LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable 8.3

LiftWEC LCOE Calculation Tool

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EXECUTIVE SUMMARY

The focus of Task 8.3 has been the refinement of the LiftWEC Levelised Cost of Energy (LCOE) Calculation Tool, incorporating a range of improvements including an updated database of costs developed under Task 8.1 and the parametric cost model developed under Task 8.2.

The LiftWEC LCOE Calculation Tool has been updated and refined including new features and improvements according to the project scope. These have been developed based on internal discussions within the LiftWEC Consortium. The refinements and their rationale will be detailed and described throughout this document.

The deliverable 8.3 encompasses two integrated elements:

- The User Guide of how to use LiftWEC Calculation Tool.
- The LiftWEC LCOE Calculation Tool, which is an open-access excel-spreadsheet, (available at https://liftwec.com/deliverables/).

Within the LiftWEC project and specifically in WP8, discussions have been held regularly to address the needs of the Tool to accurately and realistically evaluate the economic feasibility of the different LiftWEC configurations being proposed. An internal workshop was held to present the LCOE Tool to all LiftWEC project participants and collect feedback from the different WPs.

Overall, the scope of the LiftWEC LCOE Calculation Tool is to estimate the Cost of Energy of a specific LiftWEC concept based on its performance in a specified wave location and based on its costs.

The *unique* feature of the LiftWEC LCOE Tool is that it provides default values for different types of material or PTO costs, which allows comparable economic estimates to be drawn even at an early development stage (the LiftWEC project is advancing from TRL1 to TRL3/4).

One sheet of the Excel Tool considers a *Single WEC.* This is a first prototype to be i.e. installed at a test site (no electrical infrastructure is considered for example). Another sheet considers the *Wave Energy Farm* as a pre-commercial farm with an installed capacity in the range of 10 MW, i.e. composed by 5 to 20 WECs (as a very general estimate). Calculations of larger wave farms can then be estimated using Learning Curves.

The authors acknowledge that there is a large uncertainty in absolute terms and it is very challenging to provide a single unit cost as default value representative to all LiftWEC concepts. For example, a single value of 240.000 EUR for the installation of a floating configuration including mooring, umbilical cable and WEC deployment might be 50% inaccurate in some deployments. As a result, the Tool provides an error estimate, which again, shall also be considered as an estimate.

Project costs depend on several parameters intrinsic to the concept and its design characteristics. For example, the type of station keeping, the distance to shore, the water depth, the deployment location, the installation method, weather windows, the type of mooring, are all parameters which will highly influence project costs. By providing default values the authors have aimed at providing reasonable orders of magnitude which can help to draw first economic calculations. It is however expected that these default values are mainly used at low TRLs or first economic assessments, and that at higher TRLs, own expertise and

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knowledge will be used to overwrite the default values inserted in the Tool, which may be overwritten using input from other work packages when this information becomes available.

Abbreviations

AEP	Annual Energy Production
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
GPB	British Sterling
IEC	International Electrotechnical Commission
LCOE	Levelised Cost of Energy
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

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1 INTRODUCTION

1.1 SCOPE AND RATIONALE OF THE LIFTWEC LCOE CALCULATION TOOL

The LiftWEC LCOE Calculation Tool has been developed as a transparent and simple model that can evaluate LiftWECs concepts economic feasibility in a range of locations. It has been developed to ensure consistent and transparent calculation methods; and to provide a reference framework for performing LCOE analyses.

Deliverable 8.3 encompasses two elements:

- A User Guide describing how to use LiftWEC Calculation Tool.
- The LiftWEC LCOE Calculation Tool, implemented as an open-access Excel spreadsheet, available at https://liftwec.com/deliverables/.

The LiftWEC LCOE 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 absorption and conversion efficiencies, and unit costs.
- It is transparent: the understanding of calculation steps and results are explained.
- It focuses on energy production values instead of on installed power capacity.
- It can evaluate LiftWEC's LCOE in several different ocean locations.
- It allows transparent, documented and comparable LCOE calculations among the different LiftWEC concepts or alternatively between different iterations of the same LiftWEC configuration during its development.
- It further facilitates the development of LiftWEC as:
  - It allows the identification of the components or cost centres with highest impact on the cost of energy.
  - It can assist in describing the strategic LiftWEC roadmap targeting different markets, deployment rates and LCOE reductions.
  - It enhances transparency of claimed energy productions, and allows equitable comparison of the LiftWEC concept with other wave energy converters.

As mentioned above, the *unique* feature of the LiftWEC LCOE Tool is that it provides default values, which allows comparable economic estimates to be drawn even at an early development stage (the LiftWEC project is advancing from TRL1 to TRL3/4).

The LiftWEC LCOE Tool allows calculations for a single WEC and for a Wave Energy Farm. The Excel Tool assumes a *Single WEC as* a first prototype to be i.e. installed at a test site (no electrical infrastructure is considered for example). The Tool provides default values for this Single WEC. Another sheet considers the *Wave Energy Farm.* The default values provided in the calculation for the *Wave Energy Farm* are relevant for a pre-commercial or a first commercial farm with an installed capacity in the range of 10 MW, i.e. composed by 5 to 20 WECs (as a very general estimate). For example, the default values provided for the electrical

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interconnections are for 6 to 11 kV cables, and a 10% discount in costs from the *Single WEC* to the *Array* is assumed. This 10% reduction is reasonable for 10 to 20 WECs; however, for 100 WECs or more, much more reduction in costs is expected.

The LCOE estimation of large commercial arrays of 100 MW and 1 GW corresponding to the final LiftWEC objectives is very uncertain at this stage, in common with all wave farms. Such estimations require considerable efforts and detailing to provide a realistic result. Therefore, LCOE modelling of prospective test sites without extensive definition is therefore not warranted at this stage of the technology development (TRL3/4). Instead, work will be conducted to extrapolate the LCOE for a large array (100 MW, 1 GW) based on the data points obtained from the single and small array development projections covered by the LiftWEC LCOE Tool, and the use of appropriate learning curves. This work will be conducted after the selection of the final LiftWEC concept and under Task 8.6.

The authors acknowledge that it is very challenging and even not accurate to provide a single unit cost as default values representative to different configurations. For example, a single value of 240.000 EUR for a floating LiftWEC installation including mooring, umbilical cable and WEC deployment might be 50% inaccurate in some deployments.

Project costs depend on several parameters intrinsic to the nature of the WEC, its design considerations and of the specific project. For example, the type of WEC, the type of station keeping, the distance to shore, the water depth, the deployment location, the installation method, weather windows, the type of mooring, are all parameters which will highly influence project costs. These defaults values have been reviewed and updated according to the LiftWEC characteristics, see following sections. By providing default values the authors have aimed at providing reasonable orders of magnitude which can help to draw first economic calculations. It is however expected that these default values are mainly used at low TRLs or first economic assessments, and that at higher TRLs, or when relevant information is available from the other work packages, specific project costs will be used to overwrite the default values of the Tool.

As a result, it is worth mentioning that behind every calculation, there is an associated error. We have tried to provide an error estimate, which also may be uncertain.

Deliverable 8.4 of the LiftWEC Project, named “LCOE estimate of baseline configurations” will use the LiftWEC LCOE Tool to provide an economic assessment of the four baseline configurations (see LiftWEC Deliverables 2.8, (Folley and Lamont-Kane, 2022)). Two case studies will be drawn for each configuration: the device operating individually (single WEC) as well as in arrays (Wave Energy Farm). It is the aim that Del. 8.4 will detail the methodology and assumptions used, so it can eventually aid future users of the Tool by providing specific Case Studies.

1.2 Background

Consulting Engineer Julia F. Chozas together with Aalborg University and the Danish Transmission System Operator Energinet.dk, released in 2013 an open access online spreadsheet to evaluate the Levelised Cost of Energy for wave energy projects. The open-access tool was intended to calculate the LCOE based on the cost and annual energy production of a Wave Energy Converter (WEC) at a particular location; where power production data in specific sea states may derive from laboratory testing, numerical modelling or from sea trials.

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Since 2013 up to present time, the three documents concerning the LCOE Calculation Tool (the spreadsheet, the user guide and quick-star user guide) have been available at Aalborg University open library[1].

Many users around the world have used the Tool in its previous versions. Users mainly comprise the wave energy sector: academia (mainly PhD Students), technology developers, researchers, and also funding programmes like the Swedish Energy Agency – by recommending WEC developers using the LCOE Tool when applying for dedicated funding.

1.3 Updates in the LiftWEC LCOE Tool

Under the scope of the LiftWEC Project, the LiftWEC LCOE Calculation Tool has been refined and updated including new features and relevant improvements. These have been agreed by internal discussions within the LiftWEC Consortium and to some extent, through the feedback gathered from a wide range of users. Among other refinements, LiftWEC LCOE Calculation Tool incorporates an updated database of costs developed under Task 8.1 (Têtu and Fernandez Chozas, 2020) and the parametric cost model developed under Task 8.2 (Têtu and Fernandez Chozas, 2021). The LiftWEC LCOE Tool has been the main focus of Task 8.3.

Discussions have been held regularly within the LiftWEC project and specifically in WP8 to address the needs of the Tool to accurately evaluate the economic feasibility of the different LiftWEC configurations that are being proposed. An internal workshop was held in July 2021 to present the Calculation Tool to all LiftWEC project participants and collect feedback from the different WPs. The update ad refinement of the LiftWEC LCOE Tool has been done in parallel to the definition of LiftWEC Configurations.

The updated LiftWEC LCOE Tool, developed as part of Task 8.3., incorporates:

- Comprehensive updates on all default values and unit cost that the Tool provides both for the *Single WEC* and for the *Wave Energy Farm*. Specifically, for the LiftWEC project, estimates on costs of O&M and site lease and insurance will come from WP7 dealing entirely with Operation and Maintenance activities. When cost estimates are available, these will be updated accordingly in the Tool and in the user guide.
- A Scatter Diagram from the considered test-site in Brittany, west of France, has been included in the LCOE Tool to reflect the reference location for LiftWEC deployments. The wave data were obtained from the Homere database of the Ifremer, through the access provided by the ResourceCode project.
- Array cost assessment included in as a new sheet in excel tool, the *Wave Energy Farm*.
- Economic Assessment updated and modified for clarity.
- Performance Assessment included.
- Summary pages for the Single WEC and Wave Energy Farm have been included. These are in the form of a single A4 sheet, which can eventually be included in a report. Both summary pages allow adding an image (a picture) relevant to the Single WEC and the Wave Energy Farm being assessed.
- *WECs Annual Energy Production* can be input as a single value.

[1]https://vbn.aau.dk/en/publications/user-guide-coe-calculation-tool-for-wave-energy-converters-ver-16

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- New sheet which summarises all *LookUp Tables* used in the calculations. It makes the Tool more clear and easy to understand. All default values have been ordered, can be found on the same sheet and have their associated reference on the side.

1.4 General

The economic and performance assessment are based on the *Single WEC*, i.e. the reference machine. Input data of the *Single WEC* is divided in two main elements: *Main dimensions and Performances* (left-hand side of the Tool, Figure 1.5a), and *WEC costs (CAPEX and OPEX)* (right-hand side, Figure 1.5a). The *Single WEC* can be freely set.

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

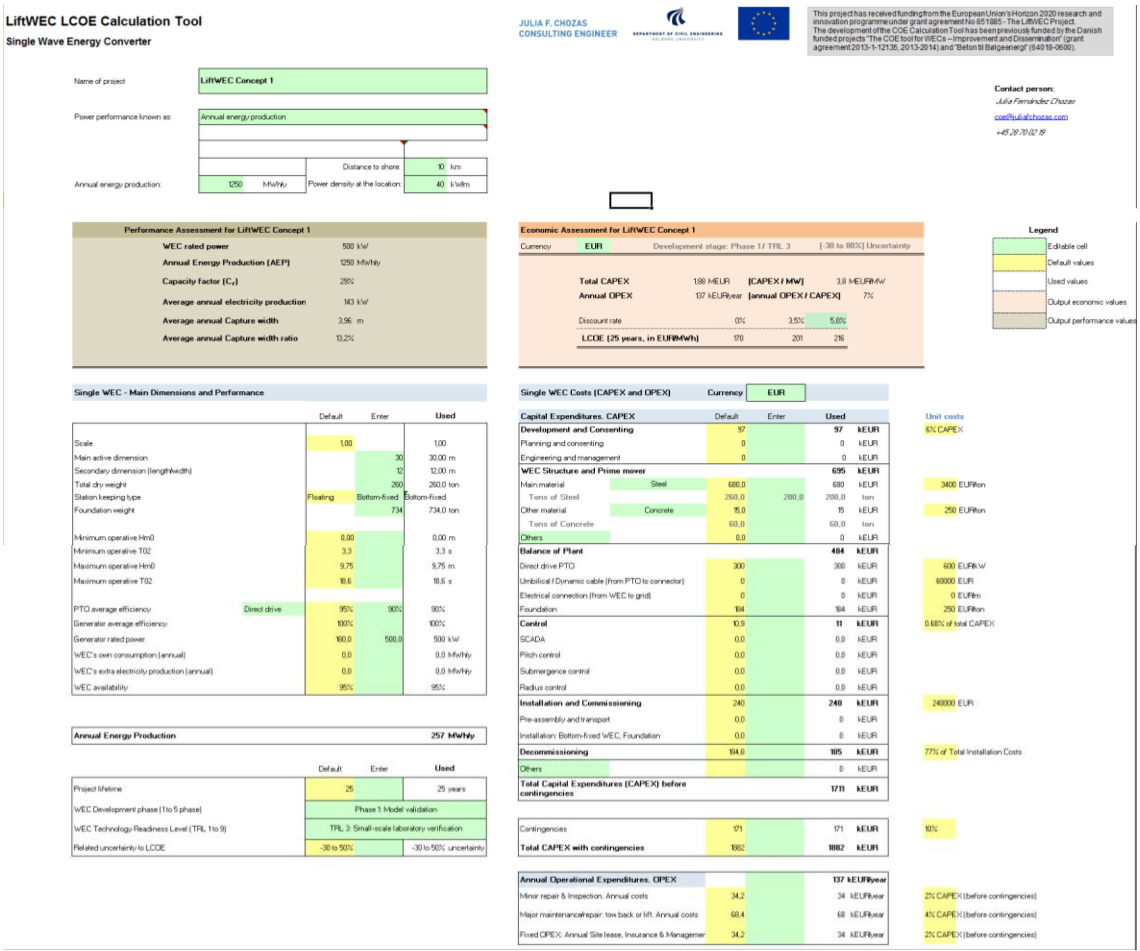

Figure 1.5a: Front-end of the LiftWEC LCOE Calculation Tool. Single WEC (numbers are fictional).

