LiftWEC

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

Deliverable D8.2

Parametric Cost Model

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EXECUTIVE SUMMARY

This document constitutes Deliverable 8.2 of the LiftWEC project and consists of the description of the parametric cost model that will be used in this project to calculate the levelized cost of energy of the LiftWEC concept. A literature review has been performed to compile the different cost models found in the literature. The document is divided into four sections. After a brief introduction, the first section concerns the state-of-the-art for cost models. The parametric cost model developed for this project is described in the second section. The following section introduces the software code where the parametric cost model has been implemented, including a description of the main features of the COE Calculation Tool (the selected software). A discussion driven by the development strategy of the LiftWEC project is concluding the report.

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1 INTRODUCTION

This document constitutes Deliverable '*D8.2 Parametric Cost Model*' of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 851885.

1.1 PROJECT OUTLINE

The LiftWEC project focuses on the development of a novel type of Wave Energy Converter (WEC), called LiftWEC, which is intended to utilise hydrodynamic lift forces to incite device motion and extract wave energy using a rotating hydrofoil, as opposed to the more traditional approach of exploiting buoyancy and diffraction force regimes. This radically different approach to the design of wave energy converters offers the opportunity of making a step-change in the potential of wave energy, and thus leads the way for its commercialisation, where no commercially viable wave energy system currently exists.

1.2 PURPOSE OF THE DELIVERABLE

The main purpose of this document is to describe the parametric cost model that will be used in the LiftWEC project for the economic assessment of the different configurations of the LiftWEC. The development strategy of the LiftWEC project is really unique, and aims at exploring the parametric space in order to find an optimum solution in the form of a cost efficient LiftWEC concept aiming at providing electricity to the grid at utility scale.

The parameters included in the parameter space for the cost model are:

- Materials, that form both the wave energy converter and the station keeping.
- Main dimensions.
- Type of station keeping (monopile, bottom-fixed, floating, etc.)
- Types of control (pitch, torque, submersion, etc.)
- Power Take-Off system.
- Power efficiency, in terms of the annual energy production of the concept for a specific deployment location.

Some of the parameters mentioned above will have a direct influence on the installation and operation and maintenance (O&M) costs. Those variables are all inputs to the parametric cost model that will help identifying the best solution in terms of costs.

A thorough literature review of cost models for wave energy converter projects was performed and the state-of-the-art is presented in this document. This exercise was performed in order to identify the most relevant base cost model on which to build the parametric cost model. The parametric cost model is derived from the chosen base taking into account all the parameters previously mentioned.

The actual use of the parametric cost model is done through the open access software COE Calculation Tool, developed by Consulting Engineer Julia F. Chozas and the Department of Civil Engineering at Aalborg University (now Department of the Built Environment). The parametric cost model has been included in the software as part of the LiftWEC project and this software is presented in this document.

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1.3 Structure of the Document

The document is divided into four sections: *State-of-the-Art*, *Parametric Cost Model*, *Implementation of the parametric cost model into the COE Calculation Tool* and *Conclusion*. In the first section, a state-of-the-art of cost models is presented. The parametric cost model developed for the LiftWEC project is described in the following section. The third section explains how the parametric cost model is implemented into the COE Calculation tool. A conclusion ends the document.

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2 STATE-OF-THE-ART

This section summarises the state-of-the-art concerning cost models found in the literature. The section is divided into subsections, where each subsection is related to a particular cost model.

2.1 OCEAN ENERGY SYSTEMS (OES)

The International voice of the ocean energy sector, grouped under the collaborative programme Ocean Energy Systems (or OES), presented in [OES (2015)] a methodology for calculating the LCoE (Levelised Cost of Energy) of a technology, which is given by:

$$LCoE = \frac{CAPEX + \sum_{t=1}^{N} \frac{OPEX(t)}{(1+r)^t}}{\sum_{t=1}^{N} \frac{AEP(t)}{(1+r)^t}} \tag{1}$$

where N stands for the project lifetime, $CAPEX$ stands for capital expenditure, AEP stands for the annual energy production at year t, $OPEX$ stands for the yearly operational expenditure at year t, r stands for the discount rate and t stands for the year where $t = 1$ is the start of the project and $t = N$ is the end of the project.

