A Parametric Cost Model for the Initial Techno-Economic Assessment of Lift-Force Based Wave Energy Converters

Julia Fernandez Chozas, Amélie Têtu and Abel Arredondo-Galeana

Abstract—**In order to accurately reflect the cost estimates of lift-force Wave Energy Converters (WECs), a parametric cost model is developed. The definition, establishment and description of the parametric cost model is the purpose of the present article. The parameters of the cost model include the costs of developing and consenting, of the wave energy converter, of the balance of plant, of the installation and commissioning, and of decommissioning. To carry out the initial techno-economic analysis, the widely used parameters Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) will be utilised and an economic modelling framework is suggested to carry out the assessment. For this purpose, the parametric cost model will be incorporated in the Danish COE Calculation Tool, which is a transparent and simple Excel-based software, free-to-download, that since 2014 has assisted many users in estimating the cost of energy of a wave energy device when operating at different locations. A description of the added capabilities and updates of the Tool will also be described in the article. Lastly, an example of the application of the Tool to three different configurations of the LiftWEC concept, where the parametric cost model is used, is presented.**

Index Terms—**CAPEX, OPEX, wave energy, lift-force based wave energy converters, LIftWEC, economic modelling, the COE Calculation Tool.**

I. Introduction

WAVE energy is a very promising renewable energy source. The resource is very large and its power output is more predictable and less variable than that of wind and solar. Wave energy is making continuous progress towards commercialisation, however and in comparison to wind energy – where the Danish 3-blade wind turbine has been largely accepted and commercialised – the wave energy sector is characterised by a large number of different technologies and working principles proposed to harness the energy in the waves. This is maybe one of the main differences between the developments of wave and offshore wind [1].

In this context, the development of a new type of Wave Energy Converter (WEC) based on a new working principle has received funding from the European Union's Horizon 2020 research and innovation programme [2]. During the project the working principle and the economic and technical feasibility of lift-based wave energy converters will be investigated, and, if possible, bring forward one or more lift-based WEC concepts from TRL 1 to TRL 3/4.

Some limitations in the design space have been defined to develop the LiftWEC concepts. The primary coupling mechanism to extract energy from the waves is through lift-forces generated by one or more hydrofoils (as shown in Fig. 1) that rotate in a single direction about one or more horizontal axes aligned orthogonal to the mean direction of wave propagation [3]. And the energy extracted is to be converted to electricity to be supplied at grid-scale through an underwater seabed cable .

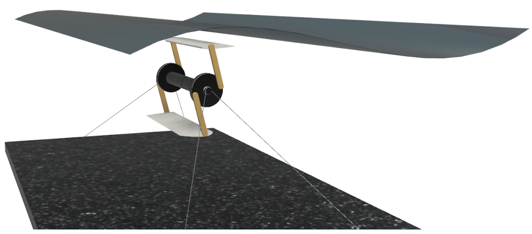

Fig. 1. Example of a Continuous Rotational Hydrofoil Concept [3].

Under this project scope, the authors of this article are working on estimating the costs of the different LiftWEC configurations and thereby, evaluating the economic viability of the concepts. As a first step, a publicly available cost database has been compiled [4]. It defines the main cost centres of a WEC and gathers typical structural and operation and maintenance costs of WECs (e.g. development and consenting costs, balance of plant costs, installation and commissioning costs, etc.). The cost database is to be updated continuously and ultimately, it should provide a sound overview of actual data representative for the wave energy sector.

After reviewing different economic models typically used in the wave energy sector and for offshore wind energy, a parametric cost-model that fulfils the purpose of the techno-economic analysis is proposed in this work. Then, the COE Calculation Tool is presented and it is also extended and updated to accommodate the main cost-centres identified in the parametric cost model. The applicability of the parametric cost model and the COE Calculation Tool is illustrated through a

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885, project LiftWEC.

Julia Fernandez Chozas is working for Julia F. Chozas, Consulting Engineer, Copenhagen, Denmark (e-mail: info@juliafchozas.com).

Amélie Têtu is with the Department of the Built Environment at Aalborg University, Aalborg, Denmark (e-mail: amt@build.aau.dk).

Abel Arredondo-Galeana is with the Department of Naval Architecture, Ocean and Marine Engineering at the University of Strathclyde, Glasgow, UK (e-mail: abel.arredondo-galeana@strath.ac.uk).

This is a preprint of paper #2005 presented at the European Wave & Tidal Energy Conference (EWTEC) 2021.
The final version of paper with the same title can be found in the EWTEC 2021 proceedings.

user case where three different configurations of the LiftWEC concept are presented.

