by the energy period:

$$\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{m_{-1}^2} - 1} \quad (16)$$

9.2.6 Directionally resolved wave power

9.2.6.1 General

Resolving the omni-directional wave power to a direction θ yields the time averaged energy flux through an envisioned vertical plane of unit width, extending from sea floor to surface, and with its normal vector parallel with θ. This directionally resolved wave power is the sum of the contributions of each component with a positive component in direction θ, and is calculated according to the formula:

$$J_\theta = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j \cos\left(\theta - \theta_j\right)\delta \qquad \begin{cases} \delta = 1, & \cos\left(\theta - \theta_j\right) \geq 0 \\ \delta = 0, & \cos\left(\theta - \theta_j\right) < 0 \end{cases} \quad (17)$$

The maximum value of J_θ is denoted as $J_{\theta_{J\max}}$ and represents the maximum time averaged wave power propagating in a single direction.

NOTE Only wave power with a positive component in the direction of resolution contributes to the directionally resolved wave power.

9.2.6.2 Direction of maximum directionally resolved wave power

The direction corresponding to the maximum value of J_θ should be taken as the direction of maximum directionally resolved wave power, $\theta_{J\max}$.

NOTE The peak wave direction is typically defined as the direction associated with f_p. The direction of maximum directionally resolved wave power, $\theta_{J\max}$ and peak wave direction, θ_p can deviate significantly from each other. It is not recommended to use the peak wave direction as it is highly unstable and does not represent the direction of wave energy propagation.

9.2.6.3 Directionality coefficient

A characteristic measure of the directional spreading of wave power is the directionality coefficient, which is the ratio of the maximum directionally resolved wave power to the omni-directional wave power. The directionality coefficient is calculated according to the following formula:

$$d = \frac{J_{\theta_{J\max}}}{J} \quad (18)$$

9.2.7 Wave system partitioning

The wave field at any given time and place can be composed of a collection of wave systems arriving from specific wind events that are occurring, or have occurred, somewhere on the ocean surface. Partitioning of measured and modelled wave spectra allows the distinct wave systems comprising the bulk wave field to be analyzed. Characteristic parameters can be calculated for each of the partitioned wave systems and the uncertainty can then be estimated based upon these refined characteristic parameters (9.5). This approach will increase confidence in the validated model results. If wave system partitioning is employed in the wave resource study, the methodology used and results shall be documented in the technical report (10.3).

9.3 Estimation of wave power using parameterized sea states

A Class 1 reconnaissance assessment can be performed using parameterized sea state data. If parameterized records are utilized, it is likely that sea state data will be limited to characteristic wave height, the characteristic period, and possibly a characteristic direction (i.e. the direction associated with the principal component of the wave spectrum). Calculation of the wave power requires assumption of a spectral shape scaled using the significant wave height, characteristic period and water depth. The selection of the spectral shape should be based on analysis of regional wave data and shall be reported and justified.

By assuming a spectral shape (e.g. Pierson-Moscowitz), a relationship between the energy period and either the peak or zero-crossing period can be established.

NOTE 1 For example, for the P-M spectrum, $T_e = 1{,}20\,T_z = 0{,}857\,T_p$.

NOTE 2 For Wallops and JONSWAP type spectra, $T_e \cong T_{1/3}$ (see [14])

By assuming that all of the variance of the sea state is propagated at the group velocity associated with the estimated energy period, the wave power can be estimated according to the following formula:

$$J = \frac{\rho g}{16} c_g \left(T_e, h\right) H_{\mathrm{m0}}^2 \tag{19}$$

The spectral width shall be calculated based on the assumed spectral shape.

If no directional information is available then the directionally resolved power and associated parameters can be omitted from the wave resource assessment.

9.4 Aggregation and statistics of results

9.4.1 General

Annual and monthly statistics for all wave energy resource parameters shall be calculated. The statistics shall include:

- Mean
- Standard deviation
- Median or 50th percentile
- 10th percentile
- 90th percentile
- Maximum value
- Minimum value
- Monthly variability

9.4.2 Mean

The mean value, μ, for each parameter, p, shall be calculated using (20)

$$\mu = \frac{1}{N} \sum_{k=1}^{N} p_k \tag{20}$$

NOTE The mean of the direction of maximum directionally resolved wave power needs to be considered carefully because the angle wraps from 360° to 0°. The mean direction can be obtained by considering each direction as a vector quantity.

$$\mu_\theta = \mathrm{atan}\left[\frac{\sum_{k=1}^{N} p_i \sin(\theta_k)}{\sum_{k=1}^{N} p_i \cos(\theta_k)}\right]$$

9.4.3 Standard deviation

The standard deviation, σ, for each parameter, p, shall be calculated using Formula (21)

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}\left(p_k - \mu\right)^2} \tag{21}$$

9.4.4 Percentiles

The x^{th} percentile for each parameter, p, shall be calculated using linear interpolation between the two nearest ranked values, where the rank, n, is calculated using Formula (22).

$$n = \frac{N}{100}x + \frac{1}{2} \tag{22}$$

The 50$^{\text{th}}$ percentile is also referred to as the median value.