Based on the *Single WEC* the Tool gives the opportunity to calculate the costs associated to an array of WECs, a *Wave Energy Farm*.

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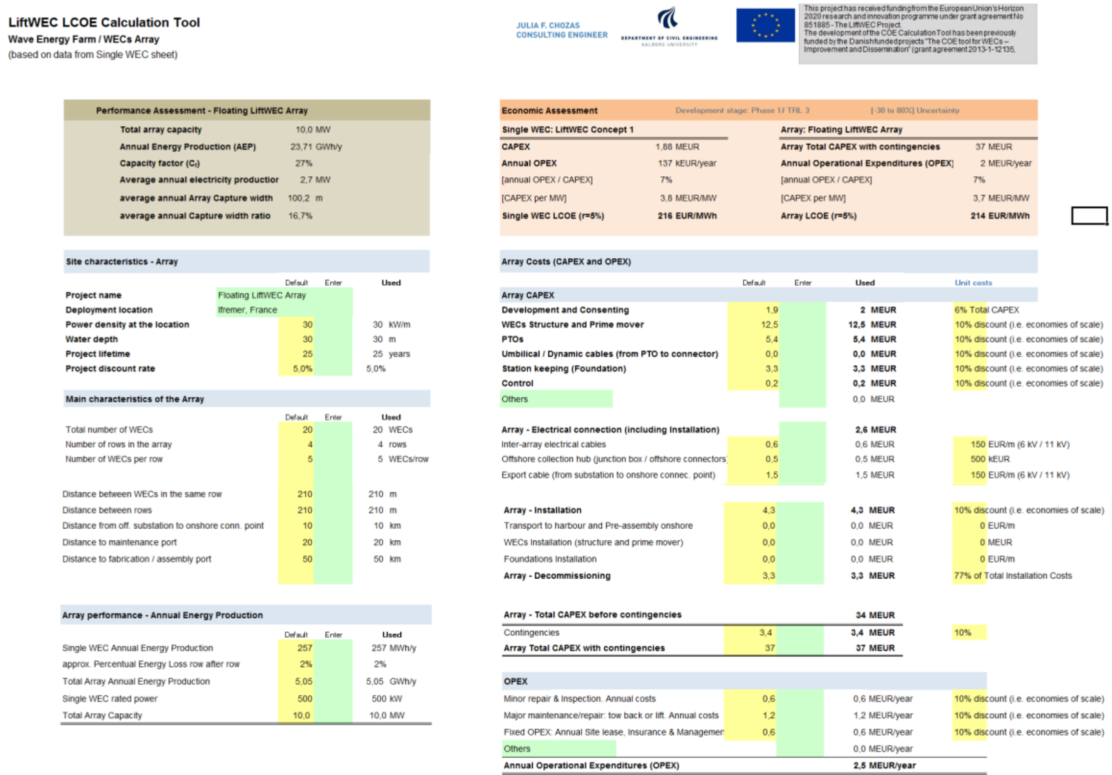
The spreadsheet is locked in order to protect the formulas and the Tool structure. The colour codes in the cells are as follows:

	Editable cells
	Default values, used if no other values are entered
	Used values
	Economic assessment (output of LiftWEC LCOE Tool)
	Performance assessment (output of LiftWEC LCOE Tool)

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

Input data to the *Wave Energy Farm* is also divided in two main elements: *Site Characteristics and Main characteristics of the Array* (on the left-hand side, Figure 1.5b), and *Array costs (CAPEX and OPEX)* (right-hand side, Figure 1.5b).



LiftWEC LCOE Calculation Tool
Wave Energy Farm / WECs Array
(based on data from Single WEC sheet)

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The development of the COE Calculation Tool has been previously funded by the Danish funded projects "The COE tool for WECs – Improvement and Dissemination" (grant agreement 2013-1-12135,

Performance Assessment - Floating LiftWEC Array	
Total array capacity	10,0 MW
Annual Energy Production (AEP)	23,71 GWh/y
Capacity factor (C_f)	27%
Average annual electricity productior	2,7 MW
average annual Array Capture width	100,2 m
average annual Capture width ratio	16,7%

Site characteristics - Array	Default	Enter	Used
Project name	Floating LiftWEC Array		
Deployment location	Ifremer, France		
Power density at the location	30		30 kW/m
Water depth	30		30 m
Project lifetime	25		25 years
Project discount rate	5,0%		5,0%

Main characteristics of the Array	Default	Enter	Used
Total number of WECs	20		20 WECs
Number of rows in the array	4		4 rows
Number of WECs per row	5		5 WECs/row
Distance between WECs in the same row	210		210 m
Distance between rows	210		210 m
Distance from off. substation to onshore conn. point	10		10 km
Distance to maintenance port	20		20 km
Distance to fabrication / assembly port	50		50 km

Array performance - Annual Energy Production	Default	Enter	Used
Single WEC Annual Energy Production	257		257 MWh/y
approx. Percentual Energy Loss row after row	2%		2%
Total Array Annual Energy Production	5,05		5,05 GWh/y
Single WEC rated power	500		500 kW
Total Array Capacity	10,0		10,0 MW

Economic Assessment	Development stage: Phase 1/ TRL 3	[-30 to 80%] Uncertainty	
Single WEC: LiftWEC Concept 1		Array: Floating LiftWEC Array	
CAPEX	1,88 MEUR	Array Total CAPEX with contingencies	37 MEUR
Annual OPEX	137 kEUR/year	Annual Operational Expenditures (OPEX)	2 MEUR/year
[annual OPEX / CAPEX]	7%	[annual OPEX / CAPEX]	7%
[CAPEX per MW]	3,8 MEUR/MW	[CAPEX per MW]	3,7 MEUR/MW
Single WEC LCOE (r=5%)	216 EUR/MWh	Array LCOE (r=5%)	214 EUR/MWh

Array Costs (CAPEX and OPEX)	Default	Enter	Used	Unit costs
Array CAPEX				
Development and Consenting	1,9		2 MEUR	6% Total CAPEX
WECs Structure and Prime mover	12,5		12,5 MEUR	10% discount (i.e. economies of scale)
PTOs	5,4		5,4 MEUR	10% discount (i.e. economies of scale)
Umbilical / Dynamic cables (from PTO to connector)	0,0		0,0 MEUR	10% discount (i.e. economies of scale)
Station keeping (Foundation)	3,3		3,3 MEUR	10% discount (i.e. economies of scale)
Control	0,2		0,2 MEUR	10% discount (i.e. economies of scale)
Others			0,0 MEUR	
Array - Electrical connection (including Installation)			2,6 MEUR	
Inter-array electrical cables	0,6		0,6 MEUR	150 EUR/m (6 kV / 11 kV)
Offshore collection hub (junction box / offshore connectors)	0,5		0,5 MEUR	500 kEUR
Export cable (from substation to onshore connec. point)	1,5		1,5 MEUR	150 EUR/m (6 kV / 11 kV)
Array - Installation	4,3		4,3 MEUR	10% discount (i.e. economies of scale)
Transport to harbour and Pre-assembly onshore	0,0		0,0 MEUR	0 EUR/m
WECs Installation (structure and prime mover)	0,0		0,0 MEUR	0 MEUR
Foundations Installation	0,0		0,0 MEUR	0 EUR/m
Array - Decommissioning	3,3		3,3 MEUR	77% of Total Installation Costs
Array - Total CAPEX before contingencies			34 MEUR	
Contingencies	3,4		3,4 MEUR	10%
Array Total CAPEX with contingencies	37		37 MEUR	
OPEX				
Minor repair & Inspection. Annual costs	0,6		0,6 MEUR/year	10% discount (i.e. economies of scale)
Major maintenance/repair: tow back or lift. Annual costs	1,2		1,2 MEUR/year	10% discount (i.e. economies of scale)
Fixed OPEX: Annual Site lease, Insurance & Managemen	0,6		0,6 MEUR/year	10% discount (i.e. economies of scale)
Others			0,0 MEUR/year	
Annual Operational Expenditures (OPEX)			2,5 MEUR/year	

Figure 1.5b: Front-end of the LiftWEC LCOE Calculation Tool for the Wave Energy Farm.

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2 SINGLE WEC

The spreadsheet is based on a *Single WEC* (a wave energy converter), which provides the core information for all calculations. This *Single WEC* can be freely set. Previously named as *Reference machine*, after internal discussions the new name has been found more appropriate.

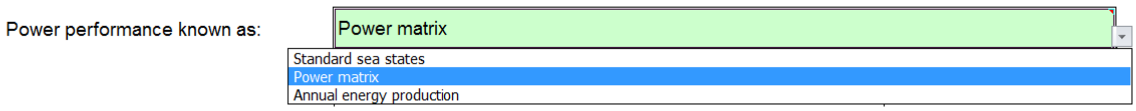
All input data such as dimensions, weight, minimum and maximum operative wave conditions, WEC rated power, conversion system efficiency, power production and costs must be based on the same Single *WEC*.

Basically, the *Single WEC* is the LiftWEC configuration that will be assessed.

2.1 POWER PERFORMANCE KNOWN AS…

Power production of the *Single WEC* can be specified in by selecting from the roll down menu one of three alternatives depending on the available data.

1. Providing the performance of the WEC in (typically 6) standard sea states.
2. Providing the performance in the form of a power matrix.
3. Introducing the Annual Energy Production (AEP) as a single value.



2.1.1 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, i.e. in the 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 and Frigaard, 2009), (Nielsen, 2003).

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’.

Wave absorption efficiency of the WEC in each sea state (according to the laboratory results) must be included.

(Hodges et al., 2021) have published a set of recommended regular and irregular sea states for controlled tank testing, which they encourage to use in addition to sea states required to satisfy the developers own test objectives.

The LiftWEC LCOE Tool allows for including the performance in up to six sea states. If a WEC only has performance values for some sea states, it should be set to 0 % for the sea state where data is not available.

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matrix A

Sea states							
Location	DK - Horns Rev						
Sea state	1	2	3	4	5	6	**Total**
Wave abs. eff (%)	48%	40%	31%	22%	15%	2%	
Absorbed power (kW)	4	29	56	79	91	19	
Electrical power (kW)	4	26	51	71	82	17	
Pwave (kW/m)	0,3	2,4	6	11,8	20,2	31,8	6
Hours (h/y)	1952	3000	1852	1122	574	284	8784
El. production (MWh/y)	7,5	78,2	93,8	79,9	47,0	4,9	**311**
El. production * Avail.	7,1	74,3	89,1	75,9	44,6	4,6	**296**
Hm0 (m)	0,5	1	1,5	2	2,5	3	
T02 (s)	1,8	3,6	4,4	5,1	5,7	6,3	
Incident energy along main active	17,6	216,0	333,4	397,2	347,8	270,9	

Figure 2.1.1: Matrix A including wave absorption efficiency for the relevant Standard Sea States where the performance of the WEC is known.

2.1.2 Power matrix

If *power matrix* is selected, the cells of Matrix B (coloured in green) must be filled in. These are 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 cell (sea state).

Power matrix

matrix B

kW		T02 (s)	3,3	4,1	5,0	5,8	6,7	7,5	8,4	9,1	10,0	10,8	11,7	12,5	13,4	14,6	15,4	16,6	17,4
Hm0 (m)			4,1	5,0	5,8	6,7	7,5	8,4	9,1	10,0	10,8	11,7	12,5	13,4	14,6	15,4	16,6	17,4	18,6
from	to		3,7	4,6	5,4	6,3	7,1	7,9	8,8	9,6	10,4	11,3	12,1	12,9	14,0	15,0	16,0	17,0	18,0
0,00	0,25	0,13	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
0,25	0,75	0,50	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	20,0	5,7		
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2,75	3,25	3,00	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	150,0	77,2		
3,25	3,75	3,50	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	175,0	82,8		
3,75	4,25	4,00	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	200,0	83,1		
4,25	4,75	4,50	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	300,0	100,0		
4,75	5,25	5,00	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	400,0	150,0		
5,25	5,75	5,50	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	160,0		
5,75	6,25	6,00	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	500,0	180,0		
6,25	6,75	6,50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
6,75	7,25	7,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
7,25	7,75	7,50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
7,75	8,25	8,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
8,25	8,75	8,50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
8,75	9,25	9,00																	

Figure 2.1.2: Power Matrix (matrix B) in the LiftWEC LCOE Calculation Tool. Units are kW. In steep waves, a value of 0 kW is typical.

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 (see Figure 2.1).

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.

2.1.3 Annual Energy Production (AEP)

A refinement to the Tool has been the introduction of the parameter Annual Energy Production, which allows inputting a single value which states the performance of the WEC. It is desired that the user will indicate at which location the AEP has been estimated, stating in addition the distance to shore and the mean power density (in kW/m) at the selected location.

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By selecting this option the LiftWEC LCOE Tool will directly use the AEP number (in MWh/y) to calculate the LCOE. It will not make use of the calculation steps involving the power matrices B, C, D, E nor F, thus bypassing them.

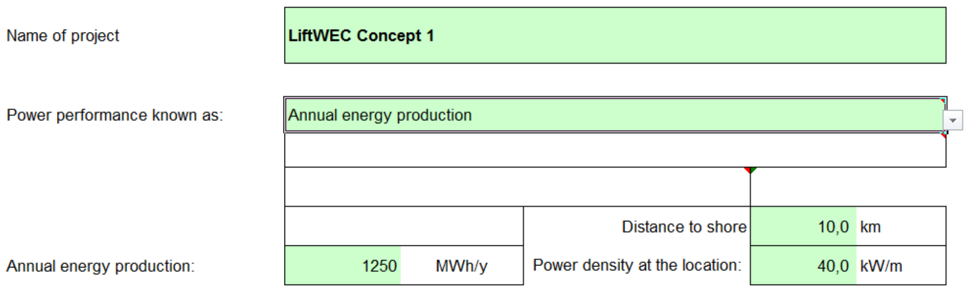

Figure 2.1.3: Selection of Annual Energy Production to indicate the Power Performance of the single WEC. This is provided as a single value.

2.2 Power matrix refers to

This option is only available when the power performance of the single WEC is provided in the form of a power matrix. Whether the power matrix corresponds to absorbed power or electrical power shall be indicated:

If *absorbed power* is selected, the Tool will assume a constant efficiency for the PTO (see section 2.3.3) 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 his owns (see Figure 2.1).

