IEC TS 62600-102

Edition 1.0 2016-08

TECHNICAL SPECIFICATION

colour inside

Marine energy – Wave, tidal and other water current converters –
Part 102: Wave energy converter power performance assessment at a second location using measured assessment data

IEC TS 62600-102:2016-08(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.140

ISBN 978-2-8322-3530-0

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC TS 62600-102, which is a technical specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
114/179/DTS	114/187A/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

This technical specification, IEC TS 62600-102, 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 (as per IEC TS 62600-100) 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 technical specification the completed field deployment location is referred to as “Location 1” and the prospective deployment location is referred to as “Location 2.”

The specification provides a methodology for arriving at the mean annual energy production (MAEP) for the WEC at Location 2. Other Technical Specifications in this series (IEC TS 62600) are drawn upon to provide the wave resource and WEC performance information needed 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 MAEP based on the composite performance characterization of the WEC.

This technical specification provides:

a) guidance on the use of observations from Location 1,
b) methods for assessing and reporting the validity of numerical and physical models,
c) limits on the permissible changes to the WEC between Locations 1 and 2,
d) limits on the use of data fitting techniques, and
e) 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 is designated as a technical specification and will be subject to change as more data is collected and experience with wave energy converters develops. This Technical Specification, when used in conjunction with other Technical Specifications in this series (IEC TS 62600), is intended for several types of users, including, but not limited to, the following:

- Project developers – income, return on investment
- Device developers – performance of device
- Utilities/investors – reliability/predictability of supply, return on investment
- Policy-makers/Planners – usage of seascape, optimisation of resource, power supply issues
- Consultants to produce resource data/due diligence – compatible/readable data format

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1 Scope

Wave Energy Converters (WEC) need to be designed to operate efficiently at different locations. Systematic methods should be 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 technical specification.

This part of IEC 62600, which is a Technical Specification, describes the required methods and the required conditions to determine the power performance of the WEC 2 in Location 2, possibly at a different scale and with configuration changes to accommodate the new site conditions, in all cases based on measured power performance of WEC 1 in Location 1. This technical specification allows for assessment at Location 1 or Location 2 based on limited/incomplete data material, as long as this is accompanied by a validated numerical model or physical model and assessment of the uncertainty involved. Another key element is transparency in the assessment.

This technical specification includes:

a) Specification of data requirements needed from the original measurements at Location 1 including an assessment of the uncertainty involved (if based on limited/incomplete data material) in addition to those specified in IEC TS 62600-100 and IEC TS 62600-101.
b) Limitation on the changes that are allowed to the WEC and the specification of the location.
c) Wave data required at Location 2, as a minimum the requirements found in IEC TS 62600-101.
d) Development of the power matrix at Location 2.
e) Validation of the power matrix at Location 2.
f) Assessment of uncertainties in the derived performance parameters at Location 2.
g) Requirements for the allowable power performance transfer by geometric, kinematic and dynamic similarity.
h) Requirements for the allowable incorporation of additional empirical model data.
i) Requirements for the allowable incorporation of additional numerical model data.

The technical specification does not cover the following items:

j) The original data measurement at Location 1 (see IEC TS 62600-100).
k) Environmental concerns.
l) Operation and maintenance.

2 Normative references

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

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1: Terminology*

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

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

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

3 Symbols and units

For the purposes of this technical specification, the symbols and units listed in Table 1 apply. The terms and definitions are in accordance with IEC TS 62600-1.

Table 1 – Symbols and units

Symbol	Definition	Units
C_{g}	Group velocity	m/s
θ_{Jmax}	Direction of maximum directionally resolved wave power	deg
f	Frequency	Hz
f_i	Frequency at component i	Hz
h	Water depth	m
H_{m0}	Spectral estimate of significant wave height	m
H_{s}	Significant wave height	m
J	Omnidirectional measured wave power	W/m
J_i	Omnidirectional measured wave power per bin	W/m
$\bar{J}$	Average wave power	W/m
$\wedge J$	Minimum wave power	W/m
$\vee J$	Maximum wave power	W/m
L	Capture length	m
L_i	Capture length per bin	m
$\bar{L}$	Average capture length	m
$\wedge L$	Minimum capture length	m
$\vee L$	Maximum capture length	m
$MAEP$	Mean Annual Energy Production	W·h
n	Number of records	-
N	Number of bins	-
P	Measured power output	W
P_i	Measured power output per bin	W
P_{h}	Hydraulic power input	W

Symbol	Definition	Units
S	Spectral density	$\frac{m^2}{Hz}$
$S(f)$	Spectral density as function of frequency	$\frac{m^2}{Hz}$
$S(f, \theta)$	Directional spectrum as a function of frequency and direction $S(f) \cdot G(\theta, f)$	$\frac{m^2}{Hz \cdot rad}$
S_i	Spectral density at frequency component i	$\frac{m^2}{Hz}$
T_e	Energy period	s
f_i	Frequency spacing	Hz
θ	Wave direction	Deg
P_{abs}	Absorbed power	W
P_e	Electrical power output	W
P_{pto}	Power loss (dissipated) in the PTO	W
η_{pto}	Power take off efficiency	-
ρ	Density	kg/m^3
σ	Standard deviation	-

4 Sequence of work

The sequence of the work is outlined below:

a) Describe the WEC technology.

b) Assess and characterize wave resource at Location 1 and Location 2 using IEC TS 62600-101.

c) Calculate the capture length matrix from WEC power capture data at Location 1 using IEC TS 62600-100.

d) Evaluate the appropriate dimensionality of the capture length matrix from Location 1 for Location 2 and complement the capture length 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 length of each bin using validated numerical model data incorporating the parameters in question. If the capture length 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 length matrix for application at Location 2.

i) Calculate MAEP at Location 2 using the complemented capture length matrix and Location 2 resource data.

j) Report separately the MAEP 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 MAEP calculated at Location 2.

