IEC TS 62600-100

Edition 2.0 2024-11
REDLINE VERSION

TECHNICAL SPECIFICATION

Marine energy – Wave, tidal and other water current converters – Part 100: Electricity producing wave energy converters – Power performance assessment

colour inside

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC TS 62600-100:2012. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC TS 62600-100 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 2012. This edition constitutes a technical revision.

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

a) Incorporation of IEC TS 62600-102 as a series of annexes in this document
b) Removal of the computation of annual energy production. This has been moved to IEC TS 62600-101.
c) Modification to the list of terms definitions, symbols and units.
d) Modification of the reporting section to align with IEC TS 62600-200

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

Draft	Report on voting
114/537/DTS	114/554/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- withdrawn, or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 publication 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 part of IEC 62600, which is a Technical Specification, provides performance assessment methods for wave energy ~~Conversion Systems (WECS)~~ converters. A wave energy converter is a device which generates electricity using the action of water waves and delivers electricity to an electrical load.

Wave energy industry development is transitioning from preliminary stages to commercial production stages. Validated data gathering and processing techniques are important to improve existing technologies. This document will be subject to changes as data are collected and processed from testing of wave energy converters.

The expected users of the document include:

- Device developers who want to validate the performance of their wave energy converter.
- Investors who want to assess the performance of a device developer's wave energy converter.
- Project developers who want to assess the performance of their project against manufacturer's claims.
- Surveyors contracted to carry out the assessment.
- Conformity assessment, test laboratories, and certification.
- Project developers – income, return on investment
- Device developers – performance of device
- Utilities and investors – reliability/predictability of supply, return on investment
- Policy-makers and planners – usage of seascape, optimisation of resource, power supply issues
- Consultants to produce resource data/due diligence – compatible/readable data format

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 100: Electricity producing wave energy converters – Power performance assessment

1 Scope

Wave Energy Converters (WEC) are designed to operate efficiently at different locations. Systematic methods are used to evaluate the power performance of a WEC at a second location (hereinafter Location 2) based on power performance assessment at a first location (hereinafter Location 1). The degree of similarity of the measured WEC (WEC 1) and the metocean conditions at Location 1 to the secondary WEC (WEC 2) at Location 2 determine the methodology and the applicability of this document.

~~This part of IEC 62600, which is a Technical Specification, provides a method for assessing the electrical power production performance of a Wave Energy Converter (WEC), based on the performance at a testing site.~~

This document applied in conjunction with the IEC Technical Specification on wave energy resource assessment and characterization (IEC TS 62600-101), provides a method for estimation of the mean annual energy production of a WEC, assessing the electrical power production performance of a single, non-array, wave energy converter, at Location 2 based on the performance at Location 1.

The scope of this document includes:

a) All wave energy converters that produce electrical power from wave energy.
b) All sea resource zones (near and offshore, deep and shallow water).
c) Capture width matrix transposition from one location to another.
d) Limitation on the changes that are allowed to the WEC and the specification of the location.
e) Wave data required at Location 2, as a minimum the requirements found in IEC TS 62600-101.
f) Development of the capture width matrix at Location 2.
g) Validation of the capture width matrix at Location 2.
h) Assessment of uncertainties in the derived performance parameters at Location 2.
i) Requirements for the allowable power performance transfer by geometric, kinematic and dynamic similarity.
j) Requirements for the allowable incorporation of additional empirical model data.
k) Requirements for the allowable incorporation of additional numerical model data.
l) The document applies to commercial scale wave energy converters that are:
   1) compliantly moored.
   2) tautly moored.
   3) bottom mounted.
   4) shore mounted.

The scope of this document does not include:

~~a) WECs that produce other forms of energy unless this energy is converted into electrical energy;~~

a) Wave energy converters that produce nonelectrical energy.
b) Resource assessment.
c) Scaled devices in test facilities (tank or scaled sea conditions) where any scaling would ~~need to~~ be carried out to extrapolate results for a full-scale device.
d) Power quality issues.
e) Environmental issues.
~~f) power matrix transposition from one location to another.~~
f) Operation and maintenance.
g) Annual energy production (AEP).

This document provides a systematic method which includes:

- measurement of WEC ~~power output~~ capture width in a range of sea states.
- ~~WEC power matrix development;~~
- transposition of capture width from one location to a second location.
- an agreed framework for reporting the results of ~~power~~ capture width and wave measurements.
- estimate of the capture width of a modified WEC at Location 2. This work would include the development of parameters for the modified WEC for the second location.

This document provides:

- guidance on the use of observations from Location 1.
- methods for assessing and reporting the validity of numerical and physical models.
- limits on the permissible changes to the WEC between Locations 1 and 2.
- limits on the use of data fitting techniques, and
- requirements for reporting.

The wave power industry is at an early stage of development. There is little practical experience with field-scale WECs deployment. Because of this, the present document will be subject to change as more data is collected and experience with wave energy converters develops.

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 60044-1, *Instrument transformers – Part 1: Current transformers*~~

IEC 60688, *Electrical measuring transducers for converting AC* and DC. *electrical quantities to analogue or digital signals*

~~IEC 61000-3 (all parts), *Electromagnetic compatibility (EMC) – Part 3: Limits*~~

IEC 61869-1, *Instrument transformers – Part 1: General requirements*

IEC 61869-2, *Instrument transformers – Part 2: Additional Requirements for current transformers*

IEC 61869-3, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers*

IEC TS 62600-3, *Marine energy – Wave, tidal and other water current converters – Part 3: Measurement of mechanical loads*

IEC TS 62600-101:2015, *Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization*

IEC TS 62600-103, *Marine energy – Wave, tidal and other water current converters – Part 103: Guidelines for the early stage development of wave energy converters – Best practices and recommended procedures for the testing of pre-prototype devices*

ISO/IEC Guide 98-1~~:2009~~, *Uncertainty of measurement – Part 1: Introduction to the expression of uncertainty in measurement*

ISO/IEC Guide 98-3~~:2008~~, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995)

ISO 8601, *Data elements and interchange formats – Information interchange – Representation of dates and times*

ISO 19901-1, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating considerations*

~~*EquiMar: Protocols for the equitable assessment of marine energy converters, Part II,* Chapters I.A.1 through I.A.5., Editors: David Ingram, George Smith, Claudio Bittencourt Ferreira, Helen Smith. European Commission 7th framework programme grant agreement number 213380, First Edition 2011~~

~~NDBC:2009, Technical Document 09-02, *Handbook of automated data quality control checks and procedures.* National Data Buoy Center, August 2009~~

3 Terms, definitions, symbols, units, and abbreviated terms

3.1 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

3.2 Symbols, units, and abbreviated terms

For the purposes of this document, the following symbols, units, and abbreviated terms listed in Table 1 apply.

Table 1 – Symbols, units, and abbreviated terms

Symbol	Definition	Units
~~fcell~~$_i$	~~Frequency of occurrence in the i^{th} bin~~	~~Hz~~
C_{cable}	total positive sequence line-to-line capacitance of subsea cable	farad
$c_{g,i}$	group velocity at frequency component i	m/s
c_{pi}	phase velocity at frequency component i	m/s
f	frequency	Hz
f_p	peak frequency	
f_i	frequency at component i	Hz
f_i	frequency spacing	Hz
$G(\theta,f)$	~~Energy at f distributed with angle θ~~ directional spreading function NOTE 1 $\int_{-\pi}^{+\pi} G(\theta,f)\times d\theta = 1$	1/rad
h	water depth	m
H_{m0}	spectral estimate of significant wave	m
H_s	significant wave height	m
I_{meas}	Line RMS current	A
J	Omni-directional ~~measured wave energy flux~~ wave power per unit width	W/m
~~J_i~~	~~Omnidirectional measured wave energy flux per bin~~	~~W/m~~
~~L~~	~~Capture length~~	~~m~~
~~L_i~~	~~Capture length per bin~~	~~m~~
$\hat{J}$	maximum omni-directional wave power per unit width	W/m
$\check{J}$	minimum omni-directional wave power per unit width	W/m
$\bar{J}$	average omni-directional wave power per unit width	W/m
k_i	wave number at frequency component i	1/m
CW	capture width	m
$\hat{CW}$	maximum capture width	m
$\check{CW}$	minimum capture width	m
$\overline{CW}$	average capture width	m
$CW_{model,i}$	model capture width for i^{th} bin	m
$CW_{measured,i}$	measured capture width for i^{th} bin	m
$CW_{err,i}$	error capture width for i^{th} bin	m
M	number of data sets in a bin	-
~~MAEP~~	~~Mean Annual Energy Production~~	~~Wh~~
m_n	frequency n^{th} order moments of the variance spectrum	Hz^n
n	number of ~~sea states~~ records	-
N	number of bins	-
~~P~~	~~measured power output~~	~~W~~
P_i	measured power output per bin	W

Symbol	Definition	Units
P_h	hydraulic power input	W
P_{abs}	absorbed power	W
P_e	measured real electrical power output	W
P_{pto}	power loss (dissipated) in the PTO	W
PF_{meas}	power factor	-
P_{meas}	real or active power	W
P_{genWEC}	power generated by WEC	W
P_{loss}	cable power loss component	W
PTO	power take off	
Q_{meas}	reactive power	~~W~~ VAR
R_{cable}	total positive sequence resistance of subsea cable	Ω
S	~~Spectral~~ variance density	$\frac{m^2}{Hz}$
$S(f)$	~~Spectral~~ variance density as function of frequency	$\frac{m^2}{Hz}$
$S(f)_{WEC}$	spectral density at WEC equals $T(f,t,\theta,h,...)\times S(f)_{wmi}$	$\frac{m^2}{Hz}$
$S(f)_{WMI}$	spectral density at WMI	$\frac{m^2}{Hz}$
$S(f, \theta)$	Directional ~~spectrum~~ wave energy spectral density $S(f)\times G(\theta,f)$	$\frac{m^2}{Hz \cdot rad}$
$S(f,\theta)_{WEC}$	Directional wave energy spectral density $S(f)\times G(\theta,f)$ at WEC	$\frac{m^2}{Hz \cdot rad}$
$S(f,\theta)_{WMI}$	Directional wave energy spectral density $S(f)\times G(\theta,f)$ at WMI	$\frac{m^2}{Hz \cdot rad}$
S_i	~~Spectral density at frequency component *i*~~ variance density over the i^{th} discrete frequency	$\frac{m^2}{Hz}$
S_{ij}	variance density of the i^{th} discrete frequency and j^{th} discrete direction	m^2/Hz/rad
~~S_p~~ σ	standard deviation	-
t	time lag or shift between the WMI and the WEC	s
T	operational hours per record	h
$T(f, t, \theta, h,...)$	Variance density spatial transfer model, for correction of the spectral density measured at the WMI to the WEC NOTE 2 not all the variables are listed. ~~The correction depends on the test site.~~ the transfer model dependencies will be specific to each test site.	-
T_e	energy period (also written as T_{-10})	s
Δf_i	frequency width of the variance density of the i^{th} discrete frequency	Hz
$\Delta \theta j$	angular width of the variance density of the j^{th} discrete direction	rad
U	line-to-line voltage	V

Symbol	Definition	Units
U_{meas}	line-to-line RMS voltage	V
V_{p1+}, V_{p1-}	WEC side positive sequence voltage	V
V_{p2}, V_{p2-}	shore side positive voltage	V
WEC	wave energy converter	
WMI	wave measurement instrument	
X_{cable}	total positive sequence reactance of subsea cable	Ω
~~Δf_i~~	~~Frequency spacing~~	~~Hz~~
ρ	fluid density	~~$\frac{g}{m^3}$~~ kg/m^3
θ	wave direction	~~°~~ rad
λ	wavelength	m
φ	phase angle	Degrees°
	voltage phase angle	Degrees°
	current phase angle	Degrees°
η_{pto}	power take off efficiency	-
$CF(X)$	Centre frequency fraction of errors that lie within the limits of ± X %	%

4 Sequence of work

Figure 1 shows the sequence of work for the assessment as described in this document. The pre-test sections shall be conducted prior to the testing period. Following the testing period, the post-test sections shall be conducted.

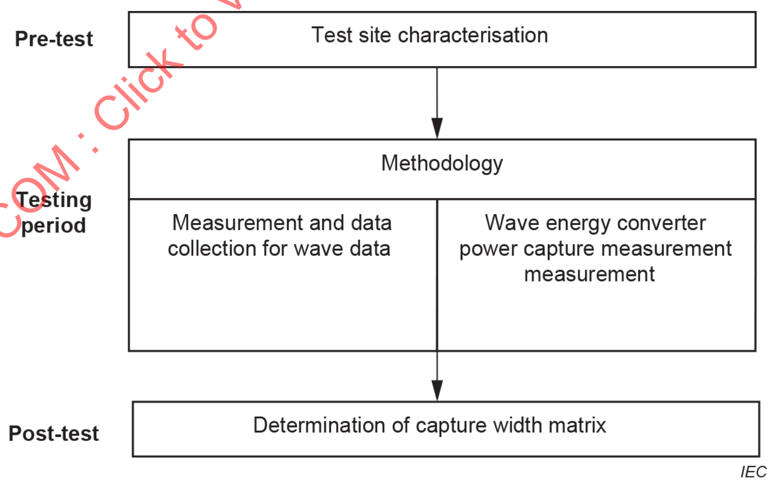


Figure 1 – Timeline of assessment

5 Test site characterisation

5.1 General

An analysis of the prospective test site shall be undertaken to ensure that it is suitable for power assessment of a WEC. The incident wave climate shall be evaluated to ensure the ~~power performance~~ capture width matrix can be populated. To infer the incident wave power at the location of a WEC, the effect of bathymetry and marine currents metocean parameters and conditions on the incident wave climate shall be sufficiently analysed to determine whether a transfer model between the Wave Measurement Instrument (WMI) and WEC will be required. If a transfer model is required, the analysis shall support the development of a suitable transfer model.

5.2 Measurements

5.2.1 General

The boundary of the test site shall be defined and documented. The main physiographic and oceanographic features of the study area shall be identified, especially those features that influence wave propagation and thus the wave characteristics at the proposed WEC location. Locations and time periods of all measurements will be recorded.

In cases where a wave propagation model is necessary to infer the wave characteristics at the WEC location, the test site boundary should be considered the wave propagation model domain.

5.2.2 Wave measurement for wave power characterisation

A WMI shall be deployed at the proposed WEC testing location prior to WEC deployment. A second WMI shall be deployed simultaneously at the proposed post-deployment wave measurement location. The WMIs shall be deployed for a minimum of 3 months prior to WEC deployment, and it is recommended the WMIs record data for 12 months prior to WEC deployment to account for seasonal variations. The frequency of WMI measurements will be at least once per hour. It is expected that during each measurement the WMI will record data defining the free surface elevation time series profile, and that this time series data will be at sufficient temporal resolution to permit subsequent transformation of the data into a frequency domain representation.

The spectral data shall be calculated from WMI time series data. Estimates of the significant wave height estimate and energy period shall be calculated from the spectral data. The following parameters, to be used to determine the power matrix, shall be included in the determination of the power matrix:

a) spectral shape;

b) directionality of waves;

c) directional frequency spectrum;

d) water depth including tidal effect;

e) tidal and marine current, direction and velocity;

f) wind speed and direction;

g) density of water;

h) occurrence and thickness of ice.

More than one WMI should be used if there is a large variation of wave direction and sea state due to bathymetric changes near the WEC location.

The directional wave energy spectrum, $S(f,\theta)$, shall be calculated from WMI recorded data. The wave spectra can be recorded in discrete form, but the maximum frequency bin width shall not exceed 0,015 Hz, and the maximum directional bin width shall not exceed 5 degrees, or 0,088 rad.

From each directional wave energy spectrum record, spectrally derived estimates of the following parameters shall be derived for use in the determination of the capture width matrix:

a) significant wave height.

b) energy period.

c) wave direction.
d) directional spread.
e) spectral width.

In addition to wave parameters mentioned, the following environmental parameters shall be recorded:

f) water depth including tidal effect.
g) tidal or ocean current speed and direction.
h) wind speed and direction.
i) density of water.
j) occurrence and thickness of ice.

Parameters from the lists (items a-j) that have not been recorded, and thus not included in the development the ~~power~~ capture width matrix, shall be identified and the rationale for their exclusion justified.

The preferred characteristic period is the energy period, but additional characteristic periods may also be calculated. These include the peak period and the zero up-crossing period.

5.2.3 ~~Current measurement~~ Tidal or ocean currents

~~Marine~~ Currents at the test site shall be recorded and documented through a current measurement instrument. The current speed and direction data shall be measured simultaneously with the wave measurement and shall extend over a minimum of 30 days. The sampling period shall be a maximum of 10 minutes. At least one current speed and direction record will be taken from the upper half of the water column during the deployment period. The primary purpose of current records is to facilitate the development of a ~~marine current~~ model of the area. Tidal and non-tidal currents shall be estimated and differentiated.

It is recommended, however, to measure current velocity and directions at different points of the water column in order to adequately describe the velocity profile at the site.

5.2.4 Tidal ~~measurement~~ elevation

Tidal heights shall be recorded at the test site. The measurements shall extend over at least 30 days and shall be analysed to estimate tidal ranges.

5.2.5 Bathymetric survey

The boundary of the test site shall be defined and documented as in IEC TS 62600-101. A bathymetric survey of the area shall be undertaken and documented. The resolution of the bathymetric survey shall be as necessary to support the wave spatial transfer model, see 5.2.7.

The survey should provide the details on the bottom profile.

5.2.6 Wind speeds

The wind speed shall be recorded as in IEC TS 62600-101.

5.2.7 Calculation of wave spatial transfer model

The sea state at the location of the WMI shall be representative of the sea state at the location of the WEC. If the difference between the ~~energy flux~~ wave power at the WMI and the WEC – as determined by the deployment of a minimum of two WMIs, one at the wave measurement location and one at the WEC location – is less than 10,0 % for 90,0 % of the records then it can be assumed that the wave field is statistically equivalent.

NOTE It is expected that this will be the case for a well-chosen deep-water test site.

If the condition is not met, then a spatial transfer model shall be generated and validated. The spatial transfer model can either be an existing modelling program or a custom modelling program. The modelling program shall be validated. The accuracy of the model shall be determined as shown in Annex D.

5.2.8 Modelling of the test site

The spatial transfer model shall predict the spectrum at the WEC based on the spectrum at the WMI. The test site should be modelled to assist in the development of a spatial transfer model. The spatial transfer model shall be acceptable if it predicts the energy flux at the WEC to within 10,0 % of the measured wave energy flux for 90,0 % of the data recorded according to 5.2.2.

NOTE The spatial transfer model would generally be in the form:

$$S(f,\theta)_{WEC} = T(f,t,\theta,h,...) \times S(f,\theta)_{WMI} \quad (1)$$

6 Methodology

6.1 General

This document governs the methodology for measurement, analysis and presentation of data to assess the power performance of an electricity generating WEC.

The sea state incident at the WEC shall be measured to the accuracy specified in Clause 7. The sea state measurements shall be analysed to give the parameters for each sample sufficient to describe the sea state as specified in Clause 7.

The electrical power production at the WEC shall be measured to the accuracy specified in Clause 8. The electrical power production measurements shall be analysed to give the parameters for each sample sufficient to describe the electrical power production as specified in Clause 8.

A ~~power~~ capture width matrix shall be compiled as specified in Clause 9 which compares the parameters of the sea state samples and the electrical power production samples (see Figure 2).

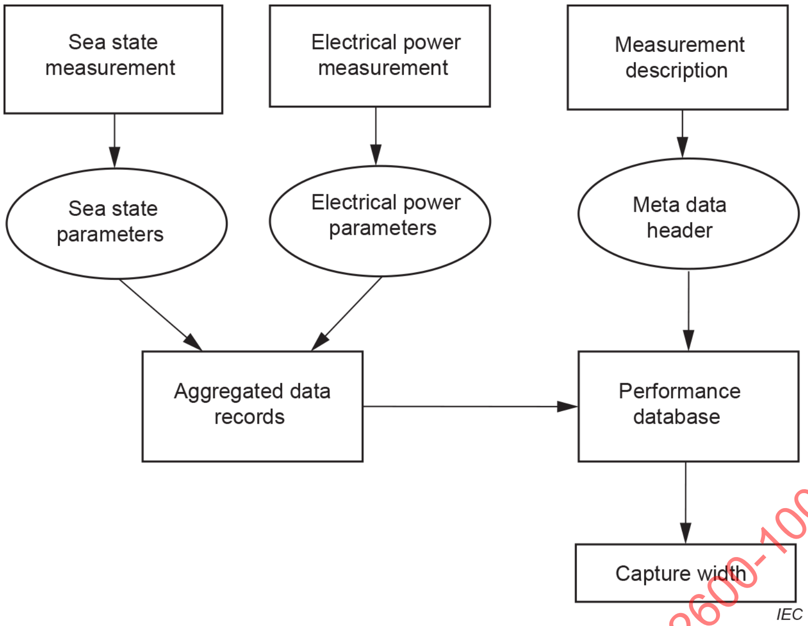


Figure 2 – Data flow diagram

6.2 Sample duration ~~and frequency~~

The parameters describing the sea state and electrical power production for each sample shall be recorded as specified in Clause ~~6~~ 7 and Clause 8. The minimum sample duration shall be 20 min. It shall be reported at least every hour.

~~The minimum sample frequency shall be 1,0 Hz.~~

NOTE Sample duration will affect the accuracy of the measurement. A short sampling duration can result in the poor characterisation of the sea state.

6.3 Simultaneity

The measurements from a WMI and WEC power output shall be measured at the same time to provide correlation between sea state and WEC output power. WMI and WEC data shall be synchronized so that the sea-state incident at the WEC can be correlated with WMI records. It is recommended that WMI data be recorded simultaneously with WEC power data for a minimum of one half of the sample duration.

~~NOTE~~ The spatial transfer model shall be used to correct any time delay between the measurements taken at the WMI and the location of the WEC. The correction for the time delay will not affect the simultaneity of the measurements.

6.4 Data recording

6.4.1 Amount of data to be recorded

The minimum amount of data recorded shall be based on the design operating envelope of interest. This shall define the amount of testing that is required to develop a power matrix.

The minimum testing duration shall be six months and be representative of the deployment location.

NOTE Spectral shape can vary with seasons leading to variations in the ~~power~~ capture width matrix.

6.4.2 Data format and retaining

The data shall provide a record of sea state and electrical power production over time. Each aggregated data record shall be date and time stamped using ISO 8601. The records shall be annotated with quality control flags giving the results of the quality control checks carried out during the recording and analysis path. The records shall be ~~recoverable in ASCII~~ convertible to a human readable format with a descriptive header for each data record.

7 Measurement and data collection for wave data

7.1 General

The purpose of Clause ~~7~~ 8 is to specify the wave and environmental data required to produce a ~~power~~ capture width matrix for a WEC. Clause ~~7~~ 8 ~~shall also~~ provides the methodology for analysing the wave data in order to characterise the environmental conditions. The minimum sample frequency shall be 1,0 Hz.

~~7.2 WMI and calibration~~

~~The calibration, accuracy, and limitation of the WMI shall be documented to reference NDBC:2009 Technical Document 09-02.~~

~~7.3 Instrumentation location~~

~~7.3.1 General~~

~~WMI deployment location or locations shall be selected toBest represent the sea state at the WEC. The WMI location will be selected to minimize its effect on the WEC and the WEC on the WMI. The effects of reflection, radiation, diffraction, and shadowing shall be considered when selecting the WMI location effects.~~

7.2 WMI calibration

7.2.1 General

The WMI shall be verified by the vendor through a factory acceptance test. This shall include at a minimum:

a) Any operating limitation of the WMI.

b) Calibration of the WMI accuracy over the operating range.

c) Last calibration date and calibration interval of the WMI.

d) The calibration method.

e) The type of data that is output by the WMI.