9.4.5 Monthly variability

The monthly variability statistic, MV, provides a convenient measure of the variability of the mean monthly wave resource over a typical year. For any parameter p, $MV(p)$ is defined as

$$MV(p) = p_{\max} - p_{\min} \tag{23}$$

9.5 Uncertainty of the resource assessment

The purpose of the uncertainty analysis is to quantify the uncertainty of the wave resource estimates that are produced. Table 7 shows the categories of uncertainty that shall be considered and reported in any wave resource assessment.

Table 7 – Uncertainty categories

	Uncertainty category
u_D	Measurement uncertainty
u_M	Modelling uncertainty
u_{LT}	Uncertainty due to long-term variability
u_C	Combined uncertainty

The measurement uncertainty shall describe all uncertainties associated with the measured wave data that is used in the resource assessment for validation of the numerical model output or for use in MCP; this includes uncertainties related to measuring properties of the physical environment and uncertainties related to deriving spectra and characteristic sea-state parameters from the measured data. The modelling uncertainty shall describe all uncertainties associated with either the wave model outputs, or MCP outputs, or both, on which the resource estimates are based. The long-term uncertainty is related to the long-term variability of the wave climate over the study region and the possibility that the period chosen for numerical modelling/analysis is not fully representative of the long-term wave climate, or the wave climate over the life of a wave energy project.

Where applicable, uncertainties should be calculated and combined using the procedures defined in either IEC/ISO Guide 98-3 or [10], or both. All methods, procedures and assumptions used to calculate the uncertainty of the wave resource assessment shall be justified and clearly reported. Further details on the evaluation of measurement uncertainty as applicable to wave energy resource estimation are provided in Annex B. Further discussion of long-term uncertainty of the wave energy resource is provided in Annex D.

NOTE Calculation of the uncertainty in the resource assessment is highly complex and it is considered that currently there are not enough definitive procedures used for Clause 9 to be overly prescriptive. It is expected that as experience in gained in calculating the uncertainty of the resource assessment that further details can be added to 9.5 in future editions of this document.

10 Reporting of results

10.1 General

A technical report shall be prepared to document the methodologies employed in the study and to present a summary of the main results. Information on the spatial variation of the wave energy resource over the study area and the temporal variation at specific locations within the study area shall be reported. The reporting formats described below are recommended in order to facilitate comparison with other resource assessment studies. The study results shall also be archived in a digital database to ensure that they are available to future studies and projects. For example, the results of a Class 1 reconnaissance resource assessment shall be archived for use in future studies to assess the feasibility or design of a project within the study area.

In cases where MCP methods are used to estimate the resource at one or more specific locations, no information on the spatial variation of the resource between these locations will be available; hence 10.5 does not apply. All of the locations where MCP methods have been used to estimate the resource shall be treated as study points (see 10.2 and 10.6).

10.2 Selection of study points

A number of specific locations within the study area shall be selected to serve as study points. Each study point is a single location at which the wave resource is of interest and detailed wave resource characteristics are produced and reported. When MCP methods have been used, all MCP measurement locations shall be treated as study points. When wave modelling has been used, the study points will normally be coincident with selected model grid points. For these locations, the wave energy resource shall be characterized and reported in greater detail. A sufficient number of study points shall be selected such that any significant spatial variability in the resource is represented. The extensive data retained for these study points (i.e. time history of the directional wave spectrum) can be considered for use as boundary conditions in subsequent studies. If only one study point is identified within the study area, the wave climate at this point should be typical of the study area.

NOTE Typically there will be more than one study point in a wave resource assessment.

10.3 Technical report

A written technical report shall be prepared to document the methodologies employed in the resource assessment and present a summary of the results. It shall include information on the following topics:

- class and purpose of the resource assessment;
- intended resolution and level of uncertainty;
- description of the study area;
- summary of raw data used as the basis of the assessment, including sources;
- description of modelling methods;
- description of MCP methodology (if MCP methods are used);

- preparation of model inputs;
- model calibration and tuning;
- data used for model validation;
- model validation procedures and validation results;
- analysis of the model outputs;
- estimation of long-term wave resource properties;
- presentation of results;
- underlying assumptions;
- assessment of uncertainty; and
- discussion of limitations and factors not taken into account.