II. Methodology

The proposed methodology to define and apply a parametric cost model for the techno-economic assessment of a wave energy device is presented in this section. The first step is to review the typical cost models utilised by the wave and the offshore wind energy sector. Then, a parametric cost model that takes into account all relevant cost centres is suggested. Afterwards, the COE Calculation Tool is presented, which allows to compute the parametric cost model for a specific device at a specific development site. Finally, the necessary updates to the Tool to accommodate for the parametric cost model and to improve it are addressed.

A. Parametric cost model

Many different cost models are found in the literature to compute the economic modelling of a renewable energy project [5]–[11]. They are all based on the knowledge of the capital (CAPEX) and operational (OPEX) expenditures of a given project, its annual energy output and a factor that takes into account the change of the value of a cash flow throughout the project lifetime. Based on [7] a further parametrisation step is performed in this work in order to evaluate the different LiftWEC concepts within the LiftWEC project [12].

From [7], the LCoE of a wave energy project is calculated using the following relation:

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

where N stands for the project lifetime, $CAPEX$ stands for capital expenditure, $OPEX(t)$ stands for the operational expenditure at year t, $AEP(t)$ stands for the annual energy production at year t and r stands for the discount rate.

The $CAPEX$ value is further developed in order to consider the different factors that influence the cost, utlimately enabling the differentiation and comparison of different LiftWEC concepts. The $CAPEX$ value is divided according to the different cost centres defined in [4]:

$$CAPEX = C_{D\&C} + C_{WEC} + C_{BoP} + C_{Inst} + C_{Decom} \quad (2)$$

where $C_{D\&C}$ stands for *Development and consenting* costs, C_{WEC} stands for *WEC (Wave energy converter) structure and prime mover* 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:

$$C_{WEC} = \sum_{i=1}^{K} c_i m_i + \sum_{j=1}^{M} Control_j \quad (3)$$

where c_i is the cost of material i, m_i is the mass of material i, K 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:

$$C_{BoP} = C_{PTO} + C_{SK} + C_{El.con} \quad (4)$$

The C_{PTO} will vary depending on the PTO chosen and the C_{SK} will vary depending on the foundation type or the mooring type if a floating solution is chosen. C_{SK} can also be taken as the sum of all materials multiplied by their cost and that way being integrated in the first term of Equation (3). $C_{El.con}$ is assumed to be the same whichever concept is investigated.

According to [4], the decommissioning costs can be expressed as a fraction of CAPEX and also as a fraction of the installation and commissioning costs, resulting into:

$$C_{Inst} = 0.13CAPEX \quad (5)$$

$$C_{Decom} = 0.1CAPEX \quad (6)$$

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

$$C_{Decom} = 0.77C_{Inst} \quad (7)$$

Hence, Equation (1) can be rewritten:

$$LCoE = \frac{C_{D\&C} + C_{PTO} + C_{Elcon} + 1.77C_{Inst}}{\sum_{t=1}^{N} \frac{AEP(t)}{(1+r)^t}} + \frac{\sum_{i=1}^{K} c_i m_i + \sum_{j=1}^{M} Control_j}{\sum_{t=1}^{N} \frac{AEP(t)}{(1+r)^t}} + \frac{\sum_{t=1}^{N} \frac{OPEX(t)}{(1+r)^t}}{\sum_{t=1}^{N} \frac{AEP(t)}{(1+r)^t}} \quad (8)$$

B. The COE Calculation Tool

The COE Calculation Tool was developed in 2014 as a simple and transparent software to evaluate the economic feasibility of wave energy converters [13]. 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