7.2.2 General

The post deployment WMI location or locations shall be selected to:

a) Best represent the sea state at the WEC deployment location.

b) Minimize the WMI's impact on the waves at the WEC location.

c) Minimize the WEC's impact on the waves at the WMI location.

The effects of reflection, radiation, diffraction, and shadowing of the wave field shall be considered when assessing impacts.

7.2.3 Direct measurement

Direct measurement can be used if the site investigations as specified in Clause 5 have not revealed any significant variations in the sea states between the WEC and WMI. The WMI data will be representative of the sea state at the WEC. The WMI and WEC data can be processed and analysed directly.

7.2.4 ~~Measures~~ Measurements with spatial transfer model

A spatial transfer model, as described in 5.2.7 and 5.2.8, shall be used to account for the changes occurring between the position of the WMI and the WEC. The spatial transfer function will provide the sea state data to be analysed with the WEC data.

7.2.5 Correction for WEC interference

The WMI shall be positioned to minimize the amount of interference from the WEC. A model shall be developed to estimate the waves induced by the WMI and the WEC from radiation and ~~refraction~~ diffraction. The WMI shall be placed in a location where the ~~average~~ effect of the radiated and diffracted waves from either body has less than 2 % to 3 % effect on the wave energy ~~has decayed by at least 90 %~~ at each location.

7.3 Metocean data

It is recommended to measure and record all relevant parameters believed to have an influence on power production. Since there are several factors that ~~may~~ can affect the ~~performance of a~~ WEC power production, depending on its type, awareness of any correlation between power production and a specific parameter should be sought and reported. A listing of the parameters is included in 5.2.2. As a minimum requirement, the significant wave height estimate H_{m0}, the wave energy period T_e, and the wave energy flux per unit width J shall be calculated using the measured wave data and reported.

Other parameters that have a significant effect on the power production of the WEC shall also be recorded and calculated. The calculation of any additional parameters shall be defined and reported in sufficient detail to allow for repeatability (see Annex C). The accuracy of the calculated parameters shall be given, according to the uncertainty estimation defined by ISO/IEC Guide 98-1 and ISO/IEC Guide 98-3.

Directly measured parameters will be expressed with indication of absolute error. Specifications on the type, location, calibration, and accuracy of the measurement instrument shall be given.

7.4 Procedure for the calculation of derived parameters

Wave data shall be described by wave spectra which provides information on how the wave elevation variance is distributed with frequency.

a) Frequency f_i: A range of frequencies will be selected for spectral analysis depending on the measurement instrument and sampling rate. The spectral frequency range used for calculation should be between 0,033 Hz and 0,50 Hz with the number of frequency bins determined from data analysis. Frequency bin width should not exceed 0,015 Hz.

b) The frequencies shall be defined using either a geometric progression where the ratio between two adjacent frequencies is constant, or a fixed frequency spacing. In either case the maximum frequency bin width shall not exceed 0,015 Hz.

   ~~NOTE 1~~ Currents ~~may~~ can have a significant effect on wave and power parameters due to Doppler shift. Refer to ISO 19901-1~~:2005~~ for the correction procedure. If the ratio of intrinsic to apparent wave frequency is between 0,9 and 1,1, corrections are not required. Any corrections from apparent to intrinsic wave shall be clearly noted.

c) Frequency moments of the variance spectrum m_n. The moments of the spectrum from n = –1 and n = 0 shall be calculated from

$$m_n = \sum_{i=1}^{N} S_i f_i^n \Delta f_i$$

$$m_n = \sum_i f_i{}^n S_i \Delta f_i \qquad (2)$$

NOTE 1 Formula (2) is the discrete approximation of the following: $m_n = \int S(f) f^n df$

d) The spectral significant wave height estimate H_{m0} is defined as:

$$H_{m0} = 4{,}00\sqrt{m_0}$$

$$H_{m0} = 4\sqrt{m_0} \qquad (3)$$

e) The energy period T_e is defined as:

$$T_e = \frac{m_{-1}}{m_0}$$

$$T_e = T_{-10} = \frac{m_{-1}}{m_0} \qquad (4)$$

f) The wave energy flux per unit width J (omnidirectional) is defined as:

$$J = \rho g \sum_i S_i c_{gi} \Delta f_i$$

$$J = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j \qquad (5)$$

where

g is the gravitation constant equal to 9,8 m/s^2.

NOTE 2 Formula (5) is the discrete approximation of the following: $J = \rho g \int S(f) c_g(f) df$

g) The group velocity is defined as:

$$c_{gi} = \frac{1}{2} c_{pi} \left[1 + \frac{2 \cdot k_i \cdot h}{\sinh(2 \cdot k_i \cdot h)} \right]$$

~~$$c_{pi} = \sqrt{\frac{g}{k_i}\tanh(k_i \cdot h)}$$~~

$$c_{g,i} = \frac{1}{2} c_{pi} \left[1 + \frac{2k_i h}{\sin h(2k_i h)} \right] \quad (6)$$

The phase velocity is defined as:

$$c_{pi} = \sqrt{\frac{g}{k_i} \tan h(k_i h)} \quad (7)$$

where

k_i is the wave number at frequency component i.

NOTE ~~2~~3 In deep water conditions, where deep water is defined as a water depth to wave length ratio greater than 0,5, Formula (5) simplifies to:

~~$$J = \frac{\rho g^2}{64\pi} H_{\mathrm{m0}}^2 T_{\mathrm{e}}$$~~

$$J = \frac{\rho g^2}{64\pi} H_{m0}{}^2 T_e \quad (8)$$

NOTE ~~3~~4 The directionality of the sea state is important when the WEC is directionally sensitive. The Metocean data will be recorded as a parameter. The directionality of the waves can be described as a mean direction and a parameter representing the spreading.

8 WEC power output measurements

8.1 WEC electrical output terminals

In the case of an AC grid-connected WEC its output terminals shall be at the point where the output power is in the form of AC at the network voltage and frequency.

In the case of a non-grid connected WEC, its output terminals shall be at the point where the power is connected directly to the load. The output power shall be in the form of AC at a commonly used network frequency (e.g. 50 Hz, 60 Hz), and at a commonly used grid connection voltage level (e.g. 400 V, 6,6 kV). These details shall be clearly stated.

The output terminal point shall be clearly stated.

8.2 Power measurement point

The power measurement point should be at the electrical output terminals of the WEC.

When this is not possible the power measurement point shall be at a point where other effects (such as losses due to cables or other electrical components) between the measurement point and the output terminals may be determined. In this case the methodology for these corrections shall be fully detailed. Power loss correction is only permitted for transmission equipment that is required for measuring the electrical power at the WEC output terminal. The power measurement point shall be clearly stated. In the case where the power measurement point differs from the output terminals the justification shall be made.

NOTE 1 Annex B contains a method for cable loss compensation where the measurement point is located on shore.

NOTE 2 DC power transmission is not included in this document.

8.3 Power measurements

8.3.1 General

The net electric power of the WEC shall be measured, inclusive of any reduction due to system energising power and necessary ancillary loads on board the WEC. The power shall be recorded with a minimum sample frequency of 2 Hz, the power signal having been subjected to a suitable anti-aliasing filter.

The mean, standard deviation, maximum and minimum of the digitized values which occur in each sample shall be recorded.

8.3.2 Limitations on power production

In the case of an AC grid connected WEC, an assessment shall be made of any potential limitations imposed on WEC power export capacity due to the grid connection. These ~~may~~ can include the capacity of the connection itself or the requirement for significant reactive power export, resulting in constraints on the WEC power output under certain conditions. In the case where such constraints can occur, a method to identify when the WEC is operating under constrained output power conditions shall be put in place. Output power data gathered during these conditions shall be identified and may be excluded for use in the power performance matrix.

It is recommended that an external dump load be installed in order to eliminate the WEC power output constraint.

8.4 Instruments and calibration

The net electric power of the WEC shall be measured using a power measurement device such as a transducer and be based upon measurements of current and voltage on a minimum of two phases.

Electrical transducers and the power measurement device used in the electrical measurements should be accuracy class ~~0,5~~ 1,0 or better, should be calibrated to traceable standards and shall meet the requirements of the following standards:

- power transducers: IEC 60688.
- current transformers: ~~IEC 60044-1~~ IEC 61869-2 and IEC 61869-1.
- voltage transformers: IEC 61869-3 and IEC 61869-1.

The operating range of the power measurement device shall be sufficient to include all positive peaks corresponding to net generation and all negative peaks corresponding to net imported power. As a guide, the full-scale working range of the power measurement device and transducers should be at least:

- export: 1 % to 200 % of rated power.
- import: –1 % to –50 % of rated power.

At the low power range of ~~±1 % of~~ the device's rated capacity, where the working range of the ~~power~~ current measurement device does not allow for ~~class 0,5 measurements~~ an accuracy better than ±3 %, the power recorded should be zero. At the low power range where the working range of the transducer does allow for accuracy class ~~0,5~~ 1,0 measurements, their measured values shall be recorded.

NOTE It is important that current transformers are specified correctly as they become non-linear for low currents (≤5 % of their range or thereabouts).

9 Determination of power performance capture width matrix

9.1 General

The power performance of the WEC shall be presented using a normalized power matrix. The normalization shall be calculated using the capture length and the average bin power. The power performance of a WEC can be determined for two distinct purposes. The first purpose is to define the power performance of a WEC so that it can subsequently be used to predict energy yield at a different site. In this case the capture length matrix should be produced as detailed in 9.2.

NOTE The capture length matrix is preferred over the power matrix because it is less sensitive to sea-state parameters and thus less affected by the method of bins. However, the calculation of the power matrix is specified in 9.3 to enable its calculation where appropriate.

The second purpose is to assess the power performance of a WEC to determine if it meets the specified power performance claims. If a capture length matrix for the WEC exists then this can be achieved by comparing the measured power performance to the capture length matrix.

The capture width matrix will be used to determine the effective operation of the WEC. The capture width matrix shall use a normalised capture width for each bin. The normalized capture width shall be calculated using the average value of the capture widths in the bin. The capture width is determined using the parameters derived in 7.2 and then calculated in 7.4. The capture width matrix is less sensitive to the sea-state parameters and thus less affected by the method of bins. In this case the capture width matrix should be produced as detailed in 9.2.3, Formula (9).

NOTE The annual energy production (AEP) is estimated in IEC TS 62600-101. The capture width in IEC TS 62600-100 is a calculated value. The capture width in IEC TS 62600-101 is calculated using IEC TS 62600-100. This allows for a common method to compare predictive to measured capabilities of a WEC.

9.2 Structure of the normalized power capture width matrix

9.2.1 Core structure

The normalized power capture width matrix shall be constructed by applying the "method of bins" to the capture lengths widths as in 9.2.3. The bins shall be defined by at least the significant wave height estimate, H_{m0} and energy period, T_e. The bins for significant wave height shall have a maximum width of 0,5 m and the bins for the energy period shall have a maximum width of 1,0 s.

9.2.2 Sub-division of the normalized power capture width matrix

Additional indices, such as the mean wave direction or spectral bandwidth, may be added to the normalized power capture width matrix to reduce the variability of capture length width in each bin.

NOTE It is advantageous to sub-divide the normalized power capture width matrix if by doing so it reduces the variability of the performance prediction, thereby giving greater confidence in the estimation of WEC energy production.

9.2.3 Calculation of the capture length width

The capture length width is equal to the net electrical power capture divided by the wave energy flux power.

$$L = \frac{P}{J}$$

$$CW = \frac{P_e}{J} \quad (9)$$

9.2.4 Representation of the capture ~~length matrix~~ width per bin

In cases where only significant wave height, H_{m0} and energy period, T_e are used to define the capture ~~length~~ width matrix a table can be used to fully represent the capture ~~length~~ width matrix. Where more indices are used to define the capture ~~length~~ width matrix the significant wave height and energy period should continue to be used together to organise the data sets to facilitate usage with wave climate scatter diagrams.

Each bin of the capture ~~length~~ width matrix shall contain at least the following information:

a) the average capture ~~length~~ width of all the data sets in the bin;

b) the standard deviation of the capture ~~length~~ width of all the data sets in the bin;

c) the maximum capture ~~length~~ width of all the data sets in the bin;

d) the minimum capture ~~length~~ width of all the data sets in the bin;

e) the number of data sets in the bin.

NOTE It is recognized that some sites can have very different spectra for the same (mean) wave direction, for example combining ocean swell with local wind driven seas. Be aware of the limitations of the methodology.

The average and standard deviation of the capture ~~length~~ width for each bin is calculated according to the formulae:

~~$$\bar{L} = \frac{1}{M} \times \sum_{i=1}^{M} L_i$$~~

~~$$s_p = \sqrt{\frac{1}{M-1} \times \sum_{i=1}^{M} \left(L_i - \bar{L}\right)^2}$$~~

$$\overline{CW} = \frac{1}{M} \sum_{i=1}^{M} CW_i \quad (10)$$

$$\sigma = \sqrt{\frac{1}{M} \sum_{i=1}^{M} \left(CW_i - \overline{CW}\right)^2} \quad (11)$$

~~9.3 Calculation of power matrix~~

~~The power matrix shall be calculated by multiplying the average and standard deviation of the capture length for each bin (as defined in 9.2.4) by the wave energy flux at the centre of the bin. The wave energy flux density at the centre of the bin shall be calculated using a representative spectral shape and the spectral shape used for each bin recorded and a justification provided. The spectral shape used can be different for each bin.~~

10 Calculation of mean annual energy production (MAEP)

10.1 General

The mean annual energy production of a WEC at the specific site shall be calculated by applying the wave energy resource data defined by *EquiMar: Protocols for the Equitable Assessment of Marine Energy Converters, Part II,* chapters I.A.1 through I.A.5 to the power performance of the particular WEC. The MAEP shall be calculated assuming an availability of 100 %.

NOTE The *EquiMar* resource assessment supports devices principally located in deep water away from the shoreline.

10.2 Standard methodology

Where a time series of the wave energy resource is available the MAEP shall be calculated in accordance with mathematical Formula (12). A minimum of 10 years of wave energy resource data should be used for the calculation of the mean annual energy production. If the mean annual energy production 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.

$$\text{MAEP} = \frac{T}{n}\sum_{i=1}^{i=n} L_i \cdot J_i \tag{12}$$

where

T is the average length of a year which is 8 766 h.

The power production shall be calculated for each individual sea-state using linear interpolation of the capture length matrix. If not available, the capture length matrix can be regenerated by dividing the bin values in the power matrix by the wave energy flux density at the centre of each bin using the recorded spectral shape represented shape as determined in 9.3.

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.

10.3 Alternative methodology

If the wave energy resource data is only available as a scatter diagram then the mean annual energy production shall be calculated using the power production at the centre of each bin in the scatter diagram in accordance with Equation (13) subject to the condition in Equation (14). The power production of the bin shall be calculated as specified in 10.2. The contribution of each bin in the scatter diagram to the mean annual energy production 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 length matrix, then two-dimensional linear interpolation of the capture length matrix can be performed to align the bins of the two matrices.

$$\text{MAEP}_{(\text{ALT})} = T \cdot \sum_{i=1}^{i=N} L_i \cdot J_i \cdot f_i \tag{13}$$

$$\sum_{i=1}^{i=N} f_i = 1{,}0 \tag{14}$$

~~10.4 Completeness of the capture length matrix for MAEP~~

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

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

10 Reporting format

10.1 General

Reporting requirements are described below. All work performed should adhere to the requirements in this document, and any deviations should be documented as described in 10.8.

10.2 WEC description report

The WEC under evaluation shall be described in full. As a minimum, the following parameters shall be provided:

- WEC make, type serial number, production year.
- Type of energy capture technology employed and the dimension of the WEC. The dimensions shall include:
  - size of floating components, fixed barriers and inter-connecting components.
  - actuators and moving components that transfer the wave motion to the Power Take-Off (PTO).
- Diagrams and drawings showing the mooring system, foundation and fixed barriers.
- Electrical generator(s) nameplate capacity.
- Description of the PTO up to the power measurement location, 8.1. This shall include the rated voltage, current and frequency of all components including the generation, converter, and other equipment used to condition the power. A diagram detailing the PTO system and location of the measurement point, 8.1, shall be provided. Where applicable, calculations to account for cable losses as described in 8.2 and Annex A should be provided in detail.

10.3 WEC test site report

The WEC test site shall be well defined in accordance with details described in Clause 4. The test site clause shall include as a minimum:

- Recording sea state and wave power, 5.2.2, during both pre-test and testing. The following information shall be reported for each testing period per 6.2:
  - Spectral shape.
  - Wave height (H_{m0}, 7.4).
  - Energy period (T_e, 7.4).
  - Wave power per unit width (J, 7.4).
  - Directionality of waves as measured (7.4).
  - Directional frequency spectrum as measured (7.4).
  - Water depth including tidal variations.
  - Tidal and ocean currents.

  - Wind velocity.
  - Temperature.
  - Density of water.
  - Occurrence and thickness of ice.

NOTE The data can be presented in either hard copy or electronically. The data can be formatted tabularly or graphically.

- Minimum of one navigation chart, with a coordinate system of the test area with the following information:
  - WEC origin location in latitude, longitude and principal axis. The watch circle will be included for floating WECs.
  - Mooring system drawing showing the anchor location and expected mooring line configuration.
  - Drawing of location and profile of the power cable, if applicable.
  - Fixed foundation location and orientation.
  - Location of wave measurement instrumentation (WMI) both pre-testing and testing, 5.2.2.
  - Reporting of external constraints affecting or having the potential to affect the WEC performance or operational periods.
  - Reporting the variation from the representative water density used in the calculations.
- Minimum of one hydrographical and navigation chart, with the coordinate system identified of the test area with the following information:
  - Shoreline and bottom profile. Unusual underwater obstacles that can affect wave and current motion shall be identified.
  - Water depth at Mean Lower Low Water (MLLW) and tables for changes in tide.
  - Currents from both ebb and flood tides. The direction and maximum shall be shown. Season current shall be shown if applicable.
  - Ocean currents if applicable.

Typical systems are World Geodetic System (WGS) 1984 and North American Datum (NAD) 1983. Other systems may be used provided they are recognized Geographical Information System (GIS).

10.4 Electrical grid and load report

Grid parameters including frequency, voltage and permitted tolerance shall be provided. Any prevailing grid conditions limiting or having the potential to limit the power output during testing period shall be reported.

If load banks are used, the parameters of that load bank shall be reported.

10.5 Test equipment report

A description of all test equipment including sensors, Data Acquisition (DAQ), WMI components and sensor locations shall be reported. For each component the minimum information shall include:

- General description of sensor including, name, model number and serial number.
- Specification sheet demonstrating ability to meet requirement.
- Reporting of all user-defined settings.
- Calibration documentation or certificate of conformance as well as the documentation of compliance to the manufacturer recommended procedures. Calibration of WMIs shall include the calibration methodology.

10.6 Measurement procedure report

A description of the measurement procedure, in accordance with Clause 7, shall be provided. The procedure report shall include as a minimum:

- Procedural steps, test conditions, sampling rate and time-drift considerations.
- Correction of WMI measured wave field conditions and wave field at WEC, 7.2.4 and 7.2.5.
- Reporting of date and time (UTC ± T) for data acquisition.
- A log book containing details of the testing including as a minimum the results from Annex C and Annex D shall be appended to the report.

10.7 Presentation of measured data

The information detailing the measured and calculated data shall be presented using the method of bins, Clause 8. The matrix can be sub-divided to account for wave direction or spectral bandwidth.

NOTE Additional sub-matrix can be used to account for unique weather conditions such as icing.

The following information shall be provided:

- Date and time of data acquisition.
- Wave height H_{m0}, energy period T_{e} and if required wave direction θ (calculated using 7.4).
- Wave power per unit width (calculated using, 7.4 Formula (5)).
- Measured output power.
- Capture width.

The following minimum matrix information shall be presented:

- Number of data points in each bin.
- Maximum capture width.
- Minimum capture width.
- Average capture width.
- Standard deviation.

A sample of the matrix (method of bins) presented is shown in Annex A.

10.8 Deviations from the procedure

Any deviations from the requirements of this document shall be clearly documented in a separate clause. Each deviation shall be supported with the technical rational and an estimate of its effect on the test results.

Annex A
(informative)

Example production of a normalized power capture width matrix

A.1 General

Clause A.2 and Figure A.1 describe the method on how to display empirical WEC data performance data in a standard format. The data has been generated from simulations of a heave only point absorber WEC and is designed to closely match what would be expected from measured sea test data. The data has been grouped using bins, with Table A.1 to Table A.6 indicating the bin centres.

A.2 Sample data

Table A.1 represents an example of an extract of the wave data as measured by WMI, and WEC performance averaged data gathered in an unprescribed format. Wave characteristics from the measurement equipment have been used to calculate the wave power for the given H_{m0} and T_e. Power is measured at the output terminals of the WEC as defined in this document.

Table A.1 – Sample data

H_{m0} m	T_e s	P kW	J kW/m	L m
4,86	6,85	443,70	79,38	5,59
1,16	6,97	27,27	4,60	5,93
1,05	7,18	25,21	3,88	6,49
1,72	7,30	72,13	10,60	6,81
1,39	7,41	49,82	7,02	7,09
1,96	7,62	109,43	14,36	7,62
3,83	7,84	458,68	56,42	8,13
1,61	8,05	87,44	10,24	8,54
3,37	8,17	397,34	45,52	8,73
1,27	8,38	59,36	6,63	8,95
2,31	8,59	203,12	22,49	9,03
2,08	8,71	166,74	18,49	9,02
1,50	8,82	89,26	9,74	9,17
-	-	-	-	-

Date/time	Wind speed (m/s)	Wind direction (°)	Wave height (m)	Wave period (s)	Absorbed power (kW)	Output power (kW)
2012-2-1 0:10	5,114	358,989	0,911	3,323	4,184	1,615
2012-2-1 0:20	4,534	358,989	0,969	3,389	4,448	1,720
2012-2-1 0:30	3,912	358,989	0,951	3,393	4,817	1,848
2012-2-1 0:40	3,382	358,989	0,905	3,308	4,074	1,733
2012-2-1 0:50	3,673	358,989	0,878	3,416	3,900	0,793
2012-2-1 1:00	4,538	358,989	0,848	3,274	3,264	1,112
2012-2-1 1:10	4,802	358,989	0,889	3,330	4,475	1,571
2012-2-1 1:20	4,706	358,989	0,839	3,234	3,349	1,196
2012-2-1 1:30	4,460	358,989	0,807	3,408	3,316	1,214
2012-2-1 1:40	4,399	358,989	0,801	3,284	3,802	1,287
2012-2-1 1:50	3,978	358,989	0,785	3,214	2,913	0,891
2012-2-1 2:00	3,860	358,989	0,758	3,259	2,544	0,823
2012-2-1 2:10	3,890	358,989	0,777	3,238	2,856	0,940
2012-2-1 2:20	3,928	358,989	0,827	3,286	3,196	1,043
2012-2-1 2:30	4,366	358,989	0,863	3,386	3,385	1,181
2012-2-1 2:40	4,447	358,989	0,782	3,190	3,022	0,808
2012-2-1 2:50	3,986	358,989	0,793	3,123	3,241	1,083
2012-2-1 3:00	4,202	358,989	0,734	3,115	2,539	0,737
2012-2-1 3:10	4,299	358,989	0,718	3,204	2,248	0,475

The full range of data measured as it occurred during the measurement period is shown in Figure A.1. ~~This represents a total of 6 180 measured data points over a period of time.~~ This plot shows the variation in electrical power output over a range of H_{m0} and T_e.