Information on other topics that are relevant to the resource assessment and necessary to gain a full understanding of the methodology and results, should also be included.

It is recommended that a short (2 to 4 page) summary of the key findings of the resource assessment is also produced, converting some of the more technical language into information that could be readily understood by a non-technical user.

10.4 Digital database

The main results/outputs of the resource assessment shall be stored in an accessible, geo-referenced, digital database. The main purpose of the database is to preserve the outputs of the resource assessment for future uses. The database shall include information for each model grid point (or MCP measurement site) where reliable estimates of the wave resource have been obtained. However, in some cases it can be necessary to exclude information for parts of the study area where reliable predictions could not be obtained due to limitations associated with the methodology, the boundary conditions, and the abilities of the wave model, the model resolution, or some other factor. Each location shall be clearly identified by the latitude, longitude and water depth below mean sea level. The Geographic Coordinate Reference System should be specified. The database shall include, for each location, full time histories for all wave resource parameters derived, in accordance with Clause 9. In addition, for Class 2 and Class 3 assessments, and Class 1 assessments where applicable, the full directional wave spectrum generated by the wave propagation model at every time step shall be stored for all study points. Where MCP methods are used in the resource assessment, the resulting wave resource parameter time-histories shall be stored in the digital database.

Where a numerical wave propagation model is used in the resource assessment, the time-varying boundary conditions, wind fields and current fields (if applicable) used to drive the numerical wave propagation model shall also be archived in the digital database. If possible, the measurements used to validate the numerical model should also be archived in the database. Where MCP methods are used, the data from the MCP reference location shall be archived in the database.

To facilitate the preparation of maps illustrating the spatial variation of the wave energy resource and graphs illustrating the temporal variation, it is recommended that the digital database be organized and formatted so that it can be integrated with or linked to a Geographical Information System (GIS).

NOTE GIS refers to a computer program designed to map and analyse multiple geo-referenced spatial data sets.

10.5 Presentation of regional information

Where information on the spatial variation of the resource parameters is available (i.e. in all cases except when MCP methods are used), a set of maps shall be prepared and included in the report to illustrate the spatial variation of key wave resource parameters across the study area. The required and recommended parameters to be mapped are summarized in Table 8. The resolution of the maps shall be consistent with the resolution of the models used to generate the data. For either large or complex areas, or both, several maps at different scales can be needed to ensure that the spatial variation in resource parameters throughout the study area can be clearly displayed. Colour contour maps, like the image in Figure 3, are recommended; however, alternative presentations are acceptable.

Table 8 – Summary of wave energy resource parameters to be archived and mapped

●Required ○Recommended

Parameter	Units	Class of assessment		
		Reconnaissance	Feasibility	Design
Mean water depth	m	●	●	●
Annual mean omni-directional wave power	kW/m	●	●	●
Extent of successful model validation	n/a	●	●	●
Monthly variability of omni-directional wave power	kW/m		○	○
Annual mean significant wave height	m	○	○	○
Monthly variability of significant wave height	m		○	○
Annual mean energy period	s	○	○	○
Monthly variability of energy period	s		○	○
Annual mean spectral width	-		○	○
Monthly variability of spectral width	-			○
Annual mean of maximum directionally resolved wave power	kW/m		○	○
Monthly variability of maximum directionally resolved wave power	kW/m			○
Annual mean direction of maximum directionally resolved wave power	deg		○	○
Monthly variability of direction of maximum directionally resolved wave power	deg			○
Annual mean directionality coefficient	-		○	○
Monthly variability of directionality coefficient	-			○