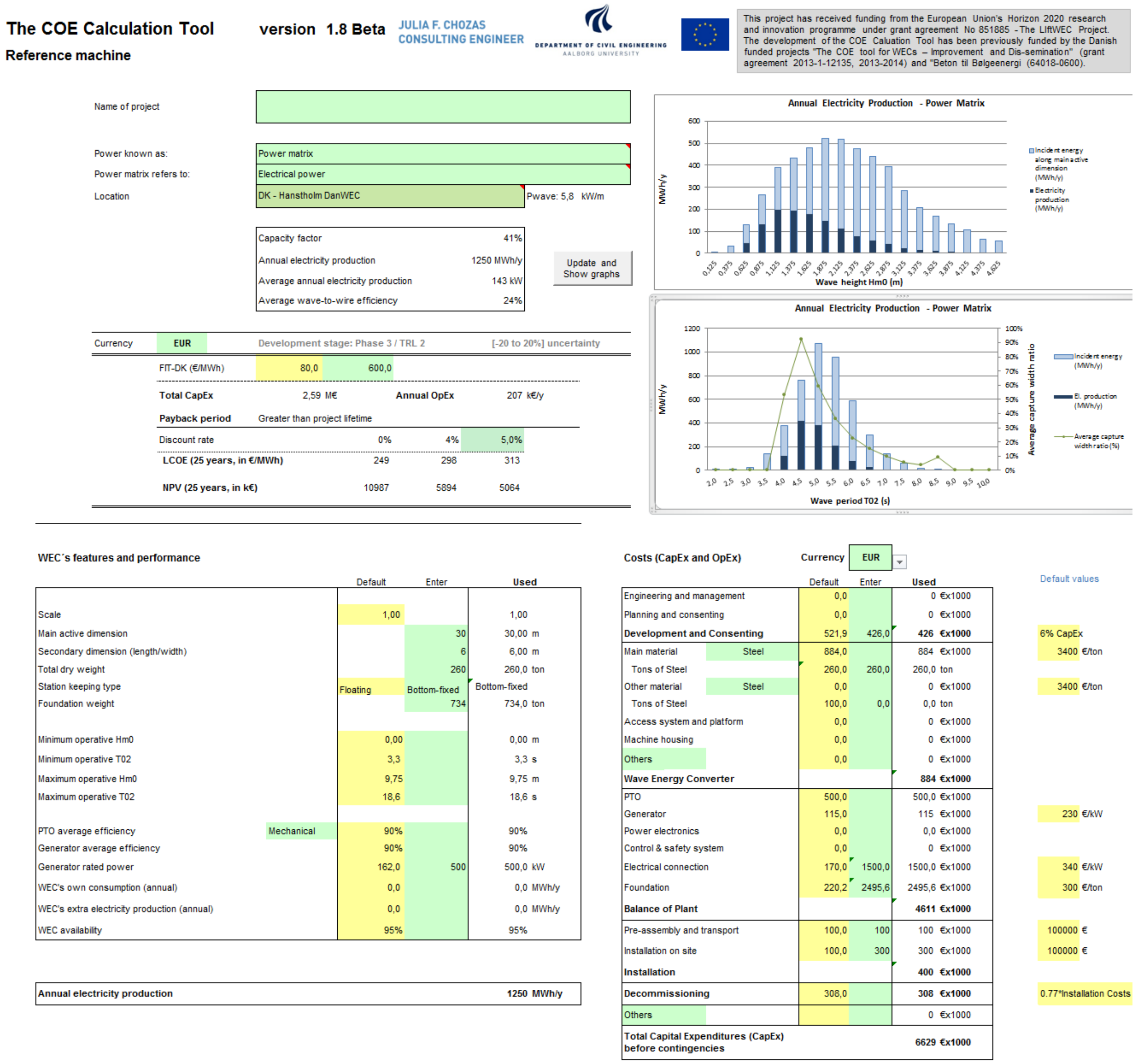

Fig. 2. Front-end of the COE Calculation Tool - numbers shown do not represent any WEC and are for illustration purposes only. Yellow cells indicate default values and green cells user-input values

the development of wave energy by contributing to open talks with key stakeholders, investors, politicians, academia and the general public. The tool has been largely used in Denmark and abroad, reaching more than 5000 number of downloads since its release.

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 [13].
- 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 on the outputs: it is conceived as an exercise for developers.
- The Tool comes together with a detailed user guide where all the assumptions, as well as input and output values are explained in detail. A quick-start user guide is also available [13].

1) Main Features of the COE Calculation Tool: The spreadsheet is based on a reference machine (i.e. a wave energy converter), which provides the core information of all calculations. This reference machine can be freely set (as shown on the left hand side of Fig. 2). 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 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 PTO 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 Fig. 2, 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 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 WEC and the wave absorption efficiency, it can choose to provide the AEP 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 AEP 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, warranty and insurance, are included in the Tool (Fig. 2, right-hand side). These have been recently updated through an extensive work looking into current and projected typical costs found by the wave energy sector [4]. 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 brief 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 (Fig. 2, 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.

Output results also include the estimated AEP, capacity factor, maximum output power and wave-to-wire efficiency of the WEC. The uncertainties associated to the output results are also shown, which vary depending on the WEC development stage. Also, a graph illustrating WEC's absorbed power for the different wave heights and wave periods at the chosen deployment location is presented (Fig. 2, top right-hand side of the Tool). An output A4-page sheet has been incorporated in the Tool, which shall enable a clear overview of output results and eventual comparison of WECs or designs of the same concept.

