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Breaking-Down and Parameterising Wave Energy Converter Costs Using the CapEx and Similitude Methods

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Abstract: Wave energy converters (WECs) can play a significant role in the transition towards a more renewable-based energy mix as stable and unlimited energy resources. Financial analysis of these projects requires WECs cost and WEC capital expenditure (CapEx) information. However, (i) cost information is often limited due to confidentiality and (ii) the wave energy field lacks flexible methods for cost breakdown and parameterisation, whereas they are needed for rapid and optimised WEC configuration and worldwide site pairing. This study takes advantage of the information provided by Wavepiston to compare different costing methods. The work assesses the Froude-Law-similarities-based "Similitude method" for cost-scaling and introduces the more flexible and generic "CapEx method" divided into three steps: (1) distinguishing WEC's elements from the wave energy farm (WEF)'s; (2) defining the parameters characterising the WECs, WEFs, and site locations; and (3) estimating elements that affect WEC and WEF elements' cost and translate them into factors using the parameters defined in step (2). After validation from Wavepiston manual estimations, the CapEx method showed that the factors could represent up to 30% of the cost. The Similitude method provided slight cost-overestimations compared to the CapEx method for low WEC up-scaling, increasing exponentially with the scaling.

Keywords: wave energy converter (WEC); capital expenditure (CapEx); CapEx method; cost model; cost breakdown and parameterisation; Froude law similarities; Similitude method; techno-economic analysis

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1. Introduction

The Paris Agreement was adopted by 196 parties at COP 21 on 12 December 2015. The legally binding treaty sets a goal to limit global warming to 1.5 °C compared to pre-industrial levels. This target requires most countries to transition to a more renewable energy mix. Electrification of the transport sector including cars [1,2] and aviation [3,4] will heavily increase the need for sustainable energy [5] achievable through multi-renewable-energy systems. Renewable energies are increasingly employed in the challenge against climate change [6,7]. However, the energy transition process is complex, especially due to the variety of actors, the diversity of supports it can receive (from crowdfunding to grants and landing, through infrastructure or production incentive and awareness) [8], and side effects it can create [9,10]. A just transition would involve social (and cultural), policy and civil changes towards a more democratised society at both centralised and decentralised levels [11]. Indeed, this transition is achievable if it involves all actors of the public (from macro—governments—to micro scale–municipalities) and private sectors, including housing, producers, distributors, providers and stakeholders (e.g., universities, research centers, trade associations, and environmental organisation to name a few) [11,12]. Policy has a major role to help this transition and Falcone et al. [12] estimated that policy procurement, taxes on traditional fuels and cooperation are the key elements to empower the niche mechanisms and especially the expectations. In this context, the exploitation of marine renewable energies (such as tides, waves, and offshore wind) provides an interesting potential, and yet wave energy is rarely considered [13] and often neglected [10,11,14]. Wave energy has a significant potential worldwide [15] for both decentralised [16] and centralised [17] approaches [18]. Although, wave renewables receive the abovementioned supports, including international collaborations and enhancing events such as the Wave Energy Prize [19] and the MARINET programs [20], this field is still at an early stage of development in comparison to other renewables such as the offshore wind. Therefore, methods must be elaborated to enable faster and more reliable calculations of the major economic indexes used to compare renewables [21,22], and thereby to foster the communication of wave renewables in order to increase the expectations. The levelised cost of energy (LCoE) is one of the most important metrics used to compare renewables [18]. The LCoE of a wave energy farm (WEF) is defined as the division of the levelised cost of the WEF over its entire lifecycle by the levelised energy produced for the same time period [23]. LCoE estimation is challenging for WEFs [24], and when estimated, it results in higher values compared to those of other renewables [25].

The device harvesting the ocean wave energy is the wave energy converter (WEC) [26]. WECs have very different designs [19], which is the main reason behind its lag in use compared to other renewables. This is due particularly to the complex resource wave climate system [27–29]. Therefore, pairing WEC and wave climate based on proper cost estimation and power production is an everyday challenge, and so is attracting investment in wave renewable energy. Pairing WEC and installation location requires selecting the WEC configuration (specific size and dimensions) [30]. Consequently, the WEC and location pairing also involves calculating the energy production component (or annual energy production, AEP) and cost over the different WEC configurations. A large part of the research in wave renewables is dedicated to AEP [28,31,32] and its calculation [25]. Therefore, AEP is probably the most reliable metric of LCoE [33,34] to date, whereas the cost remains a source of uncertainty. The cost is composed of the operation and maintenance costs (or operational expenditure, OpEx) and the capital expenditure (CapEx) that gathers all the other costs of LCoE [35]. Due to a lack of experience in WEF trials and despite the broad literature, the estimations of the OpEx are hardly trustworthy [36–38]. In contrast, wave energy companies know precisely most of the costs related to the CapEx, and OpEx has occasionally been estimated as a percentage of the CapEx [31,39–42]. Consequently, the assessment of the cost part of LCoE can be reduced to the CapEx.

This research aims to provide a systematic and comprehensive method for cost calculation adaptable to all WECs. The developed method enables automatic WEF cost, and thereby CapEx estimations for large datasets of WEC-configuration and site characteristics. This work investigates the integration of WEC, WEF, and site characteristics directly in the cost calculations. This calculation method could eventually improve WEC configuration-location pairing and selection. This pairing is often reduced to either an energy-based approach or to a small number of locations and WEC/WEF designs as:

(a) The manual cost estimation of large WEC configuration-location databases is time-demanding.
(b) CapEx is often defined for a fixed design of WEC and WEF by first distinguishing the CapEx from the WEF costs, and second by providing a breakdown of CapEx into its main components [31,43]. LaBonte et al. [44] also provided a clear decomposition of the CapEx. Their method is implemented within the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) tool [45] strongly linked to the study of Neary et al. [46] on the Reference Model Projects (RMP). Similarly, Chozas et al. [41] developed a cost of energy (COE) calculation tool. However, in these cases, no process is developed to calculate the costs for large datasets of WEC configurations. Besides, site, WEF, or WEC characteristic parameters can only be changed one at a time; these methods and programs cannot be used to compare the costs for large databases.

(c) Chang et al. [24] amongst others [35,47,48], have estimated the cost for most of the devices investigated by Barbarit et al. [49]. Furthermore, specific costs have also been provided for CorPower Ocean [50,51], Pelamis and Wavestar [52], Wave Dragon [53], Floating Power Plant A/S [54], M4 [55], and Seabased Industry AB [56], to name a few. These studies mainly used selected economic indicator-based equations such as the LCoE. Despite providing detailed costs, they did not offer clear methodologies to calculate these expenses to adapt to other machines or if present, the parameterisation of the costs, at least regarding WEC configuration scaling, remains limited.

(d) Since the number of governing parameters affecting the costs is large [43,48], studies often focus on a particular aspect of CapEx such as the mooring costs [57], or cable expenses to link the WEF to the grid [25,43,58–60]. These studies sometimes highlight the impact of parameters including site characteristics, or wave and weather conditions on the diverse component and their costs. Yet, they do not provide calculation methods, and a single and synthetic methodology is not available.

(e) CapEx is sometimes provided as a single number depending on the power production capacity of the WEF [61–63]. This number multiplied by the WEF rated power provides the CapEx in euros. However, this global approach provides a rough average of the final CapEx and lacks understanding and control on the calculation of the costs within CapEx.

(f) WEF element costs such as the WEC and moorings have also been parameterised using a single number depending on the WEC, or the WEC element, weight or characteristic mass [24,41]. For example, de Andres et al. [31] used the cost of steel from Myhr et al. [64], and they multiplied it by the WEC weight to estimate the WEC cost. However, steel prices are quite variable [64] so the cost estimation based on this approach remains approximate. Moreover, WECs are often composed of many different elements of various materials. Furthermore, WECs' dimensions are required to obtain the volume and so the mass of steel of the WEC, while they are rarely available. In some cases, the volume may need to be approximated due to complex shapes or multi-component design of the WEC. To sum up, this method can only be applied to a couple of elements from the WEF, enabling only a partial flexibility of the CapEx calculations.

(g) For a given WEC, de Andres et al. [50] provided a method (also applied by Pascal et al. [30]) scaling the CapEx with references to the Froude law similitude [65] used initially to scale marine structures in different sizes. In their study, de Andres et al. [50] adapted the Froude law for its application to CapEx. Yet, this approach remains global and lacks specific control in the calculation of the cost composing CapEx.

This work provides a comprehensive but concise synthesis of WEC and WEF cost breakdown and estimation guidelines. Moreover, these calculation methods lack the flexibility to integrate the many characteristics of WEC and site, in the cost calculation. Subsequently, this study introduces the new generic "CapEx method" for WECs, which is based on the synthesis of previous guidelines and methods. The aim is to develop a systematic techno-economic approach for CapEx and more importantly, the CapEx sub-cost calculations for large databases of WEF/WEC-configuration and site characteristics. The calculation aspect of this method could be implemented in the CapEx-calculation aspect of the software developed, for instance, by Castro-Santos and Filgueira-Vizoso [66] in the NREL-SAM-RMP and perhaps also enhance the COE tool. This calculation method is assessed alongside that of de Andres et al. [50] referred to as the "Similitude method" in the rest of the study.

The absence of information to obtain CapEx is partially driven by confidentiality matters relating to most companies. This study investigates Wavepiston [67] firstly because the company provided access to its WEC structural and economic details. Secondly, its 1:2 scale prototype has been tested in Denmark at Hanstholm test site [68], and it is planned to carry out full-scale testing at PLOCAN (Canary Islands—Spain) by the end of 2022 for possible farm installation to supply a desalinisation plant in the North of Gran Canaria [69].

In Section 2, the CapEx and Similitude methods are fully described. Section 3 shows the application of the two methods to the complex database of Wavepiston WEC configurations. Section 4 conducts the comparison and discussion between the CapEx and Similitude method for Wavepiston, including examining the effect of the different WEC-configuration and site-characteristic parameters before concluding in Section 5.

2. Methods

Figure 1 shows the main steps of the CapEx (left) and Similitude (right) methods that are presented in this section. In both approaches, the CapEx consists of overnight costs. Interest is therefore not considered in both methods' cost-calculations and is scarcely discussed in Section 2.1.1.