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2.3 Main Dimensions and Performance

Single WEC - Main Dimensions and Performance

		Default	Enter	Used
Scale		1,00		1,00
Main active dimension			30	30,00 m
Secondary dimension (length/width)			12	12,00 m
Total dry weight			260	260,0 ton
Station keeping type		Floating		Floating
Mooring weight			734	734,0 ton
Minimum operative Hm0		0,00		0,00 m
Minimum operative T02		3,3		3,3 s
Maximum operative Hm0		9,50		9,50 m
Maximum operative T02		18,6		18,6 s
PTO average efficiency	Direct drive	95%	90%	90%
Generator average efficiency		100%		100%
Generator rated power		162,0	500,0	500 kW
WEC's own consumption (annual)		0,0		0,0 MWh/y
WEC's extra electricity production (annual)		0,0		0,0 MWh/y
WEC availability		95%		95%

Figure 2.3: Single WEC - Main Dimensions and Performances of the LiftWEC LCOE Calculation Tool.

2.3.1 Main dimensions and weight

The main active dimension is used to calculate 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). For LiftWEC configurations this dimension corresponds to the length of the hydrofoil.

The secondary dimension corresponds to the other main dimension of the WEC in the same plane, i.e. length or width. In the *Single WEC*, this is only an informative parameter. It is used in the calculations for the *Wave Energy Farm* to calculate the default value for distance between WECs and rows.

The user shall also include the total dry weight of the single WEC (in tons) and the type of station keeping (to choose between ***floating WEC*** or ***bottom-fixed WEC***). This is relevant for the costs of the moorings (for a floating WEC) or the costs of foundations (when bottom-fixed is chosen).

2.3.2 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}.

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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.

2.3.3 Energy conversion efficiencies: PTO and generator efficiency

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

Table 2.3.3. PTO Efficiencies (Nielsen, 2003)

Type of PTO	Default PTO efficiencies (%)
Hydraulic	65%
Water turbines	85%
Air turbines	55%
Mechanical	90%
Direct drive	95%

PTO efficiency refers to the efficiency of the PTO (the power take-off system) including the generator. Generator efficiency has a default value of 100%.

The efficiencies only apply when the AEP is obtained from a power matrix specified in terms of absorbed power, see Sections 2.1.2 and 2.2.

2.3.4 Generator rated power

The user can include the rated power of the generator, otherwise a default value is used.

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

If *Power performance is known* as *Standard sea states,* the default value for the generator rated power is the following:

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

If *Power performance is known* as *Power matrix*, the *generator rated power* is taken into account in the calculation of power matrix C based on matrix F (detailed in Sections 10. 2 and 10.3).

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)

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

2.3.5 Annual Energy 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 95% (Fernandez Chozas *et al.*, 2015) which tries to represent that as much maintenance as possible 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, the control, 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 parameter allows the input of extra electricity generation due to co-location of renewable generation in the same structure. Accordingly, 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. For example, production from wind turbines or floating solar panels located on the same wave structure.

The value should indicate annual electricity production (in MWh/y).

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 Energy Production of the WEC is calculated by the following formula:

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

2.3.6 Project lifetime

The default value is set to 25 years (Fernandez Chozas *et al.*, 2015).

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

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2.4 SINGLE WEC COSTS (CAPEX AND OPEX)

LiftWEC LCOE Tool includes default unit cost values for all cost centres. Single WEC Costs have been divided into Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). Deliverable 8.1 of the LiftWEC Project "Cost Database" compiled all relevant costs related to a wave energy project in a cost database (Têtu and Fernandez Chozas, 2020). The main cost centres related to a wave energy project that form CAPEX and OPEX have been updated in the Tool.

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 chosen site of deployment.

It is, however, recommended that these default values are only used on projects at a very early development stage. Above a certain development stage (i.e. TRL 3-4), the user must justify and insert own cost values.

The yellow cells on the left-hand side of the costs table under column "Default" show the calculated default values, which are based on the structural weight, rated power and mooring weight input data from the *Single WEC Main Dimensions and performance (Figure 3.3)* as well as on the unit costs shown on the right-hand side of the costs table under "Unit Costs".

Single WEC Costs (CAPEX and OPEX) **Currency** **EUR**

		Default	Enter	Used			
Capital Expenditures. CAPEX						**Unit costs**	
Development and Consenting		98		**80**	**kEUR**	6% CAPEX	
Planning and consenting		0	50	50	kEUR		
Engineering and management		0	30	30	kEUR		
WEC Structure and Prime mover				**695**	**kEUR**		
Main material	Steel	680,0		680	kEUR	3400	EUR/ton
Tons of Steel		260,0	200,0	200,0	ton		
Other material	Concrete	15,0		15	kEUR	250	EUR/ton
Tons of Concrete		60,0		60,0	ton		
Others		0,0		0	kEUR		
Balance of Plant				**580**	**kEUR**		
Direct drive PTO		300		300	kEUR	600	EUR/kW
Umbilical / Dynamic cable (from PTO to connector)		60		60	kEUR	60000	EUR
Electrical connection (from WEC to grid)		0		0	kEUR	0	EUR/m
Mooring system		220		220	kEUR	300	EUR/ton
Control		11,1		**11**	**kEUR**	0.68% of total CAPEX	
SCADA		0,0		0,0	kEUR		
Pitch control		0,0		0,0	kEUR		
Submergence control		0,0		0,0	kEUR		
Radius control		0,0		0,0	kEUR		

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Installation and Commissioning	240		**240**	**kEUR**	240000 EUR
Pre-assembly and transport	0,0		0	kEUR	
Installation: Bottom-fixed WEC, Foundation	0,0		0	kEUR	
Decommissioning	184,8		**185**	**kEUR**	77% of Total Installation Costs
Others			0	kEUR	
Total Capital Expenditures (CAPEX) before contingencies			**1711**	**kEUR**	
Contingencies	171		171	**kEUR**	10%
Total CAPEX with contingencies	1882		**1882**	**kEUR**	
Annual Operational Expenditures. OPEX			**137**	**kEUR/year**	
Minor repair & Inspection. Annual costs	34,2		34	kEUR/year	2% CAPEX (before contingencies)
Major maintenance/repair: tow back or lift. Annual costs	68,4		68	kEUR/year	4% CAPEX (before contingencies)
Fixed OPEX: Annual Site lease, Insurance & Management	34,2		34	kEUR/year	2% CAPEX (before contingencies)

Figure 2.4: Costs assessment table of the LiftWEC LCOE Tool for the Single WEC including Capital Expenditures (CAPEX) – divided per cost centre: Development and Consenting, WEC Structure and Prime Mover, Balance of Plant, Control, Installation and Commissioning, and Decommissioning – and Operational Expenditures (OPEX).

2.4.1 Capital Expenditures or CAPEX

Capital Expenditure (CAPEX) is all expenditure associated with a wave energy converter development, deployment and commissioning until the operation of the WEC starts. It also includes decommissioning at the end of the project life. Cost centres in CAPEX are the following:

1. Development and Consenting
2. WEC Structure and Prime Mover
3. Balance of Plant
4. Control
5. Installation and Commissioning
6. Decommissioning

2.4.1.1 Development and Consenting

It includes all costs related to the planning and consenting, and the engineering and management. The Tool allows the user to input the values in these two categories. Since literature shows that they can typically be estimated as a fixed percentage of CAPEX (Têtu and Fernandez Chozas, 2020), the default value assumed by the Tool is 6% of CAPEX, and is calculated as 6% of the sum of the costs of the WEC Structure and Prime Mover, Balance of Plant, Control, Installation and Commissioning, and Decommissioning.

If fixed values are chosen as in the example below (Figure 2.4.1.), where 50 kEUR are used for *Planning and consenting* and 30 kEUR for *Engineering and management* – the default value of 6% of total CAPEX, accounting for 110 kEUR and shown in the yellow field, is overwritten by the specified 80 kEUR used.

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	Default	Enter	Used			Unit costs
Capital Expenditures. CAPEX						
Development and Consenting	110		80	kEUR		6% CAPEX
Planning and consenting	0	50	50	kEUR		
Engineering and management	0	30	30	kEUR		

Figure 2.4.1.1: Single WEC, Capital Expenditures (CAPEX). Development and Consenting.

2.4.1.2 WEC Structure and Prime Mover

These costs depend on the materials selected.

The user can select between four types of materials in a drop-down menu under *main material* and *other material*.

Each material (concrete, ballast concrete, steel and glass fibre) has the following cost per ton (in EUR/ton) associated.

Table 2.4.1.2. Material Costs, in EUR/ton (Nielsen, 2003), (Meyer et al., 2002) (Nielsen and Friis-Madsen, 2020).

Material	Unit cost (EUR/ton)
Concrete	250
Ballast concrete	70
Steel	3.400
Glass fibre	9.500

If "Steel" is chosen as *main material,* the default unit cost for steel 3400 EUR/ton appears to the right in the yellow cell. The actual weight of steel (in this case 200 ton) is to be entered under "Enter" and the remaining structural weight will then be calculated and shown under *Other material*. In this example this value, corresponding to tons of concrete, is 60, because the structural weight indicated under the main dimensions is 260 ton.

		Default	Enter	Used		Unit costs
Capital Expenditures. CAPEX						
WEC Structure and Prime mover				695	kEUR	
Main material	Steel	680,0		680	kEUR	3400 EUR/ton
Tons of Steel		260,0	200,0	200,0	ton	
Other material	Concrete	15,0		15	kEUR	250 EUR/ton
Tons of Concrete		60,0		60,0	ton	
Others		0,0		0	kEUR	

Figure 2.4.1.2: Capital Expenditures (CAPEX). WEC Structure and Prime mover.

2.4.1.3 Balance of Plant

This cost centre includes the costs of the PTO, the umbilical or dynamic cable (from PTO to connector), the electrical connection (from WEC to grid) and the station keeping (either the mooring or the foundation).

<u>PTO Costs</u>

The default unit cost values of the different types of PTO systems (including the cost of turbines, hydraulic motors, hydraulic pumps, gearboxes tooth racks or other types of direct mechanical actuators including the generator) are shown in Table 3.4.1.3.

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Table 2.4.1.3: Unit cost for the different types of PTO (Ricci et al., 2012), including PTO efficiencies (from Table 3.3.4).

Type of PTO	Efficiency (%)	Unit cost (EUR/kW)
Hydraulic	65%	800
Water turbines	85%	700
Air turbines	55%	1.000
Mechanical drive	90%	1.400
Direct drive	95%	600

The user must select the type of PTO (see *Section 3.3.4*). The Tool then multiplies the unit cost of the selected type of PTO with the final value of the *generator rated power*. In this example *generator rated power* has a value of 500 kW, which is multiplied by the unit cost of 600 EUR/kW for a *direct drive PTO* type, providing a default value of 300 kEUR.

Capital Expenditures. CAPEX	Default	Enter	Used		Unit costs	
Balance of Plant			**580**	**kEUR**		
Direct drive PTO	300		300	kEUR	600	EUR/kW
Umbilical / Dynamic cable (from PTO to connector)	60		60	kEUR	60000	EUR
Electrical connection (from WEC to grid)	0		0	kEUR	0	EUR/m
Mooring system	220		220	kEUR	300	EUR/ton

Figure 2.4.1.3: Capital Expenditures (CAPEX). Balance of Plant.

<u>Umbilical / Dynamic cable (from PTO to connector)</u>

Umbilical and dynamic cables costs depend on power, voltage level, cable length, etc.

This parameter is relevant when the WEC is floating (as in the example in Figure 3.4.1.3). Default value is zero when the WEC station keeping is a foundation. For floating WECs, the unit costs for umbilical cables is proposed as 60.000 EUR according to (Flannery, 2020).

The average unit cost published by Bimep (2018) for umbilical cables based on their expertise is of 70 EUR/m, which depends on the length of the umbilical cable.

A unit cost of 25 EUR/meter*MW, which combines the rated power and the length of the umbilical, has also been suggested.

<u>Electrical connection (from WEC to grid)</u>

The cost of the electrical connection also depends on power, voltage, length, etc.

It is expected that a single WEC will make use of any of the existing test sites and electrical connections available around the world (especially in Europe). This is the reason why the default value for the electrical connection of the *Single WEC* in the Tool is set to 0.

If the user would like to include the cost of the electrical connection (from WEC to onshore grid), Têtu and Fernandez Chozas (2020) provide a review of these costs. Section 4.4.1 also reviews the costs for electrical connections.

<u>Mooring system or foundation</u>

Depending on the user's selection on the station keeping type (*floating* or *bottom-fixed*), the costs table will be updated with estimates on mooring costs or foundation costs, respectively.

Mooring costs depend on the number, length of mooring cables, maximum load, anchor type and weight. In the Tool they are based on a unit cost of 300 EUR/ton (Nielsen and Friis-

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Madsen, 2020). The default value is calculated by multiplying the unit cost (300 EUR/ton) by the *mooring weight* (in tons) indicated by the user. In the example (Table 3.4.1.3) the default value is calculated by multiplying the mooring weight (734 ton) by the unit cost value, resulting into a default value of 220 kEUR.

Foundation costs are highly dependent on the type of foundation and the amount of material used. The assumption made in the Tool is that foundations are made of concrete; hence a unit price of 250 EUR/ton is used. Similarly as for the mooring costs, the default value for the foundation costs is calculated by multiplying the unit cost (250 EUR/ton) by the *foundation weight* (in tons) indicated by the user.

This cost centre does not include the cost of installation.

2.4.1.4 Control

The Tool divides the total Control system of a WEC into 4 different types of control: SCADA, Pitch Control, Submergence Control and Radius Control. The default unit cost for Control is estimated as 0.68% of total CAPEX (Wave Energy Scotland, 2016).

Capital Expenditures. CAPEX	Default	Enter	Used		Unit costs
Control	11,1		**11**	**kEUR**	0.68% of total CAPEX
SCADA	0,0		0,0	kEUR	
Pitch control	0,0		0,0	kEUR	
Submergence control	0,0		0,0	kEUR	
Radius control	0,0		0,0	kEUR	

Figure 2.4.1.4: Capital Expenditures (CAPEX). Control.

2.4.1.5 Installation and Commissioning

Capital Expenditures. CAPEX	Default	Enter	Used		Unit costs
Installation and Commissioning	240		**240**	**kEUR**	240000 EUR
Pre-assembly and transport	0,0		0	kEUR	
Installation: Floating WEC, Mooring, Umbilical cable	0,0		0	kEUR	
Decommissioning	184,8		**185**	**kEUR**	77% of Total Installation Costs

Figure 2.4.1.5.a: Cost assessment for a Floating-type, Single WEC, Installation, Commissioning, and Decommissioning.

The LiftWEC LCOE Calculation Tool divides the Installation and Commissioning costs into two categories:

1. *Pre-assembly and transport* of the WEC to site, and
2. *Installation on site*, which will be displayed differently depending on the station keeping type (floating or bottom-fixed).
    a. If it is a floating WEC, the Installation will read *Installation: Floating WEC, Mooring and Umbilical Cable* (Figure 3.4.1.5.a).
    b. If it is a bottom-fixed WEC, the Installation will read *Installation: bottom-fixed WEC, Foundation* (Figure 3.4.1.5.b).