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. While calculations to estimate the cost of energy of a WEC are already carried out by most device developers, they are often based on assumptions and methods that are not clearly specified, making results somehow incomparable and non-transparent. Moreover, the complexity of calculations can vary a lot. Overall, the COE calculation tool aims at examining the economic feasibility of wave energy projects in a transparent, homogeneous, simple and comparable approach. With this purpose in mind, in the next section a User Case is presented aiming at exemplifying the use of the COE Calculation Tool for three different possible configurations of the LiftWEC concept, and their subsequent comparison.

III. User case

Three different LiftWEC concepts are introduced in this section and a preliminary economic assessment of each of them is performed using the parametric cost model presented in Section II-A.

In all concepts the hydrofoils are identical. Their profile is a NACA 0012 with a chord length of 3 m as depicted in Fig. 3. A hydrofoil span of 30 m is considered. More details on the structural design considerations can be found in [14], [15]. Each LiftWEC concept is designed with two hydrofoils, and the total mass of the two hydrofoils is 142 tonnes.

The main structure is identical in all concepts. It namely consists of the hydrofoils, a centrally rotating shaft that drives the power take-off mechanism, and two lateral supports, at the end of the shaft, that connect the shaft to the hydrofoils. The total mass of this main structure is 260 tonnes.

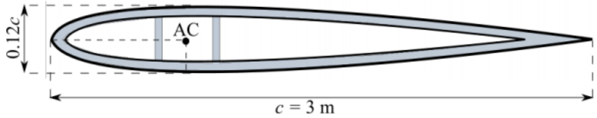

Fig. 3. Cross-section of the hydrofoils for the LiftWEC concepts (from [14]).

In all cases, the deployment location is the same. The coordinates at the chosen location are 47.84^o N, 4.83^o W corresponding to somewhere off the North Atlantic coast of France close to Quimper. The water depth at the deployment location is 50 m, distance to shore about 10 km and the wave resource is estimated at 40 kW/m.

The main characteristics that are identical for all concepts are detailed in Table I. We note that the dimensions presented in the table are for illustrative purposes only, and that these dimensions might be refined in subsequent stages of the design process.

TABLE I
COMMON CHARACTERISTICS FOR ALL LIFTWEC CONCEPTS

Characteristic		Unit
Radius of the rotor	3	m
Hydrofoil span	30	m
Number of hydrofoils	2	-
Material	Offshore steel	-
Water depth	50	m
Mass of the main structure	260	tonnes

A. LiftWEC concept 1

In the first concept the rotor is connected at both ends to a bracket substructure with bearings. The bracket structure is fixed to the seabed by means of a monopile structure as shown in Fig. 4. The monopile is a hollow structure of 53 m height where one third of its height is embedded in the seabed. The main characteristics of the concept are described in Table II.

TABLE II
CHARACTERISTICS FOR LIFTWEC CONCEPT 1

Characteristic		Unit
Station keeping type	Monopile	-
Station keeping mass	734	tonnes

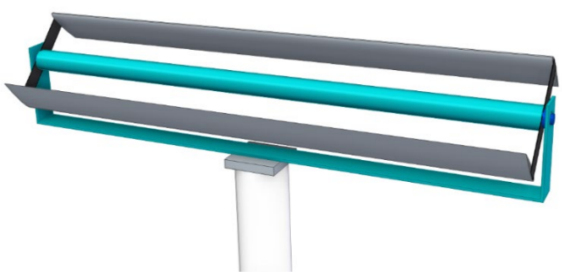

Fig. 4. Illustration of concept 1 where the rotor is fixed to the seabed by means of a monopile (from [14]).

B. LiftWEC concept 2

In the second concept the rotor is fixed at both ends to the seabed by means of a v-frame structure as shown in Fig. 5. The v-frame is composed of solid bar of 1 m in diameter. The main characteristics of the concept are described in Table III.

TABLE III
CHARACTERISTICS FOR LIFTWEC CONCEPT 2

Characteristic		Unit
Station keeping type	v-frame	-
Station keeping mass	500	tonnes

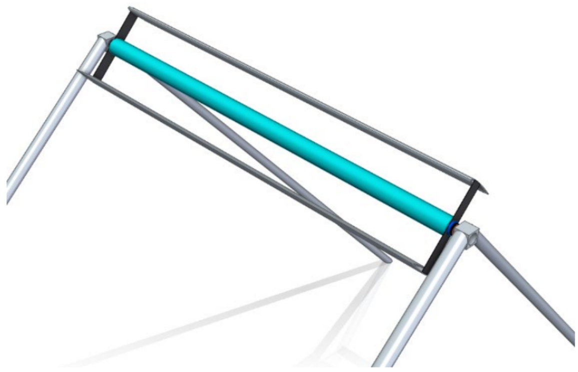

Fig. 5. Illustration of concept 2 where the rotor is fixed to the seabed at both ends by means of a v-frame structure (from [14]).