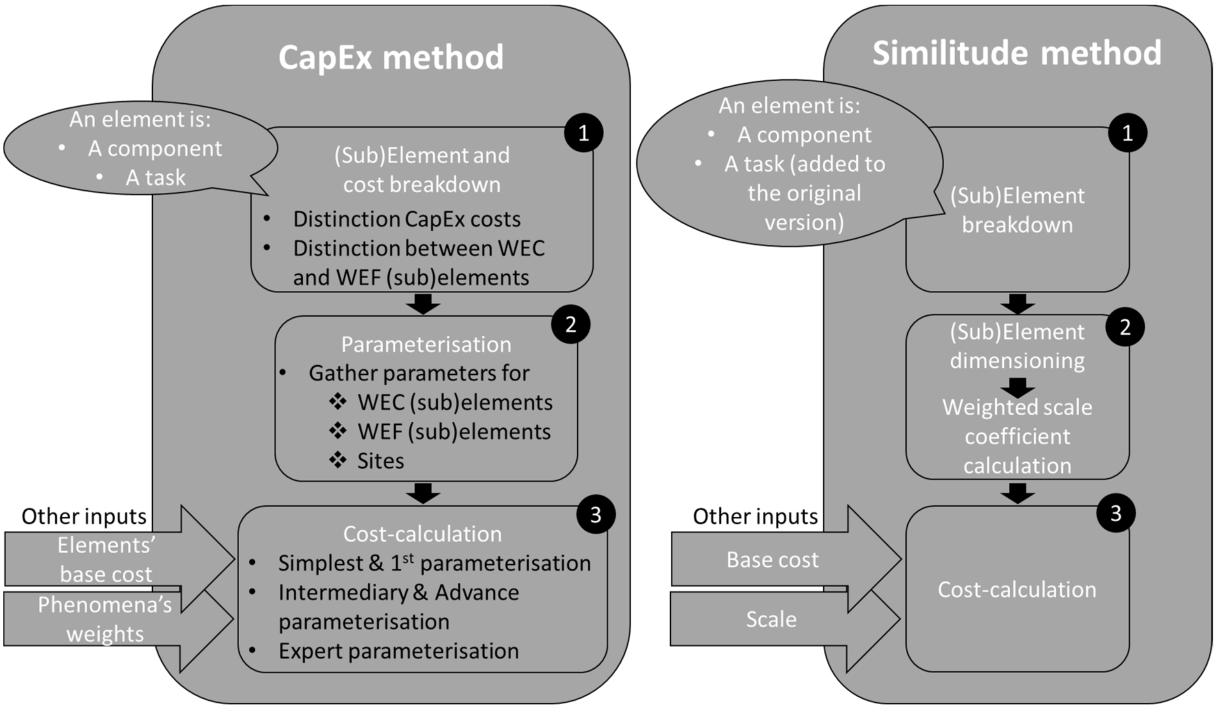

Figure 1. CapEx and Similitude method flow-chart.

2.1. CapEx Method

This section describes the CapEx method, which is organised into three steps (Figure 1, left-hand-side). It is worth noting that since this research is dedicated to wave renewables, the description of the method is associated with WEC and WEF examples, yet, the CapEx method can also be applied to other renewables.

2.1.1. Step 1: Elements and Costs Breakdown

To be able to distinguish the costs of CapEx and especially those of the WEC, it is essential to understand first the overall costs of a WEF project. These can be split into three parts:

(a) Development cost gathers all expenses from the WEC concept to WEF final design for a particular location. It includes the costs for the WEC development through all the phases of the WEC lifecycle, as well as the pre-installation costs from Clark et al. [43] including investments [31,58]. The expenses for location assessment, such as (i) bathymetry and seabed conditions, (ii) wave and weather climate, and (iii) energy demand infrastructures are also added. These three aspects will then help to select the most appropriate WEF design for the location of interest, which includes decisions on the number of WECs and the WEC configuration [35,48,51,53,54,70]; the installation location [61,71–73], the WEF arrangement, particularly regarding park effects and wave direction impact [72]; and the selection of cables, moorings, and anchors [25,57,60,74].

(b) Construction and installation costs of the WEF for each location. It accounts for the price to purchase and/or manufacture the WEF elements, deploy, install, and connect the WEF to the grid [58,75] following the WEF design decisions mentioned in part 1.

(c) Decommissioning costs is the budget allocated to WEF disconnection, uninstalling, and decommissioning. Often the disconnection and uninstall are included in the decommissioning. Clark et al. [43] broke down the decommissioning cost.

Additional WEF project costs also occur during its lifetime such as insurances, taxes, rent of the location, amongst others [56,76], but these are less substantial. CapEx can be seen as the estimation of the costs of the beginning and the end of the WEF lifetime, while the operations and maintenance costs are spent during the WEF lifetime until the moment it is decommissioned [77]. CapEx usually gathers points b. and c., and occasionally the aforementioned additional costs, whereas the operation and maintenance cost often includes location rent and associated insurances [38]. It is worth noting that the LCoE calculation is linked to a specific farm project, and the cost of development might be spread over many projects, explaining the possible disregard of point a. within CapEx. This is also the reason why the interest is commonly excluded from the CapEx calculations, although LaBonte et al. [44] provided a "fixed charge rate" factor that accounts for the interest and multiplies the overnight CapEx. Overall, financial supports for wave renewables are diverse (see Section 1) in origin (e.g., from international to local), type, and length [8,78]. They may address the WEF project either in whole or on specific and more focused aspects. The interest is challenging to estimate also considering that such a niche requires a smoother transition and inclusion of the diverse supports [8]. Furthermore, WEF construction and installation (and decommission) durations and associated interests may often be difficult to estimate due to lack of experience, and they may vary from one WEC to another [53,69,79]. In general, interest is considered in the net-present value (NPV) calculation, as a way to discount the future cash flow, but the period used for this calculation is the entire WEF lifetime and CapEx (as overnight costs) is assumed to be paid at year zero [40].

Once CapEx costs are distinguished and the clear definition of which cost is considered in the study, the complex WEF system must be transformed into simple elements that are easier to assess economically. This task also involves the WEC design breakdown [80]. This transformation consists of: (i) clearly defining the above different costs that will be considered in the CapEx; and (ii) determining which components belong to the WEC and which to the WEF. Then each major element of the WEC and WEF can be divided into sub-elements.

Moreover, similar to the tidal farms [75], each component and sub-component may be associated with the following tasks: costs of manufacturing, assembly (onshore or offshore), deployment, installation, connection, and decommission that includes the disconnection and uninstallation. The first four tasks happen at the beginning of the WEF lifetime, and the last one at the end. Additionally, tasks may be associated with sub-tasks, and so in the following, both components and tasks are called elements and sub-components and sub-tasks sub-elements.

The level of detail of element and sub-element analysis is in line with the user knowledge accumulated about WEC and WEF design. This level of experience and knowledge can be measured using the technology readiness levels (TRL) [81,82] or the WEC company phase [83].

2.1.2. Step 2: Parameter Selection

The second step of the CapEx method is the selection of the parameters for the cost parameterisation. Each WEC is characterised by significant dimensions (e.g., WEC width and length, and number of energy-collectors if more than one) that are part of parameters. The sites' wave climates and particular characteristics, as well as additional features from the WEC, should be translated into parameters that may be required for the parameterisation.

2.1.3. Step 3: Cost Estimation and Parameterisation

The last step of the CapEx method is the cost parameterisation. Once elements and tasks are sorted between the WEC and WEF, their base or default cost can be estimated. This base cost is obtained for WEC-WEF simplest and smallest conceivable design for commercialisation.

The total cost of an element is composed of a base cost, and the margin the WEC company expects to profit from selling this piece. Hence, each WEF and WEC element total cost is as follows:

$$\text{Element Total Cost} = \text{Element Base Cost}\ (1 + \text{Element Margin}) \quad (1)$$

where the margin is in percentage (e.g., for a margin of 5% the element margin equals 0.05), and the base and total costs in €. For WEF projects under TRL5, companies may not consider the margin since it requires a certain experience to be estimated. If the margins were neglected, then, total cost would equal base cost. It is worth noting that the base cost may fundamentally be dependent on a specific variable; for example, the cost of underwater cables is often provided in €/m [25,32]. In such a case, the base cost may be divided into two components with a fixed part and a part multiplied by the considered variable value, in this example, the distance to shore [77].

In the CapEx method, at the level of the CapEx or WEC/WEF main elements, the base costs are large sums of the total costs of the sub-elements, similar to the cost calculation shown by Clark et al. [43] and Castro-Santos et al. [77]. In contrast, at the level of sub-element total cost, the base cost, in this method, is the cost estimated for the smallest conceivable; but for marketable, size of the device. The value of the sub-element base costs can often be determined from subcontractors' catalogues and quotes.

A new cost in each element total cost function called factors can be introduced as:

$$\text{Element Total Cost} = (\text{Element Base Cost} + \text{Element Total Factor})\ (1 + \text{Element Margin}) \quad (2)$$

These factors try to capture future WEF local environmental, legislative, and economic phenomena. Depending on the reasoning of the company, the factors may be assessed in different ways. The objective is to provide the initial description of how to obtain the final estimation of each element for the considered parameterised WEF/WEC problem. The factors can be used in five different ways, from the simplest (first parameterisation of the costs), to the expert approaches through the intermediary and advanced levels with increasing flexibility and thereby complexity.

2.1.3.1. Simplest Approach for the Factors and First Parameterisation

The simplest approach of the factors is dedicated to companies with a small TRL. In the simplest approach, each element's total factor would be a single number estimated from the user's experience according to the element configuration or size and the site's characteristics. For instance, sites with challenging weather and high wave conditions require costlier factors than for calmer sites. However, this approach is strictly based on the developers' experience saying in a location the conceivable farm would cost this much and at the other location the cost was increased by a certain percentage due, for instance, to a rougher weather and wave climate.

The first parameterisation method consists of a single factor that is the total factor. The factor is the multiplication of a parameter, amongst those selected in step 2, by a weight that illustrates the impact of this parameter on the cost. The weight may be in the order of the base cost so that the associated factor (multiplication of the weight and parameter) could be translated as a percentage of the base cost. Examples of such factors could be based on the mass-method (item f) in Section 1) such that the parameter would be the mass, and the weight the cost of mass.