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

5 Limitations of this technical specification

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 10.

6 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.

7 Assess and characterize wave resource related to Location 1 and Location 2

7.1 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.

7.2 Ambient condition

For each location this description should include a map or 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.

7.3 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.

8 WEC power capture data at Location 1

An analysis of the WEC electrical power performance at Location 1 should be undertaken using the methodologies stated in IEC TS 62600-100. The measured WEC power production records along with the concurrent wave measurements should be used to calculate and report the following:

- Electrical power matrix.
- Capture length matrix.
- Maximum of capture length matrix.
- Minimum of capture length matrix.
- Standard deviation capture length matrix.

NOTE Other potentially useful but not strictly required deliverables of the IEC TS 62600-100 analysis are absorbed power and PTO efficiency matrices.

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

9 WEC model validation

9.1 General

A numerical and/or physical model may be required to satisfy the requirements of this specification. 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.

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

9.2 Bin selection

At minimum, 10 bins of the capture length 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 model 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 length 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.

9.3 Error per bin

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

$$L_{\text{err},i} = 100 \cdot (L_{\text{model},i} - L_{\text{measured},i}) / L_{\text{measured},i} \tag{1}$$

9.4 MAEP error

The percent error between the modelled MAEP and the measured MAEP shall be presented using formula (2).

$$MAEP_{\text{err}} = 100 \cdot (MAEP_{\text{model}} - MAEP_{\text{measured}}) / MAEP_{\text{measured}} \tag{2}$$

NOTE $MAEP_{\text{err}}$ is representative of only the portion of the MAEP contributed by those bins used in the validation procedure.

The modelled and measured MAEP quantities may be established as per IEC TS 62600-100:

$$MAEP = T\sum_{i} L_i J_i f_i \tag{3}$$

where

T is the average number of hours per year (8 766),

L is the bin-average observed capture length,

J is the wave power flux,

f is the frequency of occurrence, and

i is the index of the i th bin.

In this case i refers to only those bins used for validation.

9.5 Accounting for PTO losses

The model shall account for power conversion losses within the power take off 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 power take off efficiency shall be applied to estimate electrical power and calculate capture length values. Refer to Annex B for methodology to quantify and apply PTO efficiency.

10 Modifications to the WEC

Modifications to the WEC and ancillary hardware are permitted. The capture length 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 9 and Clause 13. Modifications may 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 9. 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 length 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 length of the unmodified WEC 1 and mean capture length of the modified WEC 2 in each bin shall be presented and evaluated. For the capture length data from deployment of WEC 1 at Location 1 to be used to characterize WEC 2, the absolute difference between the mean capture length 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 13.

11 Calculate capture length matrix for use at Location 2

11.1 Evaluate appropriate dimensionality of the capture length matrix at Location 2

Minimum dimensions of the capture length matrix are specified in IEC TS 62600-100 as including H_{m0} and T_e. IEC TS 62600-100 advises that the dimensionality of the capture length matrix should be expanded where possible to reduce the variance of capture length 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 length 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 may be necessary to expand the dimensionality of the capture length 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 above shall be considered in turn. It shall be shown that inclusion of the parameter in question impacts the calculation of MAEP at Location 2 by less than 10 %, otherwise the dimensionality of the capture length 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 may still be possible to neglect the directionality dimension when constructing the capture length matrix and calculating MAEP at Location 1. However, if the wave directionality is more variable at Location 2 it may be necessary to include directionality in the capture length matrix to accurately estimate the MAEP 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 length 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 13 shall be used to fill bins in the capture length matrix for which there are no supporting observations. The MAEP shall be calculated using both the 2D and 3D capture length matrix. If the difference between the two MAEP calculations is greater than 10 %, then the additional dimension shall be included in the capture length matrix at Location 2.

NOTE The 10 % difference limit on MAEP 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.

11.2 Calculate information for each bin of the capture length matrix

Using the performance data from Location 1 the average capture length matrix shall be constructed as outlined in IEC TS 62600-100, using the appropriate dimensionality as identified in 11.1. The following shall be calculated for each bin in the matrix:

- The average capture length.
- The maximum capture length of all the data records in the bin.
- The minimum capture length of all the data records in the bin.

- The standard deviation of the capture length of all the data records in the bin.
- The number of data records in the bin.

NOTE See Annex A for a detailed example.

12 Quality assurance for cells based on measurements at Location 1

Capture length matrix for use at Location 2 shall be quality checked and empty bins shall be labelled “undefined”. Bins of the capture length 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 A for detailed example.

13 Complement capture length matrix to cover range of conditions at Location 2

13.1 Capture length matrix complementation requirement

The capture length 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 length matrix is specified in Clause 12. The capture length 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 length matrix, it shall be validated as per Clause 9. Where several methods are available to complement a bin, the method with the least uncertainty should be used.

NOTE See Annex A for an example.

13.2 Interpolation or extrapolation of the capture length matrix

Data fitting using interpolation or extrapolation may be used to populate undefined bins in the capture length 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 A for detailed example.

13.3 Numerical model

A numerical model may be used to calculate the capture length of the WEC in any underpopulated, undefined bin of the capture length 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 9.

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

13.4 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 length matrix. The physical model testing shall be based on International Towing Tank Conference (ITTC) *Recommended Guidelines 7.5-02-07-03.7*.