This approach is similar to the one proposed within the EquiMar project [Davey *et al.* (2009)], a collaborative project within the FP7 Framework aiming at delivering a suite of "high level" protocols to allow fair comparison of marine energy converters[1]. Also, the recently published framework for the international evaluation and guidance for ocean energy technologies [Hodges et al. (2021)] refers to the same Eq.1 for the evaluation of the *Evaluation Area Affordability* of marine energy technologies.

2.2 DTOCEANPLUS

In the deliverable D6.4 "System Lifetime Costs Tools – Alpha version" of the collaborative H2020 funded project DTOceanPlus[2] [Correia da Fonseca et al. (2019)], the cost model for the system lifetime costs tool is defined and explained. In this reference the LCoE is calculated using the following equation:

$$LCoE = \frac{CAPEX + \sum_{t=1}^{N} \frac{OPEX_y(t)}{(1+\gamma)^t}}{\sum_{t=1}^{N} \frac{AEP_{array}(t)}{(1+\gamma)^t}} \tag{2}$$

where N stands for the project lifetime, $CAPEX$ stands for capital expenditure, $OPEX_y$ stands for the yearly operational expenditure and γ stands for the discount rate. The calculation of the LCoE within this framework does not include decommissioning costs.

The CAPEX value in Eq.2 is the sum of all costs before the operation of the wave farm starts, $OPEX_y$ is a yearly list of costs related to all operations done in a particular year and $AEP_{array}(t)$ is the annual

[1] Equitable Testing and Evaluation of Marine Energy Extraction (https://www.equimar.org/)
[2] Providing Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment (https://www.dtoceanplus.eu/)

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energy production for that particular year. The main difference between the DTOceanPlus model and the model introduced by OES is that the LCoE for the DTOceanPlus model is conceived for an array of WECs.

2.3 NREL Simple LCoE Calculator

The calculation of the LCoE in the tool developed by NREL [NREL (2021)] is based on the following equation:

$$LCoE = \frac{CAPEX \times C_{rf} + O\&M_{Fixed}}{8760C_F} + O\&M_{Variable} \tag{3}$$

where $CAPEX$ stands for the overnight capital cost ($/kW), 8760 is the number of hours per year, C_F is the capacity factor ([0,1]) representing the fraction of a year where power is generated and C_{rf} stands for the capital recovery factor, defined as:

$$C_{rf} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4}$$

where n is the number of annuities received and i is the interest rate. In Eq.3, $O\&M_{Fixed}$ and $O\&M_{Variable}$ stand respectively for the fixed O&M costs (in $/kW-year) and the variable O&M costs (in $/kWh).

2.4 IEA Wind. Task 26. Survey of Expert Opinions on Future Costs of Wind Energy Supporting Information

In the chapter dedicated to wind energy of the International Energy Agency (IEA Wind) together with the major research centre in wind energy in USA, the National Renewable Energy Laboratory (NREL), have developed an online tool [IEA Wind & NREL (2021)] to calculate the LCoE of wind energy projects. The calculation of the LCoE (in $/MWh) is based on the following equation:

$$LCoE = \frac{CAPEX \times C_{rf} \times T_{Adj} + OPEX}{8760NC_F} \tag{5}$$

where $CAPEX$ stands for the total capital expenditures ($/kW), 8760 is the number of hours per year, NC_F is the average annual net capacity factor of the plant (in %) representing the annual energy output of the project relative to the potential output if the project operated at its maximum capacity for a full year, and C_{rf} stands for the capital recovery factor defined as:

$$C_{rf} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

where i here stands for the real weighted average cost of capital and N is the project design life (in years). The real weighted average cost of capital can be obtained from the nominal after-tax weighted average cost of capital (N_{wacc}) with the following relation:

$$i = \frac{1 + N_{wacc}}{1 + \gamma_{inf}} - 1 \tag{7}$$

where γ_{inf} is the long-term inflation rate taken as 2%. The real weighted average cost of capital represents the average return required by the combination of equity and debt investors to make a

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project an attractive investment opportunity. The after-tax weighted average cost of capital here assumes that interest on debt serves as a tax deduction and that equity investor returns are indicative of the required threshold return after payment of taxes.