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This cost centre is also very project specific. It depends on the vessels and time needed for the installation of the specific WEC, the daily tariffs, mobilisation and demobilisation costs, weather window, and waiting time for suitable weather window.

The default cost for *Total Installation and Commissioning* in the Tool is set at 240.000 EUR (Bimep, 2018). It is assumed independent of the type of WEC (floating or bottom-fixed) and is based on following considerations:

- Mooring Installation (in total 100.000 EUR).
    - Cost of an anchor handling vessel: 10.000 EUR/day
    - 4 days for installation, plus mobilization/demobilization and waiting on weather days: 10 days
- Umbilical cable (in total 120.000 EUR):
    - Umbilical cable installation with DP1vessel, 10.000 EUR/day; 2days
    - Specialist team to assemble the connector to the umbilical cable and to assemble the connectors between them can cost around 80.000 EUR (mobilisation, demob, 3-4 days, 7 people and equipment).
    - Insurance: 20.000 EUR
- Towing and connecting the device (in total 20.000 EUR):
    - A towing vessel, 7.500 EUR/day, 2 days can be enough.
    - Diving work required for operations or supervision, 2.500 EUR/day, 2 days.

The default cost for the installation of a *bottom-fixed WEC* (figure below) is also assumed to be 240.000 EUR. It is acknowledged that installing a bottom-fixed type of WEC may require different types of installation vessel but as a first guess the default value is assumed the same as floating.

Capital Expenditures. CAPEX	Default	Enter	Used		Unit costs
Installation and Commissioning	240		**240**	**kEUR**	240000 EUR
Pre-assembly and transport	0,0		0	kEUR	
Installation: Bottom-fixed WEC, Foundation	0,0		0	kEUR	
Decommissioning	184,8		**185**	**kEUR**	77% of Total Installation Costs

Figure 2.4.1.5.b: Cost assessment for a bottom-fixed type, Single WEC, Installation, Commissioning, and Decommissioning.

It is important to note that many types of installation vessels exist, which vary greatly on capabilities and daily rates. As a guideline, approximate vessel daily rates, depending on the type of vessel, are provided below (Flannery, 2020a):

- Crew transfer = 1.200 EUR/day
- Multicat = 2.000 EUR/day
- 50-ton Tug = 8.000 EUR/day
- 70-ton Tug = 12.000 EUR/day
- Small Construction Vessel (OCV 250) = 35.000 EUR/day
- Large Construction Vessel (OCV 400 like the Viking Neptune) = 95.000 EUR/day

The user shall note that for the Single WEC, no specific electric export cable installation is considered.

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2.4.1.6 Decommissioning

Decommissioning costs include all cost related to the removal of the WEC, the foundation or mooring system and the electrical cables according to the legally binding contract (Têtu and Fernandez Chozas, 2020). Even though decommissioning happens at the end of the project, it is often required that the decommissioning costs are secured at the beginning of the project. It is therefore included in the discounted costs (Têtu and Fernandez Chozas, 2021).

The default value for decommissioning is calculated as 77% of the total *Installation and Commissioning* costs (OPERA, 2019). In the example above (Figure 3.4.1.5.b) this corresponds to 192.5 kEUR, which is the multiplication of 250 kEUR by 0.77.

2.4.1.7 Contingencies

To account for the unknown and based on the experience of the test site bimep (Bimep, 2018), which states that "Underestimation of costs is a main risk when it comes to real sea testing", 10% is the default value allocated to contingencies. Total CAPEX are provided before contingencies and after contingencies.

	Default	Enter	Used			Unit costs
Capital Expenditures. CAPEX						
Total Capital Expenditures (CAPEX) before contingencies			**1711**	**kEUR**		
Contingencies	171		171	**kEUR**		10%
Total CAPEX with contingencies	1882		**1882**	**kEUR**		

Figure 2.4.1.7: Single WEC. Capital Expenditures (CAPEX). Contingencies.

2.4.2 Operational Expenditures or OPEX

OPEX is all expenditure associated with the operation of a WEC for the moment a takeover certificate is issued. When data is scarce, annual OPEX can be estimated as a percentage of CAPEX (in units of costs per year). As shown in literature, estimates of total OPEX per year roughly range from 2% to 10% of CAPEX (Têtu and Fernandez Chozas, 2020).

Whereas CAPEX are mostly incurred at the beginning of a project (or in years -3, -2 and -1 previous to start of operation),OPEX are distributed throughout the project lifetime.

	Default	Enter	Used		
Annual Operational Expenditures. OPEX			**137**	**kEUR/year**	
Minor repair & Inspection. Annual costs	34,2		34	kEUR/year	2% CAPEX (before contingencies)
Major maintenance/repair: tow back or lift. Annual costs	68,4		68	kEUR/year	4% CAPEX (before contingencies)
Fixed OPEX: Annual Site lease, Insurance & Management	34,2		34	kEUR/year	2% CAPEX (before contingencies)

Figure 2.4.2.: Single WEC Operational Expenditures (OPEX).

The Tool classifies Annual Operational Expenditures or OPEX into three categories:

- **Minor repair and Inspection**, with a default value of 2% of CAPEX before contingencies.
- **Major maintenance / repair. Tow back or lift. Annual costs**: with a default value of 4% of CAPEX before contingencies.
- **Fixed OPEX: Annual Site lease, Insurance & Management costs**, with a default value of 2% of CAPEX before contingencies.

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As a guideline, the following figures from the offshore wind sector (COWI, 2021) are provided:

Small Commercial Vessel (SCV) has about nine technicians onboard suitable for an operation radius up to 100 km with a speed of 37 km/hour (20 knob) in sea conditions less than Hs = 2.5m. Depending on size, the daily cost is estimated between 1.500 to 2.300 EUR/day; and the cost on a yearly basis in the range 300 to 750 kEUR/year.

Service Operation Vessels (SOV) are significantly larger compared to SCVs including 305 m^2 deck and a crew of 40-60 technicians. Although more expensive, they are equipped with a hydraulic landing that is stabilized at 6 degrees of freedom so technicians can move safely from vessel to wind turbine, enabling maintenance at up to Hs=3.0m. The cost of these ships is estimated at 12.000 kEUR/year.

The Corewind Project estimates the costs for the site lease as a one-time fee of 0.2 EUR/m^2. Other site lease costs are provided in (Tëtu and Fernandez Chozas, 2020).

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3 Wave Energy Farm – Wave Arrays

A new sheet has been added into the LiftWEC LCOE Tool, named *Wave Energy Farm*, which allows carrying out a cost and performance assessment of a wave energy farm composed by several WECs.

Most of the inputs for the calculations are taken from the *Single WEC* sheet, except from few specific inputs that must be entered. Therefore, baseline information of the *Wave Energy Farm* is based on the *Single WEC* main dimensions, performance and cost estimates.

The sketch in the following figure exemplifies the farm layout assumed for all calculations, the type of electrical cables (inter-array cables connecting the WECs in the farm and export cable connecting the offshore substation to the onshore connection point).

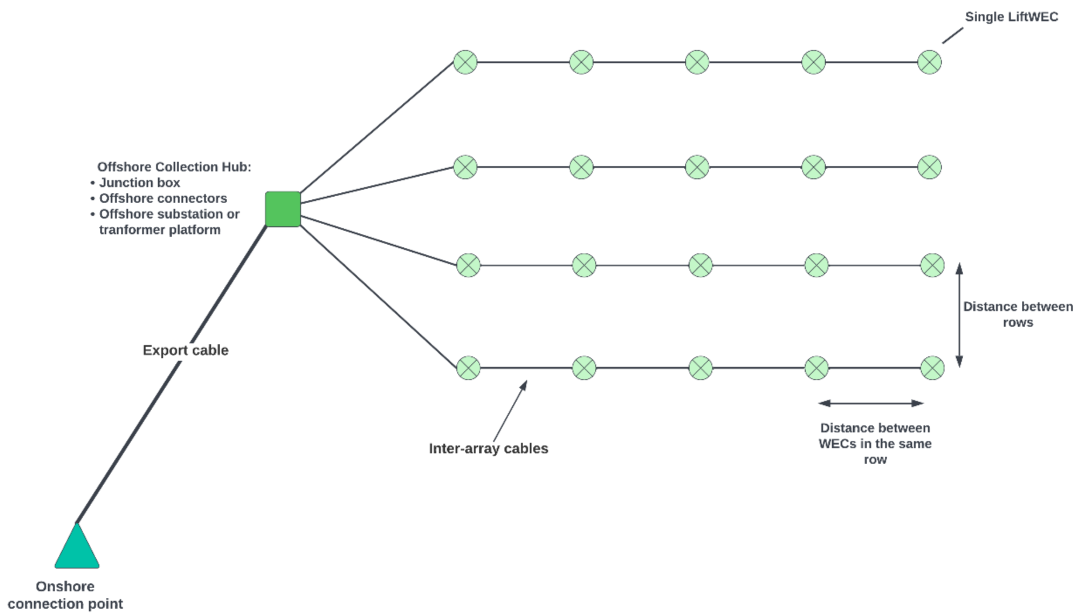

Figure 3: Assumed power transmission layout for a wave energy farm of 20 LiftWECs.

3.1 Site characteristics of the Array

The Tool takes all default values from the *Single WEC* sheet. The user must include the following information (green cells in Figure 4.1):

- *Project name*
- *Deployment location*
- *Power density at the deployment location (in kW/m)*
- *Water depth (in meters)* – this parameter is only illustrative. It is not used in the Tool.
- *Project lifetime (in years)* – it is used to calculate the discounted values relevant for the LCOE calculation.
- *Project discount rate (in %)* – it is used to calculate the discounted values relevant for the LCOE calculation.

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Site characteristics - Array	Default	Enter	Used	
Project name	Floating LiftWEC Array			
Deployment location	Ifremer, France			
Power density at the location	30		30	kW/m
Water depth	30		30	m
Project lifetime	25		25	years
Project discount rate	5%		5%	

Main characteristics of the Array	Default	Enter	Used	
Total number of WECs	20		20	WECs
Number of rows in the array	4		4	rows
Number of WECs per row	5		5	WECs/row
Distance between WECs in the same row	210		210	m
Distance between rows	210		210	m
Distance from off. substation to onshore conn. point	10		10	km
Distance to maintenance port	20		20	km
Distance to fabrication / assembly port	50		50	km

Array performance - Annual Energy Production	Default	Enter	Used	
Single WEC Annual Electricity Production	215		215	MWh/y
approx. Percentual Energy Loss row after row	2%		2%	
Total Array Annual Energy Production	4,23		4,23	GWh/y
Single WEC rated power	500		500	kW
Total Array Capacity	10,0		10,0	MW

Figure 3.1: Site characteristics and Main characteristics of the Array.

3.2 MAIN CHARACTERISTICS OF THE ARRAY

Note that *WEC main dimensions* are taken from the *Single WEC* sheet, and cannot be provided in this sheet. To be modified, these shall be changed under *Single WEC*.

In Table 3.1, the user shall enter the following array information:

- *Total number of WECs.* The default value is 20 WECs.
- *Number of rows in the array.* The default value is 4 rows.
- *Number of WECs per row:* default value is *Total number of WECs* divided by *Number of rows in the array.* In the example 20 divided by 4.

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- *Distance between WECs in the same row:* This parameter shall consider maintenance access and the footprint of the mooring. Default value is seven times the largest dimension of the *Single WEC*.
- *Distance between rows:* This parameter shall consider maintenance access and the footprint of the mooring. Default value is seven times the largest dimension of the *Single WEC*.
- *Distance from offshore substation to onshore connection point:* This value is used to calculate cost estimates of the export cable. A default value of 10 km is assumed.
- *Distance to maintenance port***.** This value is only informative. It should be combined with the cost of maintenance vessels and required maintenance per year. A default value of 20 km is assumed.
- *Distance to fabrication / assembly port.* This value is only informative. It should be combined with the cost of installation vessels and required time (weathers windows per year). A default value of 50 km is assumed.

3.3 Array Performance – Annual Energy Production

- **Single WEC Annual Energy Production***.* Default value is taken from *Single WEC* sheet.
- **approx. Percentual Energy Loss row after row**. This parameter has been introduced to take into account the eventual shadowing effect among WECs. Based on the experience gained from Pelamis, a default value of 2% losses in final AEP, row after row, has been considered as default value.

- **Total Array Annual Energy Production.** Default value is calculated as the number of WECs in each row multiplied by the annual energy production of the single WEC, discounted by the approx. percentual energy loss row after row.
- **Single WEC rated power.** Default value is the *generator rated power* for the *Single WEC*.
- **Total Array Capacity.** Default value is taken from *Single WEC* sheet, and corresponds to *Number of WECs in the array* multiplied by the *Single WEC rated power*.

3.4 Array Costs. CAPEX and OPEX

Note that the units in the cost assessment of the *Array* are in Million (i.e. MEUR); whereas in the *Single WEC* units are expressed in kilo (i.e. kEUR).

3.4.1 Array Capital Expenditures (CAPEX)

Cost centres for CAPEX in the wave energy farm are the same as in the *Single WEC*.

The default unit cost for *Development and consenting* is estimated as 6% of total array CAPEX.

It could be argued that the *Development and consenting* costs, calculated as a percentage of CAPEX, are expected to decrease proportionally as the installed power capacity of the project increases, as standard procedures are developed (Nielsen, 2001). Hence, *Development and consenting* cost for an array could maybe be proportionally lower than for the *Single WEC*. However, the experience shows that the consenting of the electrical connection, which is

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included in the Array and not in the Single WEC cost assessment, can be quite time and effort consuming.

The default unit cost for the following cost centres (*WEC Structure and Prime mover, PTO, Umbilical Cables, Station Keeping and Control*) is calculated as the number of WECs in the array multiplied by the final number used for the *Single WEC*, considering a discount of 10% due to economies of scale (i.e. when a large quantity is purchased).

For example, in the figure below the default unit cost for *Control* is of 0.2 MEUR, corresponding to the *Control costs for the Single WEC* of 11.1 kEUR, multiplied by 20 (*Total number of WECs in the array*) and multiplied by 0.9 (10% discount due to economies of scale).

	Default	Enter	Used		Unit costs
Array CAPEX					
Development and Consenting	1,9		**2**	**MEUR**	6% Total CAPEX
WECs Structure and Prime mover	12,5		**12,5**	**MEUR**	10% discount (i.e. economies of scale)
PTOs	5,4		**5,4**	**MEUR**	10% discount (i.e. economies of scale)
Umbilical / Dynamic cables (from PTO to connector)	0,0		**0,0**	**MEUR**	10% discount (i.e. economies of scale)
Station keeping (Foundation)	3,3		**3,3**	**MEUR**	10% discount (i.e. economies of scale)
Control	0,2		**0,2**	**MEUR**	10% discount (i.e. economies of scale)
Others			0,0	MEUR	

Figure 3.4.1. Cost assessment for a Wave Energy Farm. Capital Expenditures (CAPEX).