2.1.3.2. Intermediary and Advanced Parameterisation

Assuming that the company is gaining more experience with WEF costs, the total factor may take the form of a sum of *nf* factors improving the first parameterisation process described in Section 2.1.3.1:

$$\text{Total factor} = \sum_{i=1}^{nf} \text{Factor}_\text{i} = \sum_{i=1}^{nf} \text{Weight}_\text{i}\ \text{Parameter}_\text{i} \quad (3)$$

Each factor is associated with a specific phenomenon impact on the cost such that the factor's parameter is the direct translation of the phenomenon impact and the weight the strength of this phenomenon. Phenomena can be scaling, site location, alongside weather and wave-climate conditions, amongst others. It is worth mentioning that when examining the phenomenon affecting each WEC and WEF element and sub-element costs, the list of parameters determined in step 2 might be extended when there is no parameter representative enough of the phenomena.

Following Clark et al. [43] and Castro-Santos et al. [77] who decomposed the costs of a fixed hybrid offshore wind-wave farm (or from Segura et al. [75] for tidal farms), the CapEx calculation can be parameterised by:

(a) Determining all the phenomena affecting each cost,
(b) Translating these phenomena into factors, and
(c) Adding the sum of the resulting factors to each cost.

The intermediary approach of the factors is the implementation of more physical and concrete phenomena including scaling based on the WEC and WEF sizes, site characteristics as the distance to shore amongst others [25], and local or regional (example of the labour price) impacts on the costs [58].

In the advanced approach, more abstract phenomena could be considered, such as economies of scale, power absorption, and weather and wave climate effect on the costs. For instance, a factor could be based on the power-method (item e) in Section 1) such that the parameter would be the WEC rated power and the weight cost per kilowatt. Furthermore, using the example of the weather and wave conditions, a factor could be the multiplication of the average wind speed, U_{10} (m/s), or significant wave height, Hs (m), respectively. Then, tests could be conducted to estimate failures and need for WEC size change for different U_{10} and Hs values and thereby changes in the WEC (or the considered element) cost change compared to its smallest marketable design. Often when WEC companies start to investigate the costs for LCoE estimations, they have already conducted tests from calm waters to real offshore conditions, enabling them to have a great understanding on how such parameters affected the need of WEC sizing involving cost change.

2.1.3.3. Expert Approach of the Factors

A more experienced company could consider more complex weight factors as functions of other parameters by using learning curve effects often encapsulating the economies of scale [40,84,85], amongst others. Such improvement could similarly be made for the weather and wave terms, as well as the other factors in general.

2.2. Similitude Method

The Similitude method from de Andres et al. [50] uses the Froude law similitude principles [65] to scale the CapEx. Using the example of the CapEx calculation from Clark et al. [43], Castro-Santos et al. [77], and Segura et al. [75], or any other cost calculation, the Similitude method similar to the CapEx method consists of three steps (Figure 1, right-hand-side):

(1) Conduct the element distinction similar to (Step 1 of the CapEx method) as carried out in these studies,
(2) Prepare the data for calculation:

(a) Determine the source-dependency of the functionality of the modules associated with the costs. Table 1 provides a list of different dimensions (also referred to as quantities or sources), and their scaling parameter from the Froude law similitude (Sheng et al. [65] and Hughes [86] provided additional sources).
(b) Average all the scaling parameters to obtain the "weighted scale coefficient" shown in Equation (4), and

(3) Conduct the cost-calculation using the final CapEx estimation from these studies which would be interpreted as the $\text{CapEx}_{\text{Base cost}}$ in Equation (4) and be multiplied by the new scale of the farm power the weighted scale coefficient following Equation (4):

$$\text{CapEx}_{\text{Total cost}} = \text{CapEx}_{\text{Base cost}}\ \text{Scale}^{\text{Weighted scale coefficient}}. \quad (4)$$

Table 1. Scale parameter of the Froude law similarity adapted from [65,86].

Function Dimension	Scale Parameter
Acceleration	0
Area	2
Force	3
Length	1
Mass/Volume	3
Power	3.5
Pressure	1
Dimensionless quantity (such as efficiency)	0
Volume flow rate	2.5

Yet, the wave- and wind-related elements and related CapEx might need to be separated for the wave and offshore-wind different representative dimensions (such as the WEC length and the windmill circumference, respectively) and thereby scaling factor.

It is worth noting that in the study of de Andres et al. [50] $\text{CapEx}_{\text{Base cost}}$ was obtained for a WEC with a rated power of 25 kW. It is recommended to use the smallest marketable design of the WEF for $\text{CapEx}_{\text{Base cost}}$ so that the scaling would only apply for larger WEF designs. The Similitude method could be compared to the CapEx first parameterisation one; the CapEx method parameters would be the scaling factors between the referenced and scaled design of the same WEC [80], and the scale parameters the weights.

3. Materials and Application of the Methods to Wavepiston Wave Energy Converter

Since one of the objectives of this work is to illustrate an example of how to handle complex and limited databases of WEC-configuration and site characteristics, this study's factorisation level is intermediate to emphasise the description of the dataset. The CapEx method and then the Similitude method are applied to Wavepiston.

3.1. CapEx Method Applied Wavepiston WEC

3.1.1. Step 1: Wavepiston WEC Breakdown into Elements

Figure 2 (Wavepiston is currently developing a new version of their WEC without the string, but this version has not been computed yet. However, this should have little effects on costs and theoretical energy production.) shows the Wavepiston WEC, often simply called Wavepiston, and its sub-elements.

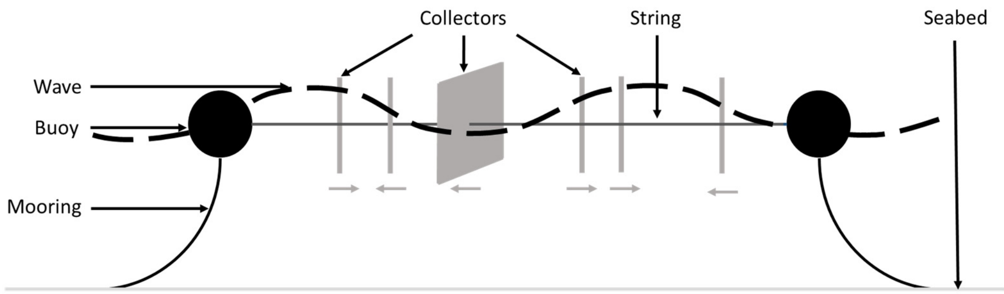

Figure 2. Wavepiston visual description.

The WEC is a string of hinged energy collectors with the ability to move back and forth in a limited space along the string [87]. The string is attached to two buoys that are anchored to the seabed (Figure 2).

Collector

The collectors are Wavepiston's Power Take-Off systems (PTOs) illustrated in Figure 3. They are made of a plate that moves using a wagon (not shown in Figure 3) along a beam. This movement actions two pumps connected to each side of the plate, so that they pump the water that is transferred to the string through the valves and the pipe [87].

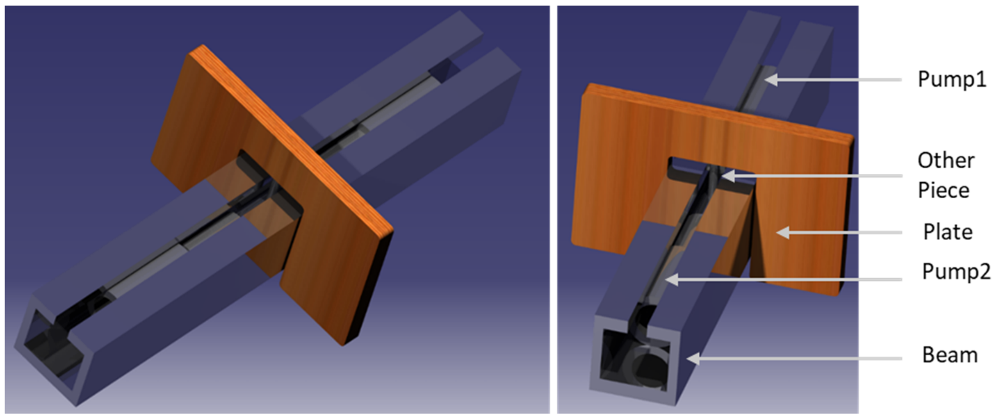

Figure 3. Collector artistic representation.

The pipes and valves are part of the "other pieces" in Figure 3, which also include bolts, joints, to name a few. Additional manufacturing is considered for the assembly of the collector.

String and Moorings

The string accounts for the two buoys and attached moorings including the anchors. The string is made of wire and rope alongside a pipe joined to the collectors using connectors, and valves. The pipe transmits the flux of water that will be used eventually to spin the turbine of the generator. Additionally, the string needs shackles and connectors to attach the collectors, buoys, and moorings. Furthermore, the string's elements gather the monitoring and control systems.

The moorings were distinguished as a sub-element of the string since filling a very particular purpose of holding the string. They are made of rope, chain, and wire [74] alongside the use of shackles. As well as for the collector, additional pieces (risers, fasteners, amongst others) are included in the string's elements that encapsulate both the additional pieces of the moorings and the string.

Summary and Tasks

Figure 4 illustrates the division of a Wavepiston WEC into elements and tasks such that all pieces combined are sub-elements or tasks of the right column element to which they are linked.