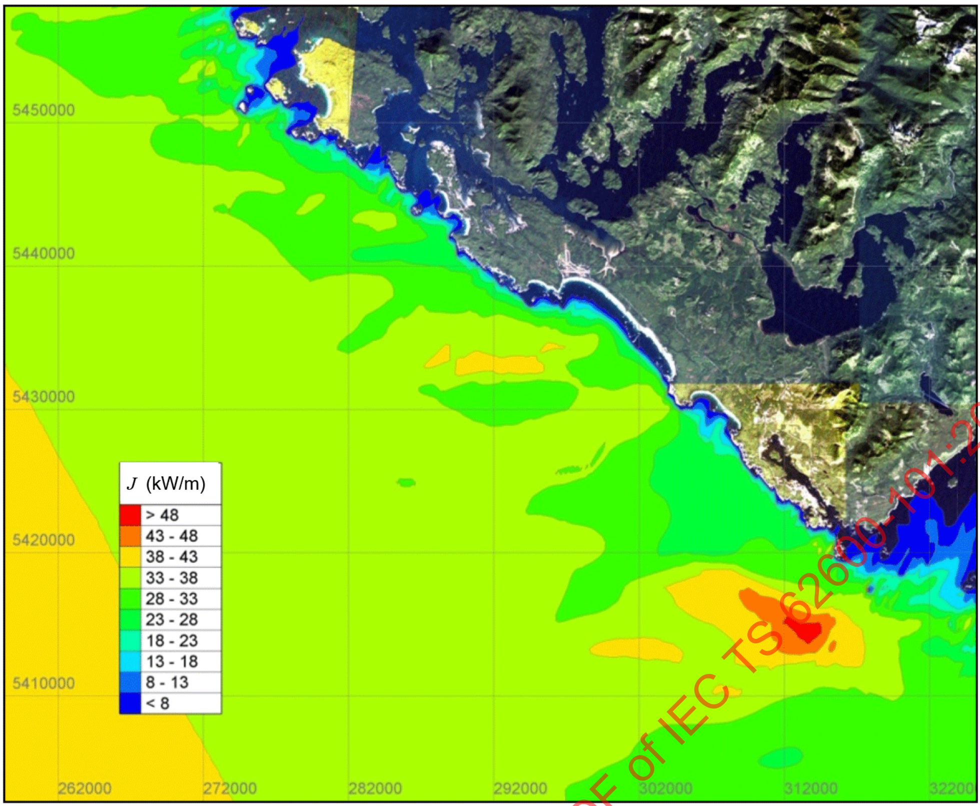

Figure 3 – Example map of mean annual wave power

NOTE It can be useful to prepare animations depicting the temporal and spatial variation of key resource parameters. These animations can depict the evolution of monthly mean values over a representative year or can depict temporal and spatial variations over shorter time scales.

10.6 Presentation of information at study points

Additional figures shall be prepared and included in the report to further illustrate key properties of the resource at one or more study points. The following figures are required, as applicable for the Class of resource assessment (Table 8).

- Annual scatter table showing the proportional frequency of occurrence of sea states, parameterized in terms of the significant wave height, H_{m0}, and energy period, T_e. The dimensions of each bin in the scatter tables shall be no larger than 0,5 m and 1,0 s. The upper and lower bounds of the scatter tables should be selected such that a minimum of 99,9 % of sea states are included. An example is presented in Figure 4. Bins that contain data but have a frequency of occurrence of less than 0,01 % shall be represented by an asterix followed by the number of occurrences, e.g. *2 represented as bin with 2 occurrences.
- Either graphical or tabular presentation, or both, of the annual variation of the long-term monthly mean values of the following parameters:
  - Significant wave height, H_{m0};
  - Energy period, T_e;
  - Omni-directional wave power, J (an example is presented in Figure 6);
  - Maximum directionally resolved wave power, $J_{\theta_{J\max}}$;

- Annual wave rose depicting the long-term joint distribution of:
  - maximum directionally resolved wave power, $J_{\theta_{J\max}}$, and the direction of maximum directionally resolved power, $\theta_{J\max}$. (an example is presented in Figure 5).

The following optional illustrations are recommended to further illustrate additional attributes of the wave resource at reference sites.

- Directionally resolved annual scatter tables showing the proportional frequency of occurrence of sea states, parameterized by H_{m0} and T_e, for various directional sectors. The dimensions of each bin in the scatter tables shall be no larger than 0,5 m and 1,0 s. The maximum size of each directional window shall be 45°; however a finer discretization of direction is preferred. It is recommended that sea states be partitioned into directional windows based on the direction of maximum directionally resolved wave power. The method used to partition sea states into directional windows shall be documented.
- Either graphical or tabular presentation, or both, of the annual variation of the long-term monthly mean values of the following parameters:
  - Direction of maximum directionally resolved wave power, $\theta_{J\max}$;
  - Directionality coefficient, d_θ;
  - Spectral width, ϵ_0;
- Graphical presentation of the annual and monthly cumulative distributions of the following parameters:
  - Significant wave height, H_{m0};
  - Energy period, T_e;
- Omni-directional wave power, J (an example is presented in Figure 6);
  - Maximum directionally resolved wave power, $J_{\theta_{J\max}}$;
  - Direction of maximum directionally resolved wave power, $\theta_{J\max}$;
  - Directionality coefficient, d_θ;
  - Spectral width, ϵ_0;

In addition, the temporal fluctuation of the following parameters over selected periods can be plotted for illustrative purposes:

- Significant wave height, H_{m0};
- Energy period, T_e;
- Omni-directional wave power, J;
- Maximum directionally resolved wave power, $J_{\theta_{J\max}}$
- Direction of maximum directionally resolved wave power, $\theta_{J\max}$
- Directionality coefficient, d_θ
- Spectral width, ϵ_0.