C. LiftWEC concept 3

For the third concept, the rotor is attached at both ends to a bracket substructure, which is supported by a floater as shown in Fig. 6. The floater consists of three hollow cylinders connected by solid rods. The main characteristics of the concept are described in Table IV.

TABLE IV
CHARACTERISTICS FOR LIFTWEC CONCEPT 3

Characteristic		Unit
Station keeping type	Floater	-
Station keeping mass	276	tonnes

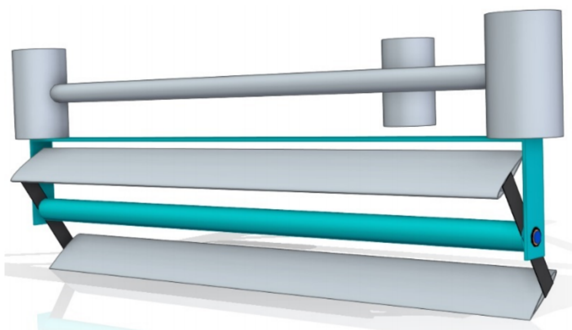

Fig. 6. Illustration of concept 3 where the whole structure is floating and moored to the seabed (from [14]).

D. Economic comparison

Since the active part of the three concepts is identical, it is fair to assume that all concepts will yield the same AEP. In principle, concept 3 could lead to higher energy production since it is not fixed to the seabed and has the possibility of weather vanning to optimize the orientation of the device with regards to the incoming waves. For the purpose of this work, the AEP is fixed to a common value for all concepts.

In the same way, the following cost centres of CAPEX can be assumed to be the same: *WEC structure and prime mover* costs (C_{WEC}), corresponding to 260 tons of steel at 3400 EUR/ton according to [16], [17]; costs related to the PTO (C_{PTO}), estimated for a 500 kW rated power mechanical PTO at 1000 EUR/kW according to [18]; costs of the generator, including power electronics and basic control and instrumentation ($\sum_{j=1}^{M} Control_j$), estimated for a 500 kW system at 230 EUR/kW according to [19]; and the electrical connection costs, estimated for establishing, including the installation, of a 10 km electrical infrastructure at 150 EUR/m according to [20]. *Development and consenting* costs are also assumed to be the same for the three concepts. Literature shows that they can typically be estimated as a fixed percentage of CAPEX [4]. Since CAPEX vary largely for the three concepts, $C_{D\&C}$ has been assumed as 6% of CAPEX of Concept 2. Lastly, and to consider for the unknown, 5% contingencies are considered for total CAPEX. Table V summarises these costs.

The costs that are concept specific are the costs related to the station keeping of the system (monopile in Concept 1, v-frame in Concept 2 and floating structure in Concept 3), the installation costs and the decommissioning costs. In all cases the station keeping is made of steel, which is assumed to have the same value as presented above of 3,400 EUR/ton. The installation and commissioning costs are divided into two categories. The first one relates to the pre-assembly and transport of the WEC to site, which is assumed to be the same for the three concepts (100,000 EUR). The second category considers the installation on site. In this exercise, the costs of installing on site of Concepts 1 and 2 is considered the same and are estimated to be of 300,000 EUR; whereas Concept 3 is expected to have a lower installation on site cost and is therefore estimated to be of 100,000 EUR.

It is acknowledged that the installation procedure of Concepts 1 and 2 will differ significantly. Concept 1 involves the installation of a steel monopile at 50 m water depth. For this, conventional hydraulic impact hammers could be utilised [21], whereas Concept 2 implies the installation of a v-frame with four anchoring points, which involves the use of anchors, such as suction piles, driven piles, gravity base or any other anchoring technology suitable for the installation site [22]. However, in terms of costs it is estimated that both installation procedures will be more expensive than a installing a floating structure as in Concept 3.

As addressed in section II-A *Decommissioning costs* are proportional to *Installation costs*, and hence concept specific. Table VI summarises the concept specific costs, which can also be visualised in Fig. 7.

The Operational Expenditures (OPEX) are divided into two categories: the costs of the site lease and insurance, which can be assumed to be the same for the three concepts, and the operation and maintenance costs. These are concept dependent and vary depending on whether it is a floating or a submerged structure.