Depending on the *Station Keeping* type, perhaps could be considered whether shared mooring piles are an option in an array.

3.4.1.1 Array - Electrical connection (including Installation)

The sketch in Figure 4 details the assumed layout for the *Wave Energy Farm*, including the layout of the inter-array cables, the offshore substation (transformer platform / offshore connectors) and the export cable (from substation to onshore connection point).

	Default	Enter	Used		Unit costs	
Array CAPEX						
Array - Electrical connection (including Installation)			**2,6**	**MEUR**		
Inter-array electrical cables	0,6		0,6	MEUR	150	EUR/m (6 kV / 11 kV)
Offshore collection hub (junction box / offshore connectors)	0,5		0,5	MEUR	500	kEUR
Export cable (from substation to onshore connec. point)	1,5		1,5	MEUR	150	EUR/m (6 kV / 11 kV)

Figure 3.4.1.1. Electrical Connection cost assessment for the Wave Energy Farm.

Inter-array electrical cables:
The unit cost assumed in the Tool is of 150 EUR/m, representative for a 6 kV and 11 kV cable and including installation. The Tool calculates the default value by multiplying the unit cost by the *Total Number of WECs*, the *Number of WECs per row* and the *Distance between WECs in the same row*. In the example (Figure 4.4.1.1.) this is 0.63 MEUR (i.e. 0.6 MEUR), corresponding to 150 EUR/m * 4 rows * 5 WECs/row * 210 m between WECs in the same row.

This unit cost is based on the research carried out by Collin *et al.* (2017), where cable cost are provided as a function of power rating, voltage level and cable distance. Costs estimates are provided both for static as well as dynamic cables. The unit cost chosen in the Tool is the average value of the following three cases (calculated by *Equation 1* and *Table A1. Static cable cost coefficients* in Collin *et al*., 2017):

- 5 MVA, 6.6 kV cable → 142 EUR/m
- 5 MVA, 11 kV cable → 98 EUR/m

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- 10 MVA, 11 kV cable → 197 EUR/m

For a large scale deployment, the estimates from COWI (2021) could be relevant. They refer to offshore wind deployments in the GW scale in the planned Danish Energy Islands (Danish North Sea), about 100 km offshore, and are the following (figures include the cost of the cables and the installation):

- 400 EUR/m (3 mio. DKK/km) for the 66 kV internal connection in the windfarm.
- 500 EUR/m for the 66 kV cables connecting the island or the platform to the first wind turbine.

Flannery (2020b) estimates the unit cost for a 33 kV connection and excluding installation as 200 EUR/m.

Offshore collection hub (junction box / offshore connectors):
The costs of these depend largely on the type, voltage level, alternate or direct current (AC or DC), and power rating. The default value provided by the Tool is of 500 kEUR (Collin *et al.*, 2017 and after internal discussions).

For large arrays, Siegel (2012) provides a unit cost for an **offshore subsea connection point** for a 200 MW wave deployment of around 1.5 MEUR, including installation.

COWI (2021) details that a 1 GW, 66/275 kV AC offshore platform is assumed to have a cost of 146 MEUR; and a 500 MW, offshore AC platform, 120 MEUR.

For a very large scale deployment, COWI (2021) details that 1 GW, HVDC (High Voltage Direct Current) platforms are assumed to cost in the range of 470 to 520 MEUR per piece including transport, installation and rental of residential platform for installation and commissioning. According to the same reference, unit prices are determined by the average of various budget figures from project-specific sources, as well as publicly available material from the Internet, and are valued at an uncertainty of 30%.

Export cable (from substation to onshore connection point):
Similarly as for the inter-array cable, the unit cost assumed in the Tool is of 150 EUR/m, representative for a 6 kV and 11 kV cable and including installation (Collin *et al.*, 2017). The default value (as in the example of Figure 4.4.1.1) is calculated by multiplying the unit cost by the *Distance from offshore substation to onshore connection point* (input value, in km). In the example this is 1.5 MEUR, corresponding to 150 EUR/m * 10 km.

For larger export cables (higher ratings and power levels), Flannery (2020b) estimates a unit cost of 1500 EUR/m, assumed for a 150 kV connection and including installation.

COWI (2021) provides the following costs for cables, depending on voltage, which also include installation costs:

- 1.745 EUR/m for a 275 kV sea cable
- 3.355 EUR/m for a 380 kV sea cable
- 1.500 EUR/m for a HVDC sea cable
- 1.450 EUR/m for a HVDC land cable

COWI (2021) also notes that an AC/HVDC, 1GW **onshore substation** has a cost around 160 MEUR (1.2 mia. DKK).

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3.4.1.2 Array – Installation, Commissioning and Decommissioning

The default unit cost for *Installation* is calculated as the number of WECs in the array multiplied by the final number used for Installation of the *Single WEC*, considering a reduction of 10% due to economies of scale.

For example, in the figure below the default unit cost is of 4.3 MEUR, corresponding to the *Installation costs for the Single WEC* of 240 kEUR, multiplied by 20 (*Total number of WECs in the array*) and multiplied by 0.9 (10% reduction due to economies of scale).

	Default	Enter	Used		Unit costs
Array CAPEX					
Array - Installation	4,3		**4,3**	**MEUR**	10% discount (i.e. economies of scale)
Transport to harbour and Pre-assembly onshore	0,0		0,0	MEUR	0 EUR/m
WECs Installation (structure and prime mover)	0,0		0,0	MEUR	0 MEUR
Foundations Installation	0,0		0,0	MEUR	0 EUR/m
Array - Decommissioning	3,3		**3,3**	**MEUR**	77% of Total Installation Costs

Figure 3.4.1.2. Installation and Decommissioning cost assessment for the Wave Energy Farm.

Installation costs are very dependent on the type of seabed and bathymetry, distance to shore and depth, as well as the type of vessel required for these operations.

Also from offshore wind projects (COWI, 2021) it is known that many types of installation ships exists which vary greatly from floating installation vessels, jack-up ships that can stand on the seabed while the crane is used, as well as barges pulled by support ships. It is important to consider the different installation scenarios as prices can vary from 20.000 to 46.000 EUR/day for combinations of tugboat / barge up to 134.000 to 200.000 EUR/day.

Decommissioning: as for the *Single WEC,* the default value for all decommissioning activities is of 77% of total installation cost (OPERA, 2019); in the example 3.3 MEUR, the result of multiplying 4.32 MEUR by 0.77.

COWI (2021) reports there are various estimates for the decommissioning cost of offshore wind farms. Based on (Topham and McMillan, 2016) decommissioning costs can be estimated at 2-3% of the total CAPEX.

3.4.1.3 Contingencies

Similarly as in the Single WEC, 10% is the default value allocated to contingencies. Total CAPEX are provided before contingencies and after contingencies.

	Default	Enter	Used		Unit costs
Array CAPEX					
Array - Total CAPEX before contingencies			**33**	**MEUR**	
Contingencies	3,3		**3,3**	**MEUR**	10%
Array Total CAPEX with contingencies	37		**37**	**MEUR**	

Figure 3.4.1.3. Contingencies and CAPEX before and after taking Contingencies into account in the Wave Energy Farm cost assessment.

3.4.2 Array Operational Expenditures (OPEX)

Similarly as in the *Single WEC*, OPEX is calculated as 8% of CAPEX, assuming the following percentages for the three categories that compose OPEX:

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Minor repair and Inspection: the default value corresponds to 2% of CAPEX before contingencies for the *Single WEC*, multiplied by the *Number of WECs* and by *0.09* (to take into account a reduction of 10% in total value due to economies of scale).

Major maintenance/repair: tow back or lift. Annual costs: the default value corresponds to 4% of CAPEX before contingencies for the *Single WEC*, multiplied by the *Number of WECs* and by *0.09* (to take into account a reduction of 10% in total value due to economies of scale).

Fixed OPEX: Annual Site lease, Insurance & Management costs: the default value corresponds to 2% of CAPEX before contingencies for the *Single WEC*, multiplied by the *Number of WECs* and by *0.09* (to take into account a reduction of 10% in total value due to economies of scale).

OPEX				
Minor repair & Inspection. Annual costs	0,6		0,6 MEUR/year	10% discount (i.e. economies of scale)
Major maintenance/repair: tow back or lift. Annual costs	1,2		1,2 MEUR/year	10% discount (i.e. economies of scale)
Fixed OPEX: Annual Site lease, Insurance & Management	0,6		0,6 MEUR/year	10% discount (i.e. economies of scale)
Others			0,0 MEUR/year	
Annual Operational Expenditures (OPEX)			**2,5 MEUR/year**	

Figure 3.4.2 Operational Expenditures cost assessment for the Wave Energy Farm.

For very large-scale projects, the following estimates could be relevant: COWI (2021) estimates the operation and maintenance (O&M) costs for the offshore wind farms and the related electrical systems at 10 EUR/MWh (75 DKK/MWh); stating that only a very general number can be given to these cost assessments and that the same figure is assumed for all wind farms. Hence, annual O&M estimates amount to 150 MEUR/year for a 3 GW offshore wind deployment and 480 MEUR for a 10 GW offshore wind deployment, as planned for the Danish Energy Islands.

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4 LOCATIONS

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

A scatter diagram is a matrix that provides an approximate value of the long-term wave climate of a location. In the LiftWEC Tool, scatter diagrams are defined in terms of H_{m0} and T_{02}; all scatter diagrams in the Tool have the same resolution: 19 different wave heights (band of 0.5 meters) and 17 wave periods (bands of 1 second). 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. In the spreadsheet, they are defined in the sheet "*Scatter Diagrams_T02*". It is not expected that these data is modified, except for when the user wishes to define a new scatter diagram.

All locations with an available scatter diagram appear in a drop down menu in the *Single WEC* sheet (Figure 4.1a). The possibility to enter a new scatter diagram is available (Figure 4.1b).

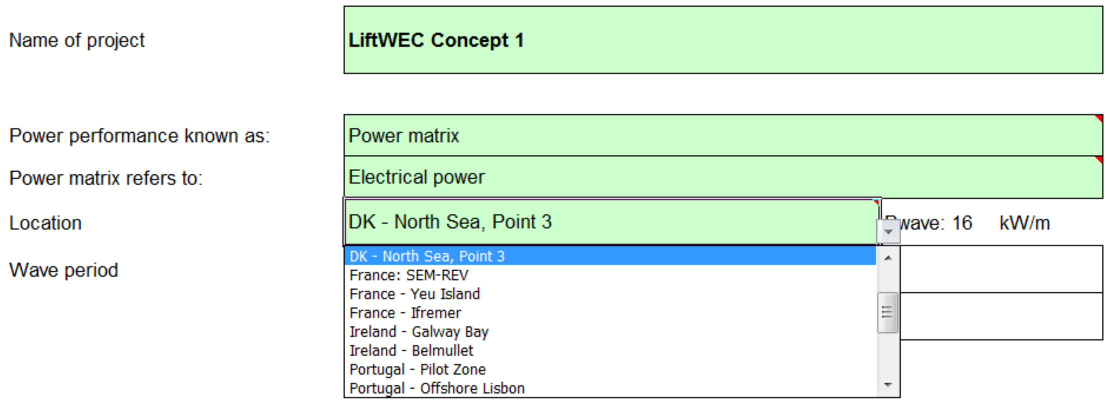

Figure 4.1a Locations' selection from a drop-down menu. Single WEC sheet.

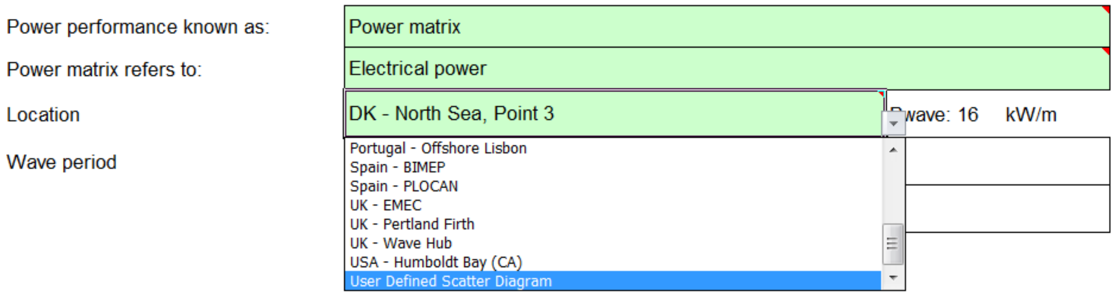

Figure 4.1b Locations' selection from a drop-down menu showing the possibility of choosing the User defined Scatter Diagram.

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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	**France – Ifremer**	**27 kW/m**	**50 m**	**10 km**	**47.84° N 4.83° W**
9	Ireland – Galway Bay	2.4 kW/m	21-24 m	2.5 km	53.228°N 9.266°W
10	Ireland – Belmullet	71 kW/m	50-100 m	6.5-10.5 km	54°N 12°W
11	Portugal – Pilot Zone	25 kW/m	30-90 m	20 km	39°54’N 9°06’W
12	Portugal – Offshore Lisbon	36 kW/m			39°N 12°W
13	Spain – BIMEP	21 kW/m	50-90 m	1.7 km	
14	Spain – PLOCAN	8 kW/m	40 m		
15	UK – EMEC	21 kW/m	12-50 m	1-2 km	
16	UK – Pentland Firth	7 kW/m	62 m	2.4 km	53°40’30’’ N 03°16’4’’W
17	UK – Wave Hub	16 kW/m	50-60 m	16 km	
18	USA – Humboldt Bay (CA)	26 kW/m	70 m	5 km	
19	*User defined*				

The locations available in the LiftWEC LCOE 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, 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 and Kofoed, 2004). Horns Rev, also located in western Denmark at 10 meter water depths, is the site of a 180 MW offshore

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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).