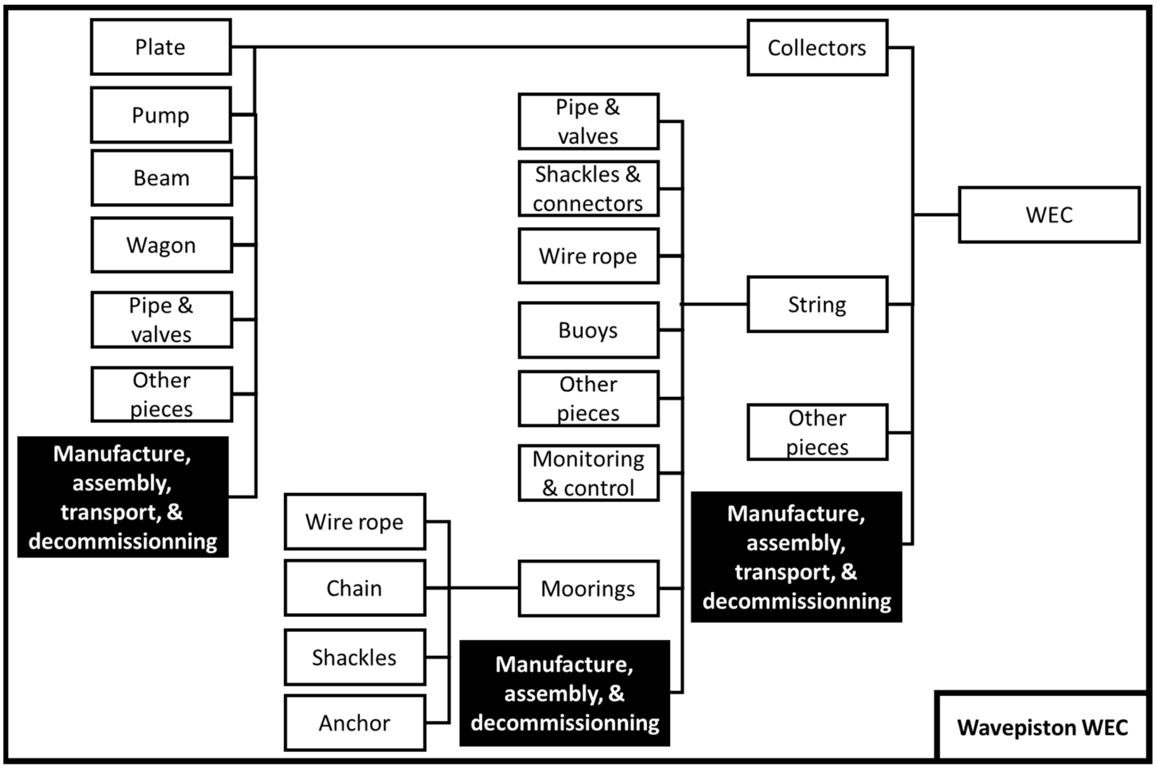

Figure 4. Wavepiston WEC main pieces and components (white cells) and tasks (dark cells) gathering tasks.

Wavepiston manufacturing (Figure 4) cost is estimated as the sum of the *Np* collectors, including their attachment to the string. The transport task implies boats' use to bring to shore either a Wavepiston or just a collector from it. Hence, the transport does not appear in the task box of the string sub-elements. Furthermore, the mooring elements possess no tasks because string elements integrate moorings, thence the actions apply the entire moorings and not its pieces individually. Tasks including deployment connection and disconnection alongside elements such as connecting cables to onshore power stations, as well as turbines and generators belong to the WEF hence are not considered here.

3.1.2. Step 2: Wavepiston WEC and Site Parameters

The parameters that determine a Wavepiston WEC configuration are: the plate shape, *ps* (–), and its dimensions: plate area, *pa* (m^2), plate width, *pw* (m), and depth, *pd* (m); as well as the number of plates (and thereby collectors) per string, *Np* (–), and the distance between the plates called plate-location configuration, *plc* (m) [87]. This study also includes the water depth at site, *s*, the wamit water depth, *h*, which is a parameter of the WEC configuration (for the numerical simulations [87]), and the site water depth, *d*, which is the expected water depth where the farm is installed, and the distance to the coastline, *q* (m).

The parameters used for the WEC model are *Np*, *plc*, *ps*, *pw*, *pd*, and *h*. They are mentioned in the following as the Wavepiston WEC configuration parameters and are the only "internal" parameters defining each WEC configuration. Table 2 display their values and combinations.

Table 2. Distribution of the wamit water depth, *h*, for the Wavepiston WEC configuration parameters. When a configuration assesses all *h*, the cell number is "4"; otherwise, the underlined numbers show the exact *h* value(s).

Plate Shape (*ps*)		**Ellipse**							**Rectangle**								
Number of Plates (*Np*)		**1**	**8**			**24**			**1**	**8**					**24**		
Plate Width (*pw*, in m)	**Plate Depth (*pd*, in m)** \ **Plate Location Configuration (*plc*, in m)**	0	7	10.5	14	7	10.5	14	0	16	13.5	7	10.5	14	7	10.5	14
1	1								$\underline{-1\ \&\ 20}$								
2	2								$\underline{-1\ \&\ 20}$	$\underline{20}$	$\underline{20}$						
3	1.5								$\underline{-1\ \&\ 20}$								
3	3	$\underline{-1}$							4		$\underline{20}$	4	4	4	4	4	4
4	4								4		$\underline{20}$	4	4	4	4	4	4
4.5	2								$\underline{-1\ \&\ 20}$								
5	5								4		$\underline{20}$	4	4	4	4	4	4
6	2.5								$\underline{-1\ \&\ 20}$								
6	6								4			4	4	4	4	4	4
6.7	6.7	4	4	4	4	4	4	4									
9	4								4			4	4	4	4	4	4

Table 2 also shows that there are 184 combinations of the *Np*, *plc*, *ps*, *pw*, *pd*, and *h* parameters, for 53 configurations excluding *h*. The elliptical plates contain only diameters of *pw* = *pd* = 3 m and *pw* = *pd* = 6.7 m, which makes them in fact circular. The biggest circular plate is assessed by the four *h* scenarios, whereas the first is only evaluated for *h* >> 100 m. The rectangular equivalent exists only for *ps* = *pd* = 3 m. Most of the combinations of *Np*, *plc*, *pw*, and *pd* parameters for rectangular plates are provided for *h* = 20 m. The smallest plates below 4.5 m^2 are only assessed as rectangular plates, for *plc* = 0, 13.5, 16 m, and for the extreme *h* >> 100 m or *h* = 20 m. Finally, most of the plates above 6 m^2 are assessed by all the combinations of *Np*-*plc*.

Figure 5 shows the considered sites and the classes they belong to with reference to Table 3's first column. Table 3 provides a review of combinations of the parameters (*d*, *s*, and *q*) considered in this research.

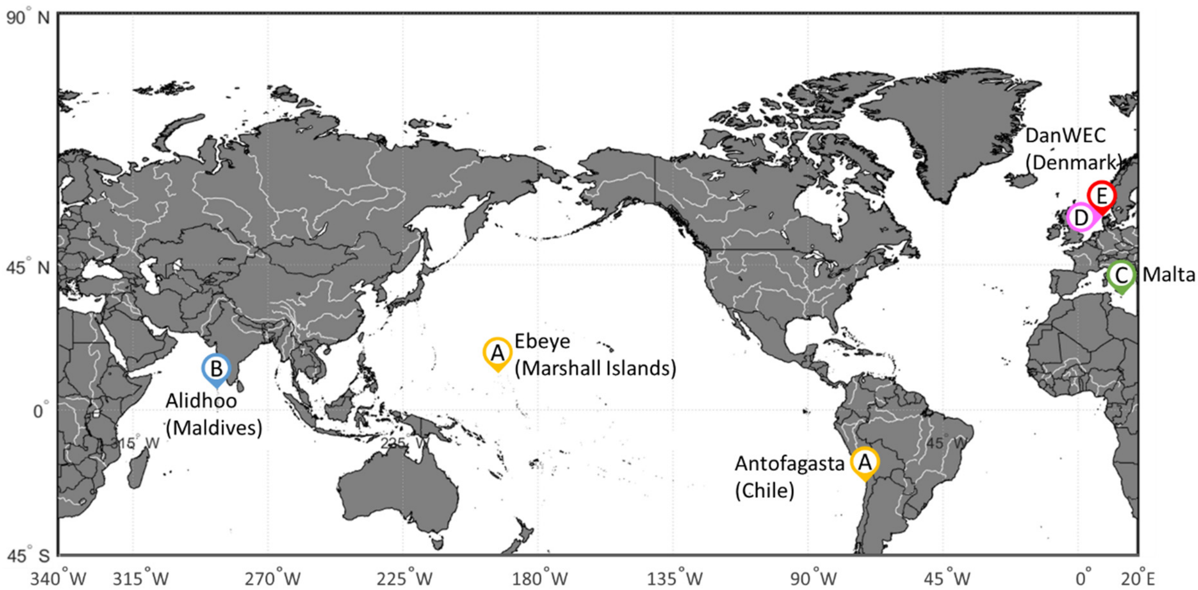

Figure 5. Sites' location and class with reference to Table 3.

Table 3. External parameters relationship of the sites.

Class of Combination of Site Parameters	Buoy/Hindcast Water Depth (s, in m)	Site Water Depth (d, in m)	Wamit Water Depth (h, in m)	Distance from the Site to Shore (q, in m)
A	If $s \geq 200$ m	100	−1	1700
B	Else if $s \geq 75$ m	80	−1	1700
C	Else if $s \geq 40$ m	50	50	4250
D	Else if $s \geq 25$ m	30	30	4250
E	Else $s < 25$ m	20	20	4250

In Table 3, only d provides a unique value per line. Therefore, d is solely used in the following to display the impact of the site parameters.

3.1.3. Step 3: Wavepiston WEC Cost Parameterisation

The total Wavepiston WEC cost, $WEC_{Total\ cost}$, (and its elements and sub-elements) is structured following Figure 4 and calculated as follows:

$$WEC_{Total\ cost} = WEC_{Base\ cost} = (Np\ [Collector_{Total\ cost} + COA_{Total\ cost}] + String_{Total\ cost} + Moorings_{Total\ cost} + WEC_{Total factor})(1 + WEC_{Margin}) \quad (5)$$

with Np the number of plates, $Collector_{Total\ cost}$ the total cost of a single collector and $COA_{Total\ cost}$ the cost of onshore assembly. Wavepiston Company estimated that the WEC dimensions and site characteristics would not impact $COA_{Total\ cost}$ and that no margin could be obtained from such a task, thus, $COA_{Total\ cost}$ equals its base cost $COA_{Base\ cost}$. $String_{Total\ cost}$ and $Moorings_{Total\ cost}$ are the total costs of the string and mooring, respectively. Additionally, the factors estimated for the WEC sub-elements are representative enough to the several phenomena affecting the costs, and so no factors were added to the overall WEC cost. As Wavepiston estimated the margin over the entire WEF, the value of the margin is not distributed among the WEF and WEC elements or their sub-elements. Thus, WEC_{Margin} equals zero and to simplify the equations, the margins factors are not shown in the other equations since they are ineffective.

