User guide – COE Calculation Tool for Wave Energy Converters

ver. 1.6 - April 2014

Chozas, Julia Fernandez; Kofoed, Jens Peter; Jensen, Niels Ejner Helstrup

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

User guide – The COE Calculation Tool for Wave Energy Converters

(Version 1.6, April 2014)

Julia Fernández-Chozas

Jens Peter Kofoed

Niels Ejner Helstrup Jensen

ISSN 1901-726X

DCE Technical Report No. 161

JULIA F. CHOZAS
CONSULTING ENGINEER

ENERGINET.DK

DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

*Contact person: coe@juliafchozas.com , Tel: (+45) 2870 0219

Aalborg University
Department of Civil Engineering
Wave Energy Research Group

DCE Technical Report No. 161

User guide – The COE Calculation Tool for Wave Energy Converters

(Version 1.6, April 2014)

by

Julia Fernández-Chozas (Julia F. Chozas, Consulting Engineer)*
Jens Peter Kofoed (Aalborg University)
Niels Ejner Helstrup Jensen (Energinet.dk)

April 2014

*Contact person: coe@juliafchozas.com , Tel: (+45) 2870 0219

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monograms or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2013 by

Aalborg University

Department of Civil Engineering

Sohngaardsholmsvej 57,

DK-9000 Aalborg, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X

DCE Technical Report No. 161

Content

Abbreviations

BIMEP	Biscay Marine Energy Platform
CAPEX	Capital Expenditures
COE	Cost of Energy
DKK	Danish krone
EC	European Commission
EMEC	European Marine Energy Centre
EUR	Euro
FIT	Feed-in Tariff
GPB	Great Britain Pound
HMRC	Hydraulic Maritime Research Institute
IEC	International Electrotechnical Commission
LCOE	Levelised Cost of Energy
NPV	Net Present Value
O&M	Operation and Maintenance
OES	Ocean Energy Systems
OPEX	Operational Expenditures
PTO	Power Take-Off
R&D	Research and Development
TRL	Technology Readiness Level
USD	US Dollar
WEC	Wave Energy Converter

1 Introduction

Consulting Engineer Julia F. Chozas (contact person at coe@juliafchozas.com) together with Aalborg University and Energinet.dk have released a freely available online spreadsheet to evaluate the Levelised Cost of Energy (LCOE) for wave energy projects. The open-access tool calculates the LCOE based on the power production of a Wave Energy Converter (WEC) at a particular location. Production data may derive from laboratory testing, numerical modelling or from sea trials.

The scope of the COE Calculation Tool is to estimate the performance, costs and economic feasibility of the demonstrations machines that are currently being developed.

The tool has been developed as a transparent and simple model that evaluates the WEC's economic feasibility in a range of locations while scaling the WEC's features to the selected site.

The aims of the COE calculation spreadsheet are as follows:

- Ensure consistent and transparent calculation methods.
- Provide a framework for performing COE analyses.
- Provide a tool for simple scaling of a machine according to different wave climates.

The COE Calculation Tool has the following characteristics:

- It is an open-access economic calculation tool.
- It uses broadly-known software: Excel.
- It includes default values for efficiencies and prices.
- It is simple and transparent: it promotes the understanding of calculation steps and results.
- It focuses on power production values instead of on installed capacity.
- It evaluates the COE in a range of locations.
- It encounters the unique feature of scaling the WEC.
- It focuses on input values rather on the outputs: it is conceived as an exercise for WEC developers.
- It is complemented by a user guide (the present document) and a quick-start user guide, where assumptions, input and output values are detailed.

The user of the COE Tool must note that he needs to hand in documentation that proves all input values for the tool whenever using the COE Tool.

1.1 Background

Wave energy and the Cost of Energy

The potential of wave power around the globe is very large. Only in Denmark it has been assessed that 15% of the electricity consumption can be provided by wave energy technologies deployed in Danish waters (Kofoed, 2009).

There are some challenges ahead before it is possible to harness the potential of wave power in a large scale. Among these challenges, two of them are of special importance. Firstly, wave energy converters need to prove their long-term survivability into the harsh sea environment as well as long-term operation; and secondly, they need to be cost competitive. This project is directly related to the latter factor.

At present time, one of the major challenges for the wave energy sector is to reduce its cost of energy. One of the sector´s aims is to get lower cost of energy values that could foster wave energy as a realistic alternative of conventional electricity generation and as a complement to other renewable energy sources.

Calculation of the cost of energy (COE) is done by most device developers. However, these calculations are based on different assumptions and different methods, which are not described or specified, hence making results incomparable and non-transparent.

The main idea behind a common accepted COE calculation tool is to make economic calculations transparent and comparable among various converters. For that, it is desired that the calculation tool does not only focus on the output economic parameters but on the input values and assumptions.

In this context, the project has developed an open-access tool to calculate the COE of wave energy projects. It is expected that the Tool boosts the development of wave energy due to the following reasons:

- It allows targeting the components/aspects with highest impact on the cost of energy.
- It helps to describe the strategic roadmap to reduce the cost of energy.
- It enhances transparency of claimed power productions, and allows equitable comparison of wave energy converters.

The Cost of Energy parameter and the creation of a COE Calculation Tool

The NPV (Net Present Value) along with the COE are the two superior values to evaluate the economics of WECs. Particularly, the COE is useful when the support mechanism i.e. the feed-in tariff, is unknown or uncertain.

Therefore, the COE has been widely used as a driving factor to select technical alternatives, as well as to answer the question “which WEC is the best” or even “which form of electricity generation is the best”.

For example, the COE has been the decision parameter to access both public and private funding i.e. bank loans. Also, in the NER300 project of the European Commission (EC) awards were based on the COE value of the WECs applying (SI Ocean, 2013b).

There are however many fictions around COE calculations. Due to this lack of transparency in the calculations, there have been different initiatives to homogenise the COE calculations, and that has also been the goal of this project – to homogenise the COE Calculation in one transparent and simple spreadsheet.

Additionally, the present COE Calculation Tool allows for sensitivity analysis. The current LCOE of wave energy converters is too high to be considered economic attractive with other sectors. As a result, there is a current and future need to decrease this value (which justifies the need for an R&D roadmap). This COE Tool may give hints of the areas where R&D is needed.

Ultimately, investor's decisions are based on the economic performance of the technology, so an understanding of the economic implications for a specified WEC is always required, also at a very preliminary development level.

It is therefore suggested to use the COE Calculation Tool and carry out an economic assessment of the technology at all the different stages of the development, especially at initial development stages where data might be available only from laboratory tests.

2 General

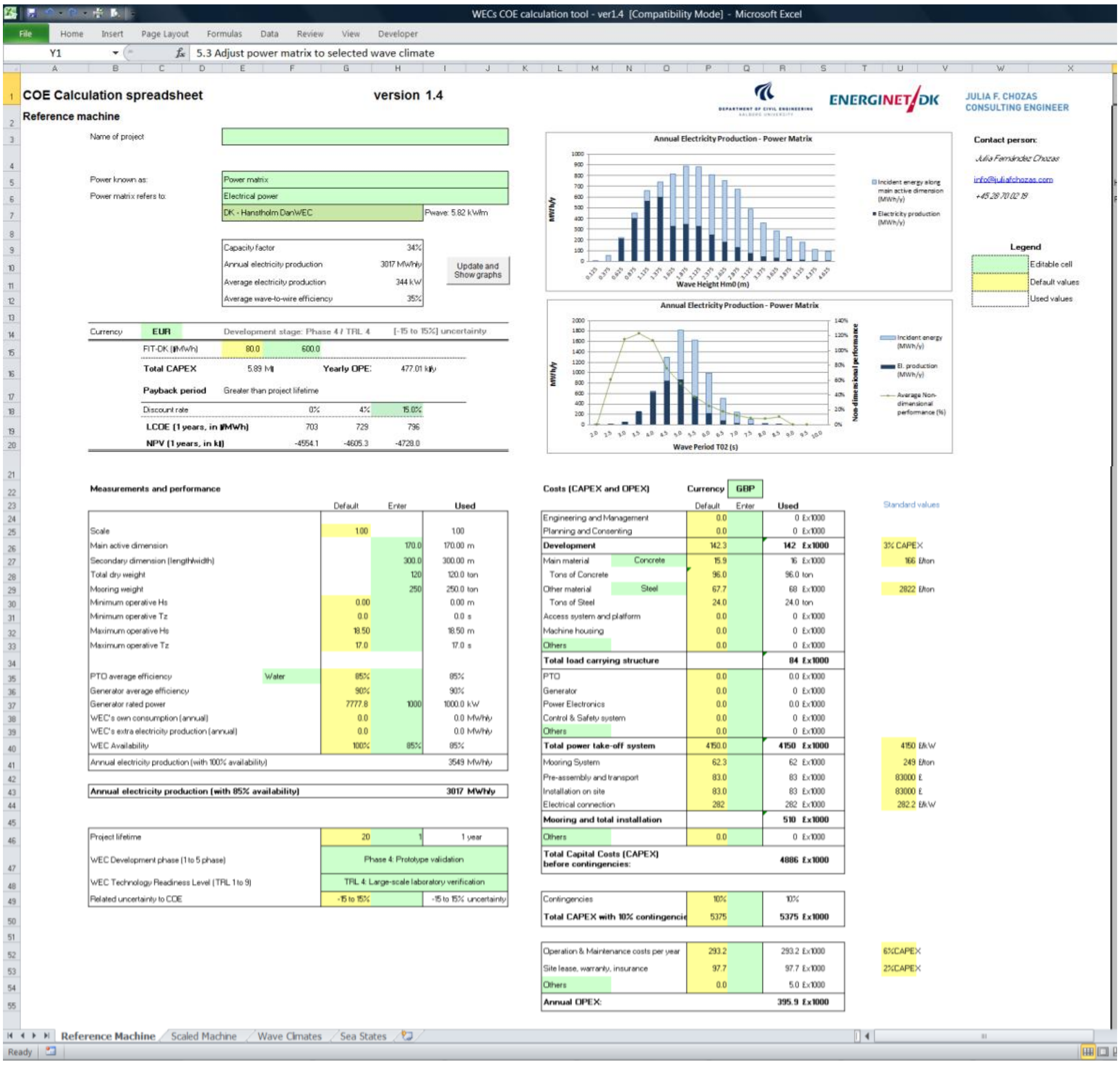
The spreadsheet is locked in order to protect the formulas and the tool structure. The colour codes in the cells are as follows:

Green	Editable cells
Yellow	Default values, used if no other values are entered
White	Used values

Thus, the green colour cells overwrite the values in the yellow cells.

The spreadsheet is based on a reference machine and gives the opportunity to calculate the scaled equipment and the costs associated to the reference and the scaled machines. The reference machine can be freely set.

The values used in the calculations are shown under *used*.



Front-end of the COE Calculation Tool (numbers shown are not inspired by any WEC)

In order to analyse the output values from the spreadsheet and, if suitable, be able to compare results among WECs and locations, the user must specify the assumptions behind all input data and include information about the WEC's development stage.