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 WEC2 to be deployed Location 2. To estimate electrical power output requires characterization of the WEC power take off (PTO) system.

The efficiency of the PTO system shall be characterized and reported (see Annex B). 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 length. The combined result of physical model and PTO characterization shall be validated using the performance data collected at Location 1 as per Clause 9.

14 Calculate MAEP at Location 2 using complemented capture length matrix and Location 2 resource data

Using the performance matrix (Clause 13) and the Location 2 wave resource data (7.3) the MAEP shall be calculated using either the standard or alternative methods described in IEC TS 62600-100.

Separate MAEP contributions shall be reported for bins of the capture length matrix which are:

- Measured bins: calculated from performance measured at Location 1 as per IEC TS 62600-100 and quality assured as per Clause 12 in this specification.
- Interpolated or extrapolated bins: as per 13.2.
- Modelled bins: numerically (13.3) or physically (13.4).

The contribution of each of the above categories of bins shall be reported both as an absolute energy value and also as a percentage of the total MAEP. See Annex A for an example of this procedure.

15 Assessment of confidence

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

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

The uncertainty of the MAEP is related to:

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

Further sources of uncertainties are described Annex D.

Annex A
(informative)

Example analysis

A.1 General

This annex gives a simplified example of the IEC TS 62600-102 analysis procedure. 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 the specification.

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 specification for demonstration purposes and based on available wave data; it is not intended to represent the intentions of Wavestar Energy.

A.2 Description of the WEC technology (Clause 6)

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 A.1).

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

A.3 Assess and characterize wave resource related to Location 1 and Location 2 (Clause 7)

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 A.1 and shown on the map in Figure A.2.

Location 1 measured parametric wave data, provided by Wavestar, are presented in figure A.3. 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 A.5.

This simple example does not provide complete details of the wave resource at Locations 1 or 2. Formal applications of this specification will require a complete metocean study as per Clause 7 and IEC TS 62600-101.

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

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

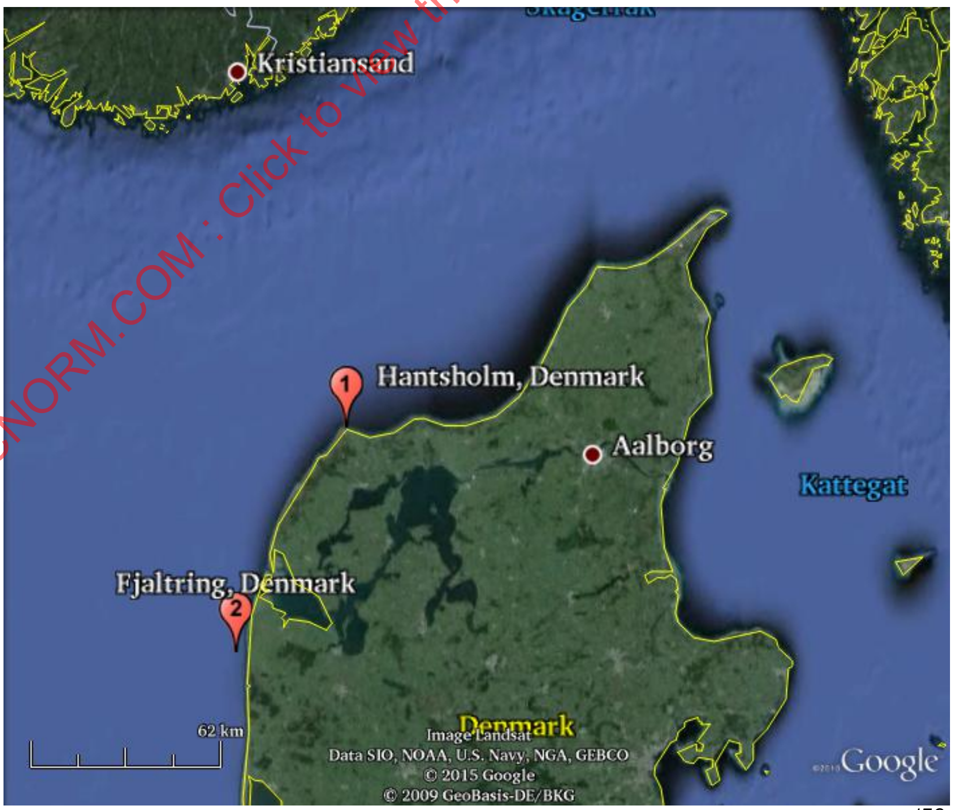


Figure A.2 – Map showing Location 1 Hanstholm and Location 2 Fjatring

A.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 2012-2013 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 calculated 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:

$$J = 1/16 \rho g \cdot C_g(h, T_e) \cdot H_{m0}{}^2 \tag{A.1}$$

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

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

1 Numbers in square brackets refer to the Bibliography.

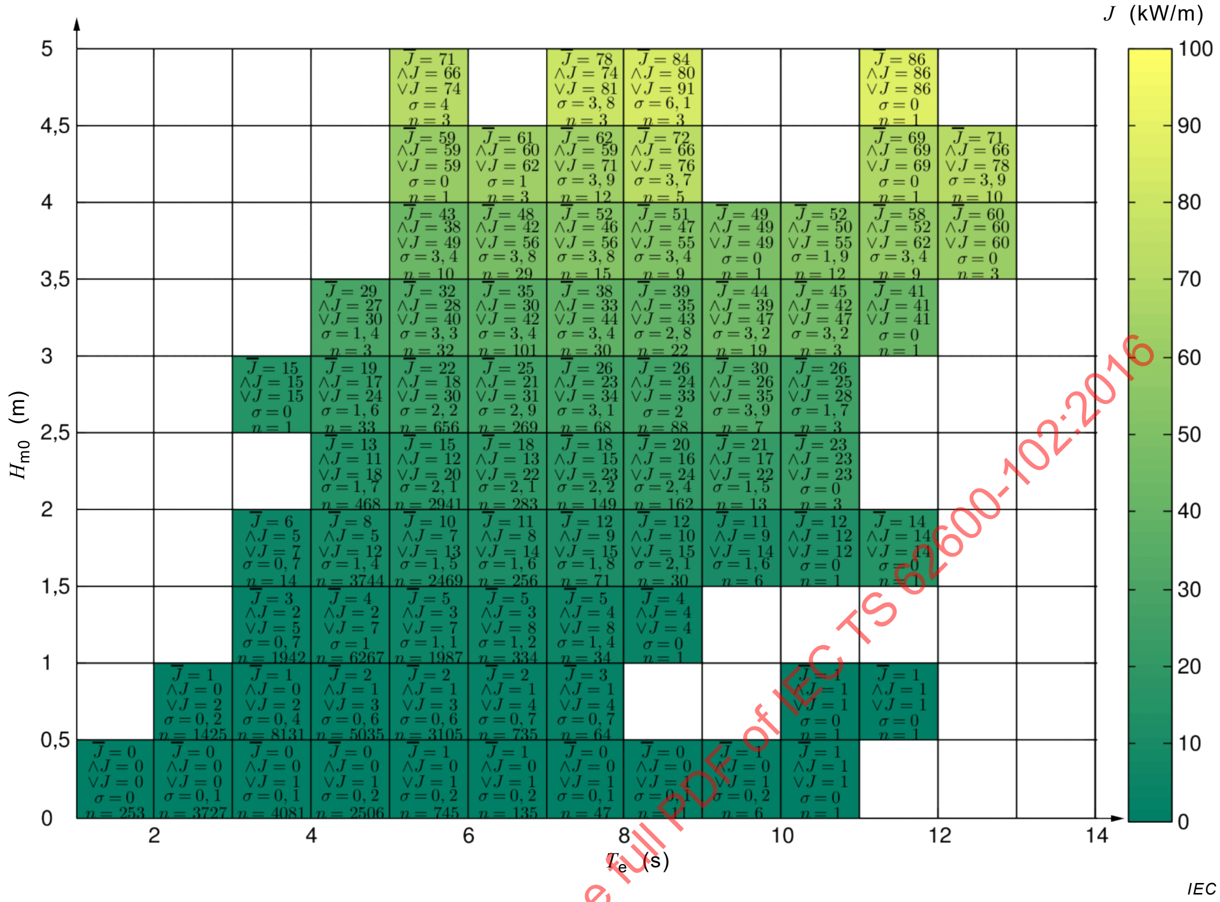


Figure A.3 – Location 1 Wave Energy Flux Matrix, Hantsholm, Denmark (based on measured data from Wavestar prototype Feb 2012 – Jan 2013)

A.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).

A summary of the wave climate at Location 2 is presented as a wave energy flux matrix shown in Figure A.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.