In the following, the equation for the cost of the three main elements of the WEC, namely, the collector, string, and moorings are investigated. The sub-element costs of the collector, string, and moorings, and the factors' weights were originally estimated from a detailed analysis of the subcontractor prices for the Wavepiston prototype, including the first 1 m × 1 m plate offshore test at DanWEC and the 8-plate prototype tested at Nissum Bredning [88]. During the testings of Wavepiston at scale 1:4 and 1:2, with different plate shapes at Hanstholm [68] these estimations were adjusted. Finally, these tests also provided the values of all the base costs from the smallest marketable design of Wavepiston consisting of one string with one rectangle plate of size 1 m × 1 m.

Collector

The equation of the total collector cost is:

$$Collector_{Total\ cost} = Collector_{Base\ cost} + Collector_{Total\ factor}, \quad (6)$$

with:

$$Collector_{Base\ cost} = Pl_{Total\ cost} + Pu_{Total\ cost} + Be_{Total\ cost} + Wa_{Total\ cost} + PV_{Total\ cost} + COP_{Total\ cost} + CAM_{Total\ cost}. \quad (7)$$

Following step 1 of the CapEx method, the total costs of the collector's sub-elements relate to plate and pump ($Pl_{Total\ cost}$ and $Pu_{Total\ cost}$), beam ($Be_{Total\ cost}$), wagon ($Wa_{Total\ cost}$), pipe and valves ($PV_{Total\ cost}$), collector's other pieces ($COP_{Total\ cost}$), and collector's assembly and manufacturing ($CAM_{Total\ cost}$). Most of the sub-elements of the collector only consist of their base cost to which is added the total factor composed of a single factor, following

Equation (2) with the margins equal to zeros, as mentioned before. These are summarised in Table 4. $CAM_{Total\ cost}$ equals zero because the assembly and manufacturing are carried out by Wavepiston. $Wa_{Total\ cost}$ and $PV_{Total\ cost}$ are equal to their base cost. Indeed, they are designed to support any size plate, and so their price is fixed. $Wa_{Total\ cost}$ costs 550 € and $PV_{Total\ cost}$ 800 €. For each sub-element of the collector, the base costs are the costs associated with a string composed of a single rectangular plate of size 1 m × 1 m.

Table 4. Collector's sub-elements' base cost and factor.

Sub-Element Name and Variable	Sub-Element Variable	Base Cost (in €)	Total Factor Name	Factor Weight	Factor Parameter	Comments
Plate	$Pl_{Total\ cost}$	400	Plate total factor	60 €/m^2	*pa*	This factor translates the quantity of material to add to the plate
Pump	$Pu_{Total\ cost}$	100	Pump total factor	60 €/m	*pw*	This factor is associated with the scaling of the pipe to engorge more or less flow
Other pieces	$COP_{Total\ cost}$	100	Other pieces total factor	20 €/m	*pw*	This factor expresses increase of the other pieces for more energy extraction in relation to the plate width
Beam	$Be_{Total\ cost}$	400	Beam total factor	30 €/m	*pw*	This factor is associated to the material required per extra meter of plate

Many of these factors are based on the plate width because as a terminator-type of device, the Wavepiston power absorption most influencing parameter is the length of the device facing the wave crest, which is the plate width. The pipe must be capable of gorging the flow actioned by the plate movement. Hence, the pump factor depends on the plate width.

String

The equation for the string total cost is:

$$String_{Total\ cost} = String_{Base\ cost} + String_{Total\ factor}, \quad (8)$$

with:

$$String_{Base\ cost} = SW_{Total\ cost} + SP_{Total\ cost} + SC_{Total\ cost} + MC_{Total\ cost} + Bu_{Total\ cost} + SOP_{Total\ cost} + SAM_{Total\ cost}. \quad (9)$$

Following step 1 of the CapEx method, the string base cost is the sum of the string's sub-elements total costs: string's wire ($SW_{Total\ cost}$), string's pipe ($SP_{Total\ cost}$), shackles and connectors ($SC_{Total\ cost}$), monitoring and control ($MC_{Total\ cost}$), buoy ($Bu_{Total\ cost}$), string's other pieces ($SOP_{Total\ cost}$), string's assembly and manufacturing that also account for the moorings' ($SAM_{Total\ cost}$). $SC_{Total\ cost}$, $MC_{Total\ cost}$, $Bu_{Total\ cost}$, and $SOP_{Total\ cost}$, were estimated to remain the same irrespective of the string size or number of plates and so they equal their base cost. The cost of $SC_{Total\ cost}$ is 600 €, $MC_{Total\ cost}$ 3 K€, and $SOP_{Total\ cost}$ 4.5 K€. $Bu_{Total\ cost}$ is 8 K€, the cost of the two buoys (one at each end of the string):

$$SW_{Total\ cost} = SW_{Base\ cost\ per\ meter}\ Np\ plc + SW_{Total\ factor}, \quad (10)$$

where $SW_{Base\ cost\ per\ meter}$ is 12 €/m, the price per meter of string length that is then multiplied by the total length of the string obtained as the product of the number of plates and the distance between them. Similarly, to the string wire, the string pipe base cost depends on the string length and its base cost per meter of string length ($SP_{Base\ cost\ per\ meter}$) is 9 €/m. The factors of both sub-elements are summarised in Table 5:

$$SP_{Total\ cost} = SP_{Base\ cost\ per\ meter}\ Np\ plc + SP_{Base\ cost} + SP_{Total\ factor}. \quad (11)$$

Table 5. String's sub-elements' base cost and factor.

Total Factor Name	Total Factor Variable	Number of Factors	Factor Name	Factor Variable	Factor Weight	Factor Parameter	Comments
String wire total factor	$SW_{Total\ factor}$	2	String wire factor 1	$SW_{Factor\ 1}$	400 €	*Np*	This factor expresses the cost impact of the sockets and start-up of the wire production
			String wire factor 2	$SW_{Factor\ 2}$	300 €	*Np*	This factor translates the cost impact of fishplates and specific non-standard shackles
String pipe total factor	$SP_{Total\ factor}$	1	String pipe factor	SP_{Factor}	20 €	*Np*	An additional base cost of 20 € is added to the base cost per meter for the end caps

Moorings

The total moorings cost is:

$$\text{Moorings}_{\text{Total cost}} = \text{Moorings}_{\text{Base cost}} + \text{Moorings}_{\text{Total factor}}, \tag{12}$$

with:

$$\text{Moorings}_{\text{Base cost}} = \text{MW}_{\text{Total cost}} + \text{Ch}_{\text{Total cost}} + \text{Sh}_{\text{Total cost}} + \text{An}_{\text{Total cost}}. \tag{13}$$

Following step 1 of the CapEx method, the total costs of the moorings' sub-elements relate to moorings' wires ($\text{MW}_{\text{Total cost}}$), chains ($\text{Ch}_{\text{Total cost}}$), shackles ($\text{Sh}_{\text{Total cost}}$), and anchors ($\text{An}_{\text{Total cost}}$). The moorings already designed to handle extreme conditions are not associated with additional factors, however, they depend on site characteristics:

$$\text{MW}_{\text{Total cost}} = \text{MW}_{\text{Base cost per meter}}\ 4\ d + \text{MW}_{\text{Base cost}}, \tag{14}$$

where $\text{MW}_{\text{Base cost per meter}}$ is 7 €/m and $\text{MW}_{\text{Base cost}}$ 1.1 K€. Dunnet and Wallace [62] estimated the length of the mooring lines as three times the site water depth. In the case of Wavepiston, this was extended to four so that it becomes three times the site water depth in addition to the original site water depth. It assumed that 40 m of chain is required per moorings and therefore $\text{Ch}_{\text{Total cost}}$ is:

$$\text{Ch}_{\text{Total cost}} = 40\ \text{Ch}_{\text{Base cost per meter}}, \tag{15}$$

with $\text{Ch}_{\text{Base cost per meter}}$ equals to 110 €/m. Such as $\text{Bu}_{\text{Total cost}}$, the base costs, costs per meter, are for two mooring's wires for $\text{MW}_{\text{Total cost}}$ and two chain for $\text{Ch}_{\text{Total cost}}$. Similarly, $\text{An}_{\text{Total cost}}$ is the cost of the two anchors of 40 K€, and $\text{Sh}_{\text{Total cost}}$ gathers the total cost of the eight shackles (four shackles per moorings) that is of 7.5 K€.

3.2. Similitude Method Applied to Wavepiston WEC

The first step of the Similitude method from de Andres et al. [50] is very similar to the first step of the CapEx method. Therefore, the (sub)element-decomposition used here is the one shown in Figure 4. As for the second step, Table 6 provides the dimension of the source-dependency of each element and sub-element of Wavepiston WEC (summarised in Figure 4) following the example provided by de Andres et al. [50] using CorPower WEC. Despite being similar, some elements from CorPower do not have the same functionality as for Wavepiston. For instance, CorPower WEC's buoy functionality dimension is the area because it is the contact of the buoy surface area with the waves that enables harvesting the wave power [50], whereas Wavepiston WEC's buoys (and attached moorings) functionality is to maintain the tension in the string and so the buoy functionality dimension is the force.

Table 6. Functionality-related dimension of Wavepiston WEC elements and sub-elements (organised as in Figure 4) following de Andres et al. [50].

Wavepiston WEC Elements	Function Dimension	Collector Sub-Elements	Function Dimension	String Sub-Element	Function Dimension	Mooring Sub-Elements	Function Dimension
Collector	Force	Plate	Area	Pipe and valves	Volume flow rate	Wire rope	Force
String	Force	Pump	Pressure	Shackles and connectors	Force	Chain	Force
Other pieces	Force	Beam	Force	Wire rope	Force	Shackles	Force
Tasks	Mass/Volume	Wagon	Acceleration	Buoys	Force	Anchor	Force
		Pipe and valves	Volume flow rate	Other pieces	Force		
		Other pieces	Area	Monitoring and control	Power		
		Tasks	Mass/Volume	Moorings	Force		
				Tasks	Mass/Volume		

Four approaches to calculate the weighted scale coefficient in Equation (4) are investigated here. The first consists of averaging all scale parameters to estimate the weighted scale parameter. In addition, the average is calculated for all elements of Table 6 (index 1 in Table 7), as well as only the sub-elements (index 2). Index 3 averages is the total average of the average of the elements' average of its sub-element functionality dimensions include the element's scale parameter. The last approach (index 4) relies on the Wavepiston WEC's elements designed scale parameters.

Table 7. Weighted scale factors.