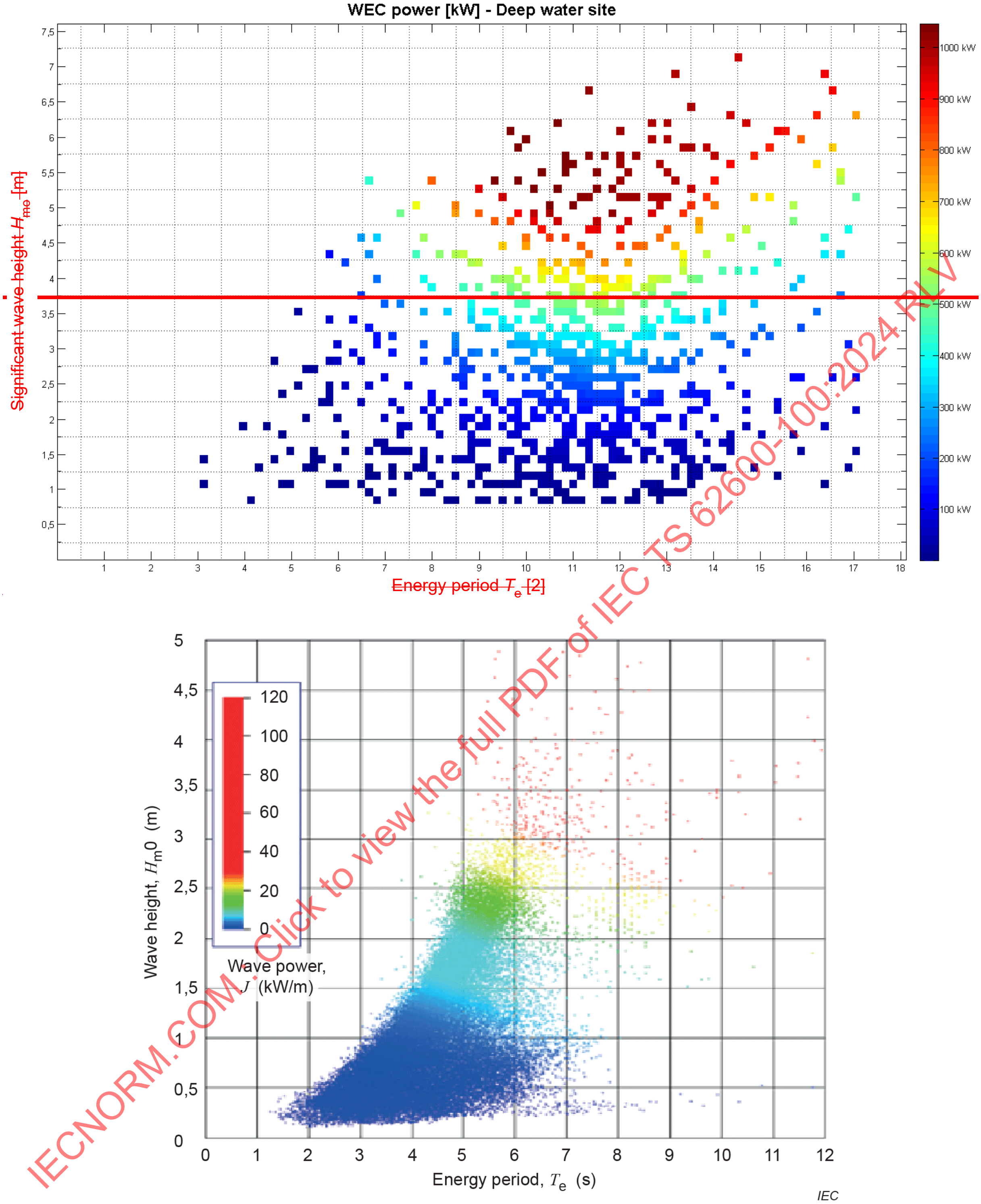


Figure A.1 – Power scatter

It is necessary to reduce this large data set to the standard discretisation. The bin sizes chosen are 0,5 m for H_{m0} and 1 s for T_e as defined by 9.2.1. The tables which follow display the value of the bin centre, e.g. all data within the interval of 8,5 s to 9,5 s, is displayed in the 9 s bin. The same method is used for the H_{m0} values.

The capture ~~length~~ width for each of the data samples is calculated on the basis of the measured power and the wave energy flux, separated into the different bins and averaged over each bin.

Table A.2 shows the average capture ~~length~~ width for each bin. Empty bins indicate no measurements were recorded for that combination of H_{m0} and T_e.

Table A.2 – Average capture ~~length~~ width

		Average capture length for each bin [m]																	
Significant wave height H_{m0} [m]	**7,5**																		
	7,0													3,88	3,15		2,91		
	6,5											5,00		4,35	4,14		3,18	2,70	
	6,0										7,12		5,65	5,29	5,21	4,10	3,32		
	5,5							5,59	8,73	9,73	8,85	7,52	6,71	6,44	5,35	4,53	3,34	2,98	
	5,0							7,09	8,13	9,41	10,03	9,28	8,41	7,27	5,86	4,41	3,68	2,74	
	4,5						2,90	5,59	8,54	9,30	10,09	9,85	8,94	7,18	5,55	4,53	3,22	2,95	
	4,0						4,23	5,93	8,63	9,52	9,99	9,97	9,45	7,29	5,14	4,30	3,64		
	3,5					1,34	2,90	5,94	8,54	9,52	10,03	10,02	9,42	7,38	5,70	4,46	3,47		
	3,0					0,53	3,32	5,89	8,54	9,24	10,04	10,05	9,28	7,23	5,37	4,49		3,04	
	2,5					1,23	3,01	6,04	8,17	9,41	10,10	10,03	9,56	7,30	5,49	4,66	3,51	3,02	
	2,0				0,09	0,90	3,24	6,64	8,61	9,45	9,96	10,05	9,42	7,31	5,59	4,37	3,51	3,12	
	1,5			0,01	0,20	1,07	2,69	6,35	8,39	9,47	10,06	10,05	9,45	7,16	5,51	4,53	3,59	3,21	
	1,0			0,01	0,15	0,97	3,55	5,99	8,51	9,46	10,06	10,00	9,47	7,34		4,07	3,33		
	0,5																		
		1,0	**2,0**	**3,0**	**4,0**	**5,0**	**6,0**	**7,0**	**8,0**	**9,0**	**10,0**	**11,0**	**12,0**	**13,0**	**14,0**	**15,0**	**16,0**	**17,0**	**18,0**
		Energy period T_e [s]																	

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	0,392	-	-	-	-	-	0,093
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,341	0,653	0,576	-	-	-	-
	3,0 to 3,5	-	-	-	-	0,718	0,888	0,974	-	-	-	-	0,231
	2,5 to 3,0	-	-	-	0,552	1,325	1,271	1,154	0,965	0,925	0,678	-	-
	2,0 to 5,5	-	-	-	-	1,771	1,627	1,325	1,254	1,041	1,151	-	-
	1,5 to 2,0	-	-	-	1,823	2,119	1,872	1,509	1,340	1,133	0,959	-	0,504
	1,0 to 1,5	-	-	-	2,066	2,085	1,868	1,711	1,245	0,916	-	-	-
	0,5 to 1,0	-	-	0,662	1,422	1,632	1,527	1,362	1,177	-	-	-	-
	0,0 to 0,5	-	-	-	-0,984	-0,081	0,959	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

The standard deviation, maximum and minimum values for each of the bins are included in Table A.3 through Table A.5. Table A.6 indicates the number of samples recorded which fall into each of the bins.

Table A.3 – Standard deviation of capture ~~length~~ width

		~~Standard deviation of capture length for each bin [m]~~																	
~~Significant wave height H_{m0} [m]~~	~~7,5~~																		
	~~7,0~~													~~0,00~~	~~0,00~~		~~0,00~~		
	~~6,5~~											~~0,00~~		~~0,00~~	~~0,00~~		~~0,22~~	~~0,00~~	
	~~6,0~~										~~0,59~~		~~0,00~~	~~0,23~~	~~0,00~~	~~0,18~~	~~0,39~~		
	~~5,5~~							~~0,00~~	~~0,00~~	~~0,00~~	~~0,61~~	~~0,38~~	~~0,41~~	~~0,24~~	~~0,31~~	~~0,00~~	~~0,00~~	~~0,00~~	
	~~5,0~~							~~0,00~~	~~0,00~~	~~0,36~~	~~0,24~~	~~0,41~~	~~0,58~~	~~0,59~~	~~0,25~~	~~0,18~~	~~0,00~~	~~0,00~~	
	~~4,5~~						~~0,00~~	~~0,33~~	~~0,41~~	~~0,37~~	~~0,14~~	~~0,13~~	~~0,37~~	~~0,60~~	~~0,69~~	~~0,18~~	~~0,00~~	~~0,10~~	
	~~4,0~~						~~0,00~~	~~0,00~~	~~0,13~~	~~0,21~~	~~0,25~~	~~0,12~~	~~0,49~~	~~0,67~~	~~0,32~~	~~0,32~~	~~0,06~~		
	~~3,5~~					~~0,00~~	~~0,00~~	~~1,09~~	~~0,00~~	~~0,23~~	~~0,22~~	~~0,16~~	~~0,62~~	~~0,47~~	~~0,39~~	~~0,09~~	~~0,17~~		
	~~3,0~~					~~0,00~~	~~0,36~~	~~0,86~~	~~0,00~~	~~0,28~~	~~0,19~~	~~0,15~~	~~0,58~~	~~0,60~~	~~0,31~~	~~0,19~~		~~0,00~~	
	~~2,5~~					~~0,39~~	~~0,91~~	~~0,64~~	~~0,78~~	~~0,29~~	~~0,19~~	~~0,14~~	~~0,46~~	~~0,65~~	~~0,50~~	~~0,00~~	~~0,23~~	~~0,00~~	
	~~2,0~~				~~0,00~~	~~0,62~~	~~0,82~~	~~0,71~~	~~0,46~~	~~0,25~~	~~0,24~~	~~0,14~~	~~0,51~~	~~0,72~~	~~0,49~~	~~0,29~~	~~0,25~~	~~0,00~~	
	~~1,5~~			~~0,00~~	~~0,00~~	~~0,52~~	~~0,95~~	~~0,58~~	~~0,46~~	~~0,23~~	~~0,20~~	~~0,12~~	~~0,58~~	~~0,51~~	~~0,41~~	~~0,00~~	~~0,00~~	~~0,06~~	
	~~1,0~~			~~0,00~~	~~0,00~~	~~0,24~~	~~0,67~~	~~0,60~~	~~0,52~~	~~0,30~~	~~0,21~~	~~0,15~~	~~0,63~~	~~0,60~~		~~0,00~~	~~0,00~~		
	~~0,5~~																		
		~~1,0~~	~~2,0~~	~~3,0~~	~~4,0~~	~~5,0~~	~~6,0~~	~~7,0~~	~~8,0~~	~~9,0~~	~~10,0~~	~~11,0~~	~~12,0~~	~~13,0~~	~~14,0~~	~~15,0~~	~~16,0~~	~~17,0~~	~~18,0~~
		~~Energy period T_e [s]~~																	

Wave height (H_{m0}) [m]	0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
4,5 to 5,0	-	-	-	-	-	0,000	-	-	-	-	-	0,000
4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
3,5 to 4,0	-	-	-	-	-	0,231	0,000	0,000	-	-	-	-
3,0 to 3,5	-	-	-	-	0,137	0,209	0,207	-	-	-	-	0,000
2,5 to 3,0	-	-	-	0,000	0,367	0,238	0,209	0,207	0,108	0,061	-	-
2,0 to 5,5	-	-	-	-	0,308	0,263	0,228	0,228	0,184	0,000	-	-
1,5 to 2,0	-	-	-	0,667	0,269	0,245	0,200	0,265	0,152	0,182	-	0,000
1,0 to 1,5	-	-	-	0,406	0,324	0,289	0,292	0,182	0,000	-	-	-
0,5 to 1,0	-	-	0,791	0,613	0,433	0,423	0,384	0,210	-	-	-	-
0,0 to 0,5	-	-	-	0,378	0,176	0,409	-	-	-	-	-	-
	Wave energy period (T_e) [s]											

Table A.4 – Maximum capture ~~length~~ width

		Maximum capture length for each bin [m]																	
Significant wave height H_{m0} [m]	7,5																		
	7,0													3,88	3,15		2,91		
	6,5											5,00		4,35	4,14		3,34	2,70	
	6,0										7,72		5,65	5,49	5,21	4,28	3,59		
	5,5							5,59	8,73	9,73	9,28	8,09	7,39	6,68	5,68	4,53	3,34	2,98	
	5,0							7,09	8,13	9,73	10,21	9,64	9,23	7,96	6,04	4,53	3,68	2,74	
	4,5						2,90	5,93	8,95	9,72	10,22	10,02	9,31	7,78	6,04	4,66	3,22	3,02	
	4,0						4,23	5,93	8,73	9,73	10,22	10,12	1	8,05	5,36	4,53	3,68		
	3,5					1,34	2,90	7,09	8,54	9,73	10,22	10,20	10,04	8,05	6,04	4,53	3,59		
	3,0					0,53	3,53	6,81	8,54	9,73	10,22	10,20	10,04	8,05	5,68	4,66		3,04	
	2,5					1,56	4,23	6,49	8,73	9,73	10,22	10,20	10,04	8,05	6,04	4,66	3,68	3,02	
	2,0				0,09	1,56	4,23	7,09	8,95	9,73	10,22	10,20	10,04	8,05	6,04	4,66	3,68	3,12	
	1,5			0,01	0,20	1,56	4,23	7,09	8,95	9,72	10,22	10,20	10,04	8,05	6,04	4,53	3,59	3,26	
	1,0			0,01	0,15	1,14	4,23	6,81	8,95	9,73	10,22	10,20	10,04	8,05		4,07	3,33		
	0,5																		
		1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0	13,0	14,0	15,0	16,0	17,0	18,0
		Energy period T_e [s]																	

Wave height (H_{m0}) [m]	4,5 to 5,0	-	-	-	-	-	0,392	-	-	-	-	-	0,093
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,571	0,653	0,576	-	-	-	-
	3,0 to 3,5	-	-	-	-	0,818	1,150	1,195	-	-	-	-	0,231
	2,5 to 3,0	-	-	-	0,552	1,831	1,860	1,581	1,290	1,126	0,760	-	-
	2,0 to 5,5	-	-	-	-	2,624	2,365	2,016	1,825	1,442	1,151	-	-
	1,5 to 2,0	-	-	-	2,794	3,207	2,737	2,126	1,917	1,468	1,214	-	0,504
	1,0 to 1,5	-	-	-	3,321	3,463	2,712	2,644	1,644	0,916	-	-	-
	0,5 to 1,0	-	-	2,190	3,389	3,130	2,827	2,450	1,645	-	-	-	-
	0,0 to 0,5	-	-	-	-0,606	0,164	1,368	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

Table A.5 – Minimum capture ~~length~~ width

		Minimum capture length for each bin [m]																	
Significant wave height H_{m0} [m]	7,5																		
	7,0													3,88	3,15		2,91		
	6,5											5,00		4,35	4,14		3,03	2,70	
	6,0										6,30		5,65	4,94	5,21	3,87	3,04		
	5,5							5,59	8,73	9,73	8,41	6,95	6,20	6,20	5,06	4,53	3,34	2,98	
	5,0							7,09	8,13	9,02	9,59	8,83	7,88	6,22	5,68	4,28	3,68	2,74	
	4,5						2,90	5,27	8,13	9,02	9,97	9,71	8,52	6,22	5,06	4,40	3,22	2,88	
	4,0						4,23	5,93	8,54	9,17	9,59	9,78	8,56	6,22	4,91	4,07	3,59		
	3,5					1,34	2,90	4,60	8,54	9,03	9,59	9,81	8,56	6,62	5,36	4,40	3,35		
	3,0					0,53	2,90	4,60	8,54	9,02	9,59	9,81	8,56	6,22	5,06	4,28		3,04	
	2,5					0,80	2,03	5,59	7,62	9,02	9,59	9,81	8,84	6,22	5,06	4,66	3,25	3,02	
	2,0				0,09	0,33	2,32	5,27	7,62	9,03	9,59	9,81	8,56	6,22	5,06	4,07	3,33	3,12	
	1,5			0,01	0,20	0,53	2,03	5,59	7,62	9,02	9,59	9,81	8,56	6,22	5,06	4,53	3,59	3,17	
	1,0			0,01	0,15	0,80	2,90	5,27	7,62	9,02	9,59	9,81	8,56	6,22		4,07	3,33		
	0,5																		
		1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0	13,0	14,0	15,0	16,0	17,0	18,0
		Energy period T_e [s]																	

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	0,392	-	-	-	-	-	0,093
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,110	0,653	0,576	-	-	-	-
	3,0 to 3,5	-	-	-	-	0,524	0,501	0,662	-	-	-	-	0,231
	2,5 to 3,0	-	-	-	0,552	0,504	0,528	0,500	0,370	0,671	0,614	-	-
	2,0 to 5,5	-	-	-	-	0,347	0,458	0,636	0,487	0,629	1,151	-	-
	1,5 to 2,0	-	-	-	0,765	1,079	0,764	0,664	0,496	0,897	0,802	-	0,504
	1,0 to 1,5	-	-	-	0,231	0,773	0,850	0,835	0,896	0,916	-	-	-
	0,5 to 1,0	-	-	-3,599	-1,796	-0,751	-0,757	-0,218	0,653	-	-	-	-
	0,0 to 0,5	-	-	-	-1,361	-0,333	0,550	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

Table A.6 – Number of data samples

		Count for each bin [-]																	
Significant wave height H_{m0} [m]	7,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7,0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0
	6,5	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	2	1	0
	6,0	0	0	0	0	0	0	0	0	0	4	0	1	6	1	4	2	0	0
	5,5	0	0	0	0	0	0	1	1	1	2	6	6	3	3	1	1	2	0
	5,0	0	0	0	0	0	0	1	1	5	7	4	5	8	2	2	2	1	0
	4,5	0	0	0	0	0	1	3	3	3	4	5	4	5	2	2	2	2	0
	4,0	0	0	0	0	0	1	1	2	6	11	9	10	8	2	2	2	0	0
	3,5	0	0	0	0	1	1	4	1	10	10	11	10	7	4	2	2	0	0
	3,0	0	0	0	0	1	3	6	2	8	17	16	14	8	3	3	0	1	0
	2,5	0	0	0	0	3	4	2	2	9	12	15	11	10	3	1	3	1	0
	2,0	0	0	0	1	3	4	6	7	13	17	16	18	11	3	5	2	1	0
	1,5	0	0	1	1	3	6	8	6	11	14	11	11	12	7	1	1	2	0
	1,0	0	0	1	1	2	3	7	5	11	15	8	9	12	0	1	1	0	0
	0,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0	13,0	14,0	15,0	16,0	17,0	18,0
		Energy period T_e [s]																	

Wave height (H_{m0}) [m]		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
	4,5 to 5,0	-	-	-	-	-	1	-	-	-	-	-	1
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	2	1	1	-	-	-	-
	3,0 to 3,5	-	-	-	-	3	8	4	-	-	-	-	1
	2,5 to 3,0	-	-	-	1	26	385	88	38	66	3	-	-
	2,0 to 5,5	-	-	-	-	399	2307	192	142	142	1	-	-
	1,5 to 2,0	-	-	-	13	3213	2140	220	71	24	3	-	1
	1,0 to 1,5	-	-	-	1409	5624	1815	299	31	1	-	-	-
	0,5 to 1,0	-	-	346	5169	3815	2531	615	59	-	-	-	-
	0,0 to 0,5	-	-	-	2	4	2	-	-	-	-	-	-
		Wave energy period (T_e) [s]											

The wave energy flux for each bin in the scatter is calculated, for example, using a JONSWAP spectrum, with gamma of 3 and the H_{m0} and T_e corresponding to the bin centres. The capture ~~length~~ width and wave energy flux are used to calculate the WEC power in each bin.

Table A.7 – Power matrix

		Average wave enery converter power for each bin [kW]																	
Significant wave height H_{m0} [m]	7,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	7,0	-	-	-	-	-	-	-	-	-	-	-	-	1 211,30	1 060,76		1 120,15	-	-
	6,5	-	-	-	-	-	-	-	-	-	-	1 141,02	-	1 173,46	1 200,68	-	1 054,79	951,25	-
	6,0	-	-	-	-	-	-	-	-	-	1 258,33	-	1 197,27	1 214,14	1 287,20	1 087,40	937,54	-	-
	5,5	-	-	-	-	-	-	580,70	1 036,33	1 299,48	1 312,95	1 227,81	1 194,43	1 241,86	1 112,58	1 008,58	793,49	751,51	-
	5,0	-	-	-	-	-	-	608,92	797,68	1 038,37	1 230,62	1 252,36	1 237,23	1 158,46	1 006,19	810,69	722,56	571,68	-
	4,5	-	-	-	-	-	172,69	389,05	678,82	831,68	1 002,83	1 076,69	1 066,30	926,69	771,80	674,70	511,71	498,93	-
	4,0	-	-	-	-	-	199,46	325,67	542,25	672,21	784,35	860,53	890,00	744,33	564,38	506,42	456,73	-	-
	3,5	-	-	-	-	40,28	104,47	250,07	410,65	514,94	602,70	662,39	679,15	576,22	479,44	402,49	333,76	-	-
	3,0	-	-	-	-	11,60	87,86	182,03	301,70	367,16	443,38	487,97	491,87	415,06	331,93	297,36	-	228,28	-
	2,5	-	-	-	-	18,92	55,45	129,66	200,52	259,61	309,83	338,38	351,76	290,98	235,52	214,17	172,04	157,45	-
	2,0	-	-	-	0,69	8,80	38,20	91,22	135,13	166,94	195,39	216,90	221,84	186,47	153,69	128,66	110,06	103,94	-
	1,5	-	-		0,88	5,93	17,84	49,06	74,07	94,08	111,00	122,06	125,13	102,68	85,23	75,02	63,43	60,33	-
	1,0	-	-		0,30	2,38	10,46	20,56	33,42	41,76	49,36	53,98	55,78	46,81	-	29,96	26,13	-	-
	0,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0	13,0	14,0	15,0	16,0	17,0	18,0
		Energy period T_e [s]																	

Annex B
(normative)

Method for power loss compensation where the measurement point is located on shore

B.1 Single-line diagram

A single-line diagram of a typical grid connected WEC system is indicated in Figure B.1.

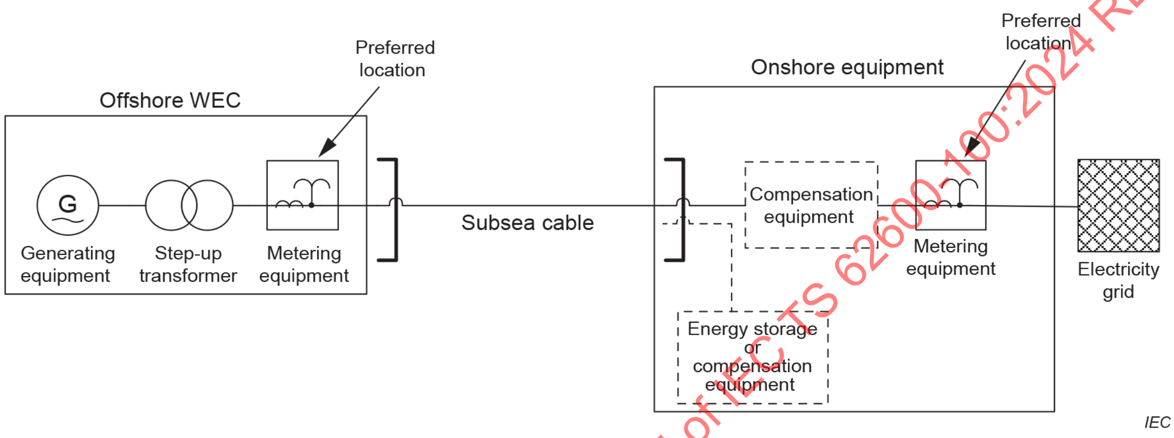


Figure B.1 – Location options for metering equipment

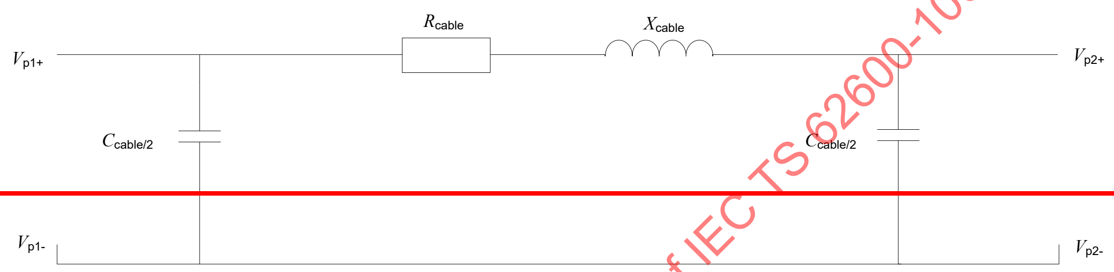
Ideally, power output should be measured at the output terminals of the WEC. This is referred to as the "Preferred Location" in Figure B.1. If the metering equipment is located on the generator side of the WEC step-up transformer, this shall be noted.