T_{Adj} in Eq.5 represents the tax adjustment considering the depreciation of the tax rate (T_R) throughout the project lifetime:

$$T_{Adj} = \frac{1 - T_R P_{VD}}{1 - T_R} \tag{8}$$

where the present value of depreciation (P_{VD}) is given by:

$$P_{VD} = \sum_{t=1}^{n} \frac{n^{-1}}{(1 + N_{wacc})^t} \tag{9}$$

2.5 Danish Energy Agency

The Danish Energy Agency developed an LCoE tool to estimate and compare the socio-economic electricity production costs [Danish Energy Agency (2018)]. The LCoE (in EUR/MWh) calculation is based on the following equation:

$$LCoE = \frac{\frac{CAPEX}{(1+\gamma)^N} + \frac{O\&M_{Fixed}}{(1+\gamma)^N}}{\frac{AEP}{(1+\gamma)^N}} + O\&M_{Variable} \tag{10}$$

where $CAPEX$ stands for the total capital expenditures (EUR/MW), $O\&M_{Fixed}$ and $O\&M_{Variable}$ stand respectively for the fixed O&M costs (in EUR/MW) and the variable O&M costs (in EUR/MWh). AEP is the annual electricity production of the plant (in MWh/MW), γ is the discount rate and N is the project lifetime (in years).

2.6 Present value approach proposed by Teillant *et al.* (2012)

Teillant *et al.* (2012) proposed a present value (PV) approach to calculate the LCoE of a WEC farm for a given project lifetime:

$$LCoE = \frac{PV(CAPEX) + PV(OPEX)}{PV(EP)} \tag{11}$$

where $CAPEX$ stands for the total capital expenditures, $OPEX$ stands for the operational expenditure and EP stands for the energy production in kWh. The PV of a given cash-flow (CF) is defined as:

$$PV(CF) = \sum_{y=y_o}^{y} \frac{CF(y)}{\left(1 + \frac{R_d}{100}\right)^y} \tag{12}$$

Where R_d is the discount rate and y_o is the first non-zero value year of the given cash-flow (CF). This approach is similar to the one described in [Carbon Trust (2006)].

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3 PARAMETRIC COST MODEL

A parametric cost model is used to evaluate the different LiftWEC concepts that are being developed throughout the LiftWEC project, and to assess the LCoE differences between the concepts. Based on the literature review provided in Section 2, the LCoE parametric cost model is based on the DTOceanPlus LCoE calculation. Recalling Eq.2:

$$LCoE = \frac{CAPEX + \sum_{t=1}^{N} \frac{OPEX_y(t)}{(1+\gamma)^t}}{\sum_{t=1}^{N} \frac{AEP_{array}(t)}{(1+\gamma)^t}} \tag{13}$$

To fulfil the purpose of the present project and in order to consider the different factors that influence the cost, the CAPEX value is further developed. Hence, it is divided into the cost centers defined in Deliverable 8.1 - Cost Database [Têtu and Fernandez Chozas (2020)].

$$CAPEX = \sum (C_{D\&C} + C_{WEC} + C_{BoP} + C_{Inst} + C_{Decom}) \tag{14}$$

where $C_{D\&C}$ stands for *Development and consenting* costs, C_{WEC} stands for *Wave energy converter* costs, C_{BoP} stands for *Balance of plant* costs, C_{Inst} stands for *Installation and commissioning* costs and C_{Decom} stands for *Decommissioning* costs.

For the LiftWEC project, the development and consenting costs will most likely be independent of the concept investigated as each concept will be developed simultaneously. Environmental studies, resource monitoring and certification will need to be performed whichever concept is chosen.

The wave energy converter (WEC) cost will differ from each concept. This cost can be expanded further:

$$C_{WEC} = \sum_{i=1}^{N} c_i m_i + \sum_{j=1}^{M} Control_j \tag{15}$$

where 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).