The time histories should be plotted at the maximum available resolution for a single representative year. The scale of the plots shall be sufficient so that the temporal variations in the records can be clearly discerned.

		Energy period (s)											
		<5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	>14	%
Significant wave height (m)	>5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01
	4,5-5	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,01
	4-4,5	0,00	0,00	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,02
	3,5-4	0,00	0,00	0,00	0,01	0,04	0,03	0,00	0,00	0,00	0,00	0,00	0,07
	3-3,5	0,00	0,00	0,00	0,12	0,22	0,09	0,00	0,00	0,00	0,00	0,00	0,43
	2,5-3	0,00	0,00	0,04	0,56	0,81	0,36	0,00	0,00	0,00	0,00	0,00	1,76
	2-2,5	0,00	0,00	0,37	1,76	2,03	0,80	0,00	0,00	0,00	0,00	0,00	4,97
	1,5-2	0,01	0,01	1,74	4,91	4,59	1,36	0,02	0,00	0,00	0,00	0,00	12,65
	1-1,5	0,06	0,32	5,19	11,74	7,76	1,97	0,05	0,00	0,00	0,00	0,00	27,08
	0,5-1	0,09	1,82	12,86	16,34	6,89	3,18	0,08	0,01	0,00	0,00	0,00	41,28
	0-0,5	0,09	0,46	3,61	2,37	2,50	2,65	0,05	0,00	0,00	0,00	0,00	11,74
	%	0,25	2,61	23,81	37,81	24,85	10,45	0,21	0,02	0,00	0,00	0,00	100,00

Figure 4 – Example of a scatter table summarizing a long-term wave climate in terms of H_{m0} and T_e