Some WECs use either energy storage or compensation equipment, or both, that are external to the WEC itself but shall be considered as a part of it for the purposes of performance assessment. Typical locations for such equipment are indicated with broken lines. The compensation equipment may be installed in series or shunt with the power flow, and auxiliary energy storage equipment is typically installed in a shunt configuration. In such situations, or in situations where power measurement is only possible shore side, the WEC power should be measured at the output terminals of the compensation equipment wherever it is situated, or at the shore station incoming bus bars, where no compensation equipment is present. This is referred to as the "alternative location" in Figure B.1. In this case, losses due to cables and other components between the WEC system and the compensation equipment should be determined, and the power output should be adjusted accordingly.

A methodology for losses incurred in a single connection cable is provided in the next section. If the connection equipment between the WEC system and the compensation equipment is more complex than this, the methodology for the power loss corrections should be fully explained in the file header and accompanied by supporting documentation as necessary.

B.2 Cable loss compensation

If the metering equipment is installed in the "alternative location" as illustrated in Figure B.1, then the losses in the cable shall be added to the power readings in order to give a realistic assessment of the performance of the WEC system. For loss purposes, the cable is modelled in positive sequence as shown in Figure B.2. R_{cable}, X_{cable}, and C_{cable} represent the total positive sequence resistance, reactance, and line-to-line capacitance of the cable. These are usually provided by manufacturers on a per km basis and shall be multiplied up by the cable length in km in order to yield the relevant total impedance values. The cable resistance will generally be determined from the AC resistance per km values provided by the manufacturer. Skin effect can be taken into account if a detailed harmonic breakdown on the device output current is available. This is generally of negligible impact since harmonic filters at the output of power conversion equipment are designed to reduce the harmonic current components on the grid side to very small levels. These levels are regulated by the appropriate power quality standards in accordance with IEC 61000-3 (all parts).



Circuit elements

R_{cable} Total positive sequence resistance of subsea cable
C_{cable} Total positive sequence line-to-line capacitance of subsea cable
X_{cable} Total positive sequence reactance of subsea cable

Connections

V_{p1+}, V_{p1-} WEC side positive sequence voltage
V_{p2+}, V_{p2-} Shore side positive sequence voltage

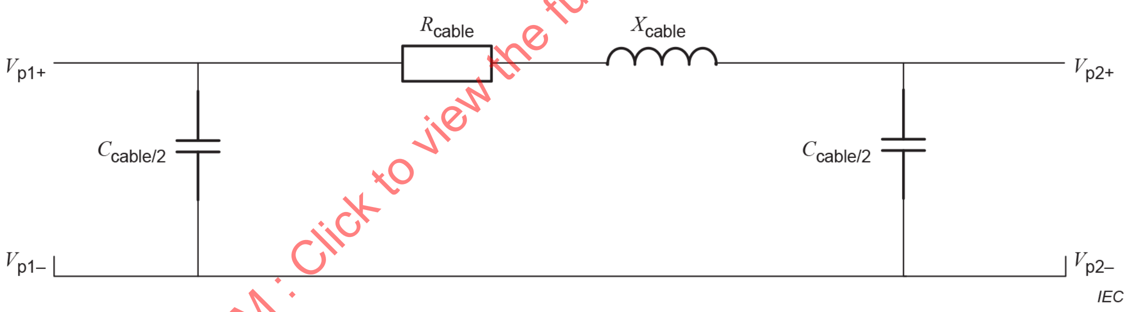


Figure B.2 – Positive sequence cable model

If a number of cables are connected in parallel between the offshore WEC system (or array) and the shore side metering station, the standard circuit theory should be used to derive the equivalent-π circuit of the combination of cables.

In order to measure the power performance and determine cable losses, one of the following sets of measurements shall be made (utilising the instrumentation outlined in the next section):

a) line-to-line RMS voltage (U_{meas}), line RMS current (I_{meas}), and the phase angle of each (φ_V, φ_I) relative to a common reference signal or relative to each other.

b) line-to-line RMS voltage, line RMS current and power factor (PF_{meas}).

c) real power (P_{meas}), reactive power (Q_{meas}), and line-to-line RMS voltage.

d) the output of the WEC system (P_{genWEC}) is then estimated by the following formula:

$$P_{\text{genWEC}} = P_{\text{meas}} + P_{\text{loss}} \tag{B.1}$$

where the measured real power is given directly by the power transducer or by appropriate combination of voltage, current, and power factor or phase angle, and where the cable loss component P_{loss} is given by:

$$P_{\text{loss}} = 3\left[\left(I_{\text{meas}}\cos\varphi_I - \frac{\omega C_{\text{cable}} U_{\text{meas}}}{2}\sin\varphi_V\right)^2 + \left(I_{\text{meas}}\sin\varphi_I + \frac{\omega C_{\text{cable}} U_{\text{meas}}}{2}\cos\varphi_V\right)^2\right] R_{\text{cable}} \tag{B.2}$$

In the case of voltage, current and phase angle or power factor measurements, the factor ω is the electrical radian frequency and is equal to 2π times the electrical system frequency in Hz.

In the case where real and reactive power measurements are obtained, the current measurement and phase angles can be derived as follows:

$$I_{\text{meas}} = \sqrt{\frac{P_{\text{meas}}{}^2 + Q_{\text{meas}}{}^2}{3U_{\text{meas}}{}^2}} \tag{B.3}$$

$$\varphi_V = 0 \qquad \varphi_I = \arctan\frac{Q_{\text{meas}}}{P_{\text{meas}}} \tag{B.4}$$

and substituted into the previous formula for calculating P_{loss}. An assumption in these calculations is that the system voltages and currents are balanced. Even in the presence of limited unbalance in the system, as permitted by the relevant national grid code, these formulae are sufficient to estimate the cable loss compensation.

Annex C
(normative)

Evaluation of uncertainty

C.1 General

The specification of the WEC power performance shall include an estimate of its uncertainty. The estimate shall be based on ISO/IEC Guide 98-1 and ISO/IEC Guide 98-3.

Following ISO/IEC Guide 98-1 and 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 as standard uncertainties.

C.2 Uncertainty analysis

The measurands for the uncertainty analysis are the power matrix, determined by the measured and normalised values of electrical power production and sea-state parameters, and the estimated annual energy production. As a minimum the significant wave height and energy period shall be considered as measurands. Uncertainties in measurements are converted to uncertainties in these measurands by means of sensitivity factors.

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

Table C.1 – List of uncertainty components

Measured/model parameter	Uncertainty component	Uncertainty category [a]
Significant wave height	Wave measuring instrument~~/~~ and model calibration	B
	Influence of moorings ~~and/~~or other local effects on WMI	B
	Data acquisition system (e.g. sampling rate, windowing)	B
	Directional spectral analysis	B
	Variability of significant wave height	A
Energy period	Wave measuring instrument~~/~~ and model calibration	B
	Influence of moorings ~~and/~~or other local effects on WMI	B
	Data acquisition system (e.g. sampling rate, windowing)	B
	Directional spectral analysis	B
	Strength of ~~marine~~ currents	B
	Variability of energy period	A
Wave power density	Water depth	A / B
	Water density	A / B
Electrical power	Current transformers	B
	Voltage transformers	B
	Power transducer or power measurement device	B
	Data acquisition system	B
	Variability of electrical power	A
[a] according to ISO/IEC Guide 98-1~~:2009~~ and ISO/IEC Guide 98-3~~:2008~~.		

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.

NOTE The production of the power matrix implicitly assumes that the electrical power production is completely defined by the sea-state parameters used in the power matrix.

In general this is not the case. Other sea-state parameters will influence the power production but presently there is a lack of knowledge to determine what these parameters are and how they can be accounted for accurately in the power matrix.

The result is that the uncertainty is not associated with the measurement, but in the specification of the appropriate sea-state parameters. In general, this uncertainty can be expected to be greater as the difference in conditions between those used to produce the power matrix and those in which the power matrix is used increases.

Annex D
(normative)

Error analysis of the wave spatial transfer model

D.1 General

The term "spatial transfer model" in this document refers to the use of analytical or numerical models to transfer measured wave parameters in one location to estimate wave parameters in another location at a known distance and direction from the location of the measured parameters. It is possible that a spatial transfer model ~~may~~ is not ~~be required~~ necessary, see 5.2.5.

Annex D covers a procedure for validation of a spatial transfer model for prediction of wave parameters at a specific location.

~~The method to validate to the transfer model is provided in this Annex D.~~

D.2 Overview

D.2.1 Validation procedure

The validation involves the following steps:

a) Identify data for validation which hasn't been used for construction of the transfer model.
b) Identify the specific parameters for validation.
c) Apply the transfer model to known measured data.
d) Measure performance of the transfer model as detailed in this Annex D.
e) Determine the suitability of the model by calculating the centre frequency fraction (CF).

D.2.2 Validation technique

Error (e) is defined as: The predicted value (p) of a parameter or variable minus the measured reference value (r) of a parameter.

$$e_i = (p_i - r_i) \qquad \text{(D.1)}$$

where

e_i is the error of one sample record;

p_i is the predicted value for sample record;

r_i is the recorded value for the sample record;

i is the sequential numerical identifier of an individual data point in a series of data.

Error percentage is defined as:

$$e_i = \frac{(p_i - r_i)}{r_i} \times 100 \qquad \text{(D.2)}$$

The series mean (SM) or the mean value of a series of data points (y) is defined as:

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \tag{D.3}$$

where

y is the general value in a data set;

N is the total number of data points in the series;

i is the sequential numerical identifier of an individual data point in the series y.

Root Mean Square Error (RMSE) of a data set is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2} \tag{D.4}$$

The standard deviation (SD) of a data set is defined as:

$$\text{SD} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(e_i - \bar{e}\right)^2}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(e_i - \bar{e}\right)^2} \tag{D.5}$$

Comparing the SM of the measured parameters to the parameters generated by the spatial transfer model and examining the RMSE and the SD provides an initial indication of the performance of the spatial transfer model.

The key statistic for meeting the performance requirements of this document is the CF which is a measure of the frequency with which errors lie within a specified limit. For example, the calculated error between the measured and estimated parameter generated by the spatial transfer model shall be less than 10 % for 9 out of 10 data records to meet the current performance requirements for this document.

Minimum thresholds for significant wave height and wave period should be set to keep error percentages manageable in small significant wave heights (e.g. less than 0,2 m) and short periods (below 2 s).

~~CF(X) is the centre frequency fraction (percentage) of errors that lie within the limits of $\pm X$ %.~~

Annex E
(normative)

Wave energy converter power performance assessment at a second location using measured assessment data

E.1 General

Annex E provides a uniform methodology for estimating and reporting the performance of a wave energy converter (WEC) at a prospective new deployment location. The performance estimation methodology is based primarily on observations and measurement results gathered during field deployment of the WEC at a primary location with different metocean conditions compared to the prospective new location. Further, it is possible that the WEC design will incorporate changes to accommodate the new site conditions. To assess the performance, inclusion of additional information based on validated numerical and physical models is specified. In this document the completed field deployment location is referred to as "Location 1" and the prospective deployment location is referred to as "Location 2."

Annex E provides a methodology for arriving at the capture width matrix for the WEC at Location 2 using Clause 10 of this document and IEC TS 62600-101 to arrive at the annual energy production (AEP). Other documents in this series (IEC TS 62600 (all parts)) are drawn upon to provide the wave resource and WEC performance information necessary to enable this analysis. The methodology involves:

- assessment of the wave resource at Location 1 and Location 2.
- characterization of the WEC performance at Location 1.
- assessment and compensation for the impact of discrepancies in the metocean conditions between Location 1 and Location 2 on the WEC performance characterization.
- assessment of the impact of changes to the WEC configuration between Location 1 and Location 2 on the WEC performance characterization.
- complementing the performance observations from Location 1 with fit, experimental or numerically modelled data.
- estimating the capture width matrix based on the composite performance characterization of the WEC.

E.2 Sequence of work

The sequence of the work is outlined as follows:

a) Describe the WEC technology.
b) Assess and characterize wave resource at Location 1 and Location 2 using IEC TS 62600-101.
c) Get the capture width matrix from WEC power capture data at Location 1 per Clause 9 of this document.
d) Evaluate the appropriate dimensionality of the capture width matrix from Location 1 for Location 2 and complement the capture width matrix from Location 1 to cover the range of metocean conditions at Location 2 using numerical or experimental data.
e) Validate the model against measured data from Location 1.
f) Specify changes to the WEC to accommodate the new metocean conditions.
g) Evaluate the impact of changes to the capture width of each bin using validated numerical model data incorporating the parameters in question. If the capture width in a bin is changed by more than 10 % it shall be filled using physical or numerical modelled data.
h) Perform quality assurance on capture width matrix for application at Location 2.

i) Calculate AEP at Location 2 using the complemented capture width matrix and Location 2 resource data.

j) Report separately the AEP at Location 2 contributed by the cells of the power matrix that are based on either:

   1) measured data at Location 1, or;

   2) interpolation or extrapolation from measured data, or;

   3) modelled data.

k) Estimate the uncertainty related to the AEP calculated at Location 2.

   The calculation of the AEP shall be in accordance with IEC TS 62600-101.

Annex F provides a detailed illustration of the concepts and calculations in each step in the sequence of work.

E.3 Limitations of this annex

This specification allows for changes to the WEC when moved from Location 1 to Location 2 in order to accommodate the new metocean conditions. Changes to the WEC should be clearly specified and may include: dimensions, geometry, power take off system, control logic and moorings system. Allowable changes and procedures are specified in Clause E.8.

E.4 Description of wave energy conversion (WEC) technology

The wave energy converter WEC 1 deployed at Location 1 and the WEC 2 to be deployed at Location 2 shall both be described in terms of:

- Operational principle.
- Geometry and dimensions.
- Mass properties.
- PTO system.
- Mooring arrangement.

E.5 Assess and characterize wave resource related to Location 1 and Location 2

E.5.1 General

Similar to 6.1 of IEC TS 62600-101:2015, a site description shall be prepared for each of the WEC locations under consideration.

E.5.2 Ambient condition

For each location this description should include a chart, geographic coordinates, the water depth as well as general description of the following:

- The shoreline geography and bathymetry.
- The prevailing wave and wind conditions.
- Typical tidal range and currents.

E.5.3 Wave resource at Location 1 and Location 2

A description of the wave resource at Location 1 and Location 2 shall be provided and include:

- Directional rose plots.
- Scatter tables and plots.
- Exceedance and persistence.
- Joint probability analysis.

E.6 WEC power capture data at Location 1

Capture width data from Clause 10 of this document shall be applied to IEC TS 62600-101 to determine the WEC electrical power performance at Location 1. The measured WEC power production records along with the concurrent wave measurements should be used to calculate and report the Electrical power matrix.

NOTE Clause G.2 provides the location for the measurement of absorbed power and PTO efficiency matrices.

The measured WEC power production records along with the concurrent wave measurements shall be preserved for further analyses.

E.7 WEC model validation

E.7.1 General

Either a numerical or physical model, or both, can be required to satisfy the requirements of this document. The validity of each model shall be assessed by comparison of the results with observations from WEC 1 at Location 1. Specific requirements for the comparison are given in the following subclauses. IEC TS 62600-103 will be used for guidance for WEC model validation.

NOTE These are the minimum requirements for communication of the level of validity of either the physical or numerical models, or both. At this stage, it is left to the users and analysts of the documentation to judge the validity of the physical or numerical model from the difference between modelled and observed performance.

E.7.2 Bin selection

At minimum, 10 bins of the capture width matrix, covering the range of occurrences at Location 1, shall be selected for validation. The bin selection process shall be documented and justified. For each of the selected bins, a minimum of three model runs shall be performed using different random wave seeds. The number of models runs used in each validation bin shall be documented.

Each model run shall use as input either: observed wave conditions from Location 1, or wave conditions representative of the capture width matrix bin being simulated. The wave conditions used in each model run shall be documented. Where representative wave conditions are used the methods for determining those representative conditions shall be documented and justified.

E.7.3 Error per bin

The percent difference between the mean modelled capture width, $CW_{\text{model},i}$, and mean observed capture width, $CW_{\text{measured},i}$, in the i^{th} bin shall be calculated and clearly presented for all bins as follows.

$$CW_{\text{err},i} = \frac{100\left(CW_{\text{model}} - CW_{\text{measured},i}\right)}{CW_{\text{measured,i}}} \tag{E.1}$$

The model capture width shall be from testing as described in IEC TS 62600-103.

NOTE $CW_{err,I}$, CW_{model}, and $CW_{measured,I}$ can be used to calculate AEP_{err}, AEP_{model}, and $AEP_{measured}$. The AEP quantities are established per IEC TS 62600-101.

E.7.4 Accounting for PTO losses

The model shall account for power conversion losses within the PTO system. Where a physical scale model is used, the power performance shall be quantified in terms of absorbed power. Then, following the appropriate scaling of absorbed power and wave parameters, the PTO efficiency shall be applied to estimate electrical power and calculate capture width values. Refer to Annex G for methodology to quantify and apply PTO efficiency.

E.8 Modifications to the WEC

Modifications to the WEC and ancillary hardware are permitted. The capture width data from deployment of WEC1 at Location 1 can only be used to characterize WEC2 including modifications if it can be shown that these modifications impact on the power performance of the device by 10 % or less per bin. If the modifications exceed this limit in a bin it shall be filled using validated numerical methods as outlined in Clause E.7 and Clause E.11. Modifications can be required to the WEC to adapt to Location 2, and shall be documented as follows:

- Description of the change.
- Purpose of the change.
- Impact on the performance of the WEC on a bin-by-bin basis.

Modifications to the WEC cannot be made without a validated model as described in Clause E.7. The validated model shall be adapted to accommodate the proposed modification to the WEC. The method(s) used for accommodating the modifications to the WEC in the numerical model shall be documented. Changes to the WEC can include, but are not limited to, the following:

- WEC dimensional geometry changes.
- PTO component design and control law.
- Ancillary hardware (mooring system, power cable connection, WEC hardware for deployment, etc.).

Each bin of the capture width matrix, covering the range of occurrences at Location 1, shall be selected to assess the impact of the WEC modification. For each of the bins, a minimum of three model runs using different random wave seeds shall be performed for the modified WEC.

The difference between the mean capture width of the unmodified WEC 1 and mean capture width of the modified WEC 2 in each bin shall be presented and evaluated. For the capture width data from deployment of WEC 1 at Location 1 to be used to characterize WEC 2, the absolute difference between the mean capture width values shall be no greater than 10 % per bin. Any bins that have greater than 10 % difference shall be populated using modelled data as outlined in Clause E.11.

E.9 Calculate capture width matrix for use at Location 2

E.9.1 Evaluate appropriate dimensionality of the capture width matrix at Location 2

Minimum dimensions of the capture width matrix, as per Clause 10, as including H_{m0} and T_e. The dimensionality of the capture width matrix should be expanded where possible to reduce the variance of capture width within each bin. In many cases the range of occurrences of metocean parameters at Location 2 will differ from Location 1. Estimation of performance at Location 2, requires that the appropriate dimensionality of the capture width matrix shall be re-evaluated. At minimum, the sensitivity of the WEC shall be investigated to the following parameters:

- Water depth.
- Wave direction.
- Spectral shape and directional spreading.
- Water current.
- Tidal range.

It can be necessary to expand the dimensionality of the capture width matrices to account for any parameters (additional to H_{m0} and T_e) found to have a major effect on WEC power performance. Each of the parameters listed shall be considered in turn. It shall be shown that inclusion of the parameter in question impacts the calculation of AEP at Location 2 by less than 10 %, otherwise the dimensionality of the capture width matrix shall be increased to account for that parameter.

As an example, suppose a WEC is directionally sensitive and that the wave direction is relatively constant at Location 1. In this case it can still be possible to neglect the directionality dimension when constructing the capture width matrix and calculating AEP at Location 1. However, if the wave directionality is more variable at Location 2 it can be necessary to include directionality in the capture width matrix to accurately estimate the AEP per TS 62600-101 at Location 2.

To test if inclusion of directionality is necessary in this demonstration case, both the 2D (H_{m0}–T_e) and 3D (H_{m0}–T_e–X) capture width matrix shall be constructed to cover the range of wave conditions observed at Location 2 (where X is a placeholder for the parameter currently under study). The complementing procedure of Clause E.11 shall be used to fill bins in the capture width matrix for which there are no supporting observations. The AEP shall be calculated using both the 2D and 3D capture width matrix. If the difference between the two AEP calculations is greater than 10 %, then the additional dimension shall be included in the capture width matrix at Location 2.

NOTE The 10 % difference limit on AEP will properly be revised in the future as more experience is gained; currently it is the same magnitude as the variability in the annual average wave energy flux.

E.9.2 Calculate information for each bin of the capture width matrix

Using the performance data from Clause 10 the average capture width matrix shall be constructed, using the appropriate dimensionality as identified in E.9.1. The following shall be calculated for each bin in the matrix:

- The average capture width.
- The maximum capture width of all the data records in the bin.
- The minimum capture width of all the data records in the bin.
- The standard deviation of the capture width of all the data records in the bin.
- The number of data records in the bin.

NOTE See Annex F for a detailed example.

E.10 Quality assurance for cells based on measurements at Location 1

Capture width matrix for use at Location 2 shall be quality checked and empty bins shall be labelled "undefined". Bins of the capture width matrix shall be labelled "underpopulated" if:

- data is known to be inaccurate.
- there are less than 3 data records in the bin.

The quality assurance methodology shall be documented and justified

NOTE Refer to Annex F for detailed example.

E.11 Complement capture width matrix to cover range of conditions at Location 2

E.11.1 Capture width matrix complementation requirement

The capture width matrix may be complemented to estimate the value in underpopulated and undefined (empty) bins. The minimum number of data records in each bin of the capture width matrix is specified in Clause E.10. The capture width matrix may be complemented by:

a) Data fitting (interpolation or extrapolation).

b) Model fitting (numerical or physical).

Bins with complemented data shall be clearly identified. Where a model is used to complement the capture width matrix, it shall be validated as per Clause E.7. Where several methods are available to complement a bin, the method with the least uncertainty should be used.

NOTE See Annex F for an example.

E.11.2 Interpolation or extrapolation of the capture width matrix

Data fitting using interpolation or extrapolation may be used to populate undefined bins in the capture width matrix. Bins populated using data fitting shall be labelled. The data fit shall be computed based on the values of observed adjoining bins. Bin populated using complementation shall not be used to compute the data fit.

NOTE 1 "Adjacent bins" refers to bins which share a cell side or corner.

NOTE 2 See Annex F for detailed example.