The balance of plant costs includes the Power Take-Off (PTO) costs (C_{PTO}), the station keeping costs (C_{SK}) and the electrical connections costs ($C_{El.con}$). It can be expressed as:

$$C_{BoP} = \sum C_{PTO} + C_{SK} + C_{El.con} \tag{16}$$

The C_{PTO} will vary depending on the PTO chosen and the C_{SK} will vary depending on the foundation type or if a floating solution is chosen. C_{SK} can also be taken as a summation of all materials multiplied by their cost and that way being integrated in the first term of Eq.15. $C_{El.con}$ is assumed to be the same whichever concept investigated.

According to Deliverable 8.1 - Cost Database [Têtu and Fernandez Chozas (2020)], the decommissioning costs can be expressed as a fraction of CAPEX and as a fraction of the installation and commissioning costs, resulting into:

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$$\begin{aligned} C_{Inst} &= 0.13\ CAPEX \\ C_{Decom} &= 0.1\ CAPEX \end{aligned} \tag{17}$$

The decommissioning costs as a function of the installation and commissioning costs are then:

$$C_{Decom} = 0.77\ C_{Inst} \tag{18}$$

Even though the 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.

Eq.13 can be rewritten:

$$LCoE = \frac{\sum(C_{D\&C} + C_{PTO} + C_{El.con} + 1.77 C_{Inst}) + \sum_{i=1}^{N} c_i m_i + \sum_{j=1}^{M} Control_j + \sum_{t=1}^{N} \frac{OPEX_y(t)}{(1+\gamma)^t}}{\sum_{t=1}^{N} \frac{AEP_{array}(t)}{(1+\gamma)^t}} \tag{19}$$

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4 Implementation of the Parametric Cost Model into the COE Calculation Tool

The parametric cost model defined in the previous section includes all the parameters relevant to the economic assessment for the evaluation of different LiftWEC concepts. This section describes the software code where the parametric cost model has been implemented. The ultimate goal of the chosen software is to enable the use of the parametric cost model in providing useful inputs to the design exercise. The software code chosen for this has been the Danish COE Calculation Tool, which main characteristics are described below.

The decision of choosing this software is based on two main considerations. Firstly, the tool is open-access and it can be freely-downloaded from the Internet [3]. And secondly, its simplicity and accessibility has resulted into more than 5000 number of downloads from users in Denmark and abroad since its release.

The COE Calculation Tool was developed in 2014 as a simple and transparent software to evaluate the economic feasibility of wave energy converters [Fernandez Chozas *et al.* (2014a)]. Commissioned by Energinet (the Danish Transmission System Operator) and developed by Consulting Engineer Julia F. Chozas and the Department of Civil Engineering at Aalborg University (now Department of the Built Environment), it has always been conceived as an open-access tool which can eventually help in the development of wave energy by contributing to open talks with key stakeholders, investors, politicians, academia and the general public.

Overall, the COE Calculation tool has the following characteristics:

- It is an open-access economic calculation tool that can be freely-downloaded from the Internet.
- It uses broadly-known software: Excel.
- It includes default values for efficiencies and prices.
- It is simple and transparent: it promotes the understanding of the calculation steps and results.
- It focuses on power production values instead of on installed capacity.
- It can evaluate the COE/LCoE in a range of relevant locations for wave energy deployments.
- It includes the unique feature of scaling the WEC according to locations.
- It focuses on input values rather than on the outputs: it is conceived as an exercise for developers.
- The Tool comes together with a detailed user guide where all the assumptions, baseline equations, calculations as well as input and output values are explained in detail [Fernandez Chozas *et al.* (2014b)]. A quick-start user guide is also available [Fernandez Chozas *et al.* (2014c)].

A front-end screenshot of the COE Calculation Tool is provided in Figure 1.