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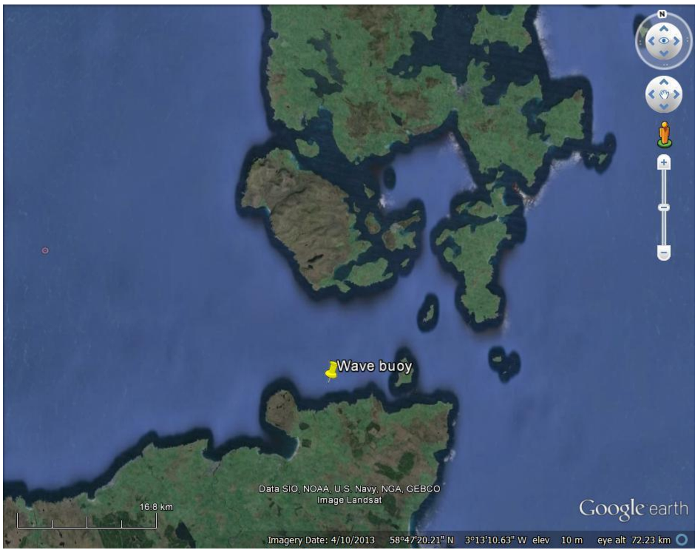
Galway Bay and Belmullet are two reference locations in the Irish Wave Energy Programme (SEAI, 2022), (HMRC, 2003). Galway Bay is an inlet sea (water depths of 22 m) generally conceived as a test area for small-scale prototypes (Nielsen and Pontes, 2010), and Belmullet represents a location with high wave potential (50 to 100 m water depths) normally more suitable for full-scale testing or commercial operation of WECs.

EMEC is the European Maritime Energy Centre established on the Orkney Islands. The scatter diagram corresponds to 50 m water depths (Nielsen and Pontes, 2010). 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.



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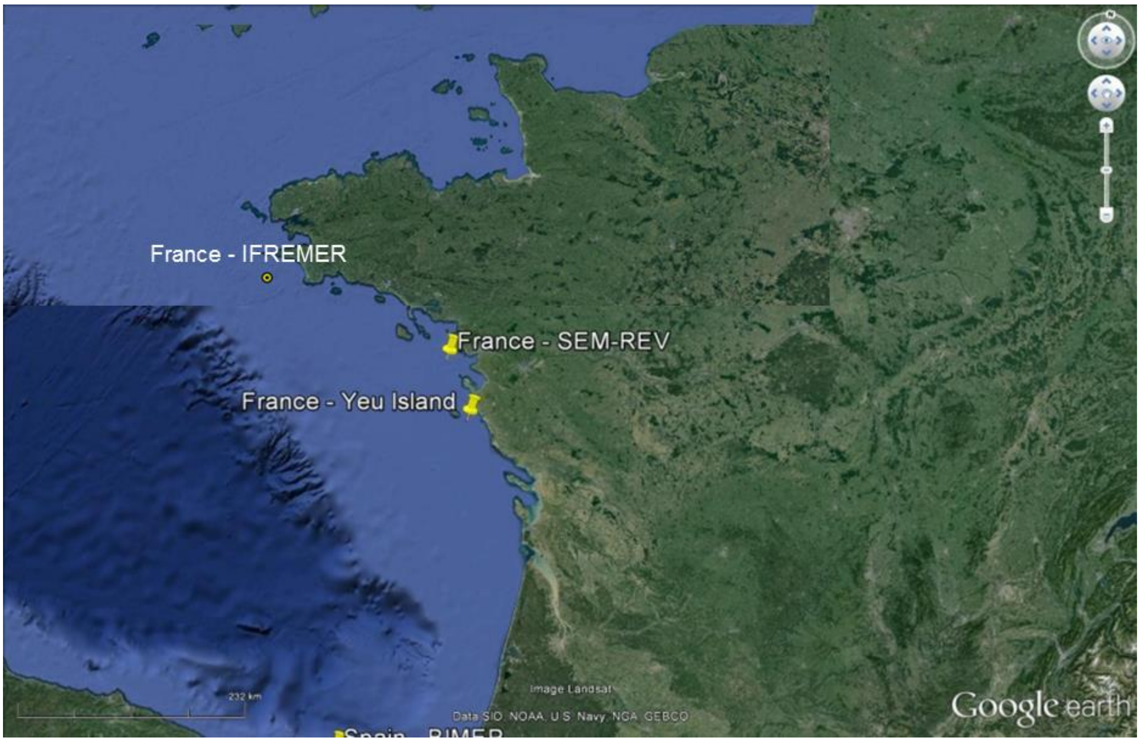
In France, SEM-REV has been established as test site for WECs (SEM-REV, 2022). Yeu Island is located south of the SEM-REV. Wave data for the latter corresponds to measurements from a wave buoy available (not anymore) at the CANDHIS database. Babarit et al. (2006) carried out a study on the wave and wind conditions at Yeu Island.



The site defined for the LiftWEC project using the Ifremer database has been named as *France – Ifremer*. Open access hindcast wave climate exist through the database HOMERE developed by the French research institution IFREMER. More details on the database can be found in (Boudière *et al*, 2013). The site considered is south-west of Brittany (47.84° N, 4.83° W) as shown in the figure above. From the HOMERE database, it is possible to quantify the wave climate for the 2001-2010 period in terms of a scatter diagram, which is included as an available location to carry out the calculations.

At the site mean water level is of 50 metres, and the average tidal range for the site is 2.0 metres. Maximum marine currents are of 0.1 m/s, and seabed conditions and sandy seabed. The closest onshore electrical connection is at about 10 km. A port suitable for service vessels is 20 km from the deployment site and a port suitable for installation vessels is 50 km from the deployment site.

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 and Pontes, 2010).

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

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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 in northern California was chosen by the US Department of Energy to assess the economic feasibility of wave energy converters (La Bonte *et al.*, 2013). NREL (2022) provides a wave resource library that includes resource data for a few locations in the United States.

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The user can also enter a scatter diagram by choosing the option *User defined scatter diagram*. In the sheet named *Scatter Diagrams_T02* 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 MARENDATA platform (2022) provides a database of wave data, including the data that was available in the SOWFIA project.

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 LiftWEC LCOE 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).

Only when needed, 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 γ=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):

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

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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*. Then, 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.

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5 UNCERTAINTIES

5.1 EVALUATION OF UNCERTAINTIES

It is important to understand there are uncertainties in all data handled by the LiftWEC LCOE Calculation Tool and, therefore, also in the output economic assessment. The uncertainties in the input data are brought by the following parameters:

- By the errors in the final Annual Energy Production value, which is calculated from the power matrix, the performance in the standard sea states, or has been input as a single final value.
- By the errors of the scatter diagrams, when the power performance is stated as *Power matrix,* or of the sea states, when power performance is stated as *Standard Sea States.* Also, some errors are added when recalculating the power matrix to fit the chosen wave climate.
- By the uncertainties on the main dimensions (concept design, i.e. amount of material), performance of the WEC and the PTO.
- By the inherent uncertainties in the cost estimates of the different components and cost centres.

In order to evaluate the cost assessment uncertainties, the Tool provides an estimation of the overall uncertainty of the output results. This value is given in percentage and covers an interval.

Table 5.1. Cost assessment uncertainty estimates for two different evaluations: simplified analysis and preliminary analysis (Previsic, 2013).

Development Phase	Uncertainty intervals (simplified cost assessment)	Uncertainty intervals (preliminary cost assessment)
Phase 1 / TRL 1, 2 and 3	-30 to 80%	-30 to 50%
Phase 2 / TRL 4	-30 to 30%	-25 to 30%
Phase 3 / TRL 5 and 6	-25 to 30%	-20 to 20%
Phase 4 / TRL 7 and 8	-20 to 20%	-15 to 15%
Phase 5 / TRL 9	-15 to 15%	-10 to 10%

The default uncertainty values provided by the Tool are presented in Table 5.1, and have been estimated by Previsic (2013). They depend on the development phase or Technology Readiness Level (TRL) of the *Single WEC* (a detailed description of development phases and TRLs is provided in Section 6.2), and on whether *Power performance is known* as standard sea states, *as* a power matrix or as a single value:

- If *Power performance is known* as standard sea states, the uncertainties related to a Simplified analysis are chosen.
- If *Power performance is known as* a power matrix, the uncertainties related to a Preliminary Analysis are chosen. These uncertainties intervals are smaller than for the Simplified Analysis.

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- If *Power performance is known as* a single value, the uncertainties related to a Simplified analysis are chosen.

5.2 WEC Development Stages

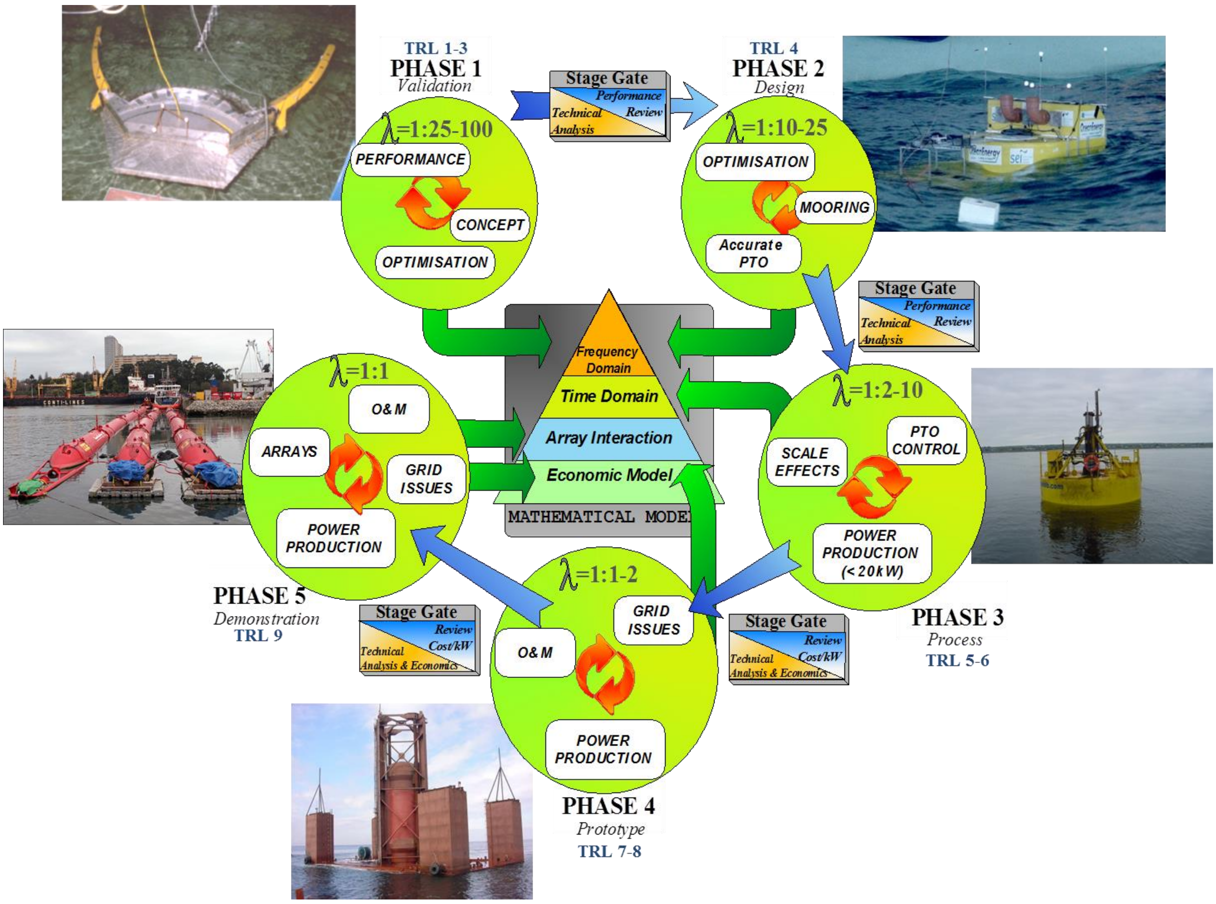
The development of a wave energy converter consists of different phases or stages, which cover from the initial concept to the industrial commercialisation. Depending on the country, the industry or the research institute of focus, these development phases may differ (Fernandez Chozas, 2013).

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

a) The five Development phases, also known as Stages, and

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).

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5.2.1 The Five development phases

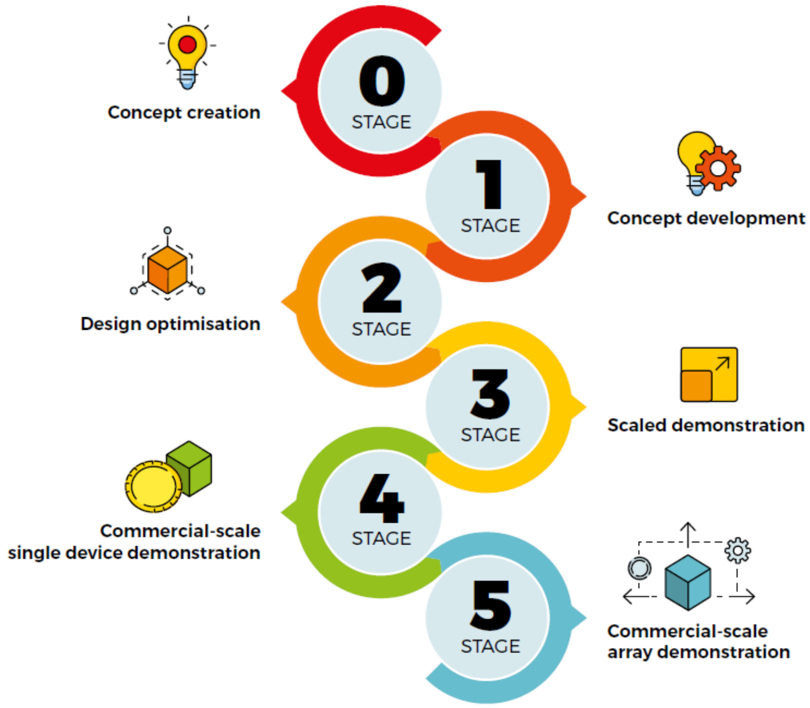
The 5 development phases of a WEC were agreed by the EquiMar consortium (Ingram *et al.*, 2011) and long time before by the Danish Wave Energy programme (Kofoed and Frigaard, 2009). These are the following:

- 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 LiftWEC configurations are currently in Phase 1 / 2 of their development.

The user must select the *Development phase* of the *Single WEC*.

The recently published document by the OES *"An international evaluation and guidance framework for ocean energy technology"* (Hodges *et al.*, 2021) also breaks the development process into six stages, from concept creation to commercialization. The six stages reflect the five stages agreed by the sector, with the addition of a Stage 0 (Concept Creation) to provide details of very early stage evaluations. *The Evaluation and Guidance Framework* defines the word Stages as "Defined periods of the development process, aligned with phases of funding and decision points. Alternative terminology: Phases."



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The following Table also relates the *Stages* to the 9 Technology Readiness Levels, and the "Early", "Mid" and "Late" stages of technical development, which some investors use to run calls of investments.