E.11.3 Numerical model

A numerical model may be used to calculate the capture width of the WEC in any underpopulated, undefined bin of the capture width matrix, including those where performance of WEC 2 differs by more than 10 % from WEC 1. The numerical model can be validated using the performance data collected at Location 1 as per Clause E.7.

The shape of the wave spectra used in each run should be representative of the range of spectral shapes observed within the bin.

E.11.4 Use of physical model

A physical model may be used to estimate the absorbed power of the WEC in any underpopulated and undefined bin of the capture width matrix. The physical model testing shall be based on IEC TS 62600-103.

The physical model shall represent the actual WEC tested at Location 2 according to Froude's law of similitude. The shape of the wave spectra used in each sea state of the physical test should be representative of the range of spectral shapes observed within the bins of the scatter diagrams at Location 1 and Location 2.

The absorbed power observed during the physical model tests shall be scaled to represent WEC 2 to be deployed Location 2. To estimate electrical power output requires characterization of the WEC PTO system.

The efficiency of the PTO system shall be characterized and reported (see Annex G). The efficiency characterization may be based on observations from WEC operation at Location 1, laboratory tests or a validated numerical model. The method for characterizing shall be documented and justified.

The absorbed power observed during physical model testing is multiplied by the PTO efficiency to estimate electrical power, which can in turn be used to calculate capture width. The combined result of physical model and PTO characterization shall be validated using the performance data collected at Location 1 as per Clause E.7.

E.12 Calculate AEP at Location 2 using complemented capture width matrix and Location 2 resource data

Using the performance matrix (Clause E.11) and the Location 2 wave resource data (E.5.3) the AEP shall be calculated using methods described in IEC TS 62600-101:2015, A.5.

E.13 Assessment of confidence

Some of the uncertainty related to the AEP at Location 2 can be found in IEC TS 62600-101:2015, A.5.3.

Annex F
(informative)

Example analysis

F.1 General

This annex gives a simplified example of the analysis procedure from Annex E. This example is intended to demonstrate only the fundamental character of the analysis procedure and omits many details which are required in formal applications of this document.

This example uses for Location 1 field testing data from the Wavestar prototype at the Danish test site DanWEC in Hanstholm facing the North Sea. The field testing data-set from Location 1 is used to characterize the performance of the prototype, and estimate energy production at a second location near Fjaltring, Denmark (Location 2).

NOTE Location 2 was selected by the authors of this document for demonstration purposes and based on available wave data; it is not intended to represent the intentions of Wavestar Energy.

F.2 Description of the WEC technology

The Wavestar prototype consists of two floats each with a diameter of 5 m. Each float activates a hydraulic cylinder that via a hydraulic system drives electrical generators connected to the electrical grid (see Figure F.1).

IEC

Figure F.1 – The Wavestar prototype (diameter of each float is 5 m)

F.3 Assess and characterize wave resource related to Location 1 and Location 2

The Wavestar prototype has been tested at Hanstholm since 2010. Data covering the period February 2012 to January 2013 were provided by Wavestar Energy for use in this example.

The geographic coordinates and depth of Locations 1 and 2 are given in Table F.1 and shown on the map in Figure F.2.

Location 1 measured parametric wave data, provided by Wavestar, are presented in Figure F.2. Location 2 wave data from wave measurement buoy 2031 were provided by Aalborg University and originally supplied by Kystdirektoratet/The Danish Coastal Authority and are described in Clause F.5.

This simple example does not provide complete details of the wave resource at Locations 1 or 2. Formal applications of this document will require a complete metocean study as per Clause E.5 and IEC TS 62600-101:2015.

Table F.1 – Locations 1 and 2, basic information

		Location	Depth m	Duration
1	Hantsholm, Denmark	57,128714° N, 8,620302° E	5,0	Feb 2012 to Jan 2013
2	Fjaltring, Denmark	56,476082° N, 8,058019° E	17,5	Dec 1991 to Feb 2009

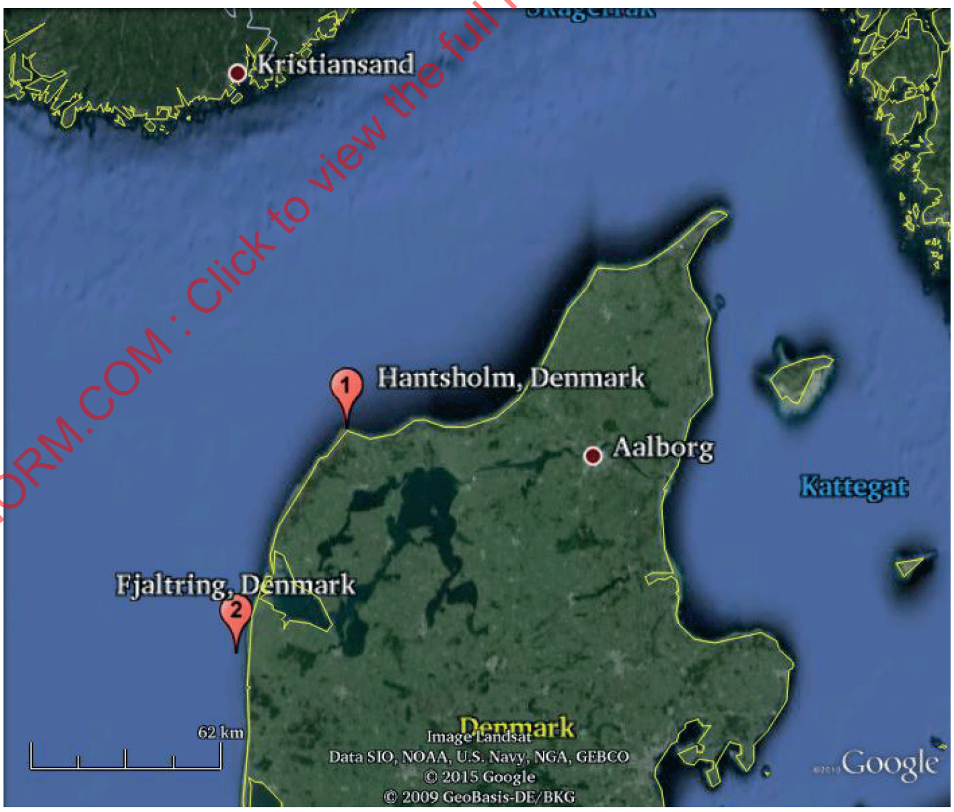


Figure F.2 – Map showing Location 1 Hanstholm and Location 2 Fjatring

F.4 Assess and characterize wave resource at Location 1

Water surface elevations were measured on board the Wavestar fixed structure using an ultrasonic sensor. Time-series analysis was performed on each record to calculate the significant wave height (H_s) and the mean wave period (T_{mean}). These parameters were available throughout the 2012 to 2013 data-set provided by Wavestar. Wave data provided by Wavestar for this example consists of time-stamped H_s, T_{mean} records and a quality flag indicating the validity of the wave record. Valid H_s and T_{mean} records were converted to H_{m0} and T_e using the location specific relations provided in [1][1].

Wave energy flux was estimated based on the parametric wave height, period values and the group velocity which was calculated as a function of water depth and wave energy period:

$$J = \frac{\rho g}{16} c_g \left(T_e, h\right) H_{m0}{}^2 \tag{F.1}$$

The mean annual wave power resource is 4,4 kW/m. The wave power flux matrix is shown in Figure F.3. In each bin is given:

- The average wave power per bin, $\bar{J}$.
- Minimum wave power per bin, $\wedge J$.
- Maximum wave power per bin, $\vee J$.
- Standard deviation of the wave power per bin, σ.
- Number of records in that bin, n.

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

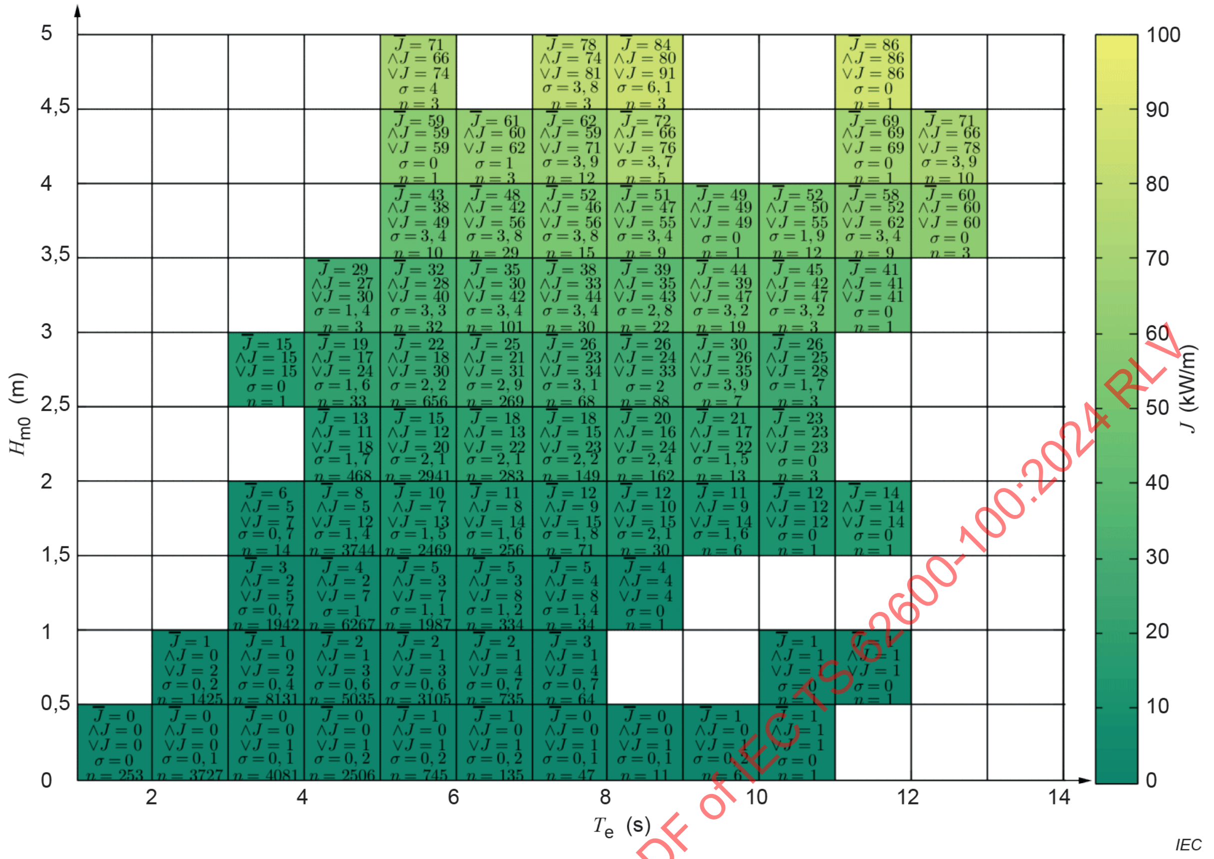


Figure F.3 – Location 1 wave energy flux matrix, Hantsholm, Denmark (based on measured data from Wavestar prototype Feb 2012 – Jan 2013)

F.5 Assess and characterize wave resource at Location 2

Wave resource data at Location 2 was obtained as wave parameters derived from measurements buoy 2031 (Fjaltring, Denmark)[2]. Wave height and period parameters from this buoy were provided as significant wave height H_s and mean wave period T_{mean}. These parameters were converted to H_{m0} and T_e using the relations provided in [1]. Wave energy flux was derived from H_{m0} and T_e using Formula (1) found in [1].

A summary of the wave climate at Location 2 is presented as a wave energy flux matrix shown in Figure F.4. The mean annual wave energy flux is 7,8 kW/m.

2 Parametric wave data from buoy 2031 were provided by Aalborg University, who received the data from the Kystdirektoratet/The Danish Coastal Authority.

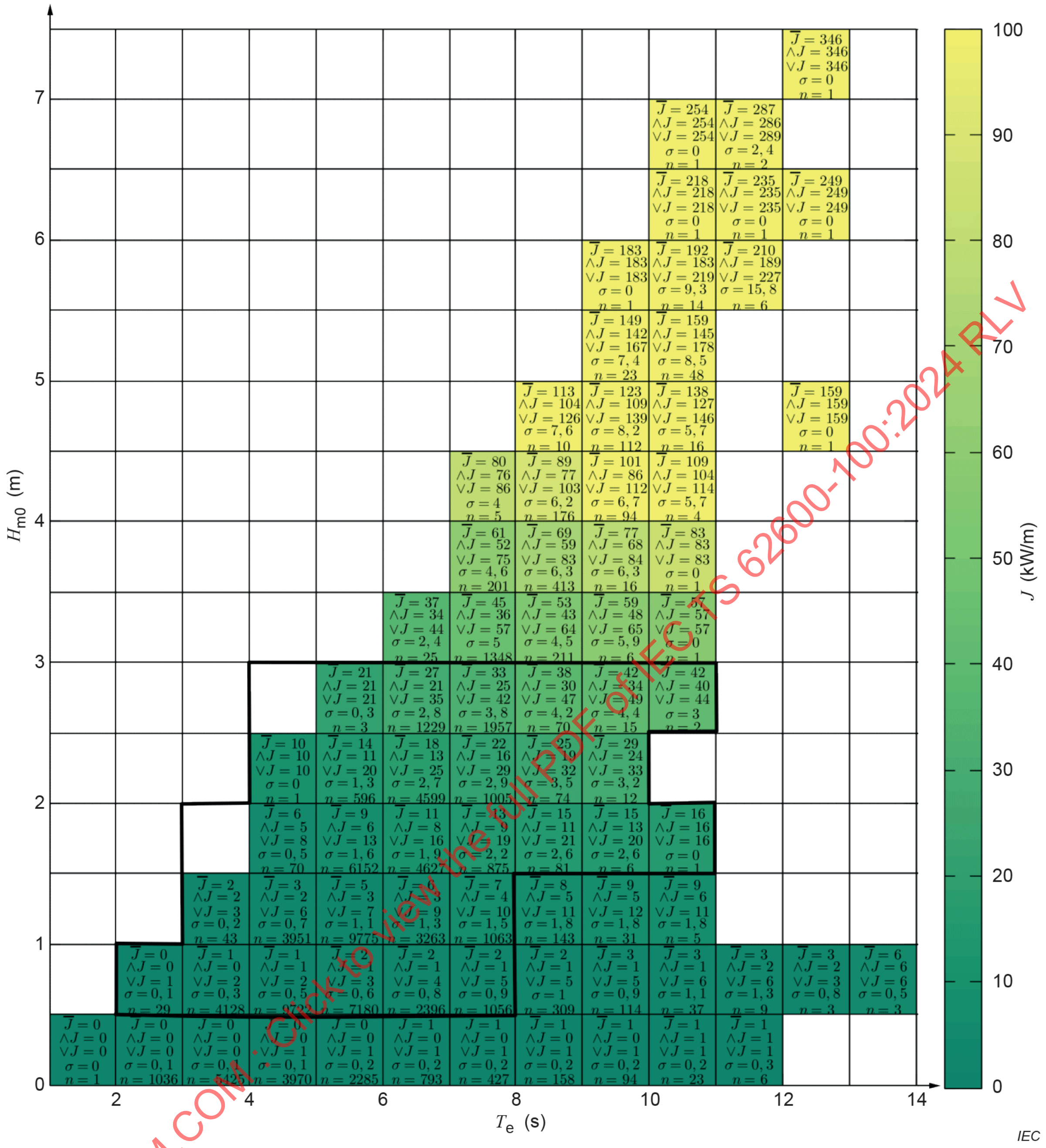


Figure F.4 – Location 2 Wave Energy Flux Matrix, Buoy 2031 (Fjaltring, Denmark)

F.6 WEC power capture data at Location 1

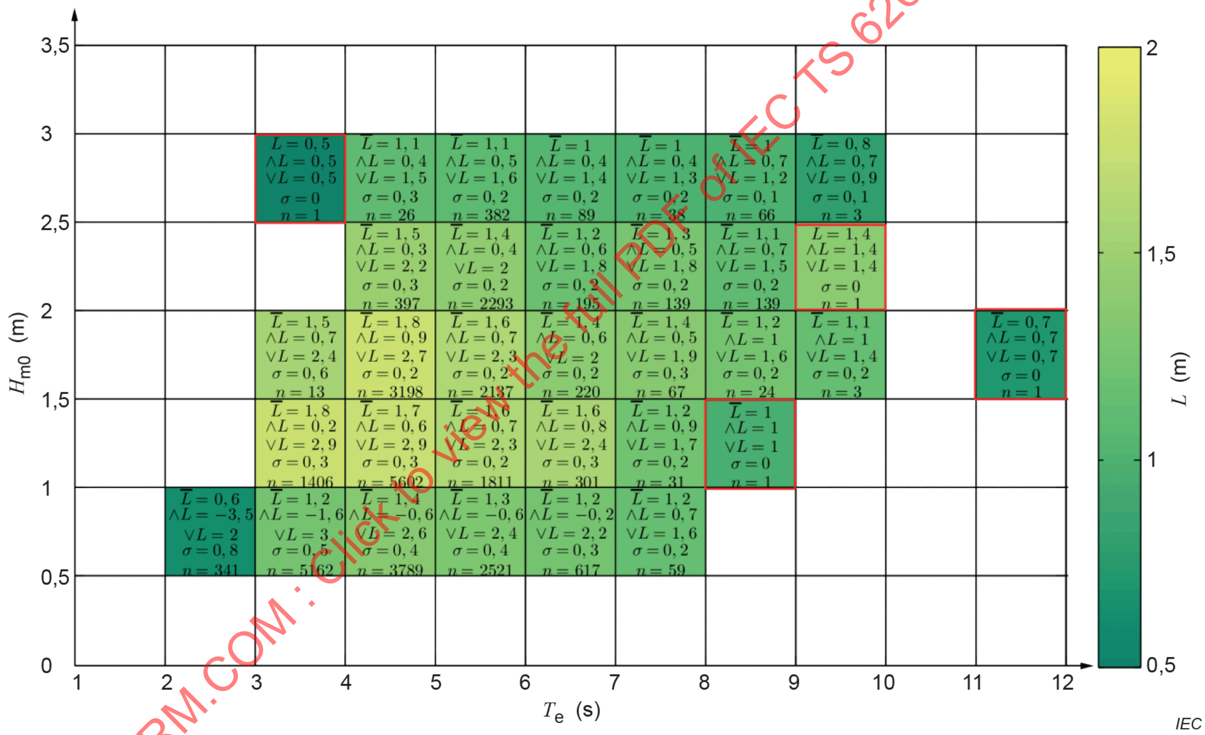
Clause F.6 presents the aspects of Clause 10 of this document performance assessment necessary to support the assessment of performance at a second location.

Electrical power was measured at the output of the generator, calculated by multiplying the voltage and current. Electrical power data was provided in intervals concurrent to the wave measurements. Included with the electrical power data were flags to indicate when the device was in normal operation mode and when the associated performance data was invalid.

The capture width matrix was calculated as per Clause E.6. Only records with both valid wave and performance data were used in the calculation. Operating policy for the Wavestar prototype specified a cut-in and cut-out significant wave height of 0,5 m and 3,0 m respectively. As a consequence of that policy, the average capture width of bins with significant wave height smaller than 0,5 m and larger than 3 m have been set to zero. The capture width matrix is given in Figure F.5. Text in each bin of the figure gives:

- The average capture width, $\overline{CW}$.
- Minimum capture width, $\wedge \; CW$.
- Maximum capture width, $\vee \; CW$.
- Standard deviation of the capture width, σ.
- The number of records in that bin, n.

It is notable that some bins with H_{m0} < 1,0 m have a negative minimum capture width. Negative capture width values occur for these sea states because the ancillary systems of the WEC require more power than it is generating so that the net production is negative.



NOTE Underpopulated bins, outlined in red, have less than 3 records, undefined bins are empty.

Figure F.5 – Wavestar prototype capture width matrix Location 1

F.7 WEC model validation

Either a numerical or physical model, or both, of the candidate WEC technology is recommended when applying this document. The computational WEC model used in this example was developed and executed by the Wavestar team. The results from the model, summarized as an electrical power performance matrix and published in [3], were used in this example assuming ancillary load of 1,2 kW. The matrix as published is defined in terms of H_s and T_{mean}; it was converted to H_{m0} and T_e by using the location specific relations in [1] and linear interpolation. The resulting power performance matrix is presented in Figure F.6.

The simulations which were used to generate the power matrix were based on observed wave conditions at Hanstholm. While it is likely that most non-zero bins are based on three or more simulations, we do not know the exact number for this example. Formal uses of this document will require that number of simulations used to calculate the average capture width in each bin is clearly stated.

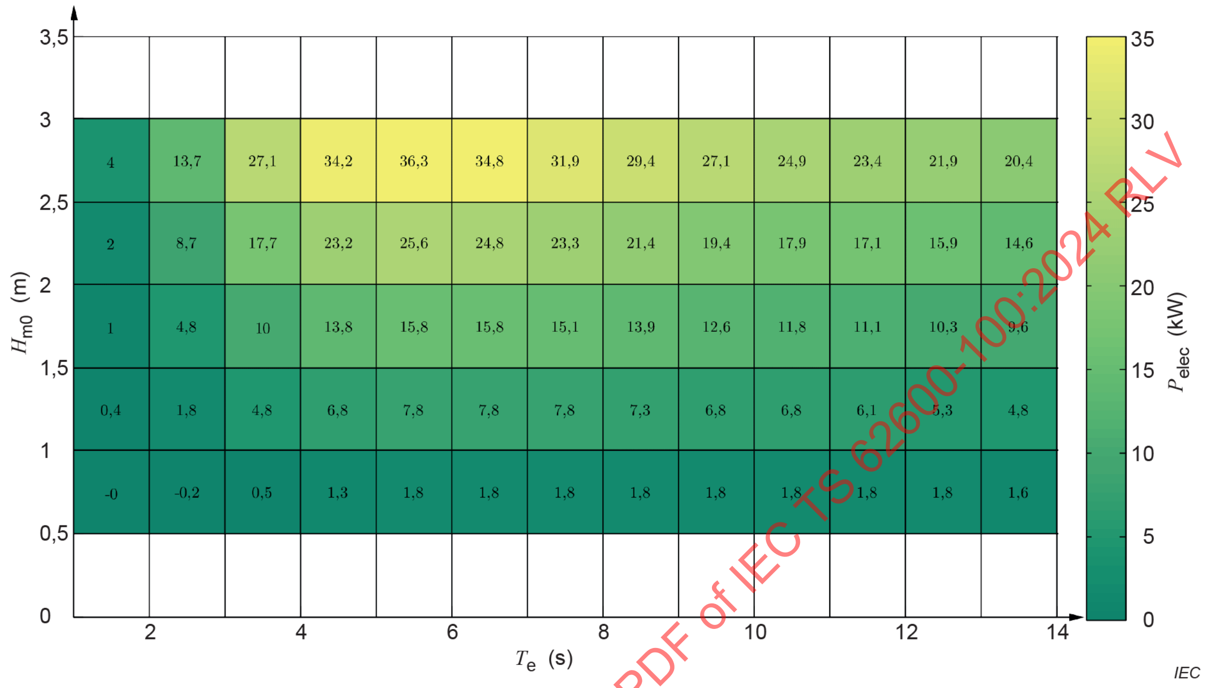


Figure F.6 – Numerically modelled electrical power matrix, adapted from [3]

The electrical power matrix was converted to capture width assuming the same bin-average wave power as the observations. The model error is calculated as in Formula (E.1).

Bins from the observed capture width matrix with less than three records were not used in the comparison (see Clause F.9). The resulting modelled capture width error matrix is shown in Figure F.7.

Larger differences in capture width of up to 54 % are observed near the wave steepness limit of the matrix. In this area the model likely fails to capture the highly non-linear nature of the near breaking waves. At the lowest wave height and period, the observed capture width is small, so that the percent difference appears very large. In bins contributing most to the power production of the matrix, the capture width difference is generally less than 10 %.