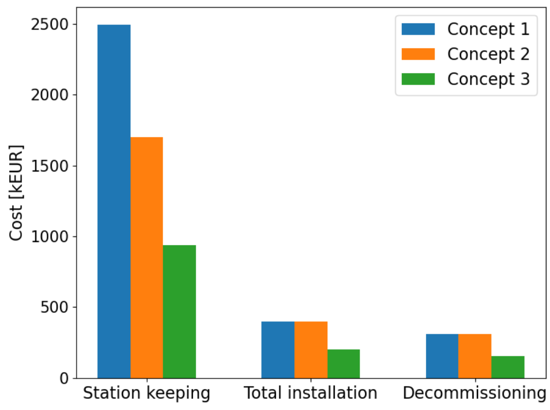

Fig. 7. Differences in station keeping costs, total installation costs and decommissioning cost for the three concepts evaluated.

Ultimately, during the LiftWEC project, O&M costs will be provided by another work package within the project consortium. As the coupling between the two tools (i.e. the O&M Tool and the COE Calculation Tool) has not been performed yet, a preliminary literature review has been carried out looking into the different annual estimates of OPEX for gravity-based tidal energy converters [23]; and estimates are on the same order of magnitude than expected OPEX for tidal energy converters mounted on a monopile [24]. Accordingly, annual OPEX of 200,000 EUR/year have been estimated for Concepts 1 and 2. For Concept 3, annual OPEX are estimated at 100,000 EUR/year based on annual OPEX estimates for a floating WEC [25]. In the three cases, estimates are considered conservative. Table VII summarises total CAPEX, annual OPEX and total OPEX throughout the whole project lifetime (estimated at 25 years) and at a discount rate of 5% for the three concepts and Fig. 8 helps visualising the difference in CAPEX and OPEX costs between the three concepts.

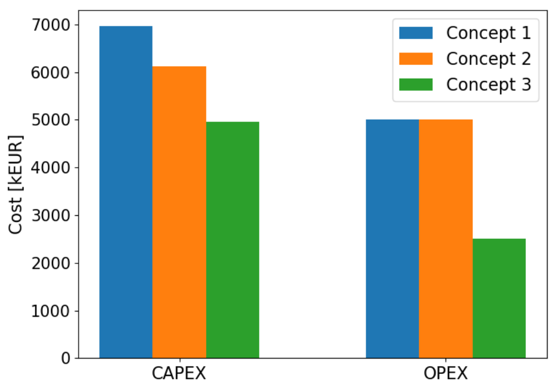

Fig. 8. CAPEX and OPEX values for the three concepts evaluated.

IV. Discussion of results and further work

CAPEX comparison for the three concepts indicates that the largest portion of CAPEX is due to the station

TABLE V
COMMON CAPITAL EXPENDITURES (CAPEX) FOR THE THREE CONCEPTS

Cost center		Unit
Development and consenting costs	426,000	EUR
WEC structure and prime mover	884,000	EUR
PTO system	500,000	EUR
Power electronics, control and instrumentation	115,000	EUR
Electrical Connection	1,500,000	EUR

TABLE VI
CONCEPT SPECIFIC CAPITAL EXPENDITURES (CAPEX)

Cost center	Concept 1	Concept 2	Concept 3	Unit
Station keeping	2,495,600	1,700,000	938,400	EUR
Total installation	400,000	400,000	200,000	EUR
Decommissioning	308,000	308,000	154,000	EUR

keeping costs (for Concepts 1 and 2) or the electrical connection costs (for Concept 3), as illustrated in Fig. 9.

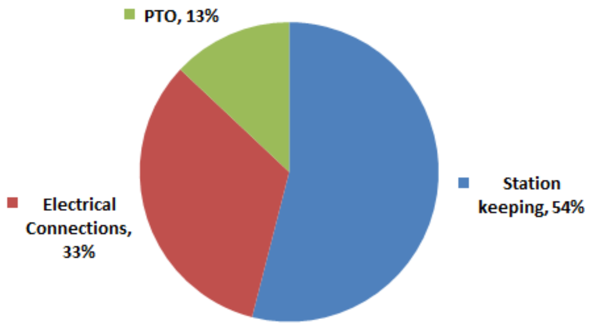

Fig. 9. Concept 1 distribution of costs for the cost center *Balance of Plant*.

Cost estimates related to the electrical infrastructure (including installation) account for 1.5 MEUR. This cost is rather indicative and aimed at fulfilling the purpose of the exercise. It is expected that if a single device is to be installed offshore, a test site where all necessary infrastructure is in place will be chosen. The installation of the electrical connection is economically-feasible once a bigger project, like a wave farm, is built.