To which extent the individual parameters have to be documented depends on how far the WEC is developed.

3 Reference machine

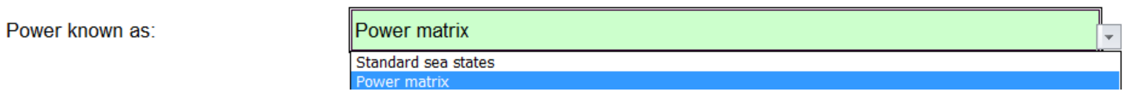
The spreadsheet is based on a reference machine (a wave energy converter), which provides the core information for all calculations. This reference machine can be freely set.

All input data such as dimensions, weight, minimum and maximum operative wave conditions, WEC rated power, conversion system efficiency, power production and prices must be based on the same reference machine.

Basically, the *reference machine* is the machine about which the user has knowledge.

3.1 Power known as

Power production of the reference machine can be inserted in the form of a power matrix or by providing the performance of the WEC in several standard sea states.



3.1.1 Power matrix

If *power matrix* is selected, the user must fill in the cells of Matrix B (coloured in green): the intervals of H_{m0} and T_{02} in which the power matrix is defined, as well as the power production (in kW) for each sea state.

69	Power matrix						
70	B	kW		Tz (s)	0.0	1.0	2.0
71		Hs (m)			1.0	2.0	3.0
72		from	to		0.5	1.5	2.5
73		0.00	0.50	0.25	0.0	0.0	0.0
74		0.50	1.50	1.00	160.0	250.0	360.0
75		1.50	2.50	2.00	360.0	420.0	540.0
76		2.50	3.50	3.00	640.0	700.0	840.0
77		3.50	4.50	4.00	1170.0	1260.0	1330.0
78		4.50	5.50	5.00		1450.0	1610.0

Note the power matrix is defined in terms of H_{m0} and T_{02}.

It is recommended to enter a detailed power matrix, i.e. the more detailed the intervals the better.

The lower and upper limits of the power matrix have to be consistent with the minimum and maximum operating conditions of the WEC.

The power matrix might include the WEC´s own electricity consumption and extra production (if any); otherwise, these values can be included later in the tool.

3.1.2 Standard sea states

Sea states are a simplified representation of the wave conditions happening at a particular location.

Most small-scale tests run in the laboratory of Aalborg University (Denmark) focus on five (sometimes six) sea states, which if correctly scaled correspond to North See conditions (Danish North Sea, Point 3). The standard sea states cover waves from 1 to 5 (or 6) meter significant wave heights (Nielsen, 1999), (Meyer et al., 2002), (Kofoed et al., 2009).

The tool allows for choosing among various standard sea states. A list of them as well as the assumptions for each location can be found in 'Annex B – Standard Sea states'.

The user must include the wave absorption efficiency of the WEC in each sea state (according to the laboratory results).

A

Sea states							
Location	DK - North Sea, Point 3						
Sea state	1	2	3	4	5	6	total
Wave abs. eff (%)	48%	40%	31%	22%	15%	2%	
(Harvested) Power (kW)	170	794	1700	2494	2907	636	
Pwave (kW/m)	2.1	11.6	32	65.6	114	187	17
Hours (h/y)	4100	1980	946	447	210	93	7776
Electricity production (MWh/y)	531.8	1202.1	1230.4	852.2	467.5	45.2	**4329**
Hm0 (m)	1	2	3	4	5	6	
T02 (s)	4	5	6	7	8	9	
Incident energy along main active	1463.6	3904.1	5146.7	4982.3	4074.5	2956.5	

The tool allows for including the performance in up to six sea states. If a WEC only has performance values for some sea states but not of all of them, it should set be to 0 % at the performance in the sixth sea state.

3.2 Power matrix refers to

This option is only available when power production is given as a power matrix.

The user can indicate whether the power matrix corresponds to absorbed power or electrical power:

Power matrix refers to: Absorbed power

Absorbed power
Electrical power

If *absorbed power* is selected, the tool will assume a constant efficiency for the PTO and unidirectional energy flow throughout the different sea states in which the WEC operates.

The worksheet includes default values for PTO and generator efficiencies. The user can either use these default values or enter their own.

3.3 Measurements and performance

3.3.1 Scale

The default value of the reference machine scale is 1. This value is only significant in the scaling process where the relative proportion of the machines influences the calculated scaled values.

A scale can only be chosen for the scaled machine.

3.3.2 Main active dimension

The main active dimension is the hydrodynamic functional dimension of the WEC.

It is the WEC's dimension along which the machine absorbs the incoming wave energy.

The *main active dimension* multiplied by the wave absorption efficiency corresponds to the capture length, defined by the IEC Standard (IEC/TS, 2011) as "the power captured by the hydrodynamically functional part of a WEC divided by power per metre of the incident wave field".

The user must indicate the main active dimension (in meters) of the reference machine. For the different conversion mechanisms, this dimension corresponds to:

- Overtopping WEC: width of the ramp
- Point absorber / heaving WEC: floater diameter
  - For a multipoint absorber: floater diameter*number of floaters
- Attenuator (i.e. Pelamis type): length of the WEC
- OWC (oscillating water column): chamber width
- Flap WEC (i.e. Oyster type): width of the flap

The secondary dimension corresponds to the other dimension of the WEC in the same plane, i.e. length or width. In the reference machine, this is only an informative parameter. It is only used in the calculations for the scaled machine.

3.3.3 Minimum and maximum operating values

The user must indicate minimum and maximum operating wave conditions for the WEC, defined in terms of H_{m0} and T_{02}.

Minimum operative H_{m0} and T_{02} indicate the sea state where the WEC starts operation. Maximum operative H_{m0} and T_{02} indicate the sea state where the WEC interrupts operation.

Below and above these two limits, respectively, power production is null.

These limits are only taken into account if power production is given as a power matrix. The power matrix must be defined within these operating limits.

Default values for minimum and maximum H_{m0} and T_{02} are the inferior and superior limits of the power matrix entered by the user, respectively.

3.3.4 Energy conversion efficiencies: PTO and generator efficiency

The worksheet includes default efficiency values for the first and second energy conversion processes: from hydraulic to rotating mechanical power, i.e. PTO efficiency, and from rotating mechanical power to electrical power, i.e. generator efficiency. These values are marked in light yellow and are used unless the user enters other values in the green fields.

The following table shows the default efficiency values for the hydraulic, water, air, mechanical and direct drive PTO systems (Nielsen, 2003):

PTO EFFICIENCIES (NIELSEN, 2003)

PTO types	**Default PTO values**
Hydraulic	65%
Water	83%
Air	54%
Mechanical	90%
Direct drive	95%

PTO efficiency refers to the efficiency of the PTO (the power take-off system) without the generator. If the generator efficiency is included in the PTO, the generator efficiency must be set up to 100 %.

Generator efficiency has a default value of 90 %. This number may also include the efficiency of power electronics (i.e. frequency converters and filters) and transformers.

If the WEC is based on direct drive generation, the PTO efficiency must be set up to 100 %, and the generator efficiency must be set up to that of the linear conversion.

3.3.5 Generator rated power

The user must include the rated power of the generator.

This value serves as an upper limit of the maximum electricity production that the WEC can produce in each sea state.

If *power known as standard sea states* is selected the default value is:

- Generator rated power default value = Max. absorbed power (in kW) * PTO efficiency

If *power known as power matrix* is selected, the *generator rated power* is taken into account in the calculation of power matrix C based on matrix F.

The default value depends on whether this power matrix refers to *absorbed power* or *electrical power*.

If power matrix refers to *absorbed power*:

- Generator rated power default value = Max. (matrix B, in kW) * PTO efficiency

If power matrix refers to *electrical power*:

- Generator rated power default value = Max. (matrix B, in kW) / Generator efficiency

Note that when the generator is overrated compared to the available resource, the resulting average capacity factor will be low.

3.3.6 Annual electricity production

Annual WEC production is calculated based on the WEC performance at the selected location, as well as on the WEC's availability, own electricity consumption and extra production:

WEC availability

Availability takes into account the scheduled and the unforeseen maintenance.

Default value for availability is 100 %, which means that all maintenance is carried out in periods where the WEC is out of operation due to very mild wave conditions.

Availability affects the annual power production linearly.

Own WEC consumption

Own WEC consumption covers the annual energy consumption of the SCADA system, vital control and communication equipment, etc.

The default value is set to 0 MWh/y.

If own WEC consumption is included in the WEC´s power matrix, it should be stated.

WEC extra electricity production

This value must be filled in when there is another power production source besides the WEC production specified as a power matrix or as standard sea states, i.e. production coming from wind turbines.

The value should indicate annual electricity production.

The default value is set to 0 MWh/y.

If WEC extra electricity production, besides the production of the wave absorption mechanism, is included in the WEC´s power matrix, it should be stated.

According to the three parameters above, annual electricity production of the WEC is calculated by:

$$\begin{aligned} Yearly\ Production\ (MWh/y) &= (Annual\ Production * Availability) - (Own\ WEC\ consumption) \\ &+ (Extra\ WEC\ production) \end{aligned}$$

3.3.7 Project lifetime

The default value is set to 20 years. A project lifetime above 20 years is considered as 20 years.

This value is taken into account to calculate the *LCOE* and *NPV* and influences the output of the *payback period*.

3.4 Costs

3.4.1 WEC materials: main and secondary frame

In the cost assessment table, the user can select among four materials for the WEC structure: concrete, ballast concrete, steel and ballast.

Two of these four materials can be included in the cost assessment under the categories *main frame* and s*econdary frame*.

Default values are provided for each material:

Material Costs, in EUR/ton (Nielsen, 2003), (Meyer et al., 2002)

Material	**Unit cost (EUR/ton)**
Concrete	200
Ballast concrete	70
Steel	3400
Glass fibre	9500

3.4.2 Default values on prices

The worksheet also includes default values on prices for the total PTO system, mooring, electrical connection and installation, as well as for O&M, site lease and insurance costs.

Default values are shown in the yellow cells. When a value is inserted in a green colour cell, it overwrites the default value of the yellow cell.

Default values are independent of the location.

It is, however, recommended that these default values are only used on projects at a very early development stage. Above a certain development stage, the user must put in his costs.

The yellow cells on the left-hand side of the costs table show the calculated default values, which are based on reference machine input data as well as on the standard values indicated below (also shown on the right-hand side of the costs table):

Other Costs

Total power take-off system (including PTO, generator, power electronics, control & safety system and others)*[1]	5000 EUR/kW

[1] The 5000 EUR/kW derives from the costs of Mutriku OWC (Oscillating Water Column) pilot plant. Rated at 296 kW, it spent 1.5 MEUR for the electro-mechanical equipment (Torre-Enciso et al., 2012).