Stage	Description	TRL
Stage 0	Concept creation	1
Stage 1	Concept development	2 3
Stage 2	Design optimisation	4
Stage 3	Scaled demonstration	5 6
Stage 4	Commercial-scale single device demonstration	7 8
Stage 5	Commercial-scale array demonstration	9

Early (1-3)
Analytical and numerical models

Mid (3-6)
Experimental tests in controlled environment

Late (6-9)
Experimental tests in representative environment

5.2.2 Technology Readiness Levels or TRLs

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

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL3 – Experimental proof of concept
- TRL4 –Technology validated in Lab
- TRL5 – Technology validated in relevant environment
- TRL6 – Technology demonstrated in relevant environment
- TRL7 – System prototype demonstration in operational environment
- TRL8 – System complete and qualified
- TRL9 – Actual system proven in operational environment

NASA's Technology Readiness Levels (TRLs) were used in aviation, space and defence to manage the development of high risk, novel and complex technologies (NASA, 2013). It was conceived as a *high-level method to determine how advanced or 'ready' a technology was for use in an application* (Hodger *et al.*, 2021). Few years ago this development schedule was re-introduced by utilities to assess the development stage of a WEC (Fitzgerald and Bollund, 2012); and since then it has been largely used by the European Commission and funding agencies to assist in the technological assessment.

To the author knowledge, the latest TRL definitions specifically for the Ocean Energy sector have been developed by Magagna *et al.*, (2018). The LiftWEC concepts are currently at considered to be at between TRL 3 and TRL 4.

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5.3 SELECTION OF UNCERTAINTIES, DEVELOPMENT PHASE AND TRL

The selection table in the Tool looks as shown in the following figure. In this example, the Tool displays as default values Phase 1 and TRL 4, and the corresponding uncertainty for Phase 1 and the Simplified cost assessment. This is because power performance has been provided as a single Annual Energy Production value. The corresponding interval for the Uncertainty is hence [-30% to 80%]. The user has the opportunity to input his owns uncertainty interval.

	Default	Enter	**Used**
Project lifetime	25		25 years
WEC Development phase (1 to 5 phase)	Phase 1: Model validation		
WEC Technology Readiness Level (TRL 1 to 9)	TRL 4: Large-scale laboratory verification		
Related uncertainty to LCOE	-30 to 80%		-30 to 80% uncertainty

Figure 5.3a WEC Development phase, TRL and Uncertainty interval for the Single WEC.

WEC Development phase (Figure 6.3b) shall be selected, and then the *WEC TRL level* (Figure 6.3c) by selecting both of them from drop-down menus.

	Default	Enter	**Used**
Project lifetime	25		25 years
WEC Development phase (1 to 5 phase)	Phase 1: Model validation		
WEC Technology Readiness Level (TRL 1 to 9)			
Related uncertainty to LCOE			

Phase 1: Model validation
Phase 2: Model design
Phase 3: Initial sea trials
Phase 4: Prototype validation
Phase 5: Prototype demonstration

Figure 5.3b Selection of WEC Development phase from a drop-down menu. Single WEC.

The TRL levels displayed depend on the development phase selected. For example, in Figure 5.3c only the TRL levels corresponding to Phase 1 are shown (i.e. TRL 1, TRL 2 and TRL 3).

	Default	Enter	**Used**
Project lifetime	25		25 years
WEC Development phase (1 to 5 phase)	Phase 1: Model validation		
WEC Technology Readiness Level (TRL 1 to 9)	TRL 3: Small-scale laboratory verification		
Related uncertainty to LCOE			

TRL 1: Concept configuration description
TRL 2: Professional desk studies
TRL 3: Small-scale laboratory verification

Figure 5.3c. Selection of WEC Technology readiness Level from a drop-down menu. Single WEC.

As explained before, in order to evaluate the cost assessment uncertainties, the Tool provides an estimation of the overall uncertainty of the output results. For example, Figure 5.3d indicates that the *Single WEC* being assessed is in *Phase 2, TRL 4*, and the output data provided in the *Economic Assessment* is estimated to have an uncertainty in the range *[-25% to 30%]*,

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which, for the LCOE calculated for a 5% discount rate, translates into an LCOE estimate in the range of 162 to 281 EUR/MWh, with an average value of 216 EUR/MWh.

Economic Assessment for LiftWEC Concept 1				
Currency	EUR	Development stage: Phase 1 / TRL 3		[-30 to 80%] Uncertainty
Total CAPEX	1,88 MEUR	[CAPEX / MW]	3,8 MEUR/MW	
Annual OPEX	137 kEUR/year	[annual OPEX / CAPEX]	7%	
Discount rate	0%	3,5%	5,0%	
LCOE (25 years, in EUR/MWh)	170	201	216	

Figure 5.3d. Example of Economic Assessment for LiftWEC Concept 1.

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6 OUTPUT – ECONOMIC ASSESSMENT

6.1 OUTPUT TABLES

The output of the LiftWEC LCOE Calculation Tool is an economic evaluation of the *Single WEC* and of the *Wave Energy Farm* at the selected wave climate, which includes the following parameters:

- WEC development stage (e.g. TRL) and uncertainty related to the data (in percentage)
- Total CAPEX
- Annual OPEX
- [CAPEX per MW], in units of cost per installed unit of power e.g. MEUR/MW.
- [Annual OPEX per CAPEX], as a percentage.
- LCOE (calculated for three different discount rates), in units of cost per unit of energy produced e.g. EUR/MWh.

Economic Assessment for LiftWEC Concept 1					
Currency	EUR	Development stage: Phase 1 / TRL 3		[-30 to 80%] Uncertainty	
Total CAPEX	1,88 MEUR		[CAPEX / MW]	3,8 MEUR/MW	
Annual OPEX	137 kEUR/year		[annual OPEX / CAPEX]	7%	
Discount rate	0%	3,5%	5,0%		
LCOE (25 years, in EUR/MWh)	170	201	216		

Figure 6.1.a. Economic Assessment for LiftWEC Concept 1.

Economic Assessment	Development stage: Phase 1 / TRL 3	[-30 to 80%] Uncertainty	
Single WEC: LiftWEC Concept 1		**Array: Floating LiftWEC Array**	
CAPEX	1,88 MEUR	**Array Total CAPEX with contingencies**	37 MEUR
Annual OPEX	137 kEUR/year	**Annual Operational Expenditures (OPEX)**	2 MEUR/year
[annual OPEX / CAPEX]	7%	[annual OPEX / CAPEX]	7%
[CAPEX per MW]	3,8 MEUR/MW	[CAPEX per MW]	3,7 MEUR/MW
Single WEC LCOE (r=5%)	**216 EUR/MWh**	**Array LCOE (r=5%)**	**214 EUR/MWh**

Figure 6.1.b. Economic Assessment for the Wave Energy Farm (Floating LiftWEC Array), including the output economic parameters for the Single WEC (LiftWEC Concept 1) on the left hand side.

The comparison of Figures 6a and 6b indicates that the LCOE for the Array is similar to the LCOE of the *Single WEC*. It shall be noted that there are three default parameters in the Tool which influences the *Array LCOE* relatively to the LCOE of the Single WEC:

- *Approximate Percentual Energy Loss row after row* – with a default value of 2%. Due to expected shadows effect in the array, the total *Array annual Energy production* is lower than the *Single WEC Annual Energy production* multiplied by the *Number of WECs*. In relative terms, this parameter influences the *Array LCOE* to be higher than the LCOE of the Single WEC.

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- The electrical connections (including installation), which amounts to zero for the *Single WEC*, have a positive value for the array. In relative terms, this parameter influences the *Array LCOE* to be higher than the LCOE of the Single WEC.
- There is a 10% discount applied to most of the cost centres in CAPEX for the *Wave Energy Array* compared to the costs of the *Single WEC*. This discount rate is meant to consider the reduction in cost due to economies of scale. In relative terms, this parameter influences the *Array LCOE* to be lower than the LCOE of the Single WEC.

6.2 Currency

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

One is used to define the cost of each component and cost centre (Figure 3.4), and the other one is used for the economic assessment (Figure 6.1.a).

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 in the Tool are the following, corresponding to the average exchange rate value in year 2021.

Table 6.2: Exchange rates used in the LiftWEC LCOE Calculation Tool (updated based on average 2021 values).

Currency	Symbol	Exchange rate to EUR
DKK	kr	7.437
EUR	€	1
USD	$	1.183
GBP	£	0.8599

6.3 [CAPEX per MW] and [Annual OPEX per CAPEX]

The two parameters [CAPEX per MW], in units of cost per installed unit of power e.g. MEUR/MW, and [Annual OPEX per CAPEX], in percentage; are mostly used to economically compare technologies or concepts of the same technology in development.

To understand the typical orders of magnitude for both (Tables 6.3a and 6.3.b), the present document quotes recently published values (Cochrane *et al.*, 2021):

Table 6.3a: CAPEX inputs for European and Global SET Plan scenario modelling for wave deployments (MEUR/MW), (Tsiropoulos et al., 2018).

Year	2020	2025	2030	2035	2040	2045	2050
CAPEX (EUR/MW)	5.6	3.3	2.5	1.6	1.5	1.4	1.3

Table 6.3b: OPEX inputs for European and Global SET Plan modelling as a percentage of CAPEX (JRC, 2018).

Year	2020	2025	2030	2035	2040	2045	2050
Annual OPEX (%)	6%	5%	4.5%	4.5%	4.5%	4%	4%

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6.4 Discount rate

The discount rate is represented by *r*, and has percentage units.

The tool has two default discount rates: 0% and 3.5%. By using a 0% discount rate, the variation of money value in time is not taken into account.

The suggested discount rate of 3.5% derives from the recent recommendations stated by Cochrane *et al.* (2021), which references (HM Treasury, 2018).

A third discount rate can be entered by the user at the *Single WEC* sheet, and will be the discount rate used to calculate the LCOE for the *Wave Energy Farm*.

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

6.5 COE and LCOE (Levelised Cost of Energy) of WECs

The Cost of Energy (COE) parameter 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 Annual Energy Production (AEP) of the WEC at a certain location, and the WEC lifetime.

The COE is used to assess WEC's economic feasibility throughout the various development stages. It is widely used as a driving or supporting number to justify the selection between technical alternatives, as well as to answer the question "which WEC is the best" or even "which form of electricity generation is the best".

It is defined as follows where the WEC's lifetime, in years, is indicated by *n*.

$$COE = \frac{CAPEX + \sum_{t=1}^{n} OPEX_t}{\sum_{t=1}^{n} Annual\ Eenergy\ Production_t}$$

Often, the COE is calculated as a Levelised Cost of Energy (LCOE). The difference between the 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*.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}}$$

If the discount rate is equal to 0%, the LCOE and the COE will lead to the same value.

The LCOE is calculated following the parametric cost model (also known as cost-function) defined in Deliverable 8.2 "Parametric Cost Model" (Têtu and Fernandez Chozas, 2021). It represents WEC costs in present value divided by the AEP also in present value, and corresponds to the following formula:

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$$LCoE = \frac{C_{D\&C} + C_{PTO} + C_{El.con} + 1.77C_{Inst} + \sum_{i=1}^{N} c_i m_i + \sum_{j=1}^{M} Control_j + \sum_{t=1}^{N} \frac{OPEX_y(t)}{(1+\gamma)^t}}{\sum_{t=1}^{N} \frac{AEP_{array}(t)}{(1+\gamma)^t}}$$

where $C_{D\&C}$ stands for *Development and consenting* costs, C_{PTO} stands for *Power Take-off system* costs, $C_{El.con}$ stands for *Electrical connection* costs, C_{Inst} stands for *Installation and commissioning* costs; c_i is the cost of material i, m_i is the mass of material i, N is the total number of materials constituting the WEC, M is the total number of control systems and $Control_j$ is the cost associated with the type j of control (instrumentation and control). In the equation γ represents the discount rate.

To make the LCOE calculations, the Tool uses the Excel formula *PV (Present value),* which returns *the present value of an investment: the total amount which a series of total payments is worth now, in the present.* The Tool calculates the PV of the estimates of annual OPEX, in the numerator, and the PV of the estimates of AEP in the denominator, both for a given discount rate and for the project lifetime. Then, the LCOE is calculated by multiplying *Total CAPEX* by the *PV (OPEX)* and by dividing this with the *PV (AEP)*.

The European Commission has recently published its climate targets for years 2030 and 2050 (European Commission, 2020). The goals for 2030 include an EU offshore wind energy capacity of 60 GW and an ocean energy capacity (including wave and tidal energy) of 1 GW. The targets for 2050 are installing 300 GW of offshore wind and 40 GW of wave and tidal energy. The economic targets are set by the European strategic energy technology plan (SET-Plan) declaration of intent for ocean energy (European Commission, 2016). Here it is indicated that wave energy technologies are expected to reach an LCOE of 200 EUR/MWh in 2025, of 150 EUR/MWh in 2030 and of 100 EUR/MWh in 2035 (export infrastructure costs or the costs for delivering the electricity to onshore substations are taken into account within the LCOE).

Current practices in the sector are that technologies are benchmarked against these expected values.

In a recently published report addressing *Evaluation and Guidance for Ocean Energy Technologies*, published by the Ocean Energy Systems (OES), nine evaluation areas are proposed (Hodges *et al*., 2021). The Evaluation Criteria *Affordability* has been defined as one of the nice areas, where:

> "*Evaluation of Affordability relates to the cost of electricity generated from the wave or tidal stream resource, relative to the market rate for electricity*".

According to the scope of the Evaluation and Guidance Framework *"Affordability represents the key Evaluation Area […], with all other Evaluation Areas acting as inputs to it".* This is represented in the following figure, where the eight areas in green are providing input to the ninth area, Affordability, in orange.

As Hodges *et al*. (2021) detail, the evaluation of Affordability provides:

- *"Calculation of a baseline LCOE from which the Affordability impact of individual innovations (e.g. subsystems) can be evaluated.*
- *An opportunity to explain how the characteristics of an innovative technology challenge or modify the typical values or assumptions, leading to further critical evaluation of the technology's Affordability credentials"*

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The affordability concept and its subsequent elements are clearly reflected in the selection of criteria for the “Selection tool” that will help the LiftWEC Consortium to discriminate between the potential concepts, as described in Del2.2 Identification of evaluation criteria (Pascal *et al*, 2020). However, the Selection tool is focused on providing a relative evaluation of the LiftWEC concepts with respect to each other, and not to provide an absolute evaluation of the viability of the LiftWEC concept within the complete marine energy sector. This is part of the LiftWEC LCOE economic assessment as detailed here.

Figure 6.5. The Nine evaluation areas included in the Evaluation and Guidance Framework (Hodger et al., 2021).