[3] https://vbn.aau.dk/files/197329239/WECs_COE_Calculation_Tool_ver1.6_4_April_2014.xls

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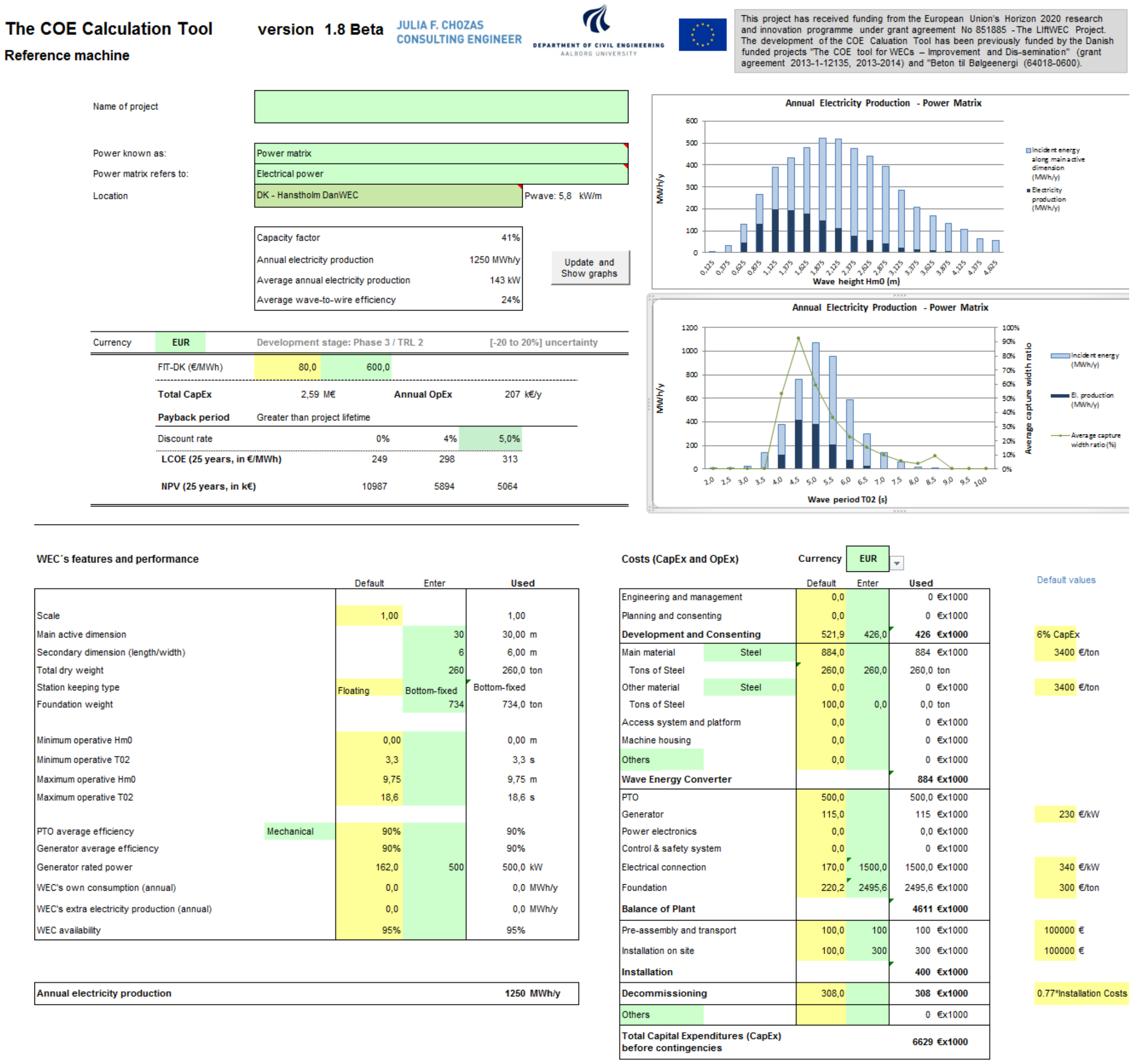

Figure 1. Front-end of the COE Calculation Tool - numbers shown do not represent any WEC and are for illustration purposes only. Yellow cells indicate default values and green cells user-input values.

The spreadsheet is based on a reference machine (i.e. a wave energy converter or WEC), which provides the core information of all calculations. This reference machine can be freely set (as shown on the left-hand side of Figure 1. All input data such as main dimensions, weight, minimum and maximum operative wave heights, rated power, conversion system type and efficiency, and values for the different cost and materials shall be based on the same machine.