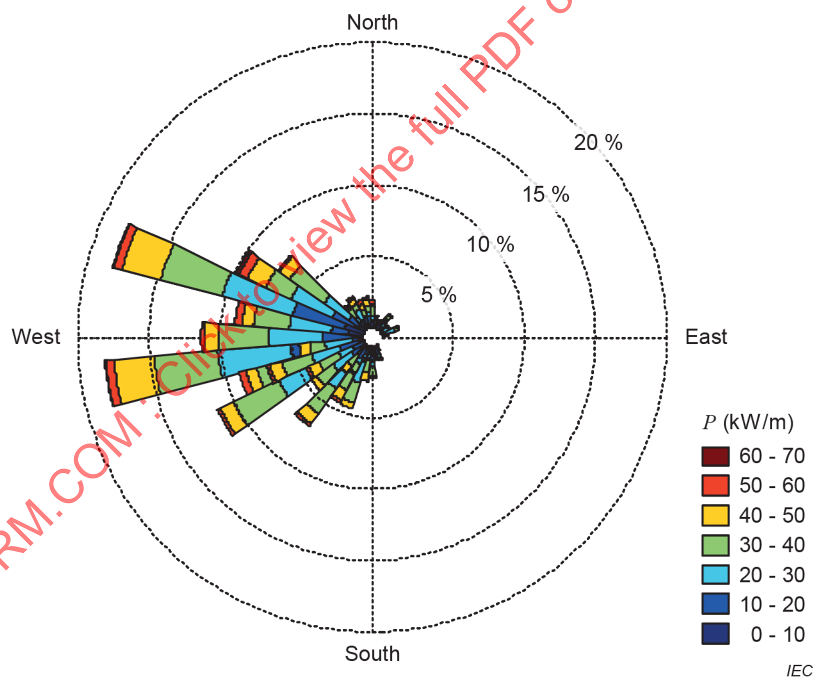

Figure 5 – Example of a wave power rose

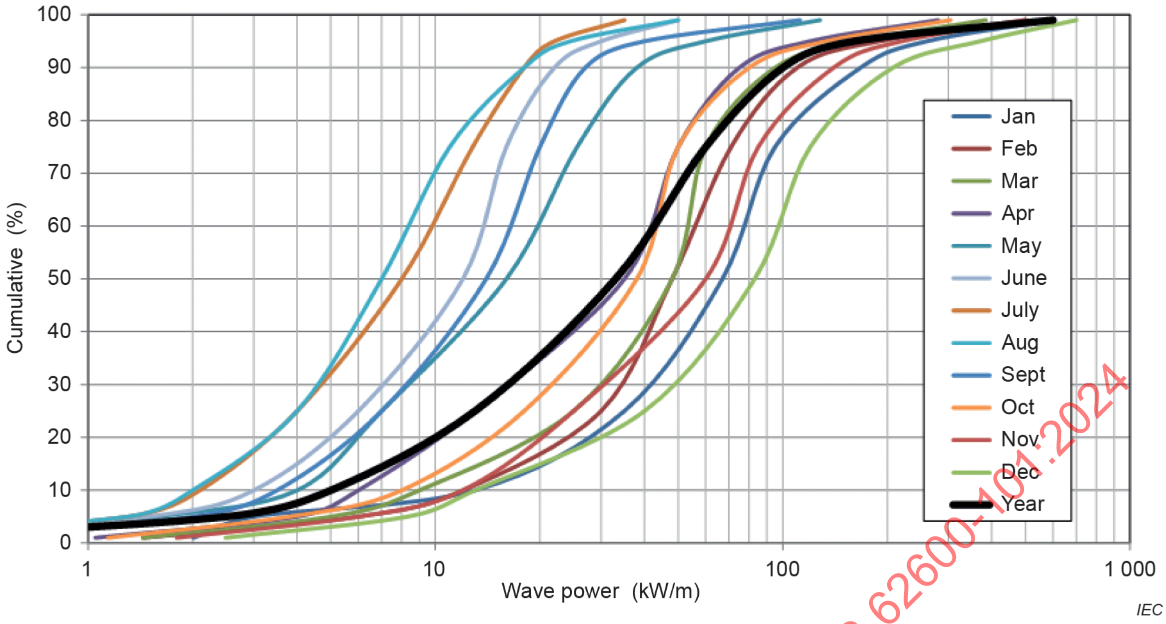

Figure 6 – Example plot showing the distribution of wave power for different months

Annex A
(normative)

Calculation of annual energy production (AEP)

A.1 Wave energy converter AEP at primary site

The annual energy production (AEP) of a WEC at the specific site shall be calculated by applying the methodology described in this Annex. This methodology uses the wave energy resource data, generated with the methodology defined by this document, in conjunction with the capture width of the particular WEC, as estimated by the methodology defined in IEC TS 62600-100. The AEP shall be calculated assuming an availability of 100 %. The methodology for determining capture width at the primary site is covered in its full form in IEC TS 62600-100, and this Annex is provided to complement this by providing the annual energy production methodology for a second site.

A.2 Standard methodology

Where a time series of the wave energy resource is available the AEP shall be calculated in accordance with mathematical Formula (A.1). A minimum of 10 years of wave energy resource data should be used for the calculation of the AEP. If the AEP is calculated with less than 10 years of wave energy resource data this shall be noted explicitly. The wave energy resource data set shall be unbiased, containing the number of sea-states for each month proportional to the number of days in the month.

$$AEP = \frac{T}{n} \cdot \sum_{i=1}^{i=n} C_{W,i} \cdot J_i \qquad \text{(A.1)}$$

where T is the average length of a year which is 8 766 h, n is the number of sea states, $C_{W,i}$ is the discrete capture width, and J_i is is omni-directional measured wave energy flux per unit width per bin.

The power production shall be calculated for each individual sea-state using linear interpolation of the capture width matrix. If not available, the capture width matrix can be regenerated by dividing the bin values in the power matrix by the wave power at the centre of each bin using the recorded spectral shape represented shape as determined in 9.3 of IEC TS 62600-100:—.

NOTE It is in a WEC developer's interest to ensure that the power matrix is appropriate for all possible sea-states. In particular, power production at high significant wave heights can affect whether the WEC will be in survival mode where power production is zero, or whether it can continue to produce power.

A.3 Alternative methodology

If the wave energy resource data is only available as a scatter diagram then the AEP shall be calculated using the power production at the centre of each bin in the scatter diagram in accordance with Formula (A.2) subject to the condition in Formula (A.3). The capture width of the bin shall be calculated as specified in IEC TS 62600-100. The contribution of each bin in the scatter diagram to the AEP shall be weighted based on the frequency of occurrence of the particular bin as defined in the scatter diagram. If the wave resource scatter diagram has different bin sizes to the capture width matrix, then two-dimensional linear interpolation of the capture width matrix can be performed to align the bins of the two matrices.

$$AEP_{(ALT)} = T \cdot \sum_{i=1}^{i=N} C_{W,i} \cdot J_i \cdot f_i \tag{A.2}$$

$$\sum_{i=1}^{i=N} f_i = 1{,}0 \tag{A.3}$$

A.4 Completeness of the capture width matrix for AEP

The AEP shall be calculated in two ways, one designated "AEP-measured", and the other "AEP-interpolated". AEP-measured is calculated assuming zero capture width in all empty bins of the capture width matrix. AEP-interpolated is calculated assuming the capture width of empty bins is equal to the average of adjacent filled bins.