Mooring system[2]	300 EUR/ton
Pre-assembly and transport[3]	100000 EUR
Installation[3]	100000 EUR
Electrical connection[4]	340 EUR/kW
Development[3]	3% of total CAPEX
Contingencies[3]	10%
Operation & Maintenance[3]	6% CAPEX
Site lease and insurance[3]	2% CAPEX

* It has been decided to provide a unique default value for the entire PTO system although PTO system costs are very WEC dependent. This default value is only provided as a reference, the user must include the costs of his particular PTO system.

According to Nielsen (2003) and Meyer et al. (2002), a unit cost of 340 EUR/kW can be used for the different PTO systems (mechanical, air, water and hydraulic) if series production is considered. These values are not, however, suitable for standalone prototypes. Also, these values might need an update according to inflation.

Re-vision (2014) has developed a cost structure breakdown for tidal current devices and wave energy converters. The cost structure breakdown might be useful for the COE Tool user to evaluate all costs involved in a project.

[2] KNSWING Project

[3] The default values for pre-assembly and transport, installation, development, contingencies, operation & maintenance, and site lease and insurance have been estimated by the authors as a compromise default value.

[4] KNSWING Project

4 Locations

Depending on whether the WEC's performance is included as a *power matrix* or as *standard sea states*, the user can select among a list of locations defined by a scatter diagram or by sea states, respectively.

A scatter diagram is a matrix that provides an approximate value of the long-term wave climate of a location. It is defined in terms of H_{m0} and T_{02}; all scatter diagrams in the tool have the same resolution: 19 different wave heights and 17 wave periods. Each bin of the matrix indicates the hours per year that a particular sea state occurs. Each sea state is defined by one H_{m0} and one T_{02}.

The standard sea states are another representation of the wave climate of a site. Each sea state is defined by H_{m0}, T_{02}, the probability of occurrence of each sea state (in hours per year) and the energy content of each sea sate (in kW/m of incoming wave).

4.1 Scatter diagrams

The scatter diagrams are used when the WEC's performance is provided by a power matrix.

The following locations are available in the scatter diagrams database:

N.	Location	Mean P_{wave}	Water depth range	Distance to shore	Coordinates of the wave buoy
1	DK - Nissum Bredning	0.2 kW/m	3 to 5 m	0.2 km	
2	DK - Horns Rev [HR I]	6 kW/m	10 m	14 km	55°28.909 N, 07°79.974 E
3	DK - Hanstholm DanWEC	7 kW/m	17 m	1.3 km	57.13° N 8.58° E
4	DK - North Sea, Point 2	12 kW/m	31 m	100 km	
5	DK - North Sea, Point 3	16 kW/m	39 m	150 km	
6	France – SEM-REV	16 kW/m	35 m	15 km	
7	France – Yeu Island	26 kW/m			
8	Ireland - Galway Bay	2.4 kW/m	21-24 m	2.5 km	53.228°N 9.266°W
9	Ireland - Belmullet	71 kW/m	50-100 m	6.5-10.5 km	54°N 12°W
10	Portugal - Pilot Zone	25 kW/m	30-90 m	20 km	39°54'N 9°06'W
11	Portugal - Offshore Lisbon	36 kW/m			39°N 12°W
12	Spain - BIMEP	21 kW/m	50-90 m	1.7 km	
13	Spain - PLOCAN	8 kW/m	40 m		

14	UK – EMEC	21 kW/m	12-50 m	1-2 km	
15	UK – Pentland Firth	7 kW/m	62 m	2.4 km	53°40’30’’ N 03°16’4’’W
16	UK – Wave Hub	16 kW/m	50-60 m	16 km	
17	USA – Humboldt Bay (CA)	26 kW/m	70 m	5 km	
18	*User defined*				

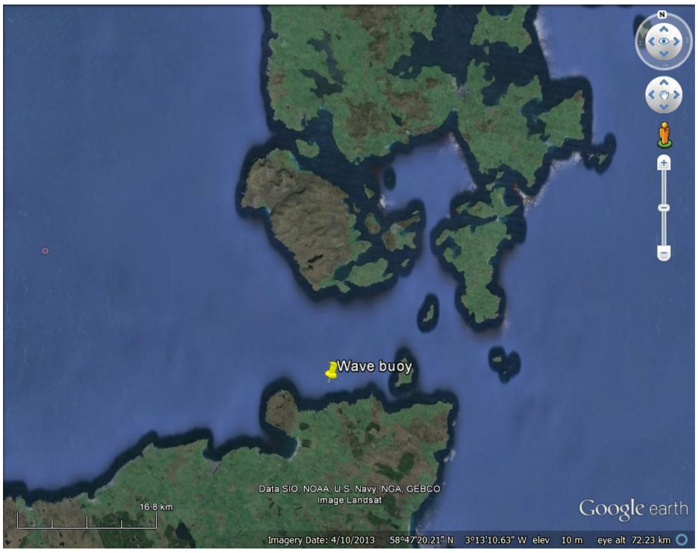
The locations available in the COE Calculation Tool cover a wide range of sites. Although some of them have the same mean wave power. it is very important to note the different sea states and environmental conditions they encompass. Additionally, normally some sites are preferred and recommended at certain development stages than others.

With regard to Denmark: Nissum Bredning is located on the western part of Jutland and is an inlet area with water depths between 3 to 5 meters (Frigaard et al., 2004). Horns Rev, also located in western Denmark at 10 meter water depths, is the site of a 180 MW offshore wind farm (Soerensen et al., 2005). Hanstholm hosts the established Danish Wave Energy Centre (DanWEC) (Margheritini, 2012); it faces the Danish North Sea and comprises intermediate to deep waters. Lastly, there are two reference locations in the Danish North Sea, Point 2 and Point 3, located 100 and 150 km offshore, respectively (Ramboll, 1999).

Galway Bay and Belmullet are two reference locations in the Irish Wave Energy Programme (HMRC, 2003). Galway Bay is an inlet sea (water depths of 22 m) generally conceived as a test area for small-scale prototypes (Nielsen et al., 2010), and Belmullet represents a location with high wave potential (50 to 100 m water depths), for full-scale testing or commercial operation of WECs (AMETS, 2014).

EMEC is the European Maritime Energy Centre established on the Orkney Islands. The scatter diagram corresponds to 50 m water depths (Nielsen et al., 2010). (There are some discrepancies with the data from EMEC; if the reader would like to learn more about it please contact the main author of the User Guide).

Data of EMEC is complemented by data from the Pentland Firth.



Data for Wave Hub has been downloaded from the SOWFIA database. It corresponds to wave buoy data measured in the period 2012/02/10 15:00:00 - 2013/04/11 15:00:00.

In France, SEM-REV is being established as test site for WECs (SEM-REV, 2014). Yeu Island is located south of the SEM-REV. Wave data for the site corresponds to measurements from a wave buoy that can be freely downloaded from the CANDHIS database (CANDHIS, 2014). Babarit et al. (2006) carried out a study on the wave and wind conditions at Yeu Island.

The Pilot Zone in Portugal has been set up as a test site for WECs (water depths between 30 and 90 m) and the offshore location represents a more energetic wave site (Nielsen et al., 2010).

BIMEP test site is located in the Cantabrian Sea, north of Spain. Data has been obtained from (Nielsen et al., 2010).

PLOCAN test site is located in the Canary Islands, east of Gran Canaria.

The tool also offers one location in USA on the west coast. Humboldt Bay (Humboldt Bay, 2014) in northern California has been chosen by the US Department of Energy to assess the economic feasibility of wave energy converters (La Bonte et al., 2013).

Alternatively, the user can enter his own scatter diagram by choosing the option *user defined scatter diagram*. In the sheet named "Wave climates" the user must fill-in the new scatter diagram. It has to be defined in terms of H_{m0} and T_{02} (19 intervals for H_{m0} and 17 intervals for T_{02}), and in hours per year of occurrence of each sea state.

The SOWFIA project (SOWFIA, 2014) provides a database of wave data worldwide.

According to IEC standards (IEC/TS, 2011) a scatter diagram should be defined by the parameters H_{m0} and T_e (the energy period). The COE Tool is based on scatter diagrams defined in terms of H_{m0} and T_{02} (when needed in the calculations, it is assumed that $H_{m0}=H_s$ and $T_{02}=T_z$).

It is also assumed that there is a constant relationship for all locations and along the scatter diagram between T_{02} and T_e, or T_{02} and T_p, defined by:

$$T_{02}=T_e*0.49/0.577$$

$$T_{02}=T_p/1.5$$

(true for a parameterised JONSWAP spectrum with $\gamma=3.3$ (average in the North Sea).

The mean wave power at each location, independently on whether it corresponds to deep or shallow waters, has been calculated according to (Nielsen, 1999):

$$P_{wave}(kW/m) = 0.577 \cdot H_{m0}^2 \cdot T_{02}$$

4.2 Standard sea states

The sea states are used when the WEC's performance is known in 5 or 6 sea states.

The following locations are available in the sea states database:

N.	Location	Mean P_{wave}	Water depth range	Distance to shore	Coordinates of the wave buoy
1	DK - North Sea, Point 3	16 kW/m	39 m	150 km	
2	DK - North Sea, Point 2	12 kW/m	31 m	100 km	
3	DK - Hanstholm DanWEC	7 kW/m	17 m	1.3 km	57.13° N 8.58° E
4	DK - Horns Rev [HR I]	6 kW/m	10 m	14 km	55°28.909 N, 07°79.974 E
5	UK – EMEC	21 kW/m	12-50 m	1-2 km	
6	*User defined sea state*				

The user can enter his own sea states by choosing the option *user defined sea states*.

In the sheet named "Sea states", the user must fill in the new sea states by including:

- Mean wave power of each sea state
- Hours per year of occurrence of each sea state
- H_{m0} that defines each sea state
- T_{02} that defines each sea state

There can be up to six sea states. The more sea states used, the more accurately the WEC's performance can be estimated.

Pecher (2012) proposes a way to define sea states for different locations. The calculation is based on a collection of bins having a maximum range of H_{m0} and Te.

5 Scaled machine

The spreadsheet allows for upscaling or downscaling the *reference machine* to a new scaled machine.

This feature allows for evaluating the production of the WEC in different locations while scaling the WEC to the selected location.

Some of these locations might have lower average energy content than the reference location while others might have larger average energy content.

The user must introduce a scale factor i.e. *scale of wave capturing mechanism*. This parameter indicates the relationship between the main active dimension of the reference machine and the main active dimension of the new scaled machine.

Note that a *scale* above one indicates that the scaled machine is bigger than the reference machine. A *scale* below one indicates the scaled machine is smaller than the reference machine.

WEC dimensions, equipment, production and costs are upscaled or downscaled according to the scale introduced. The scaling is done according to Froude law.

Up-scaling of Measured Parameters from Model in Scale S (S=100 in Example) to Full Scale (Kofoed et al., 2009)

Parameter	Model	Full scale	Example 1:100
Length	1	S	100
Area	1	S^2	10000
Volume & Weight	1	S^3	1000000
Time	1	$S^{0.5}$	10
Velocity	1	$S^{0.5}$	10
Force	1	S^3	1000000
Power	1	$S^{3.5}$	10000000

According to the table, the significant wave height linearly scales the wave period scales by the square-root of the scale and the power scales by the scale to the power of 3.5.