The AEP may be calculated using both the observed and modelled capture width matrix as per IEC TS 62600-101. Using this approach, the AEP based on the observed and modelled capture width matrices are 71,59 MWh and 71,73 MWh respectively, a difference of less than 1 %.

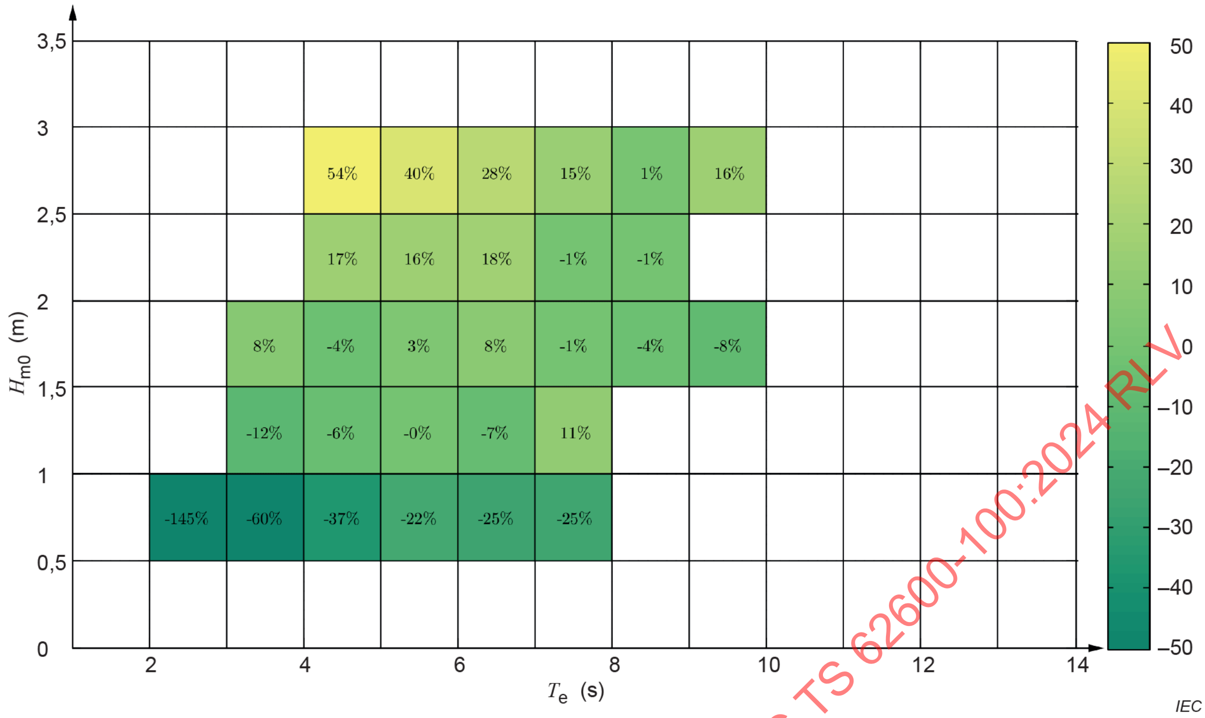


Figure F.7 – Model validation indicating percent difference in capture width between observations and model (model-observations)

F.8 Calculate capture width matrix for use at Location 2

F.8.1 Assess the appropriate dimensionality of the capture width matrix at Location 2

In many cases the prevailing metocean conditions at Location 1 and 2 will differ significantly. As detailed in Clause E.9, it is important to assess how differing metocean conditions between the two locations can impact the calculation of AEP. Particular attention should be given to those metocean parameters which are not included in the dimensionality of the capture width matrix.

The depth difference between Location 1 and Location 2 is notable and warrants investigation. However, for this example, it is assumed that a complete sensitivity analysis has been completed as per Clause E.9 and the findings show that H_{m0} and T_e are sufficient to characterize the WEC performance at both Location 1 and Location 2.

Formal uses of the document will require justification based on the full metocean study.

F.8.2 Calculate information for each bin of the capture width matrix

In this example, the appropriate dimensionality of the capture width matrix at Location 1 and Location 2 are assumed to be the same, therefore the observed capture width matrix applicable to Location 2 is the same as that determined for Location 1 (Figure F.5).

F.9 Perform quality assurance on capture width matrix for application at Location 2

To ensure a reasonable estimate of the average capture width in each bin of the capture width matrix, Clause E.10 requires that there are at least three performance records per bin. Bins of the capture width matrix not meeting the three record requirements are outlined in red in Figure F.5. These bins are noted as 'underpopulated' and removed from the observed capture width matrix.

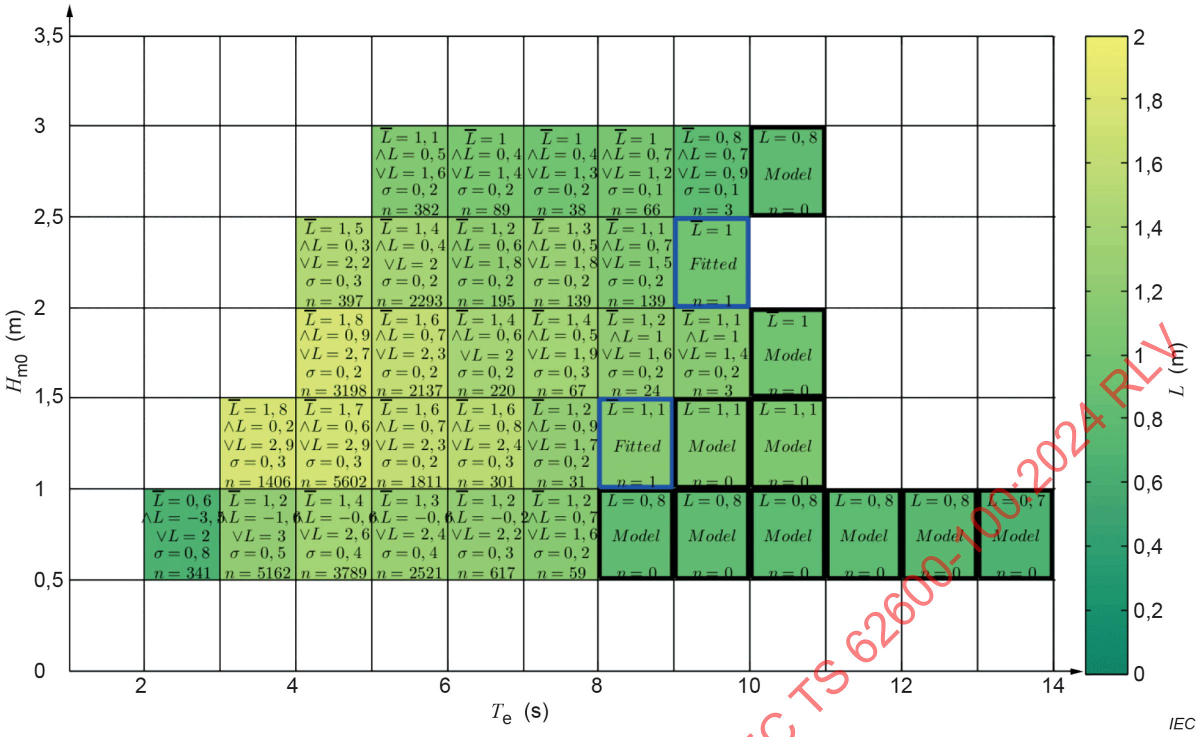
F.10 Complement capture width matrix to cover range of conditions at Location 2

On Figure F.4, the Location 2 wave power flux matrix, the populated region of the observed capture width matrix is outlined in black. Bins not covered by the capture width matrix shall be complemented in order to calculate the annual energy production at Location 2.

As outlined in E.11.1, empty bins of the capture width matrix may be estimated using data fitting techniques provided there are valid adjacent bins. Here ordinary least-squares linear regression has been used to interpolate the value of the empty bins, based on the values of the adjacent bins including the corners.

As also outlined in E.11.3, a validated device performance numerical model may be used to estimate the performance of any bin in the capture width matrix. Here the Wavestar numerical model, described in Clause F.7, is used to estimate the capture width of all bins with wave occurrences which have not been defined by wave measurements or the data fitting procedure. Additional information on the Wavestar performance model can be found in Appendix B of [4].

Figure F.8 gives the Wavestar prototype capture width matrix, complemented for use at Location 2. Fitted bins are indicated with a blue border and the word 'fitted', modelled bins are indicated with a black border and the word 'model'.



NOTE Bins not measured at Location 1 have been fitted (blue outline) or modelled (black outline).

Figure F.8 – Wavestar prototype capture width matrix for Location 2. Fjaltring, Denmark

F.11 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 IEC TS 62600-101:2015, A.6.2.

F.12 Assessment of confidence

Assessment of uncertainty is performed as specified in IEC TS 62600-101:2015, A.6.3.

Annex G
(informative)

Power take off efficiency

G.1 General

The PTO converts the energy of the prime mover into electrical energy. The PTO efficiency at location 1 can be parametrized. The parameterization can be used to predict the PTO efficiency at location 2. The PTO is all the equipment, electronics, and instrumentation between the connection to the prime mover and the electrical output as described in 8.1 WEC output terminals. Measurement of loads in the WEC and PTO shall be done in accordance with IEC TS 62600-3.

G.2 Absorbed power

Absorbed power (P_{abs}) is the amount of wave power absorbed by the WEC. The absorbed power should be measured at the connection between the WEC motion and the PTO. The connection between the waves and the PTO connection can be:

- Mechanical.
- Pneumatic.
- Hydrodynamic.

The absorbed capture width for the WEC is the time-averaged absorbed power divided by wave power, 9.2.3, Formula (G.1).

$$CW_{abs} = \frac{P_{abs}}{J} \tag{G.1}$$

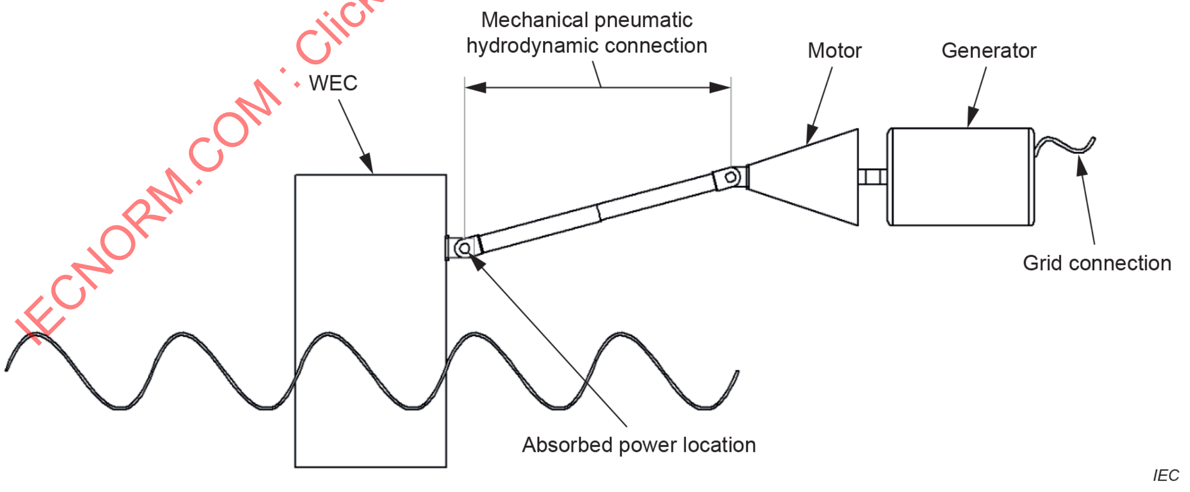


Figure G.1 – Overview of Power Take Off System

NOTE The measurement of the absorbed power requires instrumentation located as near to the connection of the WEC to the absorbing location as possible. It is prudent to determine the loss in absorbed power between the instrumentation and actual absorbing location.

G.3 WEC Power take off efficiency – location 1

The PTO efficiency is measured at location one. The PTO efficiency is defined as the electrical power output divided by the absorbed wave power. This definition can be converted into capture width with the PTO efficiency defined in Formula (G.2).

$$\eta_{PTO} = \frac{CW}{CW_{abs}} \tag{G.2}$$

The PTO efficiency is likely to be sea state dependent and therefore should be determined for each binned sea state.

G.4 Example calculation of PTO efficiency

The following is a sample calculation of PTO efficiency based on measured data. The absorbed power should be measured as close as possible to the WEC absorber. The location will be identified on the drawing of the WEC. Corrections for the measurement location will be documented. The capture width of the absorber is shown in Table G.1 and PTO efficiency is shown in Table G.1.

Table G.1 – Absorbed capture width

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	0,576	-	-	-	-	-	0,149
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,536	1,012	0,861	-	-	-	-
	3,0 to 3,5	-	-	-	-	1,081	1,331	1,415	-	-	-	-	0,370
	2,5 to 3,0	-	-	-	1,010	2,006	1,900	1,707	1,419	1,344	0,988	-	-
	2,0 to 5,5	-	-	-	-	2,689	2,437	1,971	1,849	1,536	1,788	-	-
	1,5 to 2,0	-	-	-	3,221	3,353	2,911	2,359	2,048	1,735	1,544	-	0,794
	1,0 to 1,5	-	-	-	4,066	3,728	3,265	2,904	2,383	1,870	-	-	-
	0,5 to 1,0	-	-	4,165	4,178	3,950	3,562	3,109	2,642	-	-	-	-
	0,0 to 0,5	-	-	-	3,609	3,893	4,400	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

Table G.2 – PTO efficiency

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	68 %	-	-	-	-	-	62 %
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	64 %	65 %	67 %	-	-	-	-
	3,0 to 3,5	-	-	-	-	66 %	67 %	69 %	-	-	-	-	62 %
	2,5 to 3,0	-	-	-	55 %	66 %	67 %	68 %	68 %	69 %	69 %	-	-
	2,0 to 5,5	-	-	-	-	66 %	67 %	67 %	68 %	68 %	64 %	-	-
	1,5 to 2,0	-	-	-	57 %	63 %	64 %	64 %	65 %	65 %	62 %	-	63 %
	1,0 to 1,5	-	-	-	51 %	56 %	57 %	59 %	52 %	49 %	-	-	-
	0,5 to 1,0	-	-	16 %	34 %	41 %	43 %	44 %	45 %	-	-	-	-
	0,0 to 0,5	-	-	-	-27 %	-2 %	22 %	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

G.5 Power take off efficiency – location 2

The PTO at location 2 may be modified from the PTO at location 1. The efficiency of the modified PTO will provide a method to estimate the electrical capture width at location 2. The concept of operation of the PTO at location 2 should be the same as the PTO at location one. The PTO can be divided in three basic components:

- Interaction connection between the PTO and wave power resource.
- Motor.
- Generator.

The efficiency for each basic component is given by Formula (G.3).

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{G.3}$$

NOTE 1 Changing component size will make scaling easier.

NOTE 2 Using the efficiency for each component making up a basic component can increase the accuracy of the estimated efficiency.

The total efficiency of the PTO is each of the component's efficiencies multiplied together Formula (G.4).

$$\eta_{PTO} = \prod_{i=1}^{N} \eta_i \tag{G.4}$$

Where

η_{PTO} PTO efficiency

η_i Efficiency of i^{th} component

N Number of components

The estimated capture width is the PTO efficiency times the WEC absorbed capture width, Formula (G.5).

$$CW = CW_{abs} \times \eta_{PTO} \tag{G.5}$$

The PTO and PTO component efficiency should be estimated based on computational models validated against bench testing or data obtained from absorbed power measured during field testing at Location 1 (see example in Clause G.4). How the PTO efficiency has been estimated and with how much confidence these results can substitute field data should be reported by the user. If a physical experimental model is used as described in E.11.4 the absorbed power typically is measured. To calculate the electrical power produced the efficiency of the PTO shall be characterized.

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[5] International Towing Tank Conference (ITTC), *Recommended Guidelines 7.5-02-07-03.7, Wave Energy Converter Model Test Experiments*

IEC 61000-3 (all parts), *Electromagnetic compatibility (EMC) – Part 3: Limits*

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IEC TS 62600-100

Edition 2.0 2024-11

TECHNICAL SPECIFICATION

colour inside

**Marine energy – Wave, tidal and other water current converters –
Part 100: Electricity producing wave energy converters – Power performance assessment**

IEC TS 62600-100:2024-11(en)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

Part 100: Electricity producing wave energy converters –
Power performance assessment

FOREWORD

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IEC TS 62600-100 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 2012. This edition constitutes a technical revision.

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

a) Incorporation of IEC TS 62600-102 as a series of annexes in this document
b) Removal of the computation of annual energy production. This has been moved to IEC TS 62600-101.

c) Modification to the list of terms definitions, symbols and units.

d) Modification of the reporting section to align with IEC TS 62600-200

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

Draft	Report on voting
114/537/DTS	114/554/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 part of IEC 62600, which is a Technical Specification, provides performance assessment methods for wave energy converters. A wave energy converter is a device which generates electricity using the action of water waves and delivers electricity to an electrical load.

Wave energy industry development is transitioning from preliminary stages to commercial production stages. Validated data gathering and processing techniques are important to improve existing technologies. This document will be subject to changes as data are collected and processed from testing of wave energy converters.

The expected users of the document include:

- Device developers who want to validate the performance of their wave energy converter.
- Investors who want to assess the performance of a device developer's wave energy converter.
- Project developers who want to assess the performance of their project against manufacturer's claims.
- Surveyors contracted to carry out the assessment.
- Conformity assessment, test laboratories, and certification.
- Project developers – income, return on investment
- Device developers – performance of device
- Utilities and investors – reliability/predictability of supply, return on investment
- Policy-makers and planners – usage of seascape, optimisation of resource, power supply issues
- Consultants to produce resource data/due diligence – compatible/readable data format

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 100: Electricity producing wave energy converters – Power performance assessment

1 Scope

Wave Energy Converters (WEC) are designed to operate efficiently at different locations. Systematic methods are used to evaluate the power performance of a WEC at a second location (hereinafter Location 2) based on power performance assessment at a first location (hereinafter Location 1). The degree of similarity of the measured WEC (WEC 1) and the metocean conditions at Location 1 to the secondary WEC (WEC 2) at Location 2 determine the methodology and the applicability of this document.

This document applied in conjunction with the IEC Technical Specification on wave energy resource assessment and characterization (IEC TS 62600-101), provides a method for estimation of the mean annual energy production of a WEC, assessing the electrical power production performance of a single, non-array, wave energy converter, at Location 2 based on the performance at Location 1.

The scope of this document includes:

a) All wave energy converters that produce electrical power from wave energy.
b) All sea resource zones (near and offshore, deep and shallow water).
c) Capture width matrix transposition from one location to another.
d) Limitation on the changes that are allowed to the WEC and the specification of the location.
e) Wave data required at Location 2, as a minimum the requirements found in IEC TS 62600-101.
f) Development of the capture width matrix at Location 2.
g) Validation of the capture width matrix at Location 2.
h) Assessment of uncertainties in the derived performance parameters at Location 2.
i) Requirements for the allowable power performance transfer by geometric, kinematic and dynamic similarity.
j) Requirements for the allowable incorporation of additional empirical model data.
k) Requirements for the allowable incorporation of additional numerical model data.
l) The document applies to commercial scale wave energy converters that are:
   1) compliantly moored.
   2) tautly moored.
   3) bottom mounted.
   4) shore mounted.

The scope of this document does not include:

a) Wave energy converters that produce nonelectrical energy.
b) Resource assessment.
c) Scaled devices in test facilities (tank or scaled sea conditions) where any scaling would be carried out to extrapolate results for a full-scale device.
d) Power quality issues.

e) Environmental issues.

f) Operation and maintenance.

g) Annual energy production (AEP).

This document provides a systematic method which includes:

- measurement of WEC capture width in a range of sea states.
- transposition of capture width from one location to a second location.
- an agreed framework for reporting the results of capture width and wave measurements.
- estimate of the capture width of a modified WEC at Location 2. This work would include the development of parameters for the modified WEC for the second location.

This document provides:

- guidance on the use of observations from Location 1.
- methods for assessing and reporting the validity of numerical and physical models.
- limits on the permissible changes to the WEC between Locations 1 and 2.
- limits on the use of data fitting techniques, and
- requirements for reporting.

The wave power industry is at an early stage of development. There is little practical experience with field-scale WECs deployment. Because of this, the present document will be subject to change as more data is collected and experience with wave energy converters develops.

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 60688, *Electrical measuring transducers for converting AC and DC. electrical quantities to analogue or digital signals*

IEC 61869-1, *Instrument transformers – Part 1: General requirements*

IEC 61869-2, *Instrument transformers – Part 2: Additional Requirements for current transformers*

IEC 61869-3, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers*

IEC TS 62600-3, *Marine energy – Wave, tidal and other water current converters – Part 3: Measurement of mechanical loads*

IEC TS 62600-101:2015, *Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization*

IEC TS 62600-103, *Marine energy – Wave, tidal and other water current converters – Part 103: Guidelines for the early stage development of wave energy converters – Best practices and recommended procedures for the testing of pre-prototype devices*

ISO/IEC Guide 98-1, *Uncertainty of measurement – Part 1: Introduction to the expression of uncertainty in measurement*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995)

ISO 8601, *Data elements and interchange formats – Information interchange – Representation of dates and times*

ISO 19901-1, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating considerations*

3 Terms, definitions, symbols, units, and abbreviated terms

3.1 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

3.2 Symbols, units, and abbreviated terms

For the purposes of this document, the following symbols, units, and abbreviated terms listed in Table 1 apply.