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7 OUTPUT – PERFORMANCE ASSESSMENT

7.1 PERFORMANCE ASSESSMENT TABLES

The LiftWEC LCOE Calculation Tool also provides some output parameters that could serve as a performance assessment for the *Single WEC* or the *Wave Energy Farm* in study. It includes the following parameters:

- WEC / Array rated power
- Annual Energy Production (AEP)
- Capacity factor (C_f)
- Average annual electricity production
- Average annual capture width
- Average annual capture width ratio

Performance Assessment for LiftWEC Concept 1	
WEC rated power	500 kW
Annual Energy Production (AEP)	1250 MWh/y
Capacity factor (C_f)	29%
Average annual electricity production	143 kW
Average annual Capture width	3,96 m
Average annual Capture width ratio	13,2%

Figure 7a: Performance assessment for LiftWEC Concept 1.

Performance Assessment - Floating LiftWEC Array	
Total array capacity	10,0 MW
Annual Energy Production (AEP)	23,71 GWh/y
Capacity factor (C_f)	27%
Average annual electricity production	2,7 MW
average annual Array Capture width	100,2 m
average annual Capture width ratio	16,7%

Figure 7b: Performance assessment for Floating LiftWEC Array with 20 WECs.

7.2 WEC / ARRAY RATED POWER

Single WEC rated power or the Total Array Capacity will be shown. This parameter corresponds to the rated power of the Single WEC / wave energy farm, i.e. the maximum average power that the WEC(s) can produce.

7.3 CAPACITY FACTOR

The capacity factor is calculated by the following formula:

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

7.4 Average annual electricity production

It is calculated by the following formula:

$$Average\ Annual\ Electricity\ Production\ (kW) = \frac{1000 * Annual\ Energy\ Production\left(\frac{MWh}{y}\right)}{(24 * 365.25)\ (h/y)}$$

7.5 Average annual Capture width

The Capture width (in units of length, i.e. meters) is the ratio of the mean absorbed power to the incident wave power resource. It can be interpreted as the length of wave front which has been absorbed by the WEC.

In the Tool the mean absorbed power (MWh/y) is calculated by dividing the Annual Energy Production (MWh/y) by the *PTO average efficiency* (considered constant for all sea states) times the G*enerator average efficiency*.

$$Average\ annual\ Capture\ width\ (m) = \frac{1000 * \dfrac{Annual\ Energy\ Production\ (\frac{MWh}{y})}{PTO\ average\ efficiency * Generator\ average\ efficiency}}{Mean\ Pwave\ (kW/m) * (24 * 365.25)\ \ (h/y)}$$

7.6 Average annual Capture width ratio

Capture width ratio (in percentage) is the ratio of the capture width to the typical length of the device. It is calculated either by dividing the *Average annual Capture width* by the *Main active dimension.* It serves as an indication of the hydrodynamic efficiency of the WEC.

Babarit (2011) published a summary of the typical Capture width ratios for different technologies. Most of the results are from published literature, and they derive from experiments or numerical modelling.

Category	Sub category	Min(η_1)	Average(η_1)	Max(η_1)
OWC		6%	23%	34%
Overtopping devices		2%	9.5%	23%
Wave activated bodies	Heaving	1%	15%	39%
	Pitching	8%	28.5%	60%
	Surging/heaving/pitching	12%	18%	31%
	Yawing	5%	6%	7%
Others		2%	3%	4%

Pecher (2012) also provides a summary table for the different types of WECs where the stated performances of 30 WECs, obtained through tank testing or sea trials, in literature, are presented.

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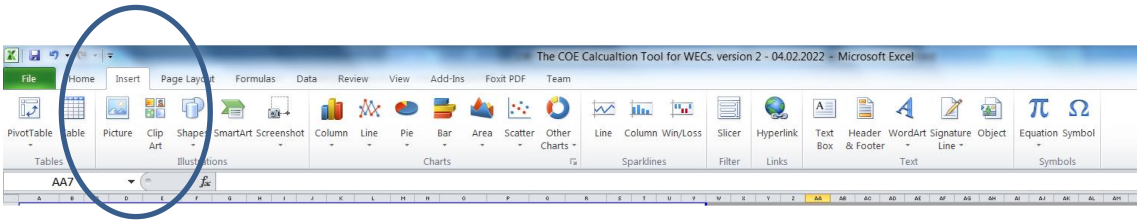
8 SUMMARY PAGES: SINGLE WEC AND WAVE ENERGY FARM

The following two output summary reports are provided by the Tool. They are intended to be printed and or copy/pasted into relevant reports (i.e. dedicated to the funding authority). A summary page is provided for the *Single WEC*, and another one for the *Array or Wave Energy Farm*.

A picture can be inserted in the two sheets by using the *Insert* → *Picture* capability of Excel:



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LiftWEC LCOE Calculation Tool

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885 - The LiftWEC Project.
The development of the COE Calculation Tool has been previously funded by the Danish funded projects "The COE tool for WECs – Improvement and Dissemination" (grant agreement 2013-1-12135, 2013-2014) and "Beton til Bølgeenergi" (64018-0600).

Output Summary. Economic and Performance Assessment. Single WEC - LiftWEC Concept 1

Project summary

Project name	LiftWEC Concept 1
Deployment location	France - Ifremer
Power density at the location	40 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight	260 ton
Station keeping type	Bottom-fixed
PTO type	Direct drive
PTO average efficiency	90%
Generator rated power	500 kW

Economic Assessment for LiftWEC Concept 1

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

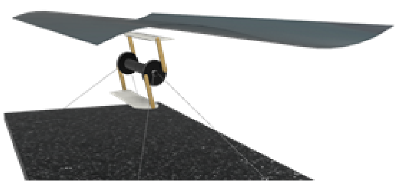
Total CAPEX	1,88 MEUR	**[CAPEX / MW]**	3,8 MEUR/MW
Annual OPEX	137 kEUR/year	**[annual OPEX / CAPEX]**	7%

Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	170	201	216

Performance Assessment for LiftWEC Concept 1

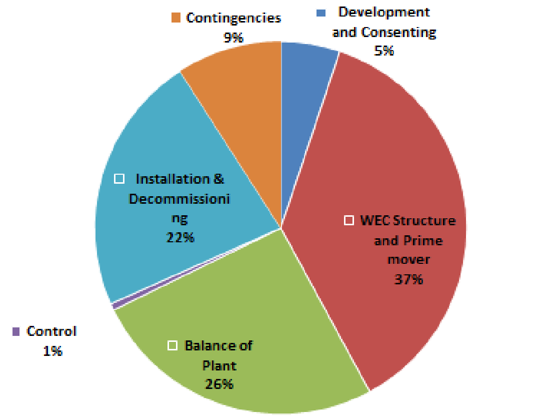
WEC rated power	500 kW	**Average annual electricity production**	143 kW
Annual Energy Production	1250 MWh/y	**Average annual Capture width**	4,0 m
Capacity factor (C_f)	29%	**Average annual Capture width ratio**	13%

Concept picture



Breakdown of costs

Total CapEx	**1,88 MEUR**
Development and Consenting	97 kEUR
WEC Structure and Prime mover	695 kEUR
Balance of Plant	484 kEUR
Control	11 kEUR
Installation & Decommissioning	425 kEUR
Contingencies	171 kEUR
Annual OpEx	**137 kEUR/year**



LiftWEC LCOE Calculation Tool

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Summary, Array. Economic and Performance Assessment - Floating LiftWEC Array

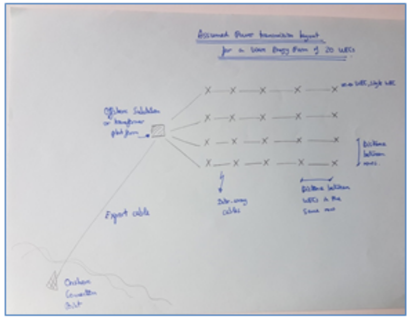
Project summary

Project name	Floating LiftWEC Array	
Deployment location	Ifremer, France	
Power density at the location	30	kW/m
Project lifetime	25	years

Main characteristics of the Array

Total number of WECs	20	WECs
Number of rows in the array	4	rows
Number of WECs per row	5	WECs/row
Station keeping type	Bottom-fixed	
Distance between WECs in the same row	210	m
Distance between rows	210	m
Distance off. substation to onshore conn. pc	10	km

Array layout - Picture



Economic Assessment for Floating LiftWEC Array

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

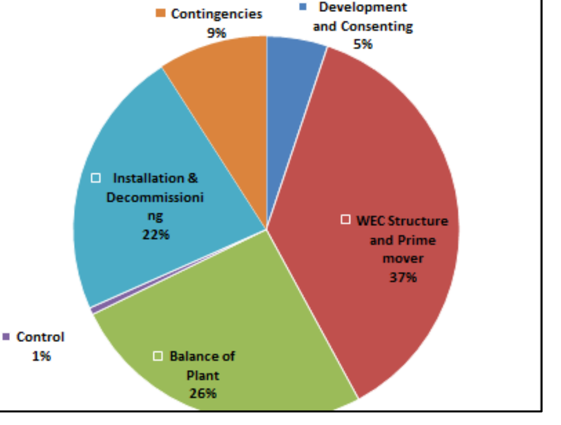
Total CAPEX	36,95	MEUR
Annual OPEX	2	MEUR/year
[CAPEX / MW]	3,7	MEUR/MW
[annual OPEX / CAPEX]	7%	
Array LCOE (r=5%)	**214**	**EUR/MWh**

Performance Assessment for Floating LiftWEC Array

Total array capacity	10 MW	**Average annual electricity producti**	2,7 MW
Annual Energy Productio	24 GWh/y	**average annual Array Capture widt**	100,2 m
Capacity factor (C_f)	27%	**average annual Capture width ratio**	17%

Breakdown of costs, Array

Total CAPEX	**36,9**	**MEUR**
Development and Consenting	1,9	MEUR
WEC Structure and Prime move	12,5	MEUR
Balance of Plant	11,3	MEUR
Control	0,2	MEUR
Installation & Decommissioning	7,6	MEUR
Contingencies	3,4	MEUR
Annual OPEX	**137**	**kEUR/year**



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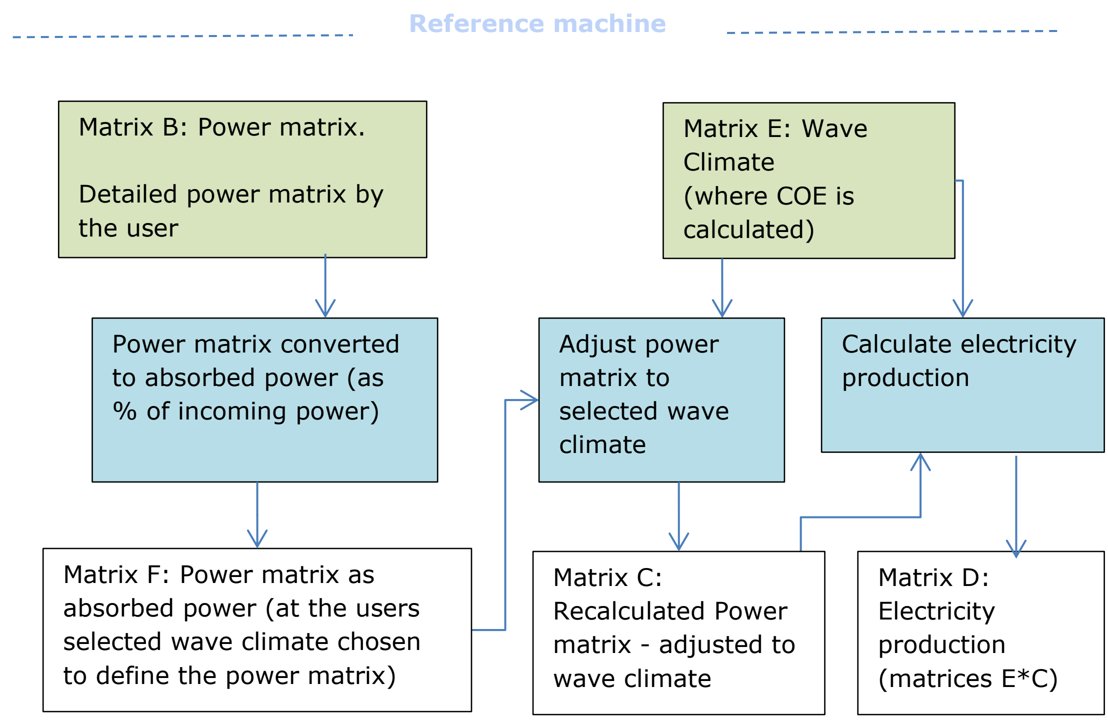
10 Annex A – Calculation Steps for Power Matrix



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).

10.1 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]

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10.2 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.

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

To calculate WEC´s *Annual Energy 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:

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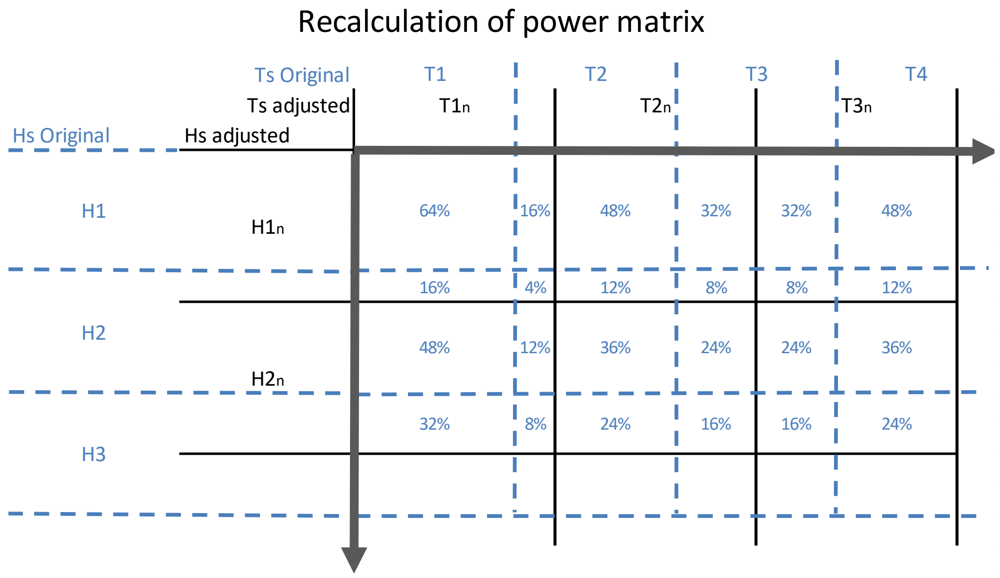

Matrix C delivers a power matrix defined for the same intervals as the chosen wave climate.

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.

10.4 Calculate Annual Energy Production

Annual Energy 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.

10.5 Annex B – Standard Sea States

Standardised Sea states Describing Energy in the Danish North Sea – Point 3 (Kofoed and Frigaard, 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

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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 LiftWEC LCOE Calculation Tool

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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 LiftWEC LCOE Calculation Tool

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