Therefore, it can be argued that the largest cost-centre for each of the three concepts is the station keeping part (i.e. accounting for 2.5 MEUR, 1.7 MEUR and 0.9 MEUR, respectively). The main reason for these high costs, specially in Concept 1 and 2, is the amount of material used for it (i.e. 734 tonnes, 500 tonnes and 276 tonnes, respectively) and the type of material used (offshore steel) with a unit price of 3400 EUR/ton. It shall also be noted that no material nor costs optimisation has been included in this study. The possibilities of building the structure in another materials such as offshore concrete shall be evaluated in further work.

OPEX also differ a lot depending on the station keeping type. OPEX for the floating concept (Concept 3) have been estimated as half the OPEX of the two submerged concepts (Concept 1 and 2); which for the 25-year lifetime of the project accounts for a difference of 1.4 MEUR (discounted values). More precise Operation & Maintenance values are needed to better evaluate the OPEX related to submerged structures.

Overall, it is important to bear in mind that there is some uncertainty behind all the calculations. At this development stage of the LiftWEC concepts (Phase 1 of Model Validation and TRL 2 of Professional Desk Studies), the uncertainty is evaluated at -30% to 40% [26].

V. CONCLUSION

A parametric cost model was defined within the LiftWEC project in order to evaluate the economic viability of the concept development from TRL 1 to TRL 3/4. The whole idea is to use the parametric cost model, presented in this work, to assist in the decision making in the development process to optimise the LiftWEC concept in terms of costs. This process was illustrated in this work for three different preliminary concepts of the LiftWEC. The main difference among those three concepts was the station keeping properties: the first consisted of a monopile, the second a v-frame structure and the last one was a floating structure. It is important to note that no optimisation in terms of material and costs has been performed so far; the concepts presented were only used as an example to showcase the parametric cost model and the COE Calculation Tool used to obtain CAPEX and OPEX values for the different concepts. Nevertheless, the parametric cost model as embedded within the COE Calculation Tool was shown to be a valuable economic model to quantify the difference in costs among concepts and to show where the higher costs of each concept are born.

ACKNOWLEDGEMENT

This paper is supported by European Union's Horizon 2020 research and innovation programme under grant agreement No 851885, project LiftWEC (Development of a novel wave energy converter based on hydrodynamic lift forces). The authors would also like to acknowledge the fruitful discussions and comments from the LiftWEC project participants, especially Matt Foley and Paul Lamont-Kane (Queens University Belfast).

TABLE VII
TOTAL CAPITAL EXPENDITURES (CAPEX) AND OPERATIONAL EXPENDITURES (OPEX) FOR EACH CONCEPT

Cost center	Concept 1	Concept 2	Concept 3	Unit
Total CAPEX with 5% contingencies	6,960,000	6,125,000	4,950,000	EUR
Annual OPEX	200,000	200,000	100,000	EUR/year
Total OPEX over a 25-year lifetime, 5% discount rate	2,800,000	2,800,000	1,400,000	EUR

REFERENCES

[1] E. Friis-Madsen, H. C. Soerensen, I. Russell, S. Parmeggiani, and J. Fernandez Chozas, "Economics of offshore wave energy – can it match offshore wind?" *The 29th International Ocean and Polar Engineering Conference, Honolulu, Hawaii, USA*, pp. ISOPE–I–19–359, 2019.

[2] European Commission, "An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future," European Commission, Tech. Rep., 2020, https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf Accessed on 8.02.2021. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf

[3] M. Folley and T. Whittaker, "Lift-based wave energy converters – an analysis of their potential," *Proceedings of the 13th European Wave and Tidal Energy Conference, 1-6 Sept 2019, Naples, Italy*, pp. ISSN 2309–1983, 2019.

[4] A. Têtu and J. Fernandez Chozas, "Deliverable D8.1 - Cost Database," LiftWEC - Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2020, https://liftwec.com/wp-content/uploads/2020/06/LW-D08-01-1x3-Cost-database.pdf Accessed February 2021.

[5] Carbon Trust, "Future marine energy, results of the marine energy challenge: Cost competitiveness and growth of wave and tidal stream energy," Carbon Trust, London, UK, Tech. Rep., 2006.

[6] B. Teillant, R. Costello, J. Weber, and J. Ringwood, "Productivity and economic assessment of wave energy projects through operational simulations," *Renewable Energy*, vol. 48, pp. 220–230, 2012.