Table 1 – Symbols, units, and abbreviated terms

Symbol	Definition	Units
C_{cable}	total positive sequence line-to-line capacitance of subsea cable	farad
$c_{\text{g,i}}$	group velocity at frequency component i	m/s
c_{pi}	phase velocity at frequency component i	m/s
f	frequency	Hz
f_{p}	peak frequency	
f_{i}	frequency at component i	Hz
f_i	frequency spacing	Hz
$G(\theta,f)$	directional spreading function NOTE 1 $\int_{-\pi}^{+\pi} G(\theta,f) \times d\theta = 1$	1/rad
h	water depth	m
H_{m0}	spectral estimate of significant wave	m
H_{s}	significant wave height	m
I_{meas}	Line RMS current	A
J	Omni-directional wave power per unit width	W/m
$\hat{J}$	maximum omni-directional wave power per unit width	W/m
$\check{J}$	minimum omni-directional wave power per unit width	W/m
$\overline{J}$	average omni-directional wave power per unit width	W/m
k_{i}	wave number at frequency component i	1/m

Symbol	Definition	Units
CW	capture width	m
$\hat{CW}$	maximum capture width	m
$\check{CW}$	minimum capture width	m
$\overline{CW}$	average capture width	m
$CW_{\text{model},i}$	model capture width for i^{th} bin	m
$CW_{\text{measured},i}$	measured capture width for i^{th} bin	m
$CW_{\text{err},i}$	error capture width for i^{th} bin	m
M	number of data sets in a bin	-
m_n	frequency n^{th} order moments of the variance spectrum	Hz^n
n	number of records	-
N	number of bins	-
P_i	measured power output per bin	W
P_h	hydraulic power input	W
P_{abs}	absorbed power	W
P_e	measured real electrical power output	W
P_{pto}	power loss (dissipated) in the PTO	W
PF_{meas}	power factor	-
P_{meas}	real or active power	W
P_{genWEC}	power generated by WEC	W
P_{loss}	cable power loss component	W
PTO	power take off	
Q_{meas}	reactive power	VAR
R_{cable}	total positive sequence resistance of subsea cable	Ω
S	variance density	$\frac{m^2}{Hz}$
$S(f)$	variance density as function of frequency	$\frac{m^2}{Hz}$
$S(f)_{\text{WEC}}$	spectral density at WEC equals $T(f,t,\theta,h,...) \times S(f)_{\text{wmi}}$	$\frac{m^2}{Hz}$
$S(f)_{\text{WMI}}$	spectral density at WMI	$\frac{m^2}{Hz}$
$S(f, \theta)$	Directional wave energy spectral density $S(f) \times G(\theta, f)$	$\frac{m^2}{Hz \cdot rad}$
$S(f,\theta)_{WEC}$	Directional wave energy spectral density $S(f) \times G(\theta, f)$ at WEC	$\frac{m^2}{Hz \cdot rad}$
$S(f,\theta)_{WMI}$	Directional wave energy spectral density $S(f) \times G(\theta, f)$ at WMI	$\frac{m^2}{Hz \cdot rad}$

Symbol	Definition	Units
S_i	variance density over the i^{th} discrete frequency	$\frac{m^2}{Hz}$
S_{ij}	variance density of the i^{th} discrete frequency and j^{th} discrete direction	m^2/Hz/rad
σ	standard deviation	-
t	time lag or shift between the WMI and the WEC	s
T	operational hours per record	h
$T(f, t, \theta, h,...)$	Variance density spatial transfer model, for correction of the spectral density measured at the WMI to the WEC NOTE 2 not all the variables are listed. the transfer model dependencies will be specific to each test site.	-
T_e	energy period (also written as T_{-10})	s
Δf_i	frequency width of the variance density of the i^{th} discrete frequency	Hz
$\Delta\theta j$	angular width of the variance density of the j^{th} discrete direction	rad
U	line-to-line voltage	V
U_{meas}	line-to-line RMS voltage	V
V_{p1+}, V_{p1-}	WEC side positive sequence voltage	V
V_{p2}, V_{p2-}	shore side positive voltage	V
WEC	wave energy converter	
WMI	wave measurement instrument	
X_{cable}	total positive sequence reactance of subsea cable	Ω
ρ	fluid density	kg/m^3
θ	wave direction	rad
λ	wavelength	m
φ	phase angle	Degrees°
	voltage phase angle	Degrees°
	current phase angle	Degrees°
η_{pto}	power take off efficiency	-
$CF(X)$	Centre frequency fraction of errors that lie within the limits of ± X %	%

4 Sequence of work

Figure 1 shows the sequence of work for the assessment as described in this document. The pre-test sections shall be conducted prior to the testing period. Following the testing period, the post-test sections shall be conducted.

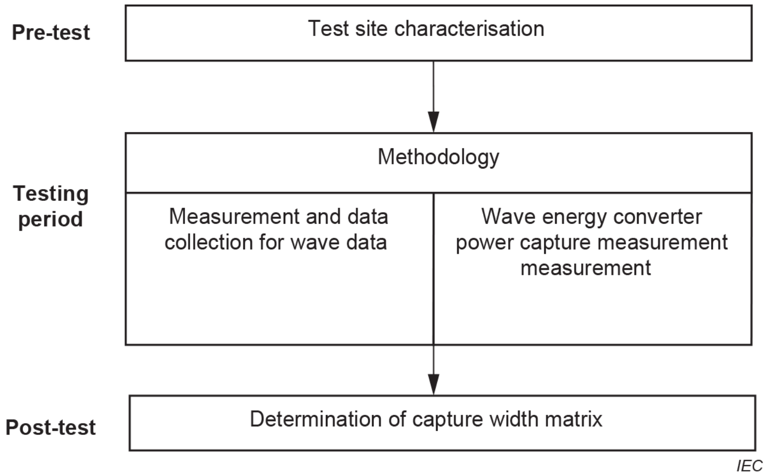

Figure 1 – Timeline of assessment

5 Test site characterisation

5.1 General

An analysis of the prospective test site shall be undertaken to ensure that it is suitable for power assessment of a WEC. The incident wave climate shall be evaluated to ensure the capture width matrix can be populated. To infer the incident wave power at the location of a WEC, the effect of bathymetry and metocean parameters and conditions on the incident wave climate shall be sufficiently analysed to determine whether a transfer model between the Wave Measurement Instrument (WMI) and WEC will be required. If a transfer model is required, the analysis shall support the development of a suitable transfer model.

5.2 Measurements

5.2.1 General

The boundary of the test site shall be defined and documented. The main physiographic and oceanographic features of the study area shall be identified, especially those features that influence wave propagation and thus the wave characteristics at the proposed WEC location. Locations and time periods of all measurements will be recorded.

In cases where a wave propagation model is necessary to infer the wave characteristics at the WEC location, the test site boundary should be considered the wave propagation model domain.

5.2.2 Wave characterisation

A WMI shall be deployed at the proposed WEC testing location prior to WEC deployment. A second WMI shall be deployed simultaneously at the proposed post-deployment wave measurement location. The WMIs shall be deployed for a minimum of 3 months prior to WEC deployment, and it is recommended the WMIs record data for 12 months prior to WEC deployment to account for seasonal variations. The frequency of WMI measurements will be at least once per hour. It is expected that during each measurement the WMI will record data defining the free surface elevation time series profile, and that this time series data will be at sufficient temporal resolution to permit subsequent transformation of the data into a frequency domain representation.

More than one WMI should be used if there is a large variation of wave direction and sea state due to bathymetric changes near the WEC location.

The directional wave energy spectrum, $S(f,\theta)$, shall be calculated from WMI recorded data. The wave spectra can be recorded in discrete form, but the maximum frequency bin width shall not exceed 0,015 Hz, and the maximum directional bin width shall not exceed 5 degrees, or 0,088 rad.

From each directional wave energy spectrum record, spectrally derived estimates of the following parameters shall be derived for use in the determination of the capture width matrix:

a) significant wave height.
b) energy period.
c) wave direction.
d) directional spread.
e) spectral width.

In addition to wave parameters mentioned, the following environmental parameters shall be recorded:

f) water depth including tidal effect.
g) tidal or ocean current speed and direction.
h) wind speed and direction.
i) density of water.
j) occurrence and thickness of ice.

Parameters from the lists (items a-j) that have not been recorded, and thus not included in the development the capture width matrix, shall be identified and the rationale for their exclusion justified.

The preferred characteristic period is the energy period, but additional characteristic periods may also be calculated. These include the peak period and the zero up-crossing period.

5.2.3 Tidal or ocean currents

Currents at the test site shall be recorded and documented through a current measurement instrument. The current speed and direction data shall be measured simultaneously with the wave measurement and shall extend over a minimum of 30 days. The sampling period shall be a maximum of 10 minutes. At least one current speed and direction record will be taken from the upper half of the water column during the deployment period. The primary purpose of current records is to facilitate the development of a model of the area. Tidal and non-tidal currents shall be estimated and differentiated.

It is recommended, however, to measure current velocity and directions at different points of the water column in order to adequately describe the velocity profile at the site.

5.2.4 Tidal elevation

Tidal heights shall be recorded at the test site. The measurements shall extend over at least 30 days and shall be analysed to estimate tidal ranges.

5.2.5 Bathymetric survey

The boundary of the test site shall be defined and documented as in IEC TS 62600-101. A bathymetric survey of the area shall be undertaken and documented. The resolution of the bathymetric survey shall be as necessary to support the wave spatial transfer model, see 5.2.7.

The survey should provide the details on the bottom profile.

5.2.6 Wind speeds

The wind speed shall be recorded as in IEC TS 62600-101.

5.2.7 Calculation of wave spatial transfer model

The sea state at the location of the WMI shall be representative of the sea state at the location of the WEC. If the difference between the wave power at the WMI and the WEC – as determined by the deployment of a minimum of two WMIs, one at the wave measurement location and one at the WEC location – is less than 10,0 % for 90,0 % of the records then it can be assumed that the wave field is statistically equivalent.

NOTE It is expected that this will be the case for a well-chosen deep-water test site.

If the condition is not met, then a spatial transfer model shall be generated and validated. The spatial transfer model can either be an existing modelling program or a custom modelling program. The modelling program shall be validated. The accuracy of the model shall be determined as shown in Annex D.

5.2.8 Modelling of the test site

The spatial transfer model shall predict the spectrum at the WEC based on the spectrum at the WMI. The test site should be modelled to assist in the development of a spatial transfer model. The spatial transfer model shall be acceptable if it predicts the energy flux at the WEC to within 10,0 % of the measured wave energy flux for 90,0 % of the data recorded according to 5.2.2.

NOTE The spatial transfer model would generally be in the form:

$$S(f,\theta)_{WEC} = T(f,t,\theta,h,...) \times S(f,\theta)_{WMI} \qquad (1)$$

6 Methodology

6.1 General

This document governs the methodology for measurement, analysis and presentation of data to assess the power performance of an electricity generating WEC.

The sea state incident at the WEC shall be measured to the accuracy specified in Clause 7. The sea state measurements shall be analysed to give the parameters for each sample sufficient to describe the sea state as specified in Clause 7.

The electrical power production at the WEC shall be measured to the accuracy specified in Clause 8. The electrical power production measurements shall be analysed to give the parameters for each sample sufficient to describe the electrical power production as specified in Clause 8.

A capture width matrix shall be compiled as specified in Clause 9 which compares the parameters of the sea state samples and the electrical power production samples (see Figure 2).

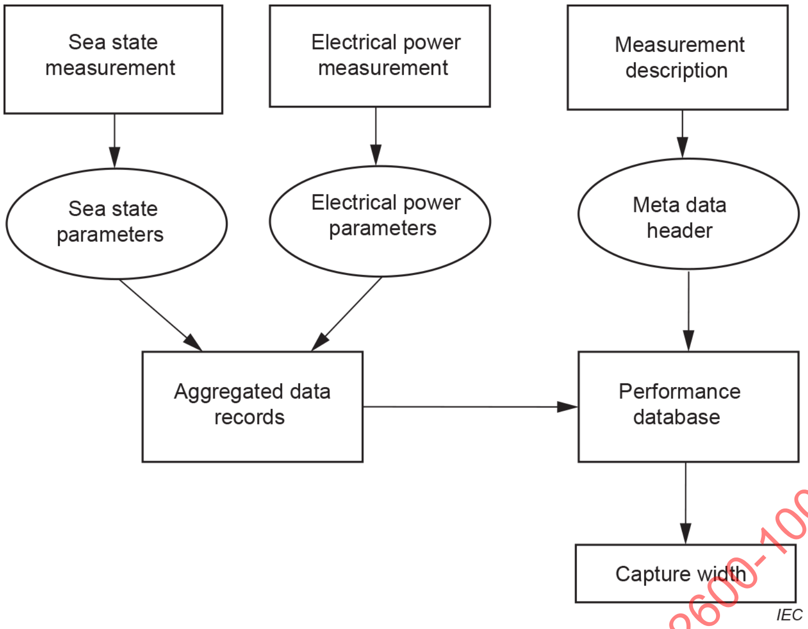

Figure 2 – Data flow diagram

6.2 Sample duration

The parameters describing the sea state and electrical power production for each sample shall be recorded as specified in Clause 7 and Clause 8. The minimum sample duration shall be 20 min. It shall be reported at least every hour.

NOTE Sample duration will affect the accuracy of the measurement. A short sampling duration can result in the poor characterisation of the sea state.

6.3 Simultaneity

The measurements from a WMI and WEC power output shall be measured at the same time to provide correlation between sea state and WEC output power. WMI and WEC data shall be synchronized so that the sea-state incident at the WEC can be correlated with WMI records. It is recommended that WMI data be recorded simultaneously with WEC power data for a minimum of one half of the sample duration.

The spatial transfer model shall be used to correct any time delay between the measurements taken at the WMI and the location of the WEC. The correction for the time delay will not affect the simultaneity of the measurements.

6.4 Data recording

6.4.1 Amount of data to be recorded

The minimum amount of data recorded shall be based on the design operating envelope of interest. This shall define the amount of testing that is required to develop a power matrix.

The minimum testing duration shall be six months and be representative of the deployment location.

NOTE Spectral shape can vary with seasons leading to variations in the capture width matrix.

6.4.2 Data format and retaining

The data shall provide a record of sea state and electrical power production over time. Each aggregated data record shall be date and time stamped using ISO 8601. The records shall be annotated with quality control flags giving the results of the quality control checks carried out during the recording and analysis path. The records shall be convertible to a human readable format with a descriptive header for each data record.

7 Measurement and data collection for wave data

7.1 General

The purpose of Clause 8 is to specify the wave and environmental data required to produce a capture width matrix for a WEC. Clause 8 provides the methodology for analysing the wave data in order to characterise the environmental conditions. The minimum sample frequency shall be 1,0 Hz.

7.2 WMI calibration

7.2.1 General

The WMI shall be verified by the vendor through a factory acceptance test. This shall include at a minimum:

a) Any operating limitation of the WMI.

b) Calibration of the WMI accuracy over the operating range.

c) Last calibration date and calibration interval of the WMI.

d) The calibration method.

e) The type of data that is output by the WMI.

7.2.2 General

The post deployment WMI location or locations shall be selected to:

a) Best represent the sea state at the WEC deployment location.

b) Minimize the WMI's impact on the waves at the WEC location.

c) Minimize the WEC's impact on the waves at the WMI location.

The effects of reflection, radiation, diffraction, and shadowing of the wave field shall be considered when assessing impacts.

7.2.3 Direct measurement

Direct measurement can be used if the site investigations as specified in Clause 5 have not revealed any significant variations in the sea states between the WEC and WMI. The WMI data will be representative of the sea state at the WEC. The WMI and WEC data can be processed and analysed directly.

7.2.4 Measurements with spatial transfer model

A spatial transfer model, as described in 5.2.7 and 5.2.8, shall be used to account for the changes occurring between the position of the WMI and the WEC. The spatial transfer function will provide the sea state data to be analysed with the WEC data.

7.2.5 Correction for WEC interference

The WMI shall be positioned to minimize the amount of interference from the WEC. A model shall be developed to estimate the waves induced by the WMI and the WEC from radiation and diffraction. The WMI shall be placed in a location where the effect of the radiated and diffracted waves from either body has less than 2 % to 3 % effect on the wave energy at each location.

7.3 Metocean data

It is recommended to measure and record all relevant parameters believed to have an influence on power production. Since there are several factors that can affect the WEC power production, depending on its type, awareness of any correlation between power production and a specific parameter should be sought and reported. A listing of the parameters is included in 5.2.2. As a minimum requirement, the significant wave height estimate H_{m0}, the wave energy period T_e, and the wave energy flux per unit width J shall be calculated using the measured wave data and reported.

Other parameters that have a significant effect on the power production of the WEC shall also be recorded and calculated. The calculation of any additional parameters shall be defined and reported in sufficient detail to allow for repeatability (see Annex C). The accuracy of the calculated parameters shall be given, according to the uncertainty estimation defined by ISO/IEC Guide 98-1 and ISO/IEC Guide 98-3.

Directly measured parameters will be expressed with indication of absolute error. Specifications on the type, location, calibration, and accuracy of the measurement instrument shall be given.

7.4 Procedure for the calculation of derived parameters

Wave data shall be described by wave spectra which provides information on how the wave elevation variance is distributed with frequency.

a) Frequency f_i: A range of frequencies will be selected for spectral analysis depending on the measurement instrument and sampling rate. The spectral frequency range used for calculation should be between 0,033 Hz and 0,50 Hz with the number of frequency bins determined from data analysis. Frequency bin width should not exceed 0,015 Hz.

b) The frequencies shall be defined using either a geometric progression where the ratio between two adjacent frequencies is constant, or a fixed frequency spacing. In either case the maximum frequency bin width shall not exceed 0,015 Hz.

   Currents can have a significant effect on wave and power parameters due to Doppler shift. Refer to ISO 19901-1 for the correction procedure. If the ratio of intrinsic to apparent wave frequency is between 0,9 and 1,1, corrections are not required. Any corrections from apparent to intrinsic wave shall be clearly noted.

c) Frequency moments of the variance spectrum m_n. The moments of the spectrum from $n = -1$ and $n = 0$ shall be calculated from

$$m_n = \sum_i f_i{}^n S_i \Delta f_i \tag{2}$$

NOTE 1 Formula (2) is the discrete approximation of the following: $m_n = \int S(f) f^n df$

d) The spectral significant wave height estimate H_{m0} is defined as:

$$H_{m0} = 4\sqrt{m_0} \tag{3}$$

e) The energy period T_e is defined as:

$$T_e = T_{-10} = \frac{m_{-1}}{m_0} \quad (4)$$

f) The wave energy flux per unit width J (omnidirectional) is defined as:

$$J = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta \theta_j \quad (5)$$

where

g is the gravitation constant equal to 9,8 m/s^2.

NOTE 2 Formula (5) is the discrete approximation of the following: $J = \rho g \int S(f) c_g(f) df$

g) The group velocity is defined as:

$$c_{g,i} = \frac{1}{2} c_{pi} \left[1 + \frac{2k_i h}{\sin h(2k_i h)} \right] \quad (6)$$

The phase velocity is defined as:

$$c_{pi} = \sqrt{\frac{g}{k_i} \tan h(k_i h)} \quad (7)$$

where

k_i is the wave number at frequency component i.

NOTE 3 In deep water conditions, where deep water is defined as a water depth to wave length ratio greater than 0,5, Formula (5) simplifies to:

$$J = \frac{\rho g^2}{64\pi} H_{m0}{}^2 T_e \quad (8)$$

NOTE 4 The directionality of the sea state is important when the WEC is directionally sensitive. The Metocean data will be recorded as a parameter. The directionality of the waves can be described as a mean direction and a parameter representing the spreading.

8 WEC power output measurements

8.1 WEC electrical output terminals

In the case of an AC grid-connected WEC its output terminals shall be at the point where the output power is in the form of AC at the network voltage and frequency.

In the case of a non-grid connected WEC, its output terminals shall be at the point where the power is connected directly to the load. The output power shall be in the form of AC at a commonly used network frequency (e.g. 50 Hz, 60 Hz), and at a commonly used grid connection voltage level (e.g. 400 V, 6,6 kV). These details shall be clearly stated.

The output terminal point shall be clearly stated.

8.2 Power measurement point

The power measurement point should be at the electrical output terminals of the WEC.

When this is not possible the power measurement point shall be at a point where other effects (such as losses due to cables or other electrical components) between the measurement point and the output terminals may be determined. In this case the methodology for these corrections shall be fully detailed. Power loss correction is only permitted for transmission equipment that is required for measuring the electrical power at the WEC output terminal. The power measurement point shall be clearly stated. In the case where the power measurement point differs from the output terminals the justification shall be made.

NOTE 1 Annex B contains a method for cable loss compensation where the measurement point is located on shore.

NOTE 2 DC power transmission is not included in this document.

8.3 Power measurements

8.3.1 General

The net electric power of the WEC shall be measured, inclusive of any reduction due to system energising power and necessary ancillary loads on board the WEC. The power shall be recorded with a minimum sample frequency of 2 Hz, the power signal having been subjected to a suitable anti-aliasing filter.

The mean, standard deviation, maximum and minimum of the digitized values which occur in each sample shall be recorded.

8.3.2 Limitations on power production

In the case of an AC grid connected WEC, an assessment shall be made of any potential limitations imposed on WEC power export capacity due to the grid connection. These can include the capacity of the connection itself or the requirement for significant reactive power export, resulting in constraints on the WEC power output under certain conditions. In the case where such constraints can occur, a method to identify when the WEC is operating under constrained output power conditions shall be put in place. Output power data gathered during these conditions shall be identified and may be excluded for use in the power performance matrix.

It is recommended that an external dump load be installed in order to eliminate the WEC power output constraint.

8.4 Instruments and calibration

The net electric power of the WEC shall be measured using a power measurement device such as a transducer and be based upon measurements of current and voltage on a minimum of two phases.

Electrical transducers and the power measurement device used in the electrical measurements should be accuracy class 1,0 or better, should be calibrated to traceable standards and shall meet the requirements of the following standards:

- power transducers: IEC 60688.
- current transformers: IEC 61869-2 and IEC 61869-1.
- voltage transformers: IEC 61869-3 and IEC 61869-1.

The operating range of the power measurement device shall be sufficient to include all positive peaks corresponding to net generation and all negative peaks corresponding to net imported power. As a guide, the full-scale working range of the power measurement device and transducers should be at least:

- export: 1 % to 200 % of rated power.
- import: –1 % to –50 % of rated power.

At the low power range of the device's rated capacity, where the working range of the current measurement device does not allow for an accuracy better than ±3 %, the power recorded should be zero. At the low power range where the working range of the transducer does allow for accuracy class 1,0 measurements, their measured values shall be recorded.

NOTE It is important that current transformers are specified correctly as they become non-linear for low currents (≤5 % of their range or thereabouts).

9 Determination of capture width matrix

9.1 General

The capture width matrix will be used to determine the effective operation of the WEC. The capture width matrix shall use a normalised capture width for each bin. The normalized capture width shall be calculated using the average value of the capture widths in the bin. The capture width is determined using the parameters derived in 7.2 and then calculated in 7.4. The capture width matrix is less sensitive to the sea-state parameters and thus less affected by the method of bins. In this case the capture width matrix should be produced as detailed in 9.2.3, Formula (9).

NOTE The annual energy production (AEP) is estimated in IEC TS 62600-101. The capture width in IEC TS 62600-100 is a calculated value. The capture width in IEC TS 62600-101 is calculated using IEC TS 62600-100. This allows for a common method to compare predictive to measured capabilities of a WEC.

9.2 Structure of the capture width matrix

9.2.1 Core structure

The normalized capture width matrix shall be constructed by applying the "method of bins" to the capture widths as in 9.2.3. The bins shall be defined by at least the significant wave height estimate, H_{m0} and energy period, T_e. The bins for significant wave height shall have a maximum width of 0,5 m and the bins for the energy period shall have a maximum width of 1,0 s.

9.2.2 Sub-division of the normalized capture width matrix

Additional indices, such as the mean wave direction or spectral bandwidth, may be added to the normalized capture width matrix to reduce the variability of capture width in each bin.

NOTE It is advantageous to sub-divide the normalized capture width matrix if by doing so it reduces the variability of the performance prediction, thereby giving greater confidence in the estimation of WEC energy production.

9.2.3 Calculation of the capture width

The capture width is equal to the net electric power capture divided by the wave power.

$$CW = \frac{P_e}{J} \tag{9}$$

9.2.4 Representation of the capture width per bin

In cases where only significant wave height, H_{m0} and energy period, T_{e} are used to define the capture width matrix a table can be used to fully represent the capture width matrix. Where more indices are used to define the capture width matrix the significant wave height and energy period should continue to be used together to organise the data sets to facilitate usage with wave climate scatter diagrams.

Each bin of the capture width matrix shall contain at least the following information:

a) the average capture width of all the data sets in the bin;
b) the standard deviation of the capture width of all the data sets in the bin;
c) the maximum capture width of all the data sets in the bin;
d) the minimum capture width of all the data sets in the bin;
e) the number of data sets in the bin.

NOTE It is recognized that some sites can have very different spectra for the same (mean) wave direction, for example combining ocean swell with local wind driven seas. Be aware of the limitations of the methodology.

The average and standard deviation of the capture width for each bin is calculated according to the formulae:

$$\overline{CW} = \frac{1}{M}\sum_{i=1}^{M} CW_i \tag{10}$$

$$\sigma = \sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(CW_i - \overline{CW}\right)^2} \tag{11}$$

10 Reporting format

10.1 General

Reporting requirements are described below. All work performed should adhere to the requirements in this document, and any deviations should be documented as described in 10.8.