Default scaled values are calculated from the reference machine, but new values can be entered in the green cells.

Ultimately, the scaled machine allows for optimizing a machine for a selected wave climate while evaluating the economic feasibility of the project.

*Note that the *scaled machine* is always based on the *reference machine*. Note also that:

- Expenses scaled by volume.
- Reducing the installed power reduces the production and the cost of PTO and generator.

All *measurements and performance* values are scaled according to Froude scaling law and the following calculations apply:

Parameter	Scale relationship
Scale (of wave capturing mechanism)	S
Main active dimension	S
Secondary dimension (length/width)	S
Total dry weight	S^3
Mooring weight	S^3
Minimum operative H_{m0}	S
Minimum operative T_{02}	same value as *reference machine*
Maximum operative H_{m0}	S
Maximum operative T_{02}	same value as *reference machine*
PTO average efficiency	same value as *reference machine*
Generator average efficiency	same value as *reference machine*
Generator rated power	S
WEC's own consumption (annual)	$S^{3.5}$
WEC's extra electricity production (annual)	$S^{3.5}$
WEC availability	same value as *reference machine*

Costs (CapEx and OpEx) are scaled according to Froude scaling law, and the following calculations apply:

Parameter	Scale relationship
Development	S
Main frame & Second. Frame	calculated based on the *weight* of materials selected
Access system and platform	S^3
Machine housing	S^3
Total load carrying structure	S^3
PTO	$S^{3.5}$
Generator	$S^{3.5}$
Power electronics	$S^{3.5}$
Control & safety system	$S^{3.5}$
Total power take-off system	$S^{3.5}$
Mooring system	S^3
Pre-assembly and transport	S^3
Installation on site	S^3

Electrical connection	$S^{3.5}$
Contingencies	same value as *reference machine*
O&M costs per year Site lease and insurance Others	Scaled by: Total el. production *scaled machine* / Total el. production *reference machine*

It should be noted that a reduction on the rated power of the generator diminishes the electricity production as well as the costs of the generator and of the PTO.

5.1 Locations for scaled machine

If the WEC's performance is inserted as a power matrix, all locations included in the scatter diagram´s database can be selected.

If the WEC's performance is inserted as *standard sea states*, the locations the user can select among are limited. This is to avoid large errors in the calculations.

- If the selected location in reference machine is *DK-Paludan Flak, Samsø* **-->** the location of the scaled machine can only be *DK-Paludan Flak, Samsø*
- If the selected location in reference machine is *UK-EMEC* **-->** the location of the scaled machine can only be *UK - EMEC*
- If the selected location in reference machine is *User Defined* **-->** the location of the scaled machine can only be *User Defined*
- If the selected location in reference machine is *DK - North Sea Point 3, DK - North Sea Point 2, DK – Hanstholm DanWEC* or *DK – Horns Rev* **-->** the user can select between all of these four as locations of the scaled machine.

Regarding the COE Calculation Tool, the user must be aware of the fact that calculating the electricity production of a WEC for a different location than the location of the sea state may induce large errors.

6 Uncertainties

6.1 Evaluation of uncertainties

The user must be aware that there are uncertainties in the data handled by the COE Calculation Tool (i.e. in the input data, electricity production and in prices) and, therefore, also in the output results:

- The uncertainties in input data correspond to the uncertainties in the power production (both from the power matrix or the performance in the standard sea states, and in the scatter diagrams) as well as on the design, i.e. amount of material.
- Then, some errors are added when recalculating the power matrix to fit the chosen wave climate.
- Finally, there are also uncertainties in the costs of the different components.

In order to evaluate these uncertainties, the tool provides an estimation of the overall uncertainty related to the calculations.

The uncertainty depends on the development phase of the WEC, and on whether power production data derives from a power matrix or from the performance in the standard sea states. These numbers are calculated according to Previsic (2013).

Development Phase	**Uncertainty** (performance as power matrix)	**Uncertainty** (performance as sea states)
Phase 1 / TRL 1, 2 and 3	-30 to 50%	-30 to 80%
Phase 2 / TRL 4	-25 to 30%	-30 to 30%
Phase 3 / TRL 5 and 6	-20 to 20%	-25 to 30%
Phase 4 / TRL 7 and 8	-15 to 15%	-20 to 20%
Phase 5 / TRL 9	-10 to 10%	-15 to 15%

6.2 WEC development stages

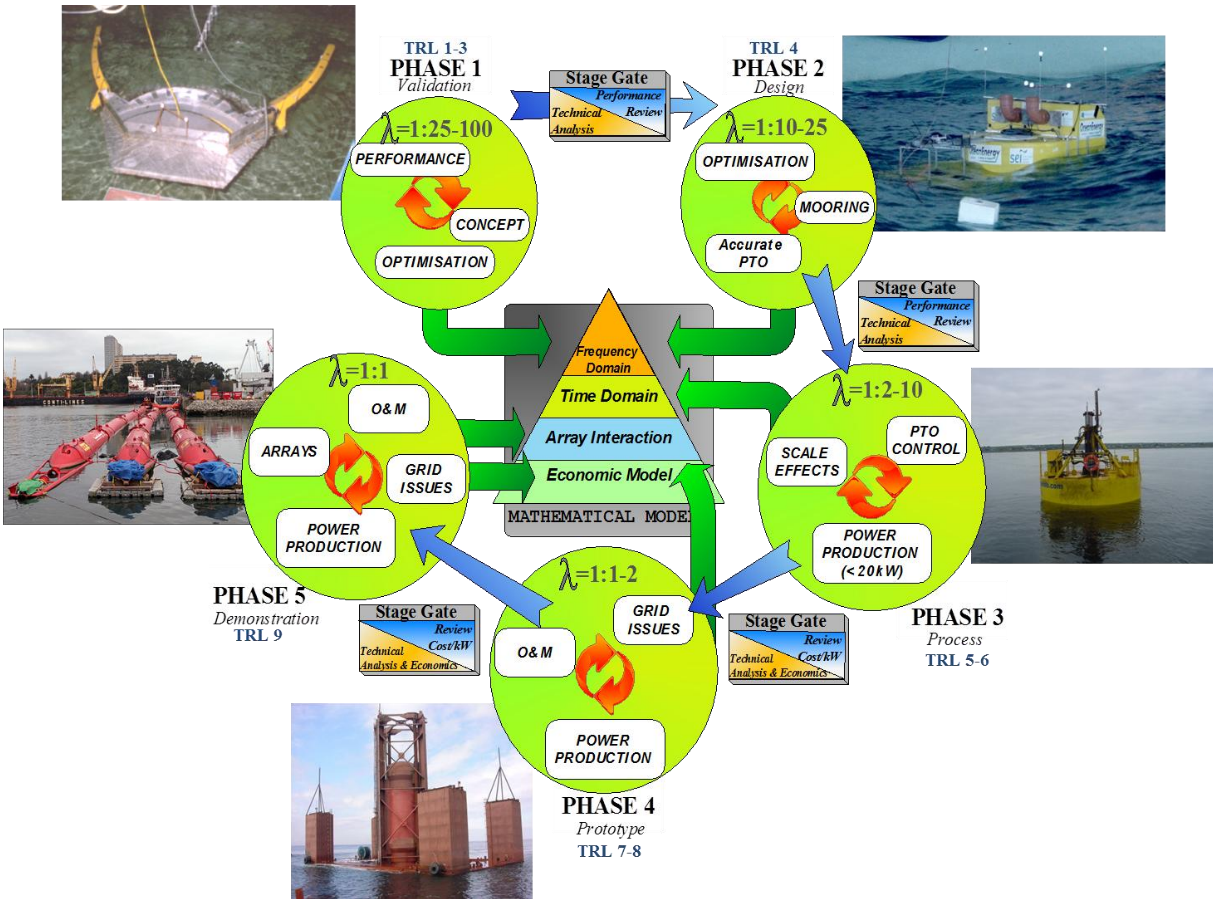
The development of a wave energy converter consists of different phases or stages, which cover from the initial concept to the industrial commercialisation. Depending on the country, the industry or the research institute of focus, these development phases may differ (Fernández-Chozas, 2013).

The COE Calculation Tool considers two different ways of evaluating the development stage of a technology:

a) The five development phases.

b) The nine Technology Readiness Levels (TRLs)

The figure below relates the five development stages with TRLs.



Overview of the five-phase WEC development protocol and TRLs supported by the Equimar project. Lambda (λ) indicates the scale of the WEC model or WEC prototype. O&M stands for Operation and Maintenance. The WECs illustrated are (clock-wise direction, starting from Stage 1): Wave Dragon at HMRC (Ireland), OE Buoy at Galway Bay (Ireland), Wavebob also at Galway Bay, Archimedes Wave Swing at Aguçadoura (Portugal) and Pelamis, also at Aguçadoura (Holmes, 2010).

6.2.1 5 development phases

The 5 development phases of a WEC have been agreed by the EquiMar consortium (Ingram et al., 2011) and long time before by the Danish Wave Energy programme (Kofoed et al., 2009). These are the following:

- Phase 1: Model Validation – Lab testing
- Phase 2: Model Design – Lab testing
- Phase 3: Initial sea trials – Sea trials at a reduced prototype scale
- Phase 4: Prototype Validation – Medium or full-scale prototype sea trials
- Phase 5: Prototype Demonstration – Full-scale or arrays sea trials

The first two phases correspond to laboratory testing, and the third to the fifth correspond to sea trials at a reduced prototype scale, at medium or full-scale, and at full-scale, respectively.

The user must select the development phase of the reference machine.

6.2.2 9 TRLs

NASA's Technology Readiness Levels (TRL) were used in aviation, space and defence to manage the development of high risk, novel and complex technologies (NASA, 2013). Quite recently, this development schedule has been re-introduced to assess the development stage of a WEC (Fitzgerald et al., 2012), (West Wave, 2014).

By definition, a TRL indicates the commercial ability of a technology. There are nine TRLs:

- TRL1: Concept configuration description
- TRL2: Professional desk studies
- TRL3: Small-scale laboratory verification and professional desk studies
- TRL4: Large-scale laboratory verification and professional desk studies
- TRL5: Sub-assembly testing, scaled benign site deployments
- TRL6: Full systems testing at benign test site, 1:4 or larger
- TRL7: Operations in the full-scale environment. Experimental prototype machine(s), ~0.5-1MW
- TRL8: First-of-type demonstration and performance verification/certification, ~1MW
- TRL9: Initial series-type machines, deployed in an array, 5-10 MW. Completion of type certification activities.

7 Output of the COE Tool – an economic assessment

The output of the COE Calculation Tool is an economic evaluation of the reference and the scaled machines at the selected wave climates, which includes:

- Capacity factor
- Annual electricity production
- Average annual electricity production
- Average wave-to-wire efficiency

- WEC development stage and uncertainty related to the data
- CapEx and OpEx
- Payback period
- LCOE (for three different discount rates)
- Net Present Value, NPV (for three different discount rates)

And finally, some graphs.