Both AEP-measured and AEP-interpolated shall be reported, The AEP-measured shall be labelled as "incomplete" when calculations show that the AEP-measured differs from the AEP-interpolate by more than 5 %. In these circumstances the capture width matrix should be considered as inadequate for calculation of the AEP and the requirement for more extensive testing highlighted.

A.5 Wave energy converter AEP at a second location using measured assessment data

A.5.1 Connection to 62600-100

Steps E.1 through E.11 from Annex E of IEC TS 62600-100:— shall be completed first.

A.5.2 Calculate AEP at Location 2 using complemented capture width matrix and Location 2 resource data

Using the capture width matrix (E.11 of IEC TS 62600-100:—) and the Location 2 wave resource data (E.5.3 of this document) the AEP shall be calculated using either the standard (A.2) or alternative (A.3) methods described in this document.

Separate AEP contributions shall be reported for bins of the capture width matrix which are:

- Measured bins: calculated from performance measured at Location 1 as reported in E.11 and quality assured as per E.10 in IEC TS 62600-100:—.
- Interpolated or extrapolated bins: as per E.11.2 of IEC TS 62600-100:—.
- Modelled bins: numerically (E.11.3 IEC TS 62600-100:—) or physically (E.11.4 IEC TS 62600-100:—).

The contribution of each of the above categories of bins shall be reported both as an absolute energy value and also as a percentage of the total AEP. See Annex F of IEC TS 62600-100:— for an example of this procedure.

A.5.3 Assessment of confidence

Some of the uncertainty related to the AEP at Location 2 is indicated by the percentage of the energy based on directly measured data bins at Location 1.

The more of the AEP at Location 2 is based on directly measured data bins at Location 1, it indicates that the WEC will operate in wave conditions similar to those in which its performance was assessed at Location 1.

The uncertainty of the AEP is related to:

- The quality of the performance and wave data measured at Location 1.
- The quality of the wave resource data gathered from Location 2.
- The accuracy and quality of the complemented data.

NOTE Annex B of this document provides guidance for the uncertainty of AEP calculations. Further sources of uncertainty are described in Clause A.7.

A.6 Example Analysis

A.6.1 Connection to 62600-100

Steps F.1 through F.10 from IEC TS 62600-100:— shall be completed first.

A.6.2 Calculate AEP at Location 2 using complemented capture width matrix and Location 2 resource data

Using the complemented Wavestar prototype capture width matrix for Location 2, the AEP is estimated using the resource data at Location 2 as specified in E.12 of IEC TS 62600-100:—. The wave data set was trimmed to remove bias, so that the ratio of the records in each month to the total number records is the same as the ratio of the number of days in that month to the total number of days in a year. The trimmed data-set contains the equivalent of 14 complete years of wave records.

The AEP was estimated using both the standard (A.2) and alternative (A.3) methodologies:

Using the standard method: AEP = 63,78 MWh

Using the alternative method: AEP = 64,06 MWh

The AEP contribution of the measured, modelled, fitted bins in the capture width matrix were calculated based on the alternative methodology. The breakdown of contributions is shown in Table A.1.

Table A.1 – Table of AEP contributions

Bins	AEP MWh	AEP % of total
All bins	64,06	100
Measured	63,74	99,5
Fitted	0,17	0,3
Modelled	0,16	0,3

A.6.3 Assessment of confidence

More than 99 % of the AEP is directly calculated based on observations from Location 1. This large percentage provides confidence in the estimate. Even though a significant number of bins in the complemented capture width matrix are modelled, they contribute only a small percentage of the overall AEP.

A.7 Sources of uncertainty for AEP at Location 2

A.7.1 Comparisons between Location 1 and Location 2

The differences between the locations can cause uncertainty in the calculation of the AEP at Location 2 if not properly accounted for in the capture width matrix. The available resources at the two locations are determined by this document; they should identify the following differences as a minimum:

- Wave resource characteristics.
- The bathymetry.
- Tidal and current conditions.
- Weather condition.

The greater the differences between the above conditions, the greater the uncertainty in the prediction of the AEP at Location 2.

A.7.2 Bathymetry and water depth

The two locations will not necessarily have the same bathymetry and water depth. The influence of depth on the AEP calculation at Location 2 should be included as part of the report.