10.2 WEC description report

The WEC under evaluation shall be described in full. As a minimum, the following parameters shall be provided:

- WEC make, type serial number, production year.
- Type of energy capture technology employed and the dimension of the WEC. The dimensions shall include:
  - size of floating components, fixed barriers and inter-connecting components.
  - actuators and moving components that transfer the wave motion to the Power Take-Off (PTO).
- Diagrams and drawings showing the mooring system, foundation and fixed barriers.
- Electrical generator(s) nameplate capacity.
- Description of the PTO up to the power measurement location, 8.1. This shall include the rated voltage, current and frequency of all components including the generation, converter, and other equipment used to condition the power. A diagram detailing the PTO system and location of the measurement point, 8.1, shall be provided. Where applicable, calculations to account for cable losses as described in 8.2 and Annex A should be provided in detail.

10.3 WEC test site report

The WEC test site shall be well defined in accordance with details described in Clause 4. The test site clause shall include as a minimum:

- Recording sea state and wave power, 5.2.2, during both pre-test and testing. The following information shall be reported for each testing period per 6.2:
  - Spectral shape.
  - Wave height (H_{m0}, 7.4).
  - Energy period (T_e, 7.4).
  - Wave power per unit width (J, 7.4).
  - Directionality of waves as measured (7.4).
  - Directional frequency spectrum as measured (7.4).
  - Water depth including tidal variations.
  - Tidal and ocean currents.
  - Wind velocity.
  - Temperature.
  - Density of water.
  - Occurrence and thickness of ice.

NOTE The data can be presented in either hard copy or electronically. The data can be formatted tabularly or graphically.

- Minimum of one navigation chart, with a coordinate system of the test area with the following information:
  - WEC origin location in latitude, longitude and principal axis. The watch circle will be included for floating WECs.
  - Mooring system drawing showing the anchor location and expected mooring line configuration.
  - Drawing of location and profile of the power cable, if applicable.
  - Fixed foundation location and orientation.
  - Location of wave measurement instrumentation (WMI) both pre-testing and testing, 5.2.2.

  - Reporting of external constraints affecting or having the potential to affect the WEC performance or operational periods.
  - Reporting the variation from the representative water density used in the calculations.
- Minimum of one hydrographical and navigation chart, with the coordinate system identified of the test area with the following information:
  - Shoreline and bottom profile. Unusual underwater obstacles that can affect wave and current motion shall be identified.
  - Water depth at Mean Lower Low Water (MLLW) and tables for changes in tide.
  - Currents from both ebb and flood tides. The direction and maximum shall be shown. Season current shall be shown if applicable.
  - Ocean currents if applicable.

Typical systems are World Geodetic System (WGS) 1984 and North American Datum (NAD) 1983. Other systems may be used provided they are recognized Geographical Information System (GIS).

10.4 Electrical grid and load report

Grid parameters including frequency, voltage and permitted tolerance shall be provided. Any prevailing grid conditions limiting or having the potential to limit the power output during testing period shall be reported.

If load banks are used, the parameters of that load bank shall be reported.

10.5 Test equipment report

A description of all test equipment including sensors, Data Acquisition (DAQ), WMI components and sensor locations shall be reported. For each component the minimum information shall include:

- General description of sensor including, name, model number and serial number.
- Specification sheet demonstrating ability to meet requirement.
- Reporting of all user-defined settings.
- Calibration documentation or certificate of conformance as well as the documentation of compliance to the manufacturer recommended procedures. Calibration of WMIs shall include the calibration methodology.

10.6 Measurement procedure report

A description of the measurement procedure, in accordance with Clause 7, shall be provided. The procedure report shall include as a minimum:

- Procedural steps, test conditions, sampling rate and time-drift considerations.
- Correction of WMI measured wave field conditions and wave field at WEC, 7.2.4 and 7.2.5.
- Reporting of date and time (UTC ± T) for data acquisition.
- A log book containing details of the testing including as a minimum the results from Annex C and Annex D shall be appended to the report.

10.7 Presentation of measured data

The information detailing the measured and calculated data shall be presented using the method of bins, Clause 8. The matrix can be sub-divided to account for wave direction or spectral bandwidth.

NOTE Additional sub-matrix can be used to account for unique weather conditions such as icing.

The following information shall be provided:

- Date and time of data acquisition.
- Wave height H_{m0}, energy period T_e and if required wave direction θ (calculated using 7.4).
- Wave power per unit width (calculated using, 7.4 Formula (5)).
- Measured output power.
- Capture width.

The following minimum matrix information shall be presented:

- Number of data points in each bin.
- Maximum capture width.
- Minimum capture width.
- Average capture width.
- Standard deviation.

A sample of the matrix (method of bins) presented is shown in Annex A.

10.8 Deviations from the procedure

Any deviations from the requirements of this document shall be clearly documented in a separate clause. Each deviation shall be supported with the technical rational and an estimate of its effect on the test results.

Annex A
(informative)

Example production of a normalized capture width matrix

A.1 General

Clause A.2 and Figure A.1 describe the method on how to display empirical WEC data performance data in a standard format. The data has been generated from simulations of a heave only point absorber WEC and is designed to closely match what would be expected from measured sea test data. The data has been grouped using bins, with Table A.1 to Table A.6 indicating the bin centres.

A.2 Sample data

Table A.1 represents an example of an extract of the averaged data gathered in an unprescribed format. Wave characteristics from the measurement equipment have been used to calculate the wave power for the given H_{m0} and T_e. Power is measured at the output terminals of the WEC as defined in this document.

Table A.1 – Sample data

Date/time	Wind speed (m/s)	Wind direction (°)	Wave height (m)	Wave period (s)	Absorbed power (kW)	Output power (kW)
2012-2-1 0:10	5,114	358,989	0,911	3,323	4,184	1,615
2012-2-1 0:20	4,534	358,989	0,969	3,389	4,448	1,720
2012-2-1 0:30	3,912	358,989	0,951	3,393	4,817	1,848
2012-2-1 0:40	3,382	358,989	0,905	3,308	4,074	1,733
2012-2-1 0:50	3,673	358,989	0,878	3,416	3,900	0,793
2012-2-1 1:00	4,538	358,989	0,848	3,274	3,264	1,112
2012-2-1 1:10	4,802	358,989	0,889	3,330	4,475	1,571
2012-2-1 1:20	4,706	358,989	0,839	3,234	3,349	1,196
2012-2-1 1:30	4,460	358,989	0,807	3,408	3,316	1,214
2012-2-1 1:40	4,399	358,989	0,801	3,284	3,302	1,287
2012-2-1 1:50	3,978	358,989	0,785	3,214	2,913	0,891
2012-2-1 2:00	3,860	358,989	0,758	3,259	2,544	0,823
2012-2-1 2:10	3,890	358,989	0,777	3,238	2,856	0,940
2012-2-1 2:20	3,928	358,989	0,827	3,286	3,196	1,043
2012-2-1 2:30	4,366	358,989	0,863	3,386	3,385	1,181
2012-2-1 2:40	4,447	358,989	0,782	3,190	3,022	0,808
2012-2-1 2:50	3,986	358,989	0,793	3,123	3,241	1,083
2012-2-1 3:00	4,202	358,989	0,734	3,115	2,539	0,737
2012-2-1 3:10	4,299	358,989	0,718	3,204	2,248	0,475

The full range of data measured as it occurred during the measurement period is shown in Figure A.1. This plot shows the variation in electrical power output over a range of H_{m0} and T_e.

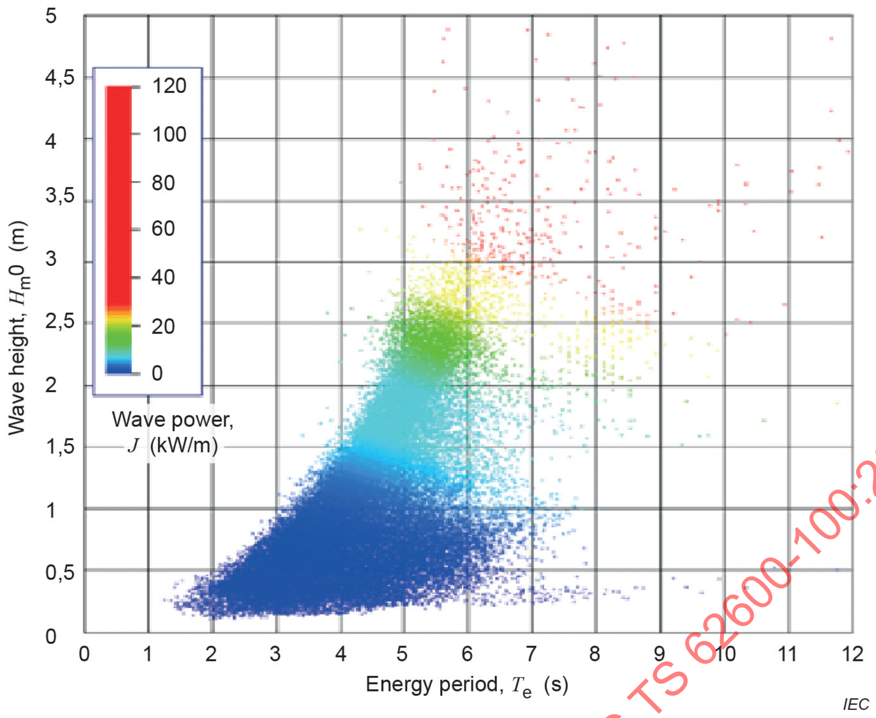

Figure A.1 – Power scatter

It is necessary to reduce this large data set to the standard discretisation. The bin sizes chosen are 0,5 m for H_{m0} and 1 s for T_{e} as defined by 9.2.1. The tables which follow display the value of the bin centre, e.g. all data within the interval of 8,5 s to 9,5 s, is displayed in the 9 s bin. The same method is used for the H_{m0} values.

The capture width for each of the data samples is calculated on the basis of the measured power and the wave energy flux, separated into the different bins and averaged over each bin. Table A.2 shows the average capture width for each bin. Empty bins indicate no measurements were recorded for that combination of H_{m0} and T_{e}.

Table A.2 – Average capture width

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	0,392	-	-	-	-	-	0,093
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,341	0,653	0,576	-	-	-	-
	3,0 to 3,5	-	-	-	-	0,718	0,888	0,974	-	-	-	-	0,231
	2,5 to 3,0	-	-	-	0,552	1,325	1,271	1,154	0,965	0,925	0,678	-	-
	2,0 to 5,5	-	-	-	-	1,771	1,627	1,325	1,254	1,041	1,151	-	-
	1,5 to 2,0	-	-	-	1,823	2,119	1,872	1,509	1,340	1,133	0,959	-	0,504
	1,0 to 1,5	-	-	-	2,066	2,085	1,868	1,711	1,245	0,916	-	-	-
	0,5 to 1,0	-	-	0,662	1,422	1,632	1,527	1,362	1,177	-	-	-	-
	0,0 to 0,5	-	-	-	-0,984	-0,081	0,959	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

The standard deviation, maximum and minimum values for each of the bins are included in Table A.3 through Table A.5. Table A.6 indicates the number of samples recorded which fall into each of the bins.

Table A.3 – Standard deviation of capture width

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	0,000	-	-	-	-	-	0,000
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,231	0,000	0,000	-	-	-	-
	3,0 to 3,5	-	-	-	-	0,137	0,209	0,207	-	-	-	-	0,000
	2,5 to 3,0	-	-	-	0,000	0,367	0,238	0,209	0,207	0,108	0,061	-	-
	2,0 to 5,5	-	-	-	-	0,308	0,263	0,228	0,228	0,184	0,000	-	-
	1,5 to 2,0	-	-	-	0,667	0,269	0,245	0,200	0,265	0,152	0,182	-	0,000
	1,0 to 1,5	-	-	-	0,406	0,324	0,289	0,292	0,182	0,000	-	-	-
	0,5 to 1,0	-	-	0,791	0,613	0,433	0,423	0,384	0,210	-	-	-	-
	0,0 to 0,5	-	-	-	0,378	0,176	0,409	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

Table A.4 – Maximum capture width

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	0,392	-	-	-	-	-	0,093
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	0,571	0,653	0,576	-	-	-	-
	3,0 to 3,5	-	-	-	-	0,818	1,150	1,195	-	-	-	-	0,231
	2,5 to 3,0	-	-	-	0,552	1,831	1,860	1,581	1,290	1,126	0,760	-	-
	2,0 to 5,5	-	-	-	-	2,624	2,365	2,016	1,825	1,442	1,151	-	-
	1,5 to 2,0	-	-	-	2,794	3,207	2,737	2,126	1,917	1,468	1,214	-	0,504
	1,0 to 1,5	-	-	-	3,321	3,463	2,712	2,644	1,644	0,916	-	-	-
	0,5 to 1,0	-	-	2,190	3,389	3,130	2,827	2,450	1,645	-	-	-	-
	0,0 to 0,5	-	-	-	-0,606	0,164	1,368	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

Table A.5 – Minimum capture width

Wave height (H_{m0}) [m]	0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
4,5 to 5,0	-	-	-	-	-	0,392	-	-	-	-	-	0,093
4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
3,5 to 4,0	-	-	-	-	-	0,110	0,653	0,576	-	-	-	-
3,0 to 3,5	-	-	-	-	0,524	0,501	0,662	-	-	-	-	0,231
2,5 to 3,0	-	-	-	0,552	0,504	0,528	0,500	0,370	0,671	0,614	-	-
2,0 to 5,5	-	-	-	-	0,347	0,458	0,636	0,487	0,629	1,151	-	-
1,5 to 2,0	-	-	-	0,765	1,079	0,764	0,664	0,496	0,897	0,802	-	0,504
1,0 to 1,5	-	-	-	0,231	0,773	0,850	0,835	0,896	0,916	-	-	-
0,5 to 1,0	-	-	-3,599	-1,796	-0,751	-0,757	-0,218	0,653	-	-	-	-
0,0 to 0,5	-	-	-	-1,361	-0,333	0,550	-	-	-	-	-	-
	Wave energy period (T_e) [s]											

Table A.6 – Number of data samples

Wave height (H_{m0}) [m]													
	4,5 to 5,0	-	-	-	-	-	1	-	-	-	-	-	1
	4,0 to 4,5	-	-	-	-	-	-	-	-	-	-	-	-
	3,5 to 4,0	-	-	-	-	-	2	1	1	-	-	-	-
	3,0 to 3,5	-	-	-	-	3	8	4	-	-	-	-	1
	2,5 to 3,0	-	-	-	1	26	385	88	38	66	3	-	-
	2,0 to 5,5	-	-	-	-	399	2307	192	142	142	1	-	-
	1,5 to 2,0	-	-	-	13	3213	2140	220	71	24	3	-	1
	1,0 to 1,5	-	-	-	1409	5624	1815	299	31	1	-	-	-
	0,5 to 1,0	-	-	346	5169	3815	2531	615	59	-	-	-	-
	0,0 to 0,5	-	-	-	2	4	2	-	-	-	-	-	-
		0 to 1,0	1,0 to 2,0	2,0 to 3,0	3,0 to 4,0	4,0 to 5,0	5,0 to 6,0	6,0 to 7,0	7,0 to 8,0	8,0 to 9,0	9,0 to 10,0	10,0 to 11,0	11,0 to 12,0
		Wave energy period (T_e) [s]											

The wave energy flux for each bin in the scatter is calculated, for example, using a JONSWAP spectrum, with gamma of 3 and the H_{m0} and T_e corresponding to the bin centres. The capture width and wave energy flux are used to calculate the WEC power in each bin.

Annex B
(normative)

Method for power loss compensation where the measurement point is located on shore

B.1 Single-line diagram

A single-line diagram of a typical grid connected WEC system is indicated in Figure B.1.

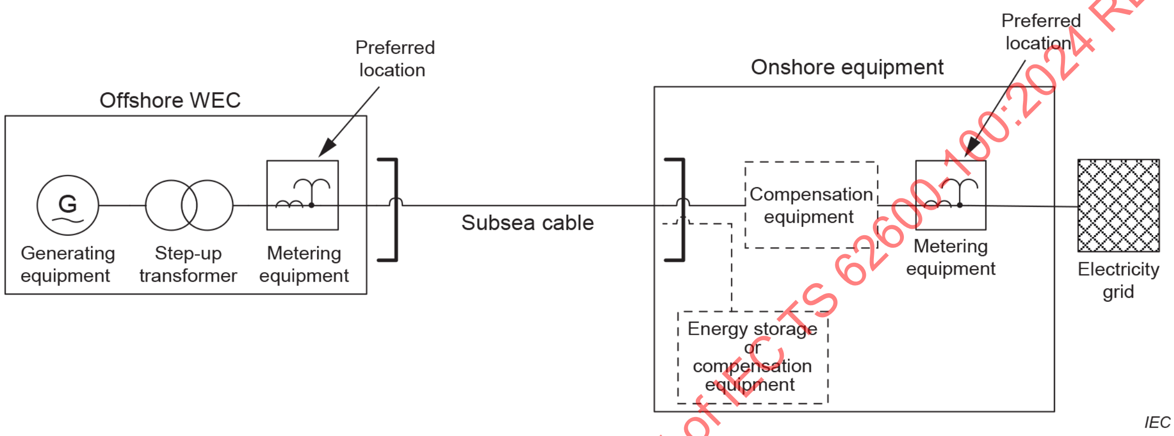

Figure B.1 – Location options for metering equipment

Ideally, power output should be measured at the output terminals of the WEC. This is referred to as the "Preferred Location" in Figure B.1. If the metering equipment is located on the generator side of the WEC step-up transformer, this shall be noted.

Some WECs use either energy storage or compensation equipment, or both, that are external to the WEC itself but shall be considered as a part of it for the purposes of performance assessment. Typical locations for such equipment are indicated with broken lines. The compensation equipment may be installed in series or shunt with the power flow, and auxiliary energy storage equipment is typically installed in a shunt configuration. In such situations, or in situations where power measurement is only possible shore side, the WEC power should be measured at the output terminals of the compensation equipment wherever it is situated, or at the shore station incoming bus bars, where no compensation equipment is present. This is referred to as the "alternative location" in Figure B.1. In this case, losses due to cables and other components between the WEC system and the compensation equipment should be determined, and the power output should be adjusted accordingly.

A methodology for losses incurred in a single connection cable is provided in the next section. If the connection equipment between the WEC system and the compensation equipment is more complex than this, the methodology for the power loss corrections should be fully explained in the file header and accompanied by supporting documentation as necessary.

B.2 Cable loss compensation

If the metering equipment is installed in the "alternative location" as illustrated in Figure B.1, then the losses in the cable shall be added to the power readings in order to give a realistic assessment of the performance of the WEC system. For loss purposes, the cable is modelled in positive sequence as shown in Figure B.2. R_{cable}, X_{cable}, and C_{cable} represent the total positive sequence resistance, reactance, and line-to-line capacitance of the cable. These are usually provided by manufacturers on a per km basis and shall be multiplied up by the cable length in km in order to yield the relevant total impedance values. The cable resistance will generally be determined from the AC resistance per km values provided by the manufacturer. Skin effect can be taken into account if a detailed harmonic breakdown on the device output current is available. This is generally of negligible impact since harmonic filters at the output of power conversion equipment are designed to reduce the harmonic current components on the grid side to very small levels. These levels are regulated by the appropriate power quality standards in accordance with IEC 61000-3 (all parts).

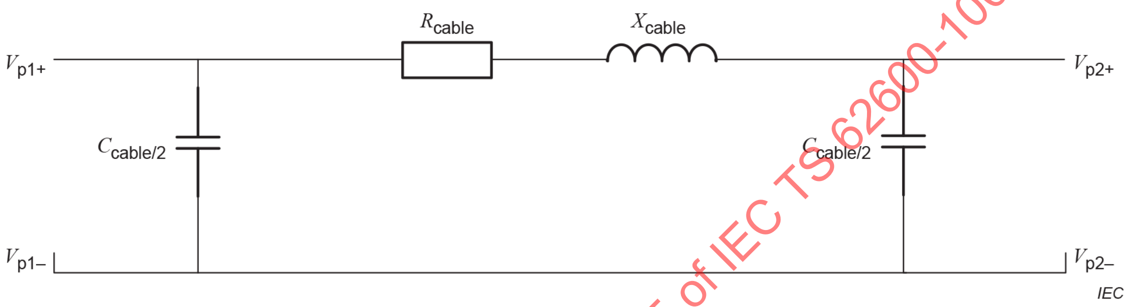

Figure B.2 – Positive sequence cable model

If a number of cables are connected in parallel between the offshore WEC system (or array) and the shore side metering station, the standard circuit theory should be used to derive the equivalent-π circuit of the combination of cables.

In order to measure the power performance and determine cable losses, one of the following sets of measurements shall be made (utilising the instrumentation outlined in the next section):

a) line-to-line RMS voltage (U_{meas}), line RMS current (I_{meas}), and the phase angle of each (φ_V, φ_I) relative to a common reference signal or relative to each other.

b) line-to-line RMS voltage, line RMS current and power factor (PF_{meas}).

c) real power (P_{meas}), reactive power (Q_{meas}), and line-to-line RMS voltage.

d) the output of the WEC system (P_{genWEC}) is then estimated by the following formula:

$$P_{\text{genWEC}} = P_{\text{meas}} + P_{\text{loss}} \tag{B.1}$$

where the measured real power is given directly by the power transducer or by appropriate combination of voltage, current, and power factor or phase angle, and where the cable loss component P_{loss} is given by:

$$P_{\text{loss}} = 3\left[\left(I_{\text{meas}}\cos\varphi_I - \frac{\omega C_{\text{cable}} U_{\text{meas}}}{2}\sin\varphi_V\right)^2 + \left(I_{\text{meas}}\sin\varphi_I + \frac{\omega C_{\text{cable}} U_{\text{meas}}}{2}\cos\varphi_V\right)^2\right] R_{\text{cable}} \tag{B.2}$$

In the case of voltage, current and phase angle or power factor measurements, the factor ω is the electrical radian frequency and is equal to 2π times the electrical system frequency in Hz.

In the case where real and reactive power measurements are obtained, the current measurement and phase angles can be derived as follows:

$$I_{\text{meas}} = \sqrt{\frac{{P_{\text{meas}}}^2 + {Q_{\text{meas}}}^2}{3{U_{\text{meas}}}^2}} \tag{B.3}$$

$$\varphi_V = 0 \qquad \varphi_I = \arctan\frac{Q_{\text{meas}}}{P_{\text{meas}}} \tag{B.4}$$

and substituted into the previous formula for calculating P_{loss}. An assumption in these calculations is that the system voltages and currents are balanced. Even in the presence of limited unbalance in the system, as permitted by the relevant national grid code, these formulae are sufficient to estimate the cable loss compensation.

Annex C
(normative)

Evaluation of uncertainty

C.1 General

The specification of the WEC power performance shall include an estimate of its uncertainty. The estimate shall be based on ISO/IEC Guide 98-1 and ISO/IEC Guide 98-3.

Following ISO/IEC Guide 98-1 and 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 as standard uncertainties.

C.2 Uncertainty analysis

The measurands for the uncertainty analysis are the power matrix, determined by the measured and normalised values of electrical power production and sea-state parameters, and the estimated annual energy production. As a minimum the significant wave height and energy period shall be considered as measurands. Uncertainties in measurements are converted to uncertainties in these measurands by means of sensitivity factors.

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

Table C.1 – List of uncertainty components

Measured/model parameter	Uncertainty component	Uncertainty category [a]
Significant wave height	Wave measuring instrument and model calibration	B
	Influence of moorings or other local effects on WMI	B
	Data acquisition system (e.g. sampling rate, windowing)	B
	Directional spectral analysis	B
	Variability of significant wave height	A
Energy period	Wave measuring instrument and model calibration	B
	Influence of moorings or other local effects on WMI	B
	Data acquisition system (e.g. sampling rate, windowing)	B
	Directional spectral analysis	B
	Strength of currents	B
	Variability of energy period	A
Wave power density	Water depth	A / B
	Water density	A / B
Electrical power	Current transformers	B
	Voltage transformers	B
	Power transducer or power measurement device	B
	Data acquisition system	B
	Variability of electrical power	A

[a] according to ISO/IEC Guide 98-1 and ISO/IEC Guide 98-3.