Power production data from the converter may derive from laboratory testing, numerical modelling or from sea trials. Input values for the power production can be in the form of mean absorbed power in a number of sea states (normally applicable in laboratory testing), in the form of a power matrix, or as a single value (i.e. the annual energy production). This latter option has been included in the ongoing update of the Tool.

When energy production is provided as the wave absorption efficiency of the WEC in a number (usually 5) of wave standard sea conditions, the WEC´s performance in the wave states are

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extrapolated into 96 wave states; thus, creating a power matrix of the WEC in terms of absorbed power. This eventually provides a smoother foundation for scaling.

When energy production is provided in the form of a power matrix, the user shall indicate whether the power matrix corresponds to energy absorbed or electricity generation. If data refers to energy absorbed, the Tool calculates the corresponding electricity production. The worksheet includes default values for power take-off and generator efficiencies. Users can either use these default values or enter their own. The user shall also indicate the location where the power matrix refers to (as shown in Figure 1, these input data are inserted on the left-hand side of the Tool).

Then, the annual energy production of the single machine is calculated by multiplying the power matrix (either given by the user or derived by the COE Calculation Tool) by the scatter diagram of the selected location, which can be either chosen from the Tool's database or directly input by the user in the form of a scatter diagram.

If the user lacks both a power matrix of the wave energy converter and the wave absorption efficiency, it can choose to provide the annual energy production as a single value. In this case and only for information purposes, it is desired to also input the mean wave power (in units kW/m) at the location where the annual energy production has been estimated at.

On the economic side of the Tool, a number of referenced costs on structure materials, PTO systems, power electronics, O&M activities, site lease and insurance, among others, are included in the Tool (Figure 1, right-hand side). These have been recently updated in Task 8.1 of the LiftWEC Project[4] through an extensive work looking into current and projected typical costs found by the wave energy sector [Têtu and Fernandez Chozas (2020)]. It is however recommended that these default values are only used on projects at an early development stage when cost data is scarce.

Then, the output of the COE Calculation Tool is a simple economic assessment of the single machine that includes project estimates of CAPEX, OPEX, LCoE, Net Present Value (NPV) and revenue (for a given feed-in tariff, FIT) of the converter at a specific location (Figure 1, left-hand side). The LCoE is given for three discount rates. Two of them are default values (r=0% and r=4%, the latter value has been recommended for Danish projects) and the third can be set-up by the user.

The parametric cost model has been implemented in the Tool to carry out these calculations. In this way, the user input on main WEC's features (scale, mass, main dimensions, etc.) is coupled to the costs inputs (or default values if data is missing) and through the mathematical relationships derived in the previous section of this report, the main output parameters are provided; ultimately presenting the expected cost of the device.

The uncertainties associated to the estimates of all output results are also presented in the Tool. These are of truly importance, as every economic calculation has an associated uncertainty to it, which directly depends on the specific WEC development stage; and can be as large as 50%.

An output A4-page sheet has been recently incorporated in the Tool, which shall enable a clear overview of output results and eventual comparison of WECs or designs of the same concept.

[4] Task 8.1: "Compile cost database" (www.liftwec.com).

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To a large extent, the main motivation of further developing a common and accepted COE Calculation Tool is to make economic calculations transparent and comparable among various WECs or different WEC stages. The LiftWEC project has a specific task related to the extension and update of the COE Calculation Tool[5]. Besides incorporating the parametric cost model, the Tool will be updated in order to reflect the latest cost estimates as well as relevant new features (i.e. array calculations). This will be thoroughly described in the next deliverable of WP8, named "Deliverable 8.3. Expanded and updated LCoE calculation tool."

[5] Task 8.3: "Expand and update LCoE calculation tool." (www.liftwec.com)

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5 CONCLUSION

The objective of the present document was to describe the parametric cost model used within the LiftWEC project for the economic assessment of the different configuration of the LiftWEC. A state-of-the-art for cost model for wave energy converter projects was presented to identify the most relevant base equation for the parametric cost model. The parametric cost model was presented while pointing out the relevant parameters that are likely to vary from one configuration of the LiftWEC to another. The parametric cost model was implemented in the COE Calculation Tool that will be used to perform the economic assessment of the LiftWEC configurations.

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