Weighted Scale Coefficient Calculation Approach Index	Weighted Scale Coefficient Calculation Approach	Weighted Scale Coefficient Value
1	Average over elements and sub-elements	2.674
2	Average over all the sub-elements	2.625
3	Average of the sub-elements' averages	2.866
4	Average over the elements	3

Finally, for this study two parameters are selected to be the "Scale" from Equation (4), to apply the Similitude method to Wavepiston, following Froude law similitude representative dimension: Wavepiston plate width and total length.

4. Results and Discussion

This section is divided into two. The first sub-section first presents and discusses the sub-element cost and factor values obtained for Wavepiston dataset, and then Wavepiston WEC cost using the CapEx method is investigated. The second sub-section presents Wavepiston WEC cost obtained using the Similitude method and the discussion aims to discuss these results in relation to the Froude law similitude, as well as comparing them with the results from the CapEx method.

4.1. Wavepiston WEC Cost and Sub-Costs Using the CapEx Method

The effect of the factors on the sub-element costs are first investigated in this section. Then, the costs of Wavepiston WEC for the whole database are provided.

4.1.1. Wavepiston WEC Elements' Costs

To summarise Section 3.1.3., the collector's factors mostly depend on the plate size (its area and width), the string's on the number of plates and distance between the plates, and the moorings' on the distance to shore. Table 8 provides the total collector cost in function of the parameters above, Table 9 for the string, and Table 10 for the moorings. To help with the reading of the following tables, a heat map was added with red representing the highest costs and blue the lowest, which applies separately for each column of Tables 8 and 9, and over all the columns of Table 10.

Table 8. Collector cost—Equation (6)—and their total factors for the combination of the relevant parameters. The darkest red cell is the highest value per column, and the darkest blue reflects the lowest one.

Plate Shape (ps, in –)	Plate Width (pw, in m)	Plate Depth (pd, in m)	Plate Area (pa, in m^2)	Collector Total Cost (in €)	Plate Total Factor (in €)	Pump Total Factor (in €)	Beam Total Factor (in €)	Other Pieces Total Factor (in €)
rectangle	1	1	1	2370	60	60	30	20
rectangle	2	2	4	2660	240	120	60	40
rectangle	3	1.5	4.5	2800	270	180	90	60
ellipse	3	3	7.07	2954	424	180	90	60
rectangle	3	3	9	3070	540	180	90	60
rectangle	4.5	2	9	3235	540	270	135	90
rectangle	4	4	16	3600	960	240	120	80
rectangle	6	2.5	15	3760	900	360	180	120
rectangle	5	5	25	4250	1500	300	150	100
rectangle	6	6	36	5020	2160	360	180	120
ellipse	6.7	6.7	35.26	5052	2115	402	201	134
rectangle	9	4	36	5350	2160	540	270	180

Table 9. String cost—Equation (8)—and their total factors obtained for the relevant parameters. The darkest red cell is the highest value per column, and the darkest blue reflects the lowest one.

Number of Plates (Np, in –)	Distance between Plates (plc, in m)	String Total Cost (in €)	String Pipe Total Factor (in €)	String Wire Factor 1 (in €)	String Wire Factor 2 (in €)
1	0	18,717	25	400	300
8	7	25,472	200	3200	2400
8	10.5	26,648	200	3200	2400
8	13.5	27,656	200	3200	2400
8	14	27,824	200	3200	2400
8	16	28,496	200	3200	2400
24	7	41,776	600	9600	7200
24	10.5	45,304	600	9600	7200
24	14	48,832	600	9600	7200

Table 10. Mooring cost—Equation (12)—in function of the relevant parameters. The darkest red cell is the highest value of the entire table, and the darkest blue reflects the lowest one.

Wamit Water Depth (h, in m)	Mooring Total Cost (in €) Per Site Water Depth (d, in m)				
	d = 100	d = 80	d = 50	d = 30	d = 20
$h \geq 100$	55,800	55,240	–	–	–
50	–	–	54,400	–	–
30	–	–	–	53,840	–
20	–	–	–	–	53,560

Table 8 shows that Wavepiston PTO, which is its collector, is below the 6 K€ estimated by Clark et al. [43]. The Wavepiston PTO cost is very close to the oscillating water column (OWC) and fixed oscillating wave surge converter (OWSC) from de Andres et al. [31] obtained from the reversed LCoE method giving PTO values around 1.1 K€. In contrast, these values are above the PTO of floating OWSC, and for the overtopping and heaving WEC around 5.5 K€ (conversion from British pound sterling, £1 = 1.1005 €) [31].

Most of the factors in Table 8 are consistent with the dependency of the collector cost on the parameters, aside from the rectangle plates from 9 m^2 with pw = 4.5 m to 25 m^2. All the factors of these lines have colors that no longer match those of the collector cost. Especially, the factors of the pump, beam, and other pieces are reversed for 9 m^2 and 16 m^2, in the sense that where the collector cost is higher for 16 m^2, and lower for 9 m^2, these factors have higher value for 9 m^2 instead. This is also the case for 15 m^2 and 25 m^2, and it is due to their dependency on pw. Moreover, the plate total factors are also reversed for the 16 m^2 and for 15 m^2. Therefore, despite being linear functions, the factors can diverge from each other and result in an even different behaviour of the total cost.

Table 9 shows that generally, the trend of the string total cost can be divided into three categories of costs for each number of plates. Then, as 8-plate and 24-plate categories are characterised by diverse distances between plates, the string total cost is nuanced within these categories, increasing with this distance. Disregarding the margin effect, the sum of the total factors represent approximatively 4% for 1-plate, 21% for 8-plate, and 39% for 24-plate, of the string cost, which is mostly affected by the wire factors (the string pipe contribution increasing linearly by only 0.6% from 0.1% for $Np = 1$). Consequently, the more plates there are on the string, the more the factors affect the string cost.

Although mooring costs are often provided for the entire WEF [40] or as a function of length [43] or unit of force [76], de Andres et al. [22] estimated a 0.4 M€ for an attenuator-type WEC. However this seems to be slightly high if considering that for a combined wind-wave farm Astariz et al. [89] estimated the mooring-costs from 318–390 K€ that would lead to 11.25–11.47 K€ if they were to be divided by the number of WECs of each farm. The low mooring cost (Table 10) is due to Wavepiston WEC Force-Cancellation characteristic [90] that enables the WEC and especially the moorings to endure more loads for less extra design (and cost) requirement, compared to other WECs [19,91] as mentioned in Section 3.2.

All in all, Tables 8–10 confirm the expectations that the element costs increase greatly with the number of plates (thereby collectors), reasonably with the plate size (especially its width), marginally with the distance between plates, and slightly with the water depth. In this situation, it is worth noting that the moorings have the lowest rate of change under the effect of the present parameterisation (Table 10), which is probably due to the absence of factors. Indeed, despite the obvious cost increase with parameter size (since all weights are positives), independently or combined, the factors have various, and possibly strong, impacts on the costs. Therefore, the factorisation should be conducted carefully with consideration of upper and lower effects on the costs for each type of WEC and its elements.

4.1.2. Wavepiston WEC Cost

Figure 6 provides the spread of the Wavepiston WEC costs using Equation (5) over the site water depth parameters (top panel) for the different configurations of Wavepiston (Table 2) that are shown in the bottom panel of the figure.

In Figure 6, all configurations are based on the Wavepiston WEC configuration parameters, excluding the wamit water depth (h) such that the spread of the boxplot is only affected by the site parameters and h. This spread is very narrow in comparison to the rate of overall change of the clusters from the effect of the number of plates and plate distance (Np and plc, respectively), and the plate width and depth (pw and pd, respectively). This is mostly due to small mooring costs variations visible in Table 10. Consequently, h and site parameters have little impact on the Wavepiston WEC cost.

Figure 6 shows that Np has the most definite impact on the WEC cost. An increase of Np increases the influence of all other parameters. The second parameter is the plate area and, more specifically, the plate width. For instance, the 9-4 plate is more expensive than the 6-6 and 6.7-6.7 plates. This aligns with the collector cost from Table 8. Additionally, elliptical plates (in fact, circular plates since $pw = pd$) cost less than the rectangular. This price difference decreases with a decrease in the pw and pd values. The weakest parameters to influence the WEC price are h and d. The fewer collectors there are on the string, the less plc affects the WEC cost, but can eventually make it a weak parameter as well.

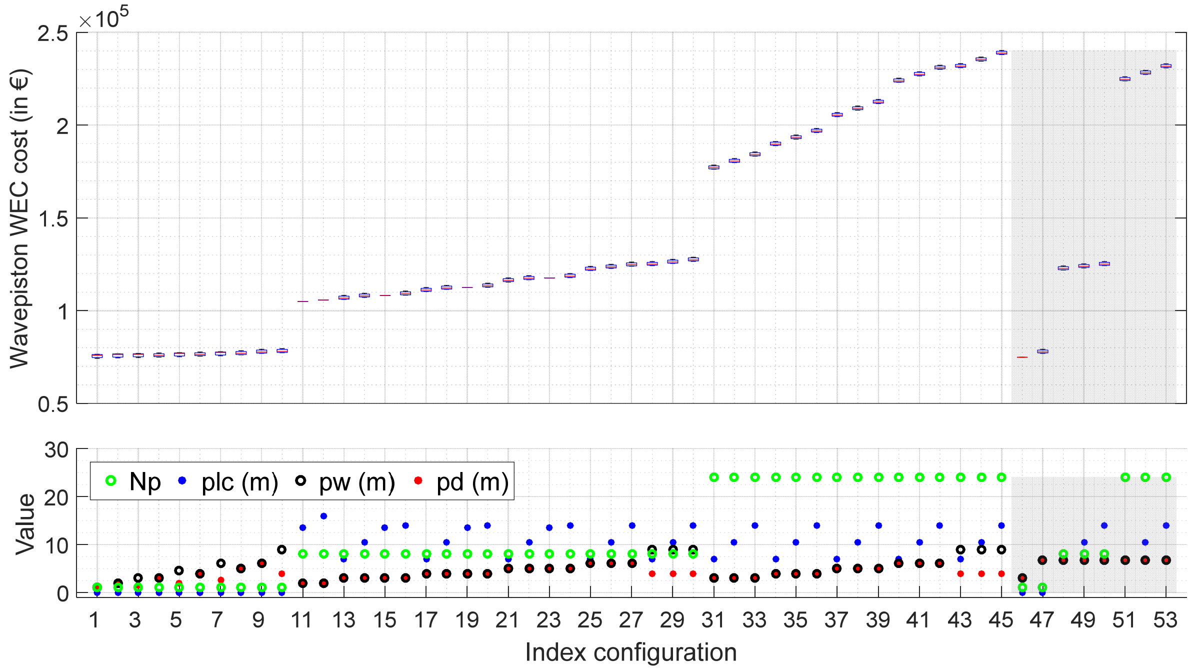

Figure 6. Boxplot that shows the spread of the WEC cost (in €) over the site water depth (see Table 3) clustered per similar configuration of Wavepiston of the other Wavepiston WEC configuration parameters (see Tables 2 and 3 for parameter definition and values), the grey sections for the elliptical plates.