[7] Ocean Energy Systems and International Energy Agency, "An analysis of the development pathway and lcoe trajectories of wave, tidal and otec technologies," Ocean Energy Systems and the International Energy Agency, Tech. Rep., 2015.

[8] Danish Energy Agency, "Levelized cost of energy (lcoe) calculator (2018)." https://ens.dk/sites/ens.dk/files/Globalcooperation/lcoe_calculator_with_ee_module.xlsm, 2018, [Online; Accessed March 2021].

[9] F. X. L. A. Correia da Fonseca, A. G. Armayor, J. Candido, F. Arede, J. Henderson, B. Hudson, V. Nava, I. Tunga, and A. Petrov, "System lifetime costs tools – alpha version – deliverable 6.4," H2020 DTOceanPlus project, Tech. Rep., 2019.

[10] "Levelized Cost of Energy Calculator," https://www.nrel.gov/analysis/tech-lcoe.html, [Online; Accessed March 2021].

[11] "IEA Wind Task 26 Survey of Expert Opinions on Future Costs of Wind Energy Supporting Information," http://rincon.lbl.gov/lcoe_v2/lcoe_calculator.html, [Online; Accessed March 2021].

[12] "A Horizon 2020 project developing a lift-based Wave Energy Converter," http://https://liftwec.com/, [Online; Accessed December 2020].

[13] J. Fernandez Chozas, J. P. Kofoed, and N. E. Helstrup Jensen, "User guide – the COE calculation tool for wave energy converters," Aalborg University, DCE Technical Report No. 161., Aalborg, Denmark, Tech. Rep., 2014.

[14] A. Arredondo-Galeana, N. Clave, R. Pascal, W. Shi, F. Brennan, and P. Lamont-Kane, "Deliverable D6.2 - Transportation and Maintenance LiftWEC ULS Assessment," LiftWEC - Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2021.

[15] A. Arredondo-Galeana, W. Shi, G. Olbert, M. Scharf, A. Ermakov, J. Ringwood, and F. Brennan, "A methodology for the structural design of liftwec: A wave-bladed cyclorotor," in *Proceedings of the 14th European Wave and Tidal Energy Conference*, 2021.

[16] A. Myhr, C. Bjerkseter, A. Ågotnes, and T. A. Nygaard, "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective." *Renewable Energy*, vol. 66, pp. 714–728, 2014.

[17] S. Siegel, "Final scientific report. cycloidal wave energy converter," Atargis Energy Corporation., Tech. Rep., 2012, dE-EE0003635.

[18] P. Ricci, J. Lopez, I. Touzón, O. Duperray, and J. Villate, "A methodology for the global evaluation of wave energy array performance," in *Proceedings of the Fourth International Conference on Ocean Energy*, Dublin, Ireland, 2012.

[19] Wave Energy Scotland (WES), "High level cost metrics for wec machine elements," Prepared by Quoceant Ltd to Wave Energy Scotland (WES), Tech. Rep., 2016.

[20] M. O'Connor, T. Lewis, and G. Dalton, "Techno-economic performance of the pelamis p1 and wavestar at different ratings and various locations in europe," *Renewable Energy*, vol. 50, pp. 889–900, 2013.

[21] L. Li, W. Guachamin Acero, Z. Gao, and T. Moan, "Assessment of allowable sea states during installation of offshore wind turbine monopiles with shallow penetration in the seabed," *Journal of Offshore Mechanics and Arctic Engineering*, vol. 138, no. 4, 06 2016.

[22] C. J. Ehlers, A. G. Young, and J.-H. Chen, "Technology assessment of deepwater anchors," in *OTC Offshore Technology Conference*, vol. All Days, 05 2004.

[23] E. Segura, R. Morales, and J. A. Somolinos, "Cost assessment methodology and economic viability of tidal energy projects." *Energies*, vol. 10, p. 1806, 2017.

[24] Y. Li and H. Keith Florig, "Modeling the operation and maintenance costs of a large scale tidal current turbine farm," in *OCEANS 2006*, Boston, USA, 2006, pp. 1–6.

[25] A. Gray, B. Dickens, T. Bruce, I. Ashton, and L. Johanning, "Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters," *Ocean Engineering*, vol. 141, pp. 493–511, 2017.

[26] M. Previsic, "Cost reduction pathways for wave energy," *Ocean Energy Systems Annual Report 2012*, pp. 108–115, 2012.

This is a preprint of paper #2005 presented at the European Wave & Tidal Energy Conference (EWTEC) 2021.
The final version of paper with the same title can be found in the EWTEC 2021 proceedings.