7.1 Currency

The user must select two currencies, although both can be the same.

One is used to define the cost of each component, and the other one is used for the economic analysis.

There are four different currencies which the user can select: Danish Krone (DKK, kr), Euros (EUR, €), British Sterling (GBP, £) and US Dollars (USD, $).

The exchange rates used are the following:

Currency	Symbol	Relationship (“currency” to Euro)
DKK	kr	7.5
EUR	€	1
USD	$	1.33
GBP	£	0.83

7.2 Capital expenditures (CapEx)

A WEC’s capital expenditures (CapEx) indicate the initial WEC’s investment costs, with units of cost per installed unit of power (i.e. EUR/MW).

CapEx include all the costs incurred by:

- Development: engineering and management, and planning and consenting.

- Structure, including materials and components: materials, access system and platform, machine housing and others.
- Power take-off system (PTO): PTO, generator, power electronics, control and safety system, and others.
- Mooring system
- Installation: pre-assembly and transport, and installation on site.
- Electrical connection
- Others

In Denmark, Energinet.dk covers the grid connection costs.

Decommissioning costs are not taken into account in the calculations.

7.3 Operational expenditures (OpEx)

A WEC's operational expenditures (OpEx) represent the annual Operation and Maintenance (O&M) costs of the WEC, as a cost per unit of energy produced (i.e. EUR/MWh).

OpEx include the following costs:

- Operation and Maintenance
- Site lease and insurance
- Others

Whereas CapEx are mostly incurred at the beginning of a project, OpEx are distributed throughout the project lifetime.

7.4 Feed-in tariff (FIT)

The following FITs are set up as default values in the tool. The user can also enter a value.

Country	FIT
Denmark(*)	80 EUR/MWh
Ireland	220 EUR/MWh
France	150 EUR/MWh
Portugal	260 EUR/MWh
Spain	86 EUR/MWh
UK (**)	367 EUR/MWh
USA (***)	100 EUR/MWh
User(****)	600 EUR/MWh

(*)(****) The Danish Partnership for Wave Energy in Denmark has proposed a FIT of 4.5 DKK/kWh – about 600 EUR/MWh – for an annual production of 7000 MWh/y during a ten-year period (2015 to

2025), to support the production of the first demonstration wave energy developments (Nielsen et al., 2012).

(**) UK FIT is set to 305 GBP until 2019.

(***) California has a renewable energy FIT for projects with capacity up to 3 MW. Renewable energy projects that are eligible are defined by the California Energy Commission (Commission Guidebook, 2014). Eligible technologies listed here includes: ocean wave, ocean thermal and tidal current. The SB32 FIT program, featuring the renewable market adjusting tariff (ReMAT), became effective July 24, 2013. This allows the FIT price to adjust in real time based on market conditions (RAM, 2014), (FIT, 2014).

A constant FIT is assumed along the project lifetime.

The FIT is used to calculate the annual revenue, NPV and payback period of the WEC at the selected location.

7.5 Payback period

It refers to the period in time, in years, required for the return of the investment.

It should be noted that this parameter does not take into account the time value of money; therefore, the cash flows are not discounted.

The displayed output value depends on the project lifetime (*n*):

- If payback period < project lifetime --> Output: payback period, in years
- If payback period > project lifetime --> Output: *Greater than project lifetime*
- If (payback period > 20 years) & (project lifetime > 20 years) --> Output: *Greater than 20 years*

7.6 Discount rate

The discount rate is represented by *r*.

The tool has two default discount rates: 0 % and 4 %. By using a 0 % discount rate, the variation of money value in time is not taken into account.

Denmark recommends using a 4 % discount rate for this kind of projects.

A third discount rate can be entered by the user.

A constant discount rate is assumed along the project lifetime. This parameter is used to calculate the LCOE and NPV.

Ingram et al. (2011) note that the typical discount rate values suggested for marine energy in the UK are between 8 % and 15 % with a higher rate applied to less developed technologies, in order to represent the greater uncertainty associated with both design and cost estimation.

The SI Ocean project uses a discount rate of 12 % in its evaluation of the cost of energy and cost reduction opportunities for arrays (SI Ocean, 2013a).

7.7 The levelised cost of energy of WECs

The COE shows the cost of each unit of energy produced by a WEC throughout its lifetime. Its value depends on the capital expenditures (CapEx), the operational expenditures (OpEx), the energy production and the lifetime of the WEC at a certain location.

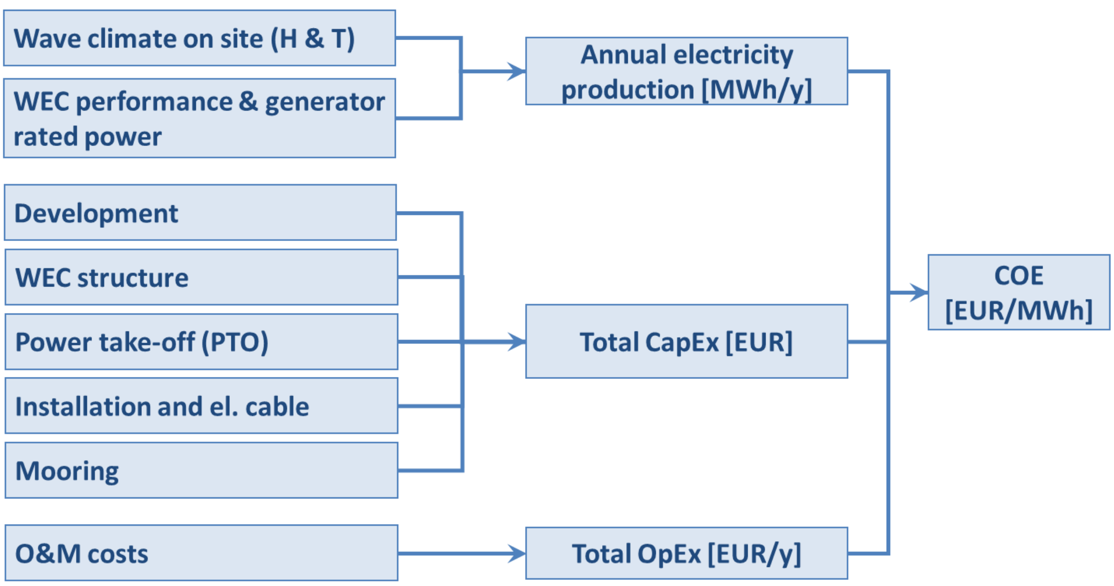
The COE is used to assess the WEC's economic feasibility throughout the various development stages. It is defined as follows where the WEC's lifetime in years is indicated by *n*.

$$COE = \frac{CapEx + \sum_{t=1}^{n} OpEx_t}{\sum_{t=1}^{n} WEC\ Production_t}$$

Often, the COE is calculated as a levelised cost of energy (LCOE). The difference between COE and the LCOE is that the latter takes into account the variation in time of the money value, which is represented by the discount rate (*r*).

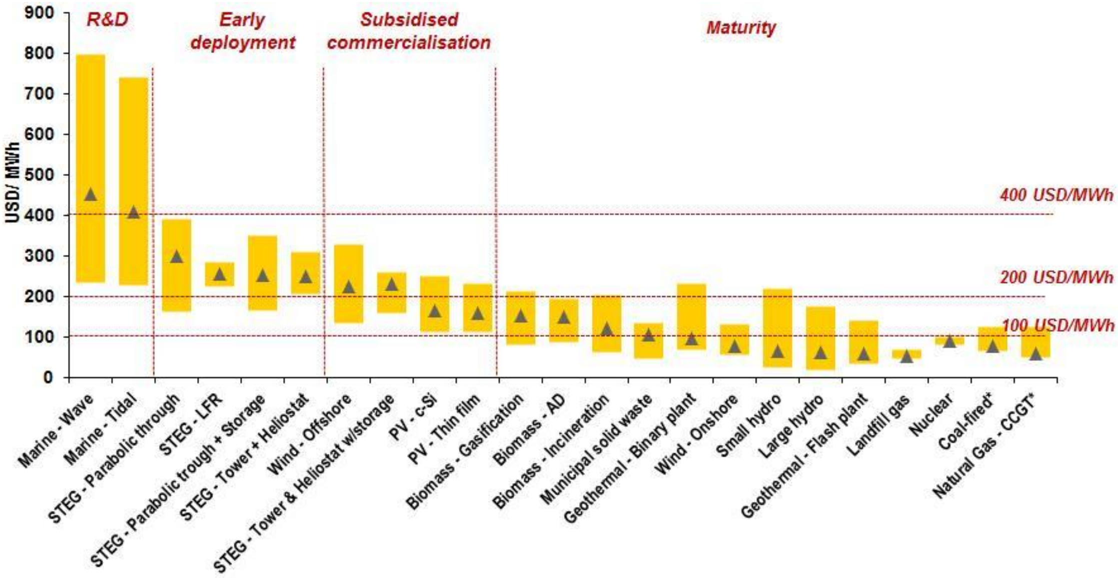
$$LCOE = \frac{CapEx + \sum_{t=1}^{n} \frac{OpEx_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{WEC\ Production_t}{(1+r)^t}}$$

The LCOE is calculated as WEC costs in present value divided by electricity generation in present value.



7.7.1 LCOE of different technologies

Many studies have evaluated current and expected COE values of WECs and marine tidal turbines (Ingram et al., 2011), (Previsic, 2013), (SI Ocean, 2013). Generally, it has been agreed that the current LCOE of WECs ranges between 300-600 EUR/MWh. A learning rate of 12-15 % is expected, which, along with a cumulative installed capacity in the large MW (or small GW) scale, can bring down to 100-200 EUR/MWh the COE of WECs. The following figure illustrates the LCOE (in USD/MWh, 2012 values) of ocean energy, other renewables and conventional technologies (O'Flynn, 2013).



LCOE (in USD/MWh, in 2012 values) of Wave Energy Converters, marine tidal turbines, other renewables and conventional technologies (O'Flynn, 2013)

The Danish Partnership for Wave Energy in Denmark carried out a comprehensive study on current and project the LCOE of wave energy projects. Among their results, they have proposed a FIT of 4.5 DKK/kWh – about 600 EUR/MWh – for an annual production of 7000 MWh/y during a ten-year period (2015 to 2025), to support the production of the first demonstration wave energy developments (Nielsen et al., 2012).