Eventually, the Wavepiston WEC cost for the largest device is similar to the estimation calculated manually from Wavepiston. It is worth noting that the company expects to reduce the mooring expenses by half with time and experience. Wavepiston has requested that this estimation remains confidential.

It is worth noting that one of the major contributions of this research is the presentation of the Wavepiston WEC costs and this is because (especially for confidentiality issues) WEC costs are often difficult to grasp from the literature as they are often directly included to the CapEx, are not provided in currency but in another dimension, or are considering more or fewer elements. For instance, Astariz et al. [89] used the 0.44 MW WEC cost of 918 K€ although this is exempt from the PTO and moorings (estimated for combined wind-wave farm) as it is only for the WEC structure. In 2015, Astariz and Iglesias [76] used [92] 16.8 M€ for 7 MW Wave Dragon [93], 25 M€ for 700 kW Pelamis [94], and 200 K€ for 250 kW Aquabuoy [95], but these may be overestimations. Indeed, O'Connor et al. [52] used 1.6 M€ for Pelamis and Wavestar based on 750 kW Pelamis [96], de Andres et al. [22] estimated 11 M€ for a 1 MW multi-point-absorber and 4.2 M€ for a 750 kW attenuator, and Piscopo et al. [32] 25–35 K€ for a 10 kW point-absorber. Therefore, it seems that, although the literature suggests a reduction of WEC cost estimations through time, the largest Wavepiston WEC cost, 240 K€, stands fairly below other renewables. Yet, this is without counting that Wavepiston estimates a marketable system to presumably contain 32 plates instead of the maximum 24-plate (1.17 MW) considered here. This price-difference is mostly explained by Wavepiston low mooring-cost (Table 10) from the WEC Force-Cancellation [90] that generally affects the whole WEC and reduces its overall cost.

4.2. Wavepiston WEC Costs Using the Similitude Method and Comparison with Wavepiston WEC Costs from the CapEx Method

The cost of a rectangular 1 m × 1 m 1-plate Wavepiston WEC is 67,564 €. Tables 11 and 12 provide Wavepiston WEC cost obtained from the Similitude method using Equation (4) with the "Scale" being the plate width and the string length, respectively as mentioned in Section 3.2, and weighted factors (Table 7). In both tables, a heat map, from red to white to blue, was provided so that the darkest red cell is the highest value of the entire table, and the darkest blue reflects the lowest.

Table 11. 1-plate-based Wavepiston WEC cost (in €) using the Similitude method over the plate width. The darkest red cell is the highest value of the entire table, and the darkest blue reflects the lowest one.

Plate Width (*pw*, in m)	Weighted Scale Coefficient			
	Sub-Elements Only 2.625	Elements and Sub-Elements 2.674	Elements Averaged 2.866	Elements Function 3
2	416,792	431,191	492,569	540,512
3	1,208,255	1,275,080	1,574,508	1,824,228
4	2,571,123	2,751,844	3,591,032	4,324,096
4.5	3,502,662	3,770,558	5,032,948	6,156,770
5	4,618,613	4,997,596	6,807,120	8,445,500
6	7,453,537	8,137,515	11,478,809	14,593,824
7	9,957,761	10,930,484	15,748,737	20,320,751
9	21,607,372	24,063,557	36,692,253	49,254,156

Table 12. Wavepiston WEC cost (in €) using the Similitude method over the string length. The darkest red cell is the highest value of the entire table, and the darkest blue reflects the lowest one.

Plate-Location Configuration (*plc*, in m)	Number of Plates (*Np*, in –)	Weighted Scale Coefficient	
		Sub-Elements Only 2.625	Elements Function 3
7	8	4,985,523,572	22,556,997,120
10.5	8	14,452,744,628	76,129,865,280
13.5	8	27,954,682,319	161,803,707,840
14	8	30,754,913,691	180,455,976,960
16	8	43,665,996,277	269,368,688,640
7	24	89,156,716,886	609,038,922,240
10.5	24	258,460,168,206	2,055,506,362,560
14	24	549,993,815,757	4,872,311,377,920

Table 11 provides for each plate width (left column) the results of the Similitude method scaling using the weighted scale coefficients for the four approaches presented in Section 3.2. Table 11 shows that the greater the scaling factor, the higher the difference between the results of larger weighted scale coefficients, which leads to more expensive WECs. The weighted factor providing the closest results to the CapEx method is the first entitled "Sub-elements only", which consists of averaging the scale parameters for all sub-elements excluding the element designed function dimension. It seems to be the most consistent application of the Similitude method with the approach of the last column (average over the designed function dimensions only), although the last-column approach provides the highest results. Henceforth, only these two approaches are presented and discussed below.

As the Similitude method scales up the entire system cost, the costs increase exponentially as the parameter increases. In fact, the strict application of the Froude law implies a linear increase of all parameters with the coefficient of increase provided as the scaling factor to a power associated with the dimension of the considered quantity (see Table 1). For instance, for *pw* = 2 m (scale factor of 2), then $pd = 1 \times 2^1 = 2$ m and $pa = 1 \times 2^2 = 4$ m. As such, each line of Table 11 (and Table 12) is associated with a very precise WEC configuration and especially they are associated with the number of plates (*Np*) equals to 1 since the WEC base cost is for *Np* = 1; and because *Np* is dimensionless, it does not scale up as the scale parameter equals zero (Table 1). Therefore, from Table 11, only the costs for *pw* below 3 m could be approximated to the CapEx method with *Np* = 1.

Moreover, due to the strong dependency of Wavepiston on *Np*, to estimate the values of scaled up Wavepiston for *Np* different from 1, the same process used to obtain Table 11 should be applied to a base cost still estimated for 1 m × 1 m plate but for the enquired number of plates. The simplest design of 8-plate and 24-plate Wavepiston WEC are obtained for plates distanced (*plc*) by 7 m, which must also be considered alongside the number of plates. Indeed, some element base costs (see Section 3.1.3.) depend on *plc*. For the 8-plate design the base cost is estimated to be 86,093 € and for 24-plate, 128,445 €, for which the results are provided in Figure 7. Eventually, for plate width of 1 m, the Similitude method results equal the base cost resulting in a starting point always below the CapEx method minimum boundaries for each category of number of plates.

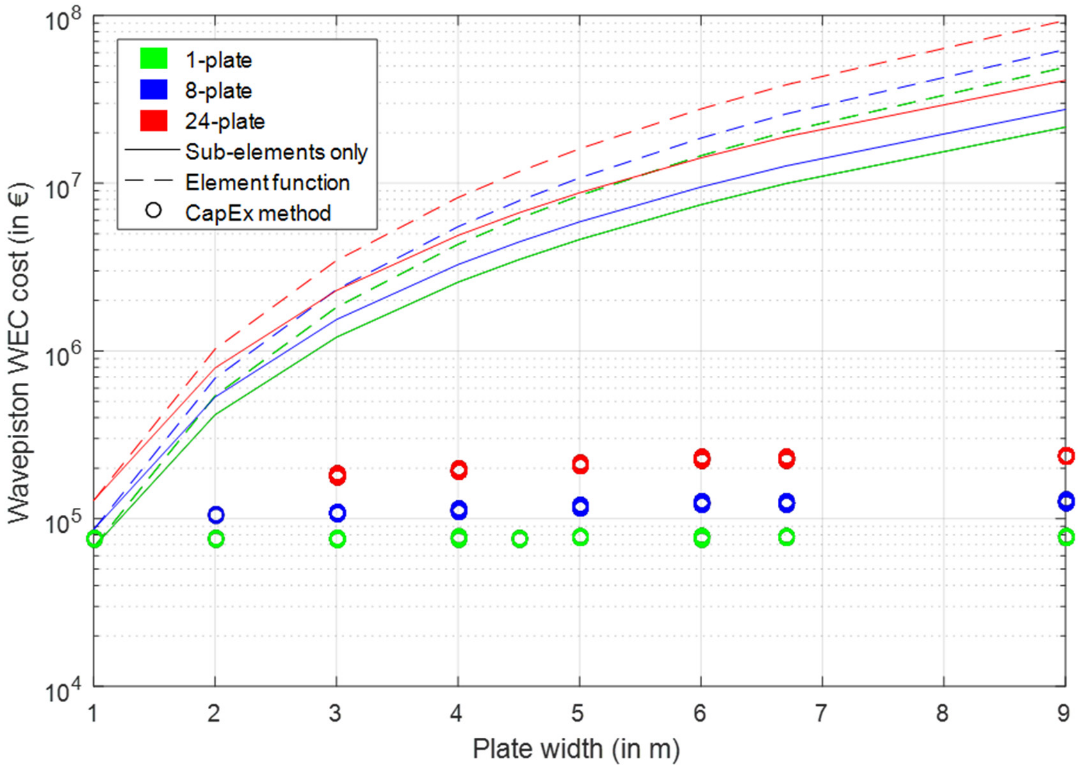

Figure 7. Wavepiston WEC cost (in €) using the Similitude method over the plate width for the "Sub-element only" and "Element function" weighted scale coefficient results from the CapEx method for the three values of number of plates from the dataset.

Figure 7 shows a clear discrepancy between the results of the Similitude and CapEx methods such that the results obtained with the Similitude method can be 5–529 times higher than those of the CapEx method. In fact, the difference between the two methods reduces with increasing number of plates and the "Element function" provides the most significant difference. Considering the "Sub-element only" weight scale coefficient, the Similitude method's results reach up to 146 times of those of the CapEx method, for the 24-plate configuration, and 232, for the 1-plate. This difference is reduced to 36 for 24-plate and 58 for 1-plate. In effect, the Similitude method based on the plate width parameter can be compared to Wavepiston for size below 3 m, and the larger number of plate is, the closer are the results from the two methods. Yet, due to the limited dataset, no concrete conclusion can be provided to determine a limit of number of plates over which the Similitude method, simpler to apply, could be used instead of the CapEx method, more complex, to estimate Wavepiston WEC costs.

It is reasonable to notice that given the values of the parameters, any Wavepiston WEC cost above 10 M€ is unrealistic. Therefore, the results from Table 12 shows that the string length parameter tested as an alternative "Scale" parameter (Equation (4)) to apply the Similitude method cannot be used for Wavepiston. A third parameter consisting of the plate width multiplied by the number of plates was also considered as a combination of the two major parameters for Wavepiston power absorption; however, similarly to Table 12, all results were above a billion euros and so were disregarded from the study. Consequently, amongst the three different "Scale" parameters tested to apply the Similitude method to Wavepiston, the closest results to the CapEx method are obtained from the plate width. Henceforth, the other parameters' analysis is not extended to the 8-plate and 24-plate Wavepiston.

In the case of Wavepiston, each parameter has a specific impact on the energy absorption, sizing of the WEC, and thereby costs, which was found to diverge from the Froude law scaling concerning the costs. Consequently, the Similitude method is less appropriate to scale the costs of Wavepiston than the CapEx method that enables the selection of specific parameters impact on the costs.

5. Summary and Conclusions

This study presents the generic "CapEx method" with application to the wave renewable energy field. The CapEx method aims to provide a systematic and comprehensive approach for WEC and WEF cost parameterisation to enable future calculations of large datasets of WEC, WEF, and site characteristics to select optimised pairs of WEC/WEF configuration and site. This method distinguishes WEC and WEF elements and sub-elements, an element and sub-elements being a system, module, component, piece, or task, in the calculations. Then, tasks such as manufacturing and assembling, are assigned to the different parts. For each element and sub-element, a base cost, a margin, and one or more factors are estimated. In its simplest form, the calculation part of the CapEx method appears as an ordinary cost estimation leading to an overall sum of costs with margins. In the alternative approach, the factors enable the encapsulation of several phenomena concerning site characteristics, and WEC and WEF configurations. In its advanced form, more abstract elements can be included such as economies of scale and weather and wave climate influence on the costs of the element and sub-elements of the WEC and WEF, through the factors leading to the complex parameterised CapEx calculation.

In this article, the CapEx method was applied to a Wavepiston farm to estimate the Wavepiston WEC cost for different WEC-configuration and site characteristics. This example is an intermediate use of the CapEx method to allow the research to focus more on the CapEx method's two first steps. Indeed, one of the significant challenges of this research was to handle limited and complex databases of configurations such as the one provided by Wavepiston. This complexity is due to the selected parameters and their limited number of combinations. Consequently, one of this study's contribution is the approach to describe, understand, and use such a database as required by the first two steps of the CapEx method.

The cost of Wavepiston WEC for the limited configurations available from the database ranges between 66 K€ (for 1-plate 1 m × 1 m Wavepiston WEC) to 240 K€ (for 24-9 m × 4 m plates distanced by 14m) bearing in mind that these WEC dimensions are more theoretical than practical as Wavepiston estimates the first commercial system to consist of 32 plates or energy collector. The number of plates was found to be the most influencing parameter on the WEC cost, also increasing other parameters effect as it increases. The plate dimensions and especially the plate width were the second most influent parameters. It was also found that the factors could represent more than 30% of the costs and their combination could lead to cost trends over the parameters differing from each factor trend. Finally, the study showed that Wavepiston WEC cost parameterised using the CapEx method resulted in the site's parameters having little effect on the WEC and WEC element costs, in comparison to other parameters such as Wavepiston's number of plates and plate width, more related to the WEC configuration.

The results from the CapEx method in line with manual estimations from Wavepiston, were also compared to the method of de Andres et al. [50] referred to as the "Similitude method". It was found that (a) when considering sub-elements of the WEC main elements, the weighted scale coefficient should be estimated only over the sub-elements regardless the dimension associated with the top-element; (b) the plate width is the most reliable parameter to apply the method to Wavepiston; (c) for low values of the plate width, the Similitude and CapEx methods provide close costs; (d) the more plates there are on the string, the closer the costs estimated by the CapEx and Similitude methods are; and (e) despite that, due to its multi-parameterised configuration design, Wavepiston cost is better estimated using the CapEx method than by the method of de Andres et al. [50] that provides results up to 36 times those from the CapEx method. Yet, it is important to notice that the Similitude may be less appropriate to Wavepiston than to other devices especially for Wavepiston's particularity of being a multi-energy-collector-based WEC instead of single-energy-collector-based devices as the one used to develop this method.

Although WEC cost estimation seems to have decreased over time, probably from learning processes, Wavepiston WEC costs (for high energy production potential around 1.17 MW) were below the reported values from literature. The Similitude method (as well as other widely-used methods including based on mass or power parameterisation) has can potentially overestimate costs. Consequently, the current LCoE of the wave energy field, higher compared to other renewables, may be overestimated since WEC costs (including the moorings) represents 33% of the LCoE [97] and replacement (including WEC cost) 45% of the OpEx [38], itself representing 40% of the LCoE [85,97].

Windows of improvements of the WEC cost estimations based on the CapEx method consist of including forces and loads effects, such as the moorings' effects on the string. Indeed, the size and strength of different pieces relate to the loads they are expected to endure; thus, even if this could be thought of more as an operational-and-maintenance-related phenomenon, it also influences the capital costs. This is also the case of the effect of weather and wave climates, and economies of scale, which can be included using the advanced or expert levels of the CapEx method cost-calculation. For instance, in future work, the impact of availability and protection mode could be considered for the device elements and sub-elements fatigue influencing their strength, and thereby cost.

The CapEx method enables flexible selection of parameters to translate different phenomena affecting the costs. Still, a comprehensive application of this method requires much experience from the user to be accurate, which is currently difficult to reach due to the Research and Development stage of the field. Therefore, the automated CapEx estimated using the CapEx method should be considered for a single type of WEC at a time to select the most accurate configuration for a given site, and vice-versa, and not between WECs. Once the selection is made, a final CapEx estimation is recommended based on a more precise analysis of the local subcontractors' prices and the costs of the pieces requiring importation from other regions or countries. The CapEx method's primary limitation is the need for complete access to the WEF and WEC elements and sub-elements details, and this is often confidential information. Notably, the costs of the different elements are usually not accessible. Future work should provide Wavepiston CapEx and particularly the costs for the Wavepiston WEF elements and sub-elements, giving a sense of translating the impact of the wave climate on the WEF. For instance, this phenomenon would affect the sizing of the WEF through the need for the WEC to have the capacity to absorb the yearly wave energy. Applying the CapEx method for WEF cost estimations could help to better assess the direct impact that WEFs could have on diversifying the energy renewable mix. Moreover, the application of the CapEx method to the operation and maintenance cost estimation should be investigated. Indeed, operation and maintenance tasks can be evaluated for each WEC and WEF element and sub-element, and for each task, factors could be estimated for the calculation of the operation and maintenance costs. The occurrence of each task within the WEF lifecycle is an example of a parameter for these factors. In turn, the operation and maintenance cost alongside the CapEx and AEP could enable the calculation of several selected economic indicators such as the aforementioned LCoE as well as the NPV, and their comparison with the research from de Andres et al. [50].

The Similitude method is more rigid than the CapEx method but requires less information. It is worth noting that originally the Similitude method is applied to the entire CapEx of a WEF, whereas in this case, the application was reduced to the Wavepiston WEC cost. The sensitivity of the WEC cost using the Similitude method may be increased as the scaling effect's implication is shared amongst a few components compared to the total WEF and WECs number of pieces involved in the CapEx calculation. Additionally, more research should be undertaken about the Similitude method to determine which approach (amongst the four proposed in this study) represents the system weighted scale coefficient best. Future work could provide two extensions of the Similitude method that align with the CapEx method to make the Similitude method more flexible: (a) Simplest extension: The method could be extended to each cost rather than the final CapEx. Each cost would then be multiplied by the scaling factor power of the selected scaling parameter. By doing so, the overall representative dimension, and thereby the scaling factor, may no longer be representative enough of each module; hence, for each cost, a new dimension should be determined. (b) Advanced extension: In order to include more than one parameter affecting the costs, two extensions could be investigated: setting SS as the scaling factor power of the scaling parameter, the total factor could either be (1) the sum, or (2) the multiplication of these SSs. However, in both cases, each SS's contribution to the total factor and the cost is hardly traceable or transparent, and is difficult to understand and control, since the resulting total factor multiplies the base cost. The multiplying effect is the reason why in the presence of more than one parameter translating more than one phenomena affecting cost estimations, Equations (2) and (3) may bring more transparency for a more fundamental understanding and assessment of the final costs.

For WEC scaling, this study extended the method of de Andres et al. [50] to parameterise the cost in the case of limited access to the WEF and WEC elements and sub-elements information and costs. However, the application to multi-parameter WECs is limited and should be conducted carefully. For a more complete access to information and costs, the CapEx method was found to be a robust framework that enables flexible and transparent cost calculations for both simple and complex cost parameterisations. This method has the benefit to generate automatically the costs for large databases of pairs of sites and WEC configurations. Even though the manual estimation may be more accurate, (more research is required to assess both methods uncertainty levels) this method enables assessing site-WEC configuration pairing worldwide, which cannot be carried out manually due to the tremendous amount of information.

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Abbreviations

List of Symbols

d	m	Site water depth
h	m	Wamit water depth
Hs	m	Wave significant height
Tp	s	Wave peak period
Np	–	Wavepiston number of plates
pd	m	Wavepiston plate depth
plc	– and m	Wavepiston plate location configuration (associated with the distance between the plates)
ps	–	Wavepiston plate shape
q	m	Distance to shore
s	m	Data water depth
θp	degrees	Wave peak direction

List of Abbreviation /Nomenclature

AEP	MWh/year	Annual Energy Production
CapEx	Euros	Capital Expenditure
LCoE	Euros/kW	Levelised Cost of Energy

List of Abbreviations

2D	2-Dimensional space based on Hs and Tp
3D	3-Dimensional space that adds θp to Hs and Tp
PM	Power Matrix
PTO	Power-Take-Off
TRL	Technology Readiness Levels
WEC	Wave Energy Converter
WEF	Wave Energy Farm

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