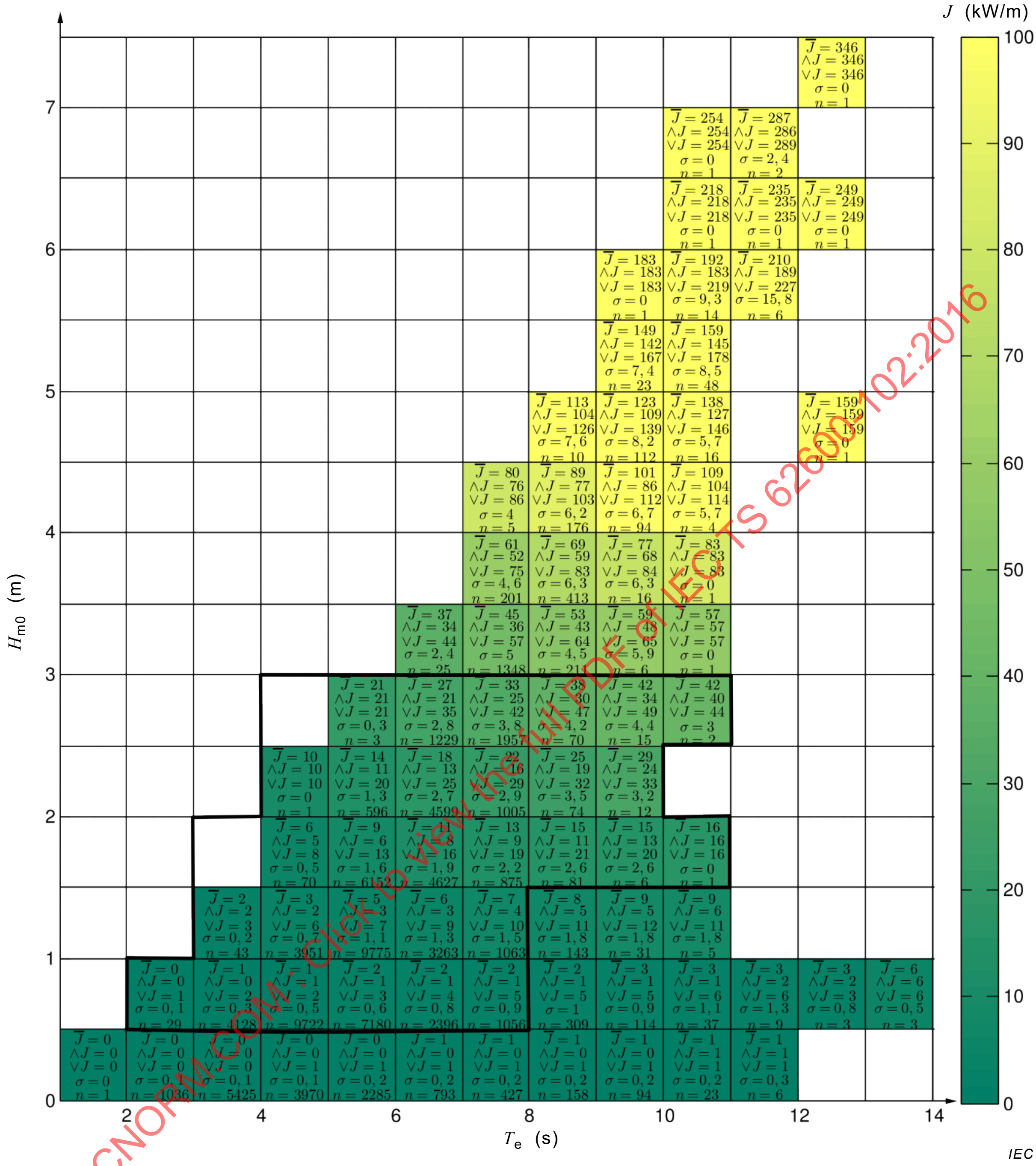


Figure A.4 – Location 2 Wave Energy Flux Matrix, Buoy 2031 (Fjaltring, Denmark)

A.6 WEC power capture data at Location 1 (Clause 8)

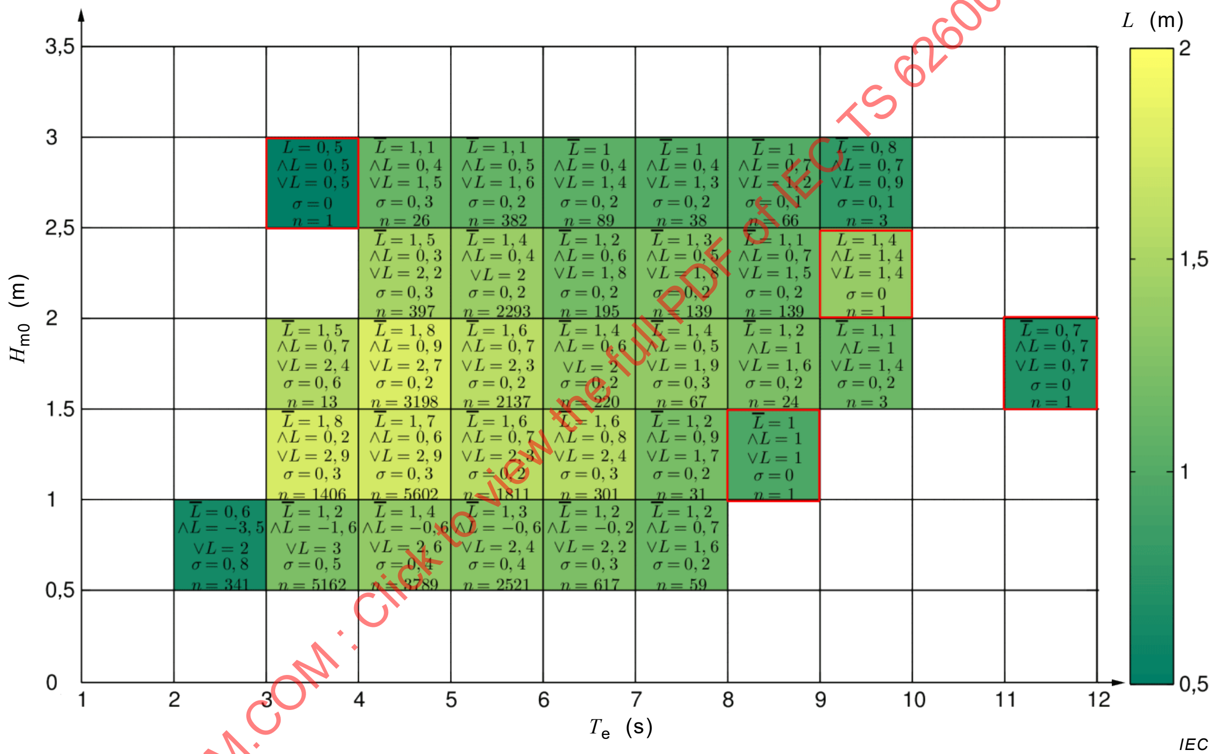
This clause presents the aspects of the IEC TS 62600-100 performance assessment needed to support the IEC TS 62600-102 assessment of performance at a second location.

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 length matrix was calculated as per Clause 8. Only records with both valid wave and performance data were used in the calculation. Current operating policy for the Wavestar prototype specifies 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 length of bins with significant wave height smaller than 0,5 m and larger than 3 m have been set to zero. The capture length matrix is given in Figure A.5. Text in each bin of the figure gives:

- The average capture length, $\overline{L}$.
- Minimum capture length, $\wedge L$.
- Maximum capture length, $\vee L$.
- Standard deviation of the capture length, 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 length. Negative capture length 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 A.5 – Wavestar prototype capture length matrix Location 1

A.7 WEC model validation (Clause 9)

A numerical and/or physical model of the candidate WEC technology is recommended when applying this specification. 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 [1], 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 [2] and linear interpolation. The resulting power performance matrix is presented in Figure A.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 specification will require that number of simulations used to calculate the average capture length in each bin is clearly stated.