The projected LCOE of wave energy up to 2050 (in accordance to the Danish wave energy roadmap) is as follows:

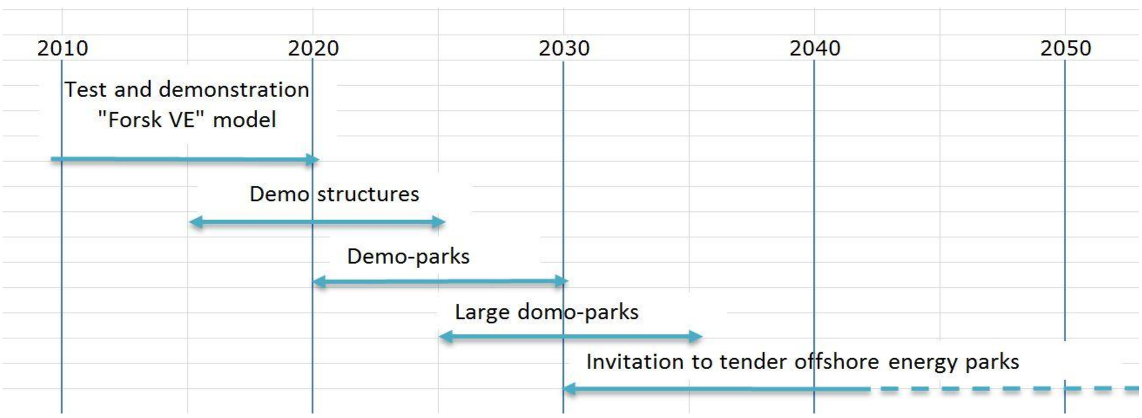


TABLE 1 TABLE STRATEGIC TARGETS FOR THE DEVELOPMENT OF WAVE POWER IN DENMARK

Year	**Demonstration Capacity (MW)**	**Production Limit per Year (MWh/y)**	**Tariff (FIT) (EUR/MWh)**
2015-2025	2-5	7.000	600
2020-2030	10-20	30.000	400
2025-2035	30-60	100.000	200
2030 -	500 – 1.000	1.500.000	120

7.8 Net Present Value

The NPV is calculated with the following formula:

$$NPV = \sum_{t=0}^{n} \frac{(Cash\ Flows)_t}{(1+r)^t} = -CapEx + \sum_{t=0}^{n} \frac{(Annual\ revenue - OpEx)_t}{(1+r)^t}$$
$$= -CapEx + \sum_{t=0}^{n} \frac{((Annual\ Energy\ Production * FIT) - OpEx)_t}{(1+r)^t}$$

Where *n* is the WEC's lifetime, in years.

A constant discount rate and FIT along the project lifetime are assumed.

7.9 Capacity factor

The capacity factor is calculated by the following formula:

$$Cf\ (Capacity\ Factor) = \frac{1000 * Yearly\ Production\ (MWh/y)}{Rated\ power\ generator\ (kW) * (24 * 365.25)\ (h/y)}$$

7.10 Average electricity production

The average electricity production is calculated by the following formula:

$$Average\ Electricity\ Production = \frac{Annual\ Energy\ Production\left(\frac{MWh}{y}\right)}{(24 * 365.25)\ (h/y)}$$

7.11 Average wave-to-wire efficiency

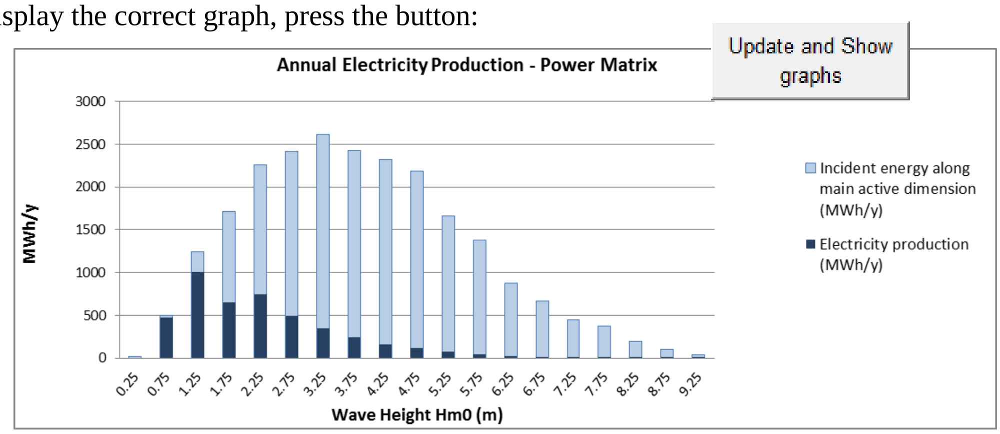
The average wave-to-wire efficiency is calculated by the following formula:

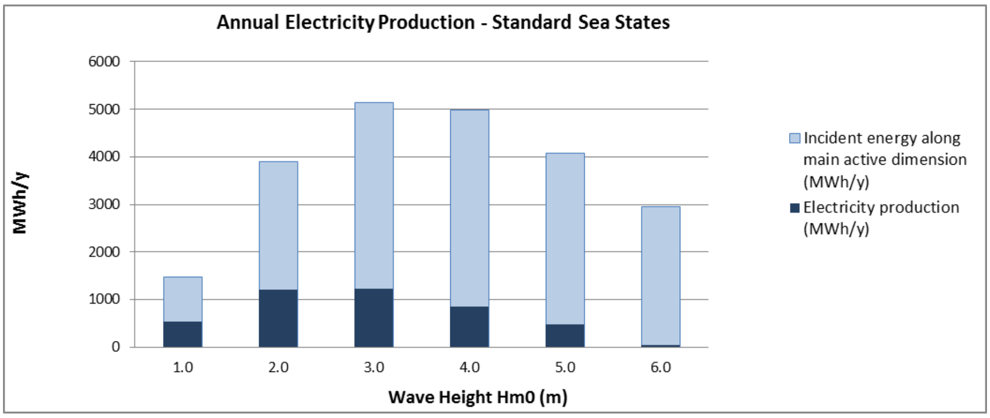
$$Average\ Wave\ to\ wire\ eff.(\%) = \frac{1000 * \ Yearly\ Production\ (MWh/y)}{Mean\ Pwave\ (kW/m) * Main\ dimension\ (m) * (24 * 365.25)\ \ (h/y)}$$

7.12 Graphs: annual electricity production and available potential

The COE Calculation Tool provides one or two graphs – depending on whether *standard sea states* or *power matrix* is selected – that show the annual electricity production of a WEC at the selected location and the available incoming power to the WEC in terms of H_{m0} and T_{02}.

To display the correct graph, press the button:





The x-axis of the graphs shows:

- The 19 significant wave heights that represent the wave climate of the chosen location (if *power matrix* is selected).
- The 17 zero crossing periods that represent the wave climate of the chosen location (if *power matrix* is selected).
- The 5 or 6 significant wave heights that represent the sea states of the chosen location (if standard sea states is selected).

All graphs show two sets of bars overlapping. The light blue bars indicate the annual incident wave power along the main dimension of the WEC (in MWh/y), and the dark blue bars show the WEC's annual electricity production, as electrical output (in MWh/y).

The WEC's annual electricity production takes into account the *WEC's availability*, but does not consider *WEC´s own consumption* or *WEC´s extra electricity production*.

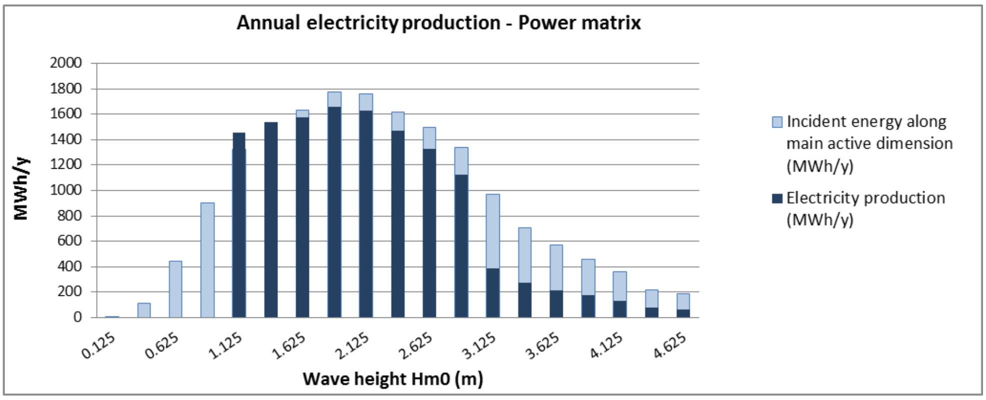
Graphs defined for T_{02} also show the average capture width ratio (η) of the WEC, based on the average values of T_{02}.

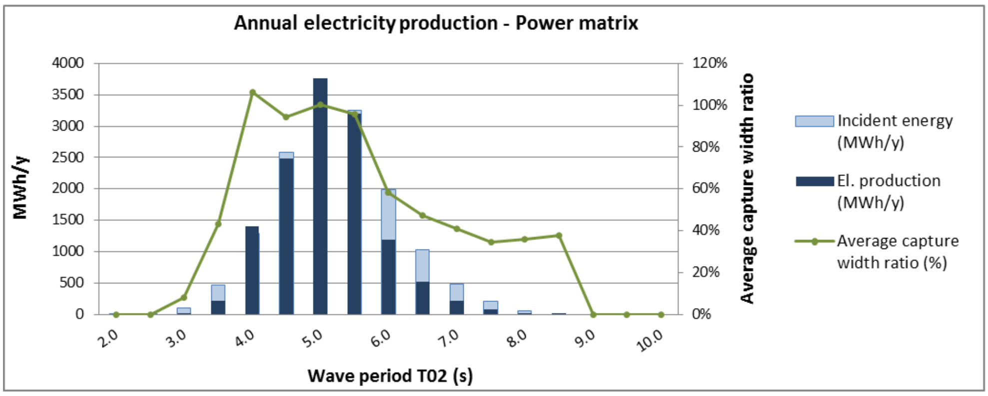
The fact that the average capture width ratio is non-dimensional presents the advantage that the same value can be used for different scales of the WEC, which only affects the corresponding wave parameters (Pecher, 2012).

The capture width ratio (η) has been calculated as the weighted average of the capture width ratio (or non-dimensional performance) of all the cells with the same T_{02} against the contribution of each cell:

$$\eta_{Ti} = \frac{\sum_{Tz=1}^{Tz=17}\left(\eta_i \cdot \mathrm{Pr}ob_i \cdot P_{wave,i}\right)}{\sum_{Tz=1}^{Tz=17}\left(\mathrm{Pr}ob \cdot P_{wave,i}\right)}$$

There are some sea states where the dark blue bars overlap and are higher than the light blue bars:





This means that the WEC has an average absorption efficiency, capture width ratio or non-dimensional performance, above 100 % in the sea states defined with the significant wave height or wave period where that is happening.

The capture width ratio is a good indicator of the right sizing of the device.

8 Future work and improvements on the COE Tool

The following improvements could improve the functioning of the COE Calculation Tool:

Arrays:

The tool does not take into account wave farms composed by different WEC arrays. It only focuses on the performance and costs of one device. The tool can be improved by adding the evaluation of the COE of array configurations:

Parameters to take into account:

- Device size
- Array size: number of WECs
- Array area
- Wave farm lay-out
- Distance between WECs
- Spacing factor and shadowing effect among WECs
- Location features: depth, distance to shore
- Electrical configuration: cable costs to the common offshore substation or hub

It would be interesting to carry out this analysis for an array configuration of 1, 10, 50 and 100 WECs and compare the output of the tool.