The omni-directional wave power can be calculated from the wave spectrum by Formula (9).

The group velocity $c_{\mathrm{g}i}$ is a function of water depth. Significant changes in water depth can significantly change the wave energy flux as function of wave period.

NOTE The effect of water depth can generally be divided into:

Deep water $h > \lambda/2$.

Intermediate $\lambda/2 > h > \lambda/20$.

Shallow $h < \lambda/20$.

The bottom topography could be different at Location 2, which could either affect the wave energy or direction (or both) to the WEC. Such differences should be captured and presented in the Metocean study (E.6 of IEC TS 62600-100:—), and for Locations 1 and 2.

A.7.3 Current

Current can be a result from tidal changes, ocean circulation, river outfall (or inflows), wind driven current, or any combination. Current can influence the wave height, period, and direction. The current should be recorded at the two locations and should be compared to determine the type of current and significance on the wave resource and WEC performance.

For example, attenuator style WECs could respond differently at Location 2 compared to Location 1 if currents impact the orientation of the WEC to the waves during certain operational times. A different mooring system can be required to maintain the position of the WEC.

NOTE If the wave resource at a location is influenced by currents, this could impact WEC orientation and response, which would, in turn, impact power performance assessment (IEC TS 62600-100) and mooring design (IEC 62600-10).

A.7.4 Wave spectrum

IEC TS 62600-100 uses the wave spectrum to determine the available wave power. This method can lead to inaccurate results if not completely understood. WECs have been deployed in some areas with bi-modal spectra. This is a result of different wave types; wind driven and swell perhaps coming from different directions. The wave spectrums in the bins contributing significantly to the AEP should be compared for differences between Location 1 and Location 2. The differences should be included in the prediction of the AEP at Location 2. Refer to Clause 9 of this document for guidance on characterization of wave spectra.

A.7.5 Wave direction and short-crested waves

Wave direction should be documented, as stated in Clause E.5 of IEC TS 62600-100:—, using wave direction rose plots for Location 1 and Location 2.

Some WECs might be sensitive not only to wave directions, but also to the nature of spreading creating the short-crested waves.

Characterization of the directionality of spectra is discussed in 9.2. The directional characteristics of the binned resources of Locations 1 and 2 should be compared, as any differences can affect the AEP at Location 2 for WECs sensitive to wave directionality.

A.7.6 Wave converter modifications

Wave energy converters are to be designed to IEC TS 62600-2. The design conditions at Location 2 can require changes to the WEC, which have the potential to impact the AEP at Location 2, such as:

- Mooring system.
- Submarine cables.
- Deployment hardware.

The changes to the ancillary components should be documented. A comparison between the WEC at the two locations should be made. Changes to the WEC operation at Location 2 should be documented with the potential change in the AEP and possible implications in the operation of the WEC.

Annex B
(normative)

Evaluation of measurement uncertainty

B.1 General

The specification of the wave energy resource shall include an estimate of its uncertainty. The estimate shall be based on ISO/IEC Guide 98-3.

Following ISO/IEC Guide 98-3, there are two types of uncertainty: category A, the magnitude of which can be deduced from measurements, and category B, which are estimated by other means. For both categories, uncertainties are expressed as standard deviations and are denoted standard uncertainties.

B.2 Uncertainty analysis

The wave energy resource is defined by a multitude of parameters, for each of which an uncertainty can be calculated. The choice of parameters for which the uncertainty should be calculated depends on the purpose of the wave energy resource analysis. However, as a minimum, the uncertainty of the significant wave height, energy period and estimated annual average wave power shall be calculated.

Uncertainties in measurements and model outputs are converted to uncertainties in these parameters by means of sensitivity factors.

Table B.1 contains a minimum list of uncertainty components that shall be included in the uncertainty analysis.

Table B.1 – List of uncertainty components

Measured/model parameter $MAEP = \frac{T}{n} \cdot \sum_{i=1}^{i=n} C_{W,i} \cdot J_i$	**Uncertainty component**	**Uncertainty category**
Significant wave height	Wave measuring instrument or model calibration	B
	Influence of moorings or other local effects on WMI	B
	Data acquisition system (e.g. sampling duration)	B
Energy period	Wave measuring instrument or model calibration	B
	Influence of moorings or other local effects on WMI	B
	Data acquisition system (e.g. sampling duration, windowing)	B
	Strength of marine currents	B
Annual mean wave power	Water depth	A / B
	Water density	A / B
	Interannual variability of significant wave height or energy period	A

Where category A uncertainties are used the measurement and analysis methods shall be described. Where category B uncertainties are used the means by which the standard deviation has been determined shall be described.