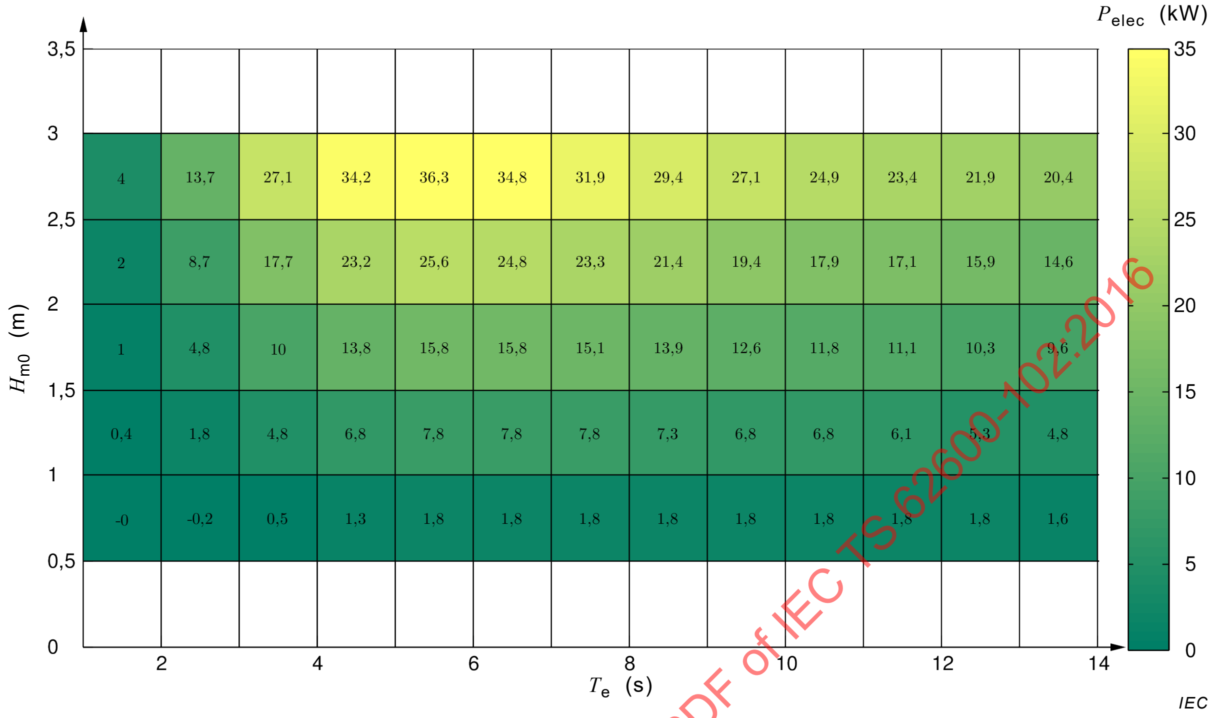


Figure A.6 – Numerically modelled electrical power matrix, adapted from [2]

The electrical power matrix was converted to capture length assuming the same bin-average wave power as the observations. The model error is calculated as in formula (1) of Clause 9.

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

Larger differences in capture length 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 areas contributing most to the power production of the matrix, the capture length difference is generally less than 10 %.

The MEAP may be calculated using both the observed and modelled capture length matrix as per 9.4. Using this approach, the MAEP based on the observed and modelled capture length matrices are 71,59 MWh and 71,73 MWh respectively, a difference of less than 1 %.

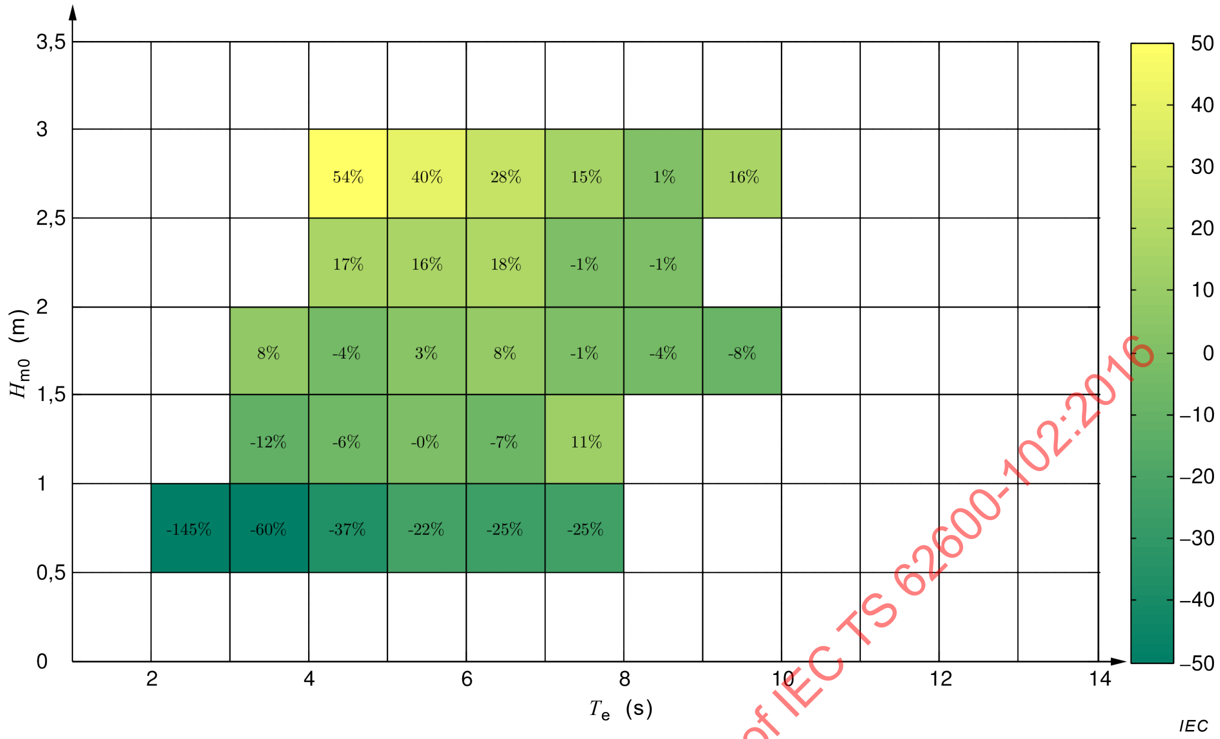


Figure A.7 – Model validation indicating percent difference in capture length between observations and model (model-observations)

A.8 Calculate capture length matrix for use at Location 2 (Clause 11)

A.8.1 Assess the appropriate dimensionality of the capture length matrix at Location 2 (11.1)

In many cases the prevailing metocean conditions at Location 1 and 2 will differ significantly. As detailed in Clause 11, it is important to assess how differing metocean conditions between the two locations may impact the calculation of MAEP. Particular attention should be given to those metocean parameters which are not included in the dimensionality of the capture length 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 11 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 specification will require justification based on the full metocean study.

A.8.2 Calculate information for each bin of the capture length matrix (11.2)

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

A.9 Perform quality assurance on capture length matrix for application at Location 2 (Clause 12)

To ensure a reasonable estimate of the mean capture length in each bin of the capture length matrix, Clause 12 requires that there are at least three performance records per bin. Bins of the capture length matrix not meeting the three record requirements are outlined in red in

Figure A.5. These bins are noted as 'underpopulated' and removed from the observed capture length matrix.

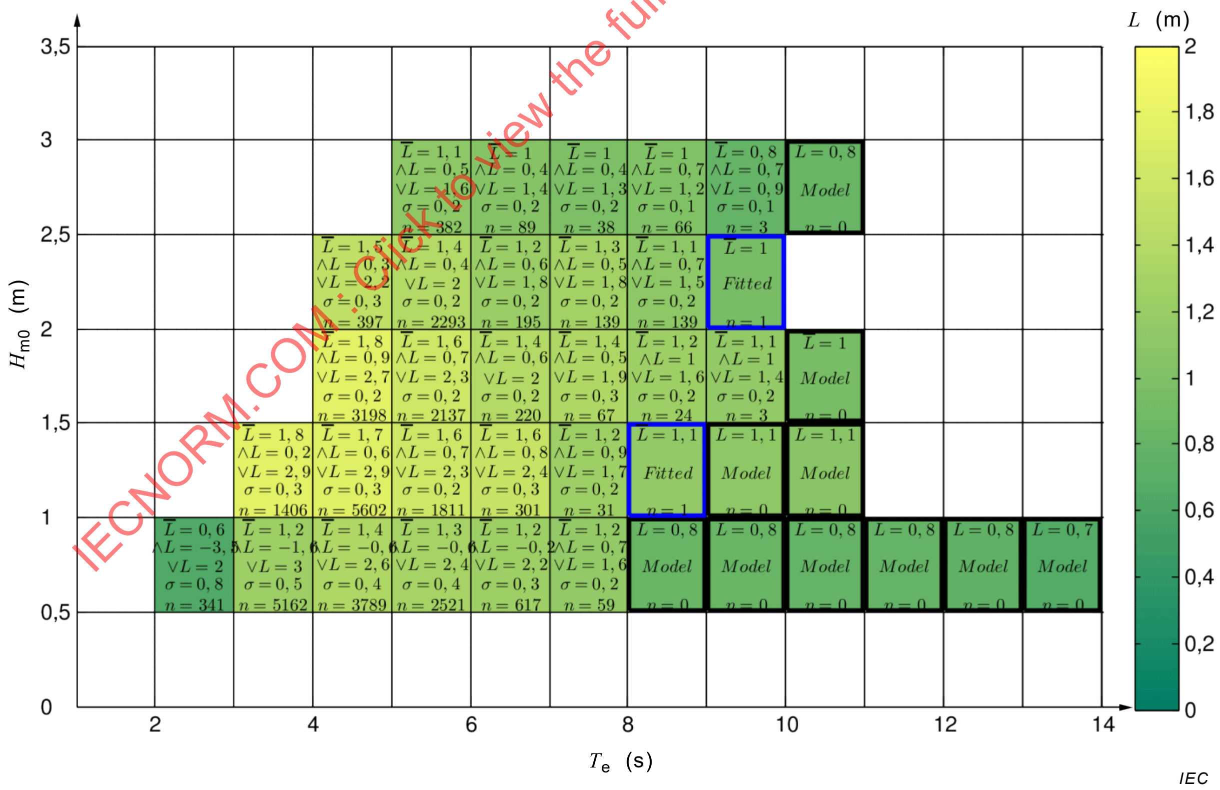
A.10 Complement capture length matrix to cover range of conditions at Location 2 (Clause 13)

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

As outlined in 13.1, empty bins of the capture length 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 13.3, a validated device performance numerical model may be used to estimate the performance of any bin in the capture length matrix. Here the Wavestar numerical model, described in Clause A.7, is used to estimate the capture length 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 may be found in Appendix B of [2].