More parameters:

- Introduce other parameters (as constant values or matrices) that may influence the WEC power production, i.e. wave directionality, wave spectrum influence, etc.

- Allow the user to input a varying (non-constant) PTO and generator efficiency that is dependent on the significant wave height. Currently, the PTO efficiency is a constant value. This could be implemented by a pop-up table in which the user can introduce the PTO efficiency versus H_{m0} – provided *absorbed power* has been selected.

  This number will directly affect the *annual electricity production*.

- Include further interesting deployment locations (scatter diagrams and standard sea states).

Establish a methodology to evaluate the uncertainties in input values, costs and output results:

There are many uncertainties in the data handled by the COE Calculation Tool (i.e. in the input data, electricity production and in prices) and, therefore, also in the output results:

- The uncertainties in input data correspond to the uncertainties in the power production (both from the power matrix or the performance in the standard sea states, and in the scatter diagrams) as well as on the design, i.e. amount of material.
- Then, some errors are added when recalculating the power matrix to fit the chosen wave climate.
- Finally, there are also uncertainties in the costs of the different components.

Currently, an overall uncertainty value is provided in the output table of the COE Calculation Tool. However, it would be beneficial to the users that there were an evaluation of the uncertainty for each parameter provided in the tool.

9 Case studies

Several case studies showing how to use the tool have been created. These are available upon request. Please email the corresponding author for further information.

10 References

AMETS (2014). [Online]: www.seai.ie/Renewables/Ocean_Energy/Belmullet_Wave_Energy_Test_Site/Atlantic_Marine_Energy_Test_Site_AMETS_.html [Accessed January 29th, 2014].

Babarit A., Ben Ahmed H., Clément A. and Debusschere V. (2006). "Simulation of electricity supply of an Atlantic island by offshore wind turbines and wave energy converters associated with a medium scale local energy storage". Renewable Energy, Vol. 31, pp. 153-169.

CANDHIS. (2014). [Online]: www.candhis.cetmef.developpement-durable.gouv.fr [Accessed January 29th, 2014].

Commission Guidebook. (2014). "Renewables portfolio standard eligibility" [Online]: www.energy.ca.gov/2010publications/CEC-300-2010-007/CEC-300-2010-007-CMF.PDF [Accessed January 29th, 2014].

Fernández-Chozas J. (2013). "Technical and Non-technical Issues Towards the Commercialisation of Wave Energy Converters", Aalborg: PhD Thesis (DCE Thesis no. 44), Aalborg University.

FIT. (2014). [Online]: http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=CA167F [Accessed January 29th, 2014].

Fitzgerald J. and Bolund B. (2012). "Technology Readiness for Wave Energy Projects. ESB and Vattenfall classification system", in Proceedings of the 4th International Conference on Ocean Energy (ICOE). Dublin.

Frigaard P. and Kofoed J.P. (2004). "Hydraulic Response of the wave energy converter wave dragon in Nissum Bredning". Aalborg University Technical Report.

HMRC. (2003). "Ocean Energy: Development and Evaluation Protocol. Part 1: Wave Power". Cork, Ireland: HMRC: Hydraulic Maritime Research Centre.

Holmes B. (2010). "EquiMar: Engineering and Technical Overview", EquiMar workshop. Bilbao. [Available Online]: www.chrissmithonline.co.uk/files/engineering-overview.pdf [Accessed January 10th, 2013].

Humboldt Bay (2014). [Online]: en.openei.org/community/files/lcoe_reference_resource.xlsx [Accessed January 29th, 2014].

IEC/TS (2011). "Marine energy – Wave, tidal and other water current converters. Part1: Terminology". International Electrotechnical Commission, Technical Specification (IEC/TS) 62600-1.

Ingram D., Smith G., Bittencourt-Ferreira C. and Smith H. (2011). "Protocols for the Equitable Assessment of Marine Energy Converters". The University of Edinburgh on behalf of the EquiMar consortium.

Kofoed J.P. (2009). "Ressourceopgørelse for bølgekraft i Danmark". Report No.59 for the Clima Commission.

Kofoed J.P. and Frigaard P. (2009). "The Development of wave energy devices the Danish case". The Journal of Ocean Technology, Maritime and Port Security, Vol. 4 (2).

La Bonte A., O'Connor P., Fitzpatrick C., Hallett K. and Li Y. (2013). "Standardized cost and performance reporting for marine and hydrokinetic technologies". Proceedings of the 1st Marine Energy Technology Symposium, Washington D.C.

Margheritini L. (2012). "Review on available information on waves in the DanWEC area" Dep. Civil Engineering, Aalborg University.

Meyer N. I. and Rambøll. (2012). "Bølgekraftprogram - Afsluttende rapport fra Energistyrelsens Rådgivende Bølgekraftudvalg".

NASA Technology Readiness Level Definitions. (2013). [Online]: esto.nasa.gov/files/TRL_definitions.pdf [Accessed January 3rd, 2013].

Nielsen K. (1999). "Bølgekraft - forslag til forsøg og rapportering". Bølgekraftudvalgets secretariat. Danish Energy Agency.

Nielsen K. (2003). "Development of Recommended Practices for Testing and Evaluating Ocean Energy Systems". OES (Ocean Energy Systems), Annex II.

Nielsen K., Krogh J., Helstrup Jensen N., Kofoed J.P., Friis-Madsen E., Vang Mikkelsen B. and Jensen A. (2012). "Bølgekraftteknologi : strategi for forskning, udvikling og demonstration 2012". Partnership of Wave Energy, Aalborg University, DCE Technical Report 146.

Nielsen K. and Pontes T. (2010). "Generic and Site-related Wave Energy Data". Annex II. Task 1.1 International Energy Agency Ocean Energy Systems (IEA-OES).

O'Flynn B. (2013). "Securing Investors and Reaching Bankability: The Challenges Ahead". HMRC 4th Forum, Connecting Finance, Environment and Project Developers for Sustainable Projects in Ocean Energy, Ernst&Young Presentation, Cork.

Pecher A. (2012). "Performance evaluation of Wave Energy Converters". Aalborg: PhD Thesis (DCE Thesis no. 38), Aalborg University.

Previsic M. (2013). "Cost-reduction pathways for wave energy". OES Annual Report 2012.

Previsic M. (2014). "Reference Model 1: Cost Breakdown Structure for Tidal Current Device", [Available Online]: www.re-vision.net/documents/ReferenceModel1-CBS-V2-MP_10-26-12.xlsx [Accessed January 29th, 2014].

RAM. (2014). [Online]: www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=CA244F&re=1&ee=1 [Accessed January 29th, 2014].

Ramboll (1999). "Kortlægning af Bølgeenergiforhold i den Danske del af Nordsøen". Ramboll, Danish Hydraulic Institute, Danish Meteorological Institute.

Re-vision. (2014). [Online]: www.re-vision.net/projects.shtml [Accessed January 29th, 2014].

SEM-REV (2014). [Online]: www.semrev.fr/en/en-presentation [Accessed January 29th, 2014].

SI Ocean (2013a). "Cost of Energy and Cost Reduction Opportunities". SI Ocean Project.

SI Ocean (2013b). "SI Ocean Consultation Report, 27 February 2013, London". SI Ocean Project.

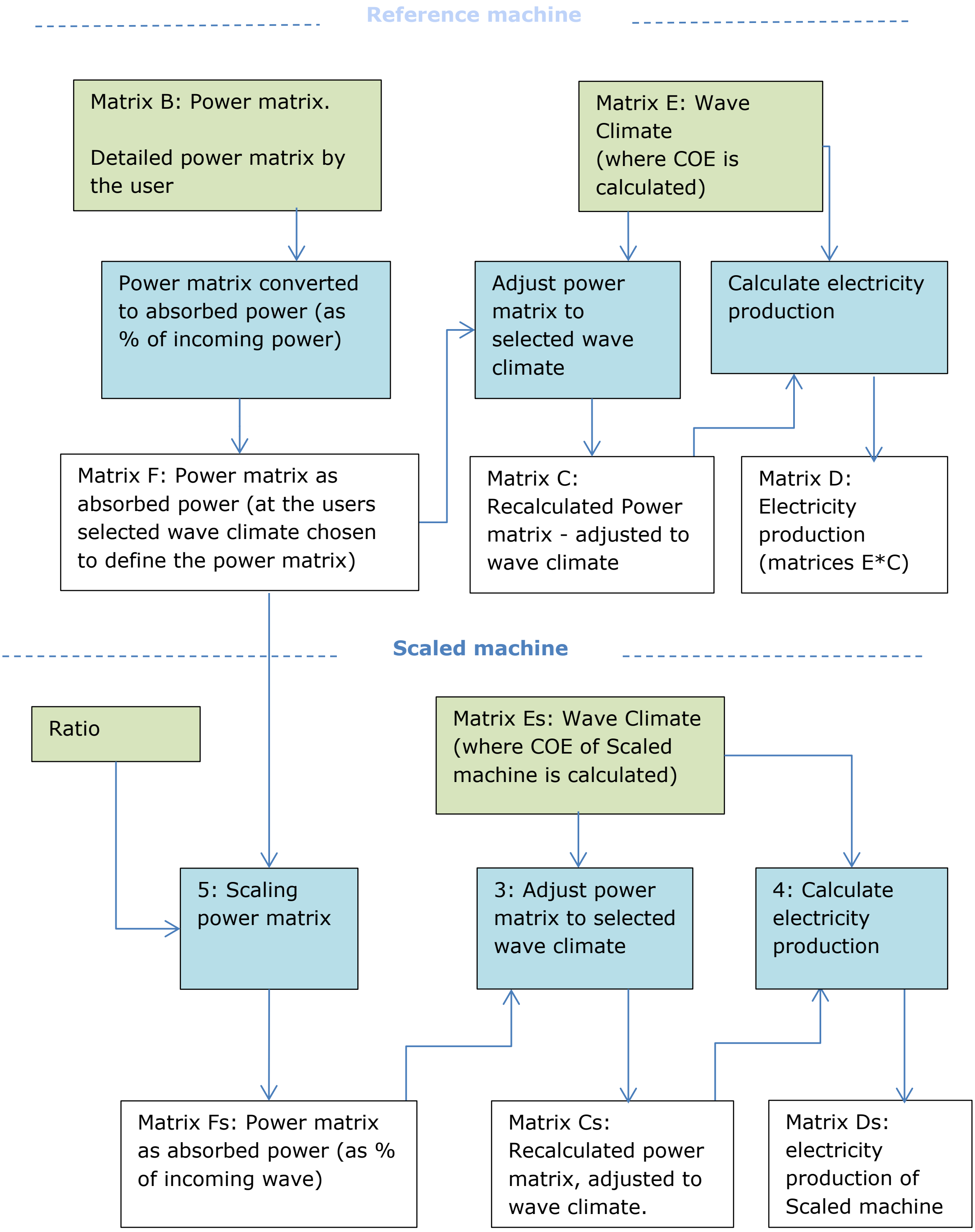
Soerensen H.C., Nielsen K., Steenstrup P., Friis-Madsen E. and Wigant L. (2005). “Bølgekraftanlæg ved Horns Rev – Screening (Wave energy deployment at Horns Rev Wind Farm)”. Copenhagen: PSO project 2004: 5705.