Figure A.8 below gives the Wavestar prototype capture length 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 A.8 – Wavestar prototype capture length matrix for Loaction 2. Fjaltring, Denmark

A.11 Calculate MAEP at Location 2 using complemented capture length matrix and Location 2 resource data (Clause 14)

Using the complemented Wavestar prototype capture length matrix for Location 2, the MAEP is estimated using the resource data at Location 2 as specified in Clause 14. As specified in IEC TS 62600-102, the wave data set was trimmed to remove bias, so that the ratio of the records in each month to the total number records is the same as the ratio of the number of days in that month to the total number of days in a year. The trimmed data-set contains the equivalent of 14 complete years of wave records.

The MAEP was estimated using both the standard and alternative methodology (described in IEC TS 62600-100):

Using the standard method: MAEP = 63,78 MWh

Using the alternative method: MAEP = 64,06 MWh

The MAEP contribution of the measured, modelled, fitted bins in the capture length matrix were calculated based on the alternative methodology. The breakdown of contributions is shown in Table A.2.

Table A.2 – Table of MAEP contributions

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

A.12 Assessment of confidence

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

Annex B
(informative)

Power take off efficiency

B.1 General

If a physical experimental model is used as described in 13.4 the absorbed power typically is measured. To calculate the electrical power produced the efficiency of the PTO shall be characterized.

B.2 Absorbed power

Absorbed power (P_{abs}) is measured as close to the interface between the WEC's prime mover and the wave – before power conversion. How the absorbed power measured should be reported by the user: As in the example shown on Figure B.1 the absorbed power P_{abs} of the Wavestar is measured as hydraulic input power $P_{h1} + P_{h2}$ measured at each of the hydraulic actuators (pressure across the cylinder multiplied by the flow in the cylinder). The electrical power $P = P_{e1} + P_{e2}$ is measured at the output of the generator (voltage multiplied by current).

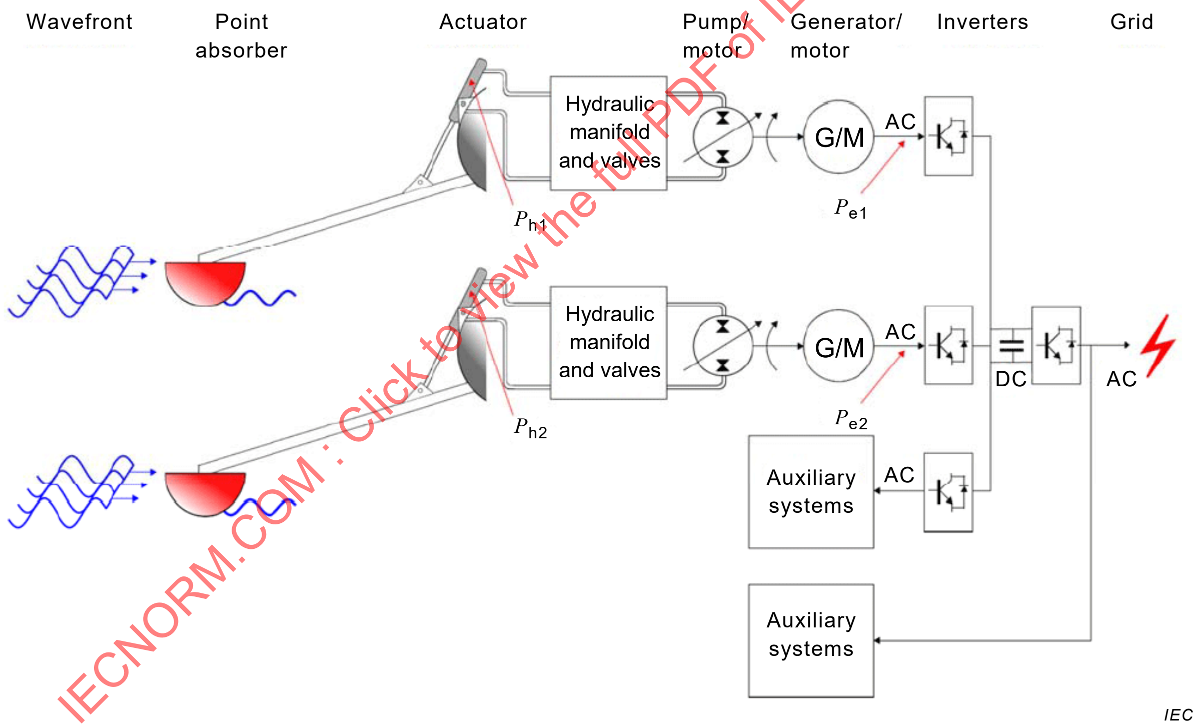


Figure B.1 – Overview of the PTO system used in the prototype of Wavestar

B.3 Power take off efficiency

The PTO efficiency is defined as the electrical power output divided by the absorbed power:

$$\eta_{pto} = \frac{P}{P_{abs}} \tag{B.1}$$

where η_{pto} is the PTO efficiency and P_{abs} is the absorbed power as defined above.

NOTE The best method to determine the efficiency is to measure the WEC absorbed power and the output power per IEC TS 62600-100.

The PTO efficiency is likely to be sea state dependent and therefore should be determined for each binned sea state. The PTO efficiency should be estimated based on computational model validated against bench testing or data obtained from absorbed power measured during field testing at Location 1 (see example in Annex C). How the PTO efficiency has been estimated and with how much confidence these results can substitute field data should be reported by the user.