SOWFIA (2014). [Online]: www.sowfia.hidromod.com/PivotMapViewer/ [Accessed January 29th, 2014].

Torre-Enciso Y., Marqués J. and Marina D. (2012). “Mutriku-First year review”, in Proceedings of the 4th International Conference on Ocean Energy (ICOE). Dublin

West Wave (2014). “Appendix 2 Technology Readiness Levels for Supply Chain Study for West Wave”. [Available Online]: www.westwave.ie/wp-content/uploads/downloads/2011/12/Appendix-2.pdf [Accessed January 29th, 2014].

Annex A – Calculation steps for *power matrix*



Matrix F and matrix B are defined in the same intervals of H_{m0} and T_{02} (i.e. intervals that the user has chosen to define WEC's power matrix – matrix B).

Matrix E, matrix D and matrix C are defined in the same intervals of H_{m0} and T_{02} (i.e. intervals of the chosen wave climate by the user, where the COE is calculated).

Defining matrices intervals

For a given average value of H_{m0} or T_{02}, the following formulas are used to calculate the interval range (i.e. upper and lower value) which defines that average value:

From	To	Average Hs(m)
k	e	a
f	g	b
h	i	c
…	…	…
…	…	…
…	…	…

e: if[(b-a)=a; a+(b-a)/2; 2a-k]

f: f=e ,, h=g ,, …..

g, i, …: if [(b-c)=f; b+(c-b)/2; 2b-f]

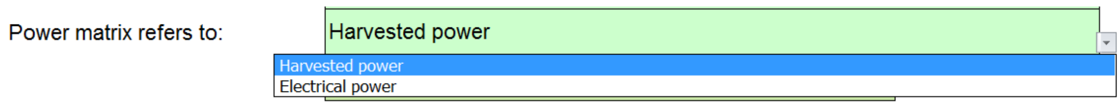
Power matrix (matrix B) converted to absorbed power (matrix F)

Matrix F shows the non-dimensional performance of the WEC (i.e. percentage of absorbed power with respect to incoming wave power):

$$Matrix\ F = \frac{Power\ production\ of\ each\ bin: power\ matrix}{Energy\ content\ in\ each\ bin}$$

The calculation to go from matrix B to matrix F depends on whether the power matrix has been defined as *absorbed power* or as *electrical power*.

If the power matrix refers to *absorbed power*:



Pabs (%) = Pprod (same as matrix B) / (0.577* H_{m0}^2 * T_{02} * Main Dimension)

$$Matrix\ F\ (Pabs_{\%}) = \frac{Power\ production\ (same\ as\ in\ power\ matrix\ B)}{0.577 * Hm0^2 * T02 * Main\ Active\ Dimension}$$

If the power matrix refers to *electrical power*: the absorbed power is calculated by dividing the electrical power by the efficiency of the PTO multiplied by the eff. of the generator:

$$Matrix\ F\ (Pabs_{\%}) = \frac{\dfrac{Power\ production\ as\ in\ power\ matrix\ B}{eff.PTO * eff.Gen.}}{0.577 * Hm0^2 * T02 * Main\ Active\ Dimension}$$

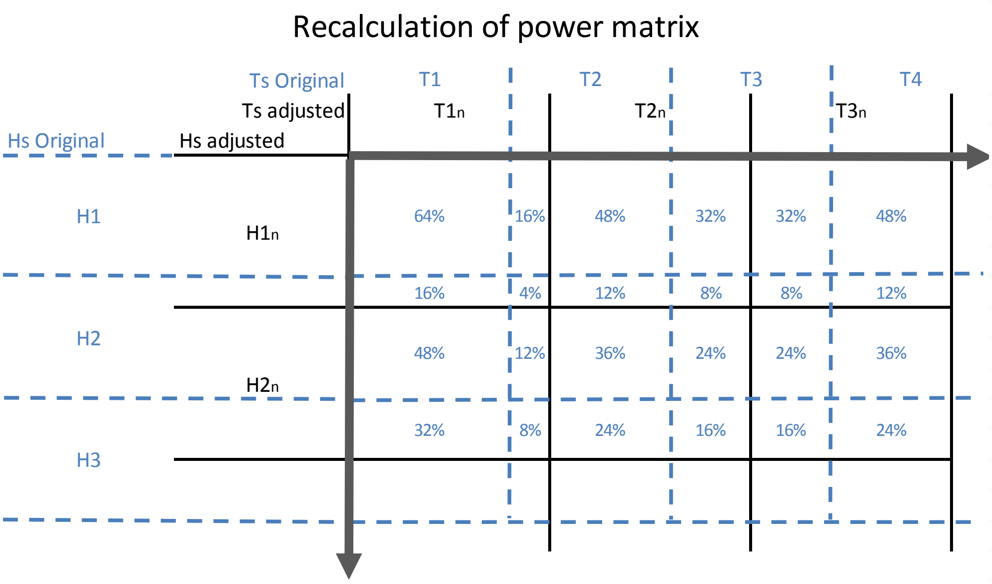
where H_{m0} and T_{02} are the average values of each cell.

Adjust power matrix to selected wave climate (from matrix F to matrix C)

To calculate WEC´s *annual electricity production*, the scatter diagram (defined in terms of H_{m0} and T_{02}) is multiplied by the power matrix (also defined in terms of H_{m0} and T_{02}).

Due to computational requirements, both matrices need to have the same resolution and be defined for the same intervals of H_{m0} and T_{02}.

The resolution of both matrices is the same (19 rows for H_{m0} and 17 columns for T_{02}) but the intervals might not be the same. In order to match the intervals, each of the bins of the power matrix is recalculated according to the intervals of the scatter diagram. The recalculation is done according to an interpolation (i.e. a weighted average calculation) between the closest upper bin values and the closest lower bin values:



Matrix C delivers a power matrix defined for the same intervals as the chosen wave climate.

Matrix C inserts an upper and lower limit for each cell (each sea state) based on the minimum and maximum operating conditions defined for the WEC.

To avoid that the power changes its intervals while being recalculated, the user shall enter the power matrix exactly in the same intervals of H_{m0} and T_{02} in which the chosen wave climate is defined.

Calculate annual electricity production

Annual electricity production is calculated by multiplying the recalculated power matrix (matrix C) by the scatter diagram of the selected location (matrix E).

This step is done in matrix D.

Scaling power matrix

Matrices corresponding to the scaled machine have their name followed by “s”.

The user shall include a scale for the *scaled machine*. This number is used to upscale or downscale matrix Fs based on the values of matrix F. Since matrix F and matrix Fs show WEC’s non-dimensional performance, the cells of matrix Fs and F are the same. Only the axis (i.e. intervals of H_{m0} and T_{02}) in which they are defined change.

Annex B – Standard sea states

STANDARDISED SEA STATES DESCRIBING ENERGY IN THE DANISH NORTH SEA – POINT 3 (KOFOED ET AL., 2009)

Sea states	**H_{m0}** (m)	**T_{02}** (s)	**T_p** (s)	**Energy flux** (kW/m)	**Prob. occurrence** (h/y)	**Prob. occurrence** (%)
1	1.0	4.0	5.6	2.1	4100	46.8
2	2.0	5.0	7.0	11.6	1980	22.6
3	3.0	6.0	8.4	32.0	946	10.8
4	4.0	7.0	9.8	65.6	447	5.1
5	5.0	8.0	11.2	114.0	210	2.4
6	6.0	9.0	12.6	187.0	93	1.2

STANDARDISED SEA STATES DESCRIBING ENERGY IN THE DANISH NORTH SEA – POINT 2

Sea states	**H_{m0}** (m)	**T_{02}** (s)	**T_p** (s)	**Energy flux** (kW/m)	**Prob. occurrence** (h/y)	**Prob. occurrence** (%)
1	1.0	4.0	5.6	2.1	4170	47.6
2	2.0	5.0	7.0	11.6	1875	21.4
3	3.0	6.0	8.4	32.0	841	9.6
4	4.0	7.0	9.8	65.6	360	4.1
5	5.0	8.0	11.2	114.0	114	1.3

STANDARDISED SEA STATES DESCRIBING ENERGY IN DENMARK HANSTHOLM (PECHER, 2012)

Sea states	**H_{m0}** (m)	**T_e** (s)	**T_{02}** (s)	**Energy flux** (kW/m)	**Prob. occurrence** (h/y)	**Prob. occurrence** (%)
1	1.01	4.93	4.26	2.49	2015	23
2	1.39	5.65	4.89	5.34	1927	22
3	1.91	6.37	5.51	11.45	1139	13
4	2.55	7.11	6.15	11.71	421	4.8
5	3.15	7.84	6.78	38.09	149	1.7

STANDARDISED SEA STATES DESCRIBING ENERGY IN DENMARK - HORNS REV I (SOERENSEN ET AL., 2005)

Sea states	**H_{m0}** (m)	**T_{02}** (s)	**T_p** (s)	**Energy flux** (kW/m)	**Prob. occurrence** (h/y)	**Prob. occurrence** (%)
1	0.5	1.8	2.8	0.3	1956	21.3
2	1.0	3.6	5.5	2.4	3000	34.2
3	1.5	4.4	6.2	6.0	1856	21.2
4	2.0	5.1	6.9	11.8	1126	12.9
5	2.5	5.7	7.6	20.2	575	6.6
6	3.0	6.3	8.3	31.8	285	3.3
7	3.5	6.9	9.0	46.9	51	0.6

*Note: sea state 7 of (Soerensen et al., 2005) is not included in the COE Calculation Tool

STANDARDISED SEA STATES DESCRIBING ENERGY IN EMEC, UK (PECHER, 2012)

Sea states	**H_{m0}** (m)	**T_{02}** (s)	**T_e** (s)	**Energy flux** (kW/m)	**Prob. occurrence** (h/y)	**Prob. occurrence** (%)
1	1.52	5.2	6.4	7.2	3942	45
2	1.72	6.8	8.3	11.9	1226	14
3	3.09	6.4	7.8	36.3	1226	14
4	3.66	7.7	9.4	61.4	964	11
5	5.18	8.3	10.1	133.4	350	4
6	5.69	9.6	11.7	186	88	1
7	7.43	10.1	12.3	332	88	1

*Note: sea state 7 of (Pecher, 2012) is not included in the COE Calculation Tool

ISSN 1901-726X
DCE Technical Report No. 161

JULIA F. CHOZAS
CONSULTING ENGINEER

ENERGINET.DK

DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY