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Estimating the Cost of Wave Energy Converters at an Early Design Stage: A Bottom-Up Approach

Enrico Giglio [1,2,3,*,†], Ermando Petracca [1,2,†], Bruno Paduano [1,2], Claudio Moscoloni [1,4], Giuseppe Giorgi [1,2] and Sergej Antonello Sirigu [1,2]

1 Marine Offshore Renewable Energy Lab (MOREnergy Lab), Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy; ermando.petracca@polito.it (E.P.)
2 Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
3 Energy Center Lab, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
4 STS Class Scuola, Universitaria Superiore IUSS di Pavia, Palazzo del Broletto, Piazza della Vittoria, 15, 27100 Pavia, Italy
* Correspondence: enrico.giglio@polito.it
† These authors contributed equally to this work.

Abstract: The role of ocean energy is expected to grow rapidly in the coming years, and techno-economic analysis will play a crucial role. Nowadays, despite strong assumptions, the vast majority of studies model costs using a top-down approach (the TdA) that leads to an unrepresentative economic model. WEC developers usually go through the the TdA approach because more detailed cost data are not available at an earlier design stage. At a very advanced design stage, some studies have also proposed techno-economic optimisation based on the bottom-up approach (BuA). This entails that the detailed cost metrics presented in the literature are very specific to the WEC type (hence not applicable to other cases) or unrepresentative. This lack of easily accessible detailed cost functions in the current state of the art leads to ineffective optimisations at an earlier stage of WEC development. In this paper, a BuA for WECs is proposed that can be used for techno-economic optimisation at the early design stage. To achieve this goal, cost functions of most common components in the WEC field are retrieved from the literature, exposed, and critically compared. The large number of components considered allows the results of this work to be applied to a vast pool of WECs. The novelty of the presented cost functions is their parameterization with respect to the technological specifications, which already enables their adoption in the design optimisation phase. With the goal of quantifying the results and critically discuss the differences between the TdA and the BuA, the developed methodology and cost functions are applied to a case study and specifically adopted for the calculation of the capital cost of PeWEC (pendulum wave energy converter). In addition, a hybrid approach (HyA) is presented and discussed as an intermediate approach between the TdA and the BdA. Results are compared in terms of capital expenditure (CapEx) and pie cost distribution: the impact of adopting different cost metrics is discussed, highlighting the role that reliable cost functions can have on early stage technology development. This paper proposes more than 50 cost functions for WEC components. Referring to the case study, it is shown that while the total cost differs only slightly (11%), the pie distribution changes by up to 22%. Mooring system and power take-off are the cost items where the TdA and the HyA differ more from the BuA cost estimate.

Keywords: wave energy converter; cost assessment; bottom-up; top-down; economic analysis; CapEx

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1. Introduction

In the near future, ocean energy will grow considerably, and various devices for the exploitation of marine energy will be developed [1], although the scientific and industrial community still has work to do to achieve true competitiveness with other RES technologies. The growth of marine energy harvesting technologies is certainly driven by their enormous but still untapped potential [2]. The term ocean energy generally refers to a mix of renewable sources consisting of wave and tidal energy, ocean thermal energy, and salinity gradient. Among these sources, wave energy is particularly promising, considering the enormous and widespread energy potential [3], and the predictability of the resource, which can be predicted for days [4].

Ocean energy is not yet mature enough to compete economically with other renewable energies, such as solar or wind power. Nevertheless, IRENA and Ocean Energy Europe forecast a significant cost reduction (up to EUR 90/MWh in 2030) and a large number of installations around the world (an installed capacity of about 70 GW by 2030 and 350 GW by 2050, worldwide) [5,6]. In addition, the European Commission has set ambitious targets for wave and tidal energy technologies through the SET-Plan declaration of intent for ocean energy [7]: tidal technologies are expected to reach a levelised cost of energy (LCoE) of EUR 150/MWh by 2025 and EUR 100/MWh by 2030, while wave energy technologies are expected to reach the same targets with a 5-year delay. The expected cost-reduction is planned to be achieved with:

- Increased technology deployments [8,9];
- Further knowledge gained by the pilot farms [10];
- Scale economies (large industrial production, optimised operation and maintenance) [11];
- Techno-economic optimizations [12,13].

Regarding the last point, technical optimisation plays a particularly important role for less mature technologies, i.e., with technology readiness level (TRL) < 6, as it leads developers to design more efficient devices [14–16]. Indeed, optimisation models are able to define the best device depending on user-defined metrics, such as the LCoE of the device; however, cost estimates for the main subcomponents of the device are needed as input, and their representativeness influences the effectiveness of the optimisation. One of the challenges tackled by this paper is cost estimation, which is not trivial for emerging technologies [17] because:

- Data of previous installations are not easily accessible;
- When accessible, data are very specific and then unrepresentative for other case studies;
- Uncertainties in the manufacturing processes' cost scalability [11].

Despite these difficulties, developers need the techno-economic optimisations to advance their technologies, and they can take three different approaches for the selection of cost functions: top-down (TdA), bottom-up (BuA), and hybrid approaches (HyA). The differences among the three approaches are summarized in Figure 1 and explained hereafter.

the TdA is based on macroeconomic modeling principles and techniques: the estimation of cost functions is based on percentage costs distribution among main macro-parts of the devices, starting from the total cost of an entire project [17–19]. The TdA is usually adopted by:

- Policy makers who trace out the direction to reach a cost target (e.g., European Commission and EtipOcean);
- Top management strategists who identify the technological development to explore.

Regardless of the objective, when the TdA is applied, the method is entered with an absolute cost value, i.e., the cost objective of the whole system that a decision maker wants to achieve or the cost of a single component whose impact on the rest of the system cost is to be calculated (TdA1). The next step is to study previous WEC projects to find out how the percentage of costs has been distributed among the different main cost items (TdA2). All studies are compared, and a percentage cost distribution is assumed (TdA3). Based on the previously assumed absolute cost value (regardless of whether it is the total cost or the cost of a single group of components) and the determined percentage costs distribution, the other costs are calculated (TdA4). Considering that there is no link with the design specifications, the shortcoming of such an approach is that the cost functions generated are not representative [20,21]: therefore, no feedback mechanism for optimisation can be built.

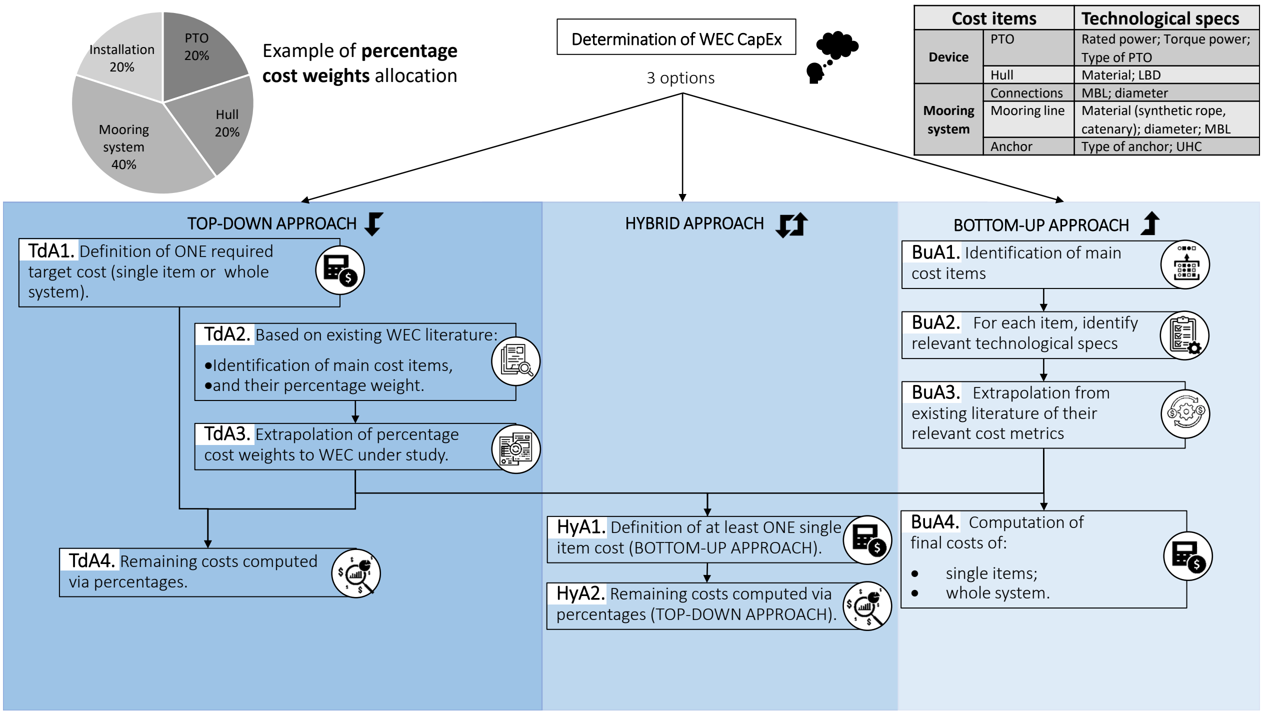

Figure 1. Representation of the top-down (TdA), the bottom-up (BuA), and the hybrid approach (HyA).

In contrast, BuA is based on disaggregation of the whole system into its subcomponents and the inclusion of a large number of technical parameters [18,20]. The implementation of BuA starts dividing the whole system into all its components (or component groups) and its installation into all main phases (BuA1). Each component group or installation phase is analysed to highlight the technical specification that mainly affects the specific final cost (BuA2). Specific studies on the costs of the different component groups and installation phase are evaluated to define the cost functions for each item depending on the technical specification previously identified (BuA3). The costs for all components are calculated using the cost functions specific to each component, and this approach, which is based strictly on the properties of the subcomponents, ensures a reduction in uncertainty in the development of cost estimates. In principle, the BuA can cope with the TdA shortcomings; however, the main challenge lies on the practical implementation of this method, which has to deal with the data accessibility and representativeness in relation to the technological specification. Indeed, the cost functions developed using this method are directly related to the design specification but must deal with the difficulty of implementation due to the information to be obtained, especially in the early design phase. This paper addresses this shortcoming and develops representative cost metrics for the most common WEC components.

The HyA is based on merging the pros of the TdA and the BuA. For the first time, this paper tackles the explicit implementation of HyA in the ocean energy field, transferring experience from other more mature research fields [18,22–25]: i.e., Böhringer and Rutherford [22] define HyA as the approach that "combines technological explicitness of bottom-up models with the economic comprehensiveness of top-down models". Böhringer and Rutherford [22] also add that the hybrid approach does not result in an equal merging of the two approaches, "but one could focus on one model type—either bottom-up or top-down—and use 'reduced form' representations of the other". According to the scheme shown in Figure 1, the HyA is entered by both the TdA and the BuA. In particular, following the TdA, the percentage cost distribution is determined (Td2), and a BuA is used to calculate the costs for at least one group of components. The other costs are calculated taking into account the percentage weighting (HyA1-2). Note that this method differs from the TdA because the absolute cost used to calculate the other cost components of the pie distribution is defined with a BuA and not as an external input. The HyA can be implemented in different ways depending on the aim of a study. The following are some examples where the developers have used such a method, even if they have not explicitly defined it:

- Anerdi et al., Tan et al. [26,27] focus on the development and cost reduction of a specific WEC subsystem (BuA); the consequent economic impact on the total cost of the system is computed by applying pie costs distribution (TdA);
- In [28–30], the HyA is entered with the absolute cost of more items, using cost functions (BuA) based on sector-wise knowledge. This case corresponds to the definition of "reduced form" introduced by [22].

It follows that BuA is the most suited to develop representative cost functions; however, its widespread use in the economic assessment of WECs at an early stage is limited by the shortcomings mentioned above. Nevertheless, some studies on the assessment of WEC costs using BuA are published in the literature [17,27,29,31–36]. The direct adoption of the cost functions developed in these works could lead to unrepresentative approximations, as further discussed in Section 2.8.

To the best of the authors' knowledge, this paper proposes for the first time in the field of WEC an analysis of the state of the art of cost function development methods: a comprehensive comparison between the BuA, the TdA, and the HyA is structured, and the cost functions for the main components in WECs are reviewed with respect to the three approaches. This paper compares the three methods and analyses how the choice of an approach affects the cost estimation and consequently the whole optimisation process. Furthermore, BuA-based cost functions are proposed to exhaustively quantify to what extent and how the adoption of non-representative cost functions can change the final cost of the whole system and component groups. With this aim, this paper:

- Aggregates BuA-based parametric cost functions and critically analyses those existing in the literature (addressing any discrepancies and providing a comprehensive technological understanding of the systems);
- Retrieves and updates cost functions presented in more dated works;
- Addresses new functions for components missing in the literature;
- Restricts the proposed cost functions with a range of validity, where necessary, to guide developers towards more appropriate use;
- For the first time, it specifically focuses on a cost function formulation suitable for early design phases and with the explicit aim of being applicable to a wide variety of WECs rather than to a particular technology. The applicability to a wide range of WECs is due to the dependence of the developed cost functions on the technical specifications.

The remainder of this paper begins with a short overview of the state of the art of the cost functions proposed in the literature (Section 1.1). In Section 2, we present the most common WEC components and address a cost function for each item from the technological point of view, including its range of validity. In order to evaluate the impact of adopting such cost functions developed with a BuA, cost functions bases on the TdA and the HyA are introduced (Sections 2.7 and 2.8) and a case study is proposed in Section 3. With this goal, the pendulum wave energy converter (PeWEC) with a related mooring system is considered, and in Section 4, the CapEx is computed for the case study site of Pantelleria Island (Sicily, Italy). The different results are presented and discussed (in Section 5) in order to highlight the impact of the proposed solution. Note that to evaluate the techno-economic performances of the technologies, LCoE would be the proper metric, taking into account the productivity of the device. This paper focuses on the evaluation of the cost, and the CapEx is computed [37–39].

State of the Art

In the literature, many studies report total costs for the realization of the first case study installation, adopting a TdA [17,25,29,40]. For example, in [40] the authors study the wave point absorber "RM3 device" and report the construction, installation, and maintenance costs grouped in electrical subsystem, moorings, and installation; all such cost parameters are expressed with respect to the power installed (EUR/kW), hence not directly related to the cost of each subcomponent. Têtu and Chozas [17] propose a methodology for the economic assessment of a WEC, adopting a TdA for the identification of bottlenecks and possibilities for the improvement of the analyzed technology. Choupin et al. [29] highlight that cost information for WECs is often limited due to confidentiality. Consequently, they propose a systematic and comprehensive method for cost calculation adaptable to several WEC technologies: detailed information is provided by Wavepiston (co-author of the work), validating the proposed costs with ones reported in the catalogue published by the same company. It follows that, although [29] provides cost metrics with a really high degree of fidelity, it strongly focuses on the analyzed case study. From the anchors cost to the connection elements, cost are expressed as capital costs or normalized over dimension, such that the replicability of the proposed cost functions is relatively limited.

In [27,41–43], cost functions for specific groups of components are proposed. with a high level of detail. This also allows the adoption of the proposed functions for other WECs with similar components. In this sense, the proposed cost functions are representative and highly applicable to other case studies. These studies correspond to the definition of the HyA. Indeed, the BuA is adopted for defining the cost function of the specific component, while the costs of the rest of the WECs are calculated using the pie distribution (TdA). Note that while these papers provide examples of the application of the HyA to wave energy, they do not clearly define such an approach, as this was not one of the aims of the mentioned papers.

Pena-Sanchez et al. [44] propose a cost metric that can be applied in the PTO optimisation phase using detailed design parameters: a valuable example of how a techno-economic study should be conducted in the advanced design phase.

Different open-access databases, whose studies have been financed with public funds from the European Commission, propose the application of a BuA methodology for the determination of the capital costs for a WEC. In [33], the authors adopt a BuA for the assessment of the installation costs, and with this purpose it provides useful information, such as the daily costs for renting the vessel needed for the installation procedure. At the same time, the tool strongly focuses on a statistical method application, which limits the use to more mature or well-known technologies (where enough data are available about the operational behavior of the plant). For this reason, the data provided can be directly used for the economic assessment of a new technology whose feasibility is evaluated with a BuA; however, the underlying equations are not provided, so extrapolation to different conditions is not directly viable. The Open Sea Operating Experience to Reduce Wave Energy Cost (OPERA) project provides detailed information about metrics for the evaluation of the technical and economical performances of its system, i.e., an array of point absorbers with oscillating water columns (OWCs) [45]. In [46], a life-cycle assessment study is performed based on metrics obtained with the BuA, but information about costs are not provided at the same degree of knowledge. In 2016, Quoceant Ltd published a set of deliverables [31,32] that provide costs related to the construction and installation of the Pelamis energy converter, computed with a BuA; however, such reports present two main limitations:

- Cost metrics are at least 7 years old, and they need to be compared to more up-to-date values to confirm their validity;
- Some of the reported cost metrics are too specific to the application analyzed (limiting their use).

Conversely to this last point, the Liftwec project recently published a wide set of costs and different cost metrics for several types of PTO and structural materials [28]. Because of this variety of considered systems, Têtu and Chozas [28] go exactly in the direction that this study wants to pursue. However, various simplifying assumptions are made, which limit the wider applicability; for example, the cost of mooring lines depends only on the length, while other meaningful parameters are neglected, such as the diameter, density, buoyancy, and connections. The mooring system lines costs have been proposed normalized over the length, but no information regarding their diameter or density is provided, even if these parameters are meaningful for a reliable cost assessment. Always regarding the mooring system, any information about the buoyancy or the connections are explicitly considered.

Bosserelle et al. [47] report information about the total costs of five different projects. Moreover, in addition to the costs, information about the size of the WEC generators are reported as the characteristic of the installation site. The mentioned study represents excellent input for a study with a fully TdA.

Castro-Santos et al. [36] report the total costs for the main items of four different projects of a hybrid offshore platform (wind and wave). It also provides the equation for calculating the partial costs and defines all the required cost functions. The limitation of this paper is to provide information only in a symbolic equation without any explicit numerical quantity.

As remarked, each one of these last mentioned data sets partially contribute to fill the gap in the literature, which is one of the main goals of this paper. The contribution of this paper is in the aggregation of the information presented in the literature, updating the values where it is needed and providing cost functions for components yet without quotation.The study relies on a comprehensive data set that investigates the intersection between offshore wind and wave energy sectors. Notably, these sectors share numerous commonalities, including mooring and electrical systems [32,48], as well as mechanical components and ballast [49,50]. In addition, this paper proposes a comprehensive study on the BuA for cost assessment for WECs. Lastly, Table 1 summarises the component on which the different studies provide cost metrics and information that will be also used in the next sections, also reporting the section in which they are discussed.

Table 1. Summary of the most relevant cost items and relative studies available in the literature. In the last column, the section in which each type of component is discussed is listed.

Type of Components	References	Section
Hull	[26,28,41,42,51]	Section 2.1
Ballast	[28]	Section 2.1
PTO	[17,28,31,44]	Section 2.2
Mechanical components	[43,49,51]	Section 2.3
Mooring	[28,29,32,52–59]	Section 2.4
Installation	[28,33–36]	Section 2.6

2. Assessment of Common WEC Components

The proposed methodology identifies the cost functions of the following most common WEC components in the vast majority of devices:

- Elements of the mooring system;
- Different types of power take-off (PTO);
- Subparts of the hull and for the different structural materials;
- marine cable;
- Installation procedures.

The above elements are the main drivers of capital and operational cost for virtually every WEC. The following subsections gather, update when necessary, and critically compare their available cost functions; when information gaps are found, new cost functions are herein proposed. Such metrics are framed in the novel, flexible, and device-agnostic BuA, such that they can be applied to various subsystems and technologies. In addition, this study provides tools for comparing different solutions and subsystems, quantify their impact on the total cost, and evaluate alternative development branches for cost reduction.

2.1. Device: Hull

The hull of WECs is usually in steel, reinforced concrete, or, in a few cases, in fiberglass [26,51,60,61]. To satisfy the requested inertial properties, some devices use ballast as dead mass [62,63] in material such as concrete, sand, or black slag. The hull also needs to be arranged with structural fittings to support the installation of the components suitable for the transformation and transmission of the produced energy.

Starting from the hull structure, steel is the most used material. In [42], the authors propose the range EUR 2.5–3/kg of the steel weight. The model takes into account the man-hours per tons of steel (EUR 45/h) and the purchasing of the rough steel (EUR 950/ton). In [42], the authors compute the man-hours per t of steel with the formulation addressed by Kernel [64]:

$$k_{fr}\left(\frac{h}{t}\right) = 45.36 \cdot \left(\frac{LBD}{1000}\right)^{-0.115} \cdot \frac{0.866}{\sqrt[3]{C_B}} + x_{II} \quad (1)$$

where C_B is the block coefficient, and LBD is the product of L_{BP}, B, and D. L_{BP} is the length between perpendiculars, B is the width at the waterline, and D is the submerged hull height. x_{II} represents a compensation for yard-specific variations. The total cost for the hull can be computed multiplying the k_{fr} per the man-hour cost and summing up the material cost. The block coefficient C_B corresponds to the ration between the hull volume and the LBD coefficient: it represents how much of the block is actually filled by the hull. Note that the computations of this metric have been performed under the hypothesis of 20,000 m^3 < LBD <100,000 m^3. Under the assumption that the cost metric changes with the variation of the selected LBD range only, the new cost metric can be computed re-scaling the range EUR 2.5–3/kg to a range also valid in the range 1600 m^3 < LBD < 2500 m^3 (which would be more effective for the typical dimension of a WEC [63,65]). In Appendix A.1, how the cost metric range has been re-scaled is shown.

From the treatment reported in the Appendix, starting from Equation (1), the cost function proposed in Table 2 has been identified. The proposed cost function is valid for WECs with an LBD in the range 1600 m^3 < LBD < 2500 m^3, and in such an interval, it returns the cost range EUR 3.6–4.1/kg. Note that [28] reports a cost for steel used in the hull structure equal to EUR 3.4/kg; it also reports previous studies where this cost was stated at EUR 3.8/kg. Such values, whose differences are tracked back from public references, are consistent with the approach herein proposed, further validating its fit. Concerning the ballast that can be used as dead mass in the hull, materials such as sand [14], black slag [50], or concrete [28] can be adopted without meaningful variation on the specific cost. Many references in the literature express the ballast cost, and for this reason, a BuA is not necessary to be applied. For example, both [28,50] converge on the value of EUR 0.07/kg, which is herein confirmed. Moreover, for the reinforced concrete, which can be used in the hull structure, both [28,50] converge on EUR 0.25/kg. It is worth noting that [26] suggests how the hull concrete-made cost could be (for a series production) 42% of the analogous hull made of steel. Although fiberglass can also be used in the hull structure, detailed information about its manufacturing cost have not been traced in the literature; therefore, the proposed value is the one suggested in [28], which is to EUR 9.5/kg.

Several attachments, fittings, accessories, and mechanical components (such as bollards, chain stoppers, paintings, and other technical equipment) are also needed in order to ensure the installation of essential components, such as the PTO or the mooring system. Ref. [49] proposes the costs for the mechanisms in machined steel used for supporting components, such as the mechanical brake and high-speed coupling: the cost metric proposed is USD 10/kg, but it refers to the steel cost in 2004. In [66], the historical price index of the machined steel is proposed considering the suggested increase in value of 1.61, and a conversion factor euro to dollar equals 0.96 EUR/USD [67]; the proposed cost metric is

EUR 15/kg. Note that since this cost metric refers to the weight of the fitting components themselves, if the fitting components weighted 20% of the total hull, the same cost metric would be EUR 3/kg, with respect to the mass of the hull.

In Table 2, the proposed cost metrics are summarized for the hull and its accessories component.

Table 2. Summary of the cost metrics (BuA) for the construction of the hull.

Subcomponent	Cost Metric
Hull steel (EUR/kg)	$\frac{LBD(m)^{-0.115}}{0.285} \cdot 2.75$
Generic ballast (EUR/kg)	0.07
Reinforced concrete (EUR/kg)	0.25
Fiberglass (EUR/kg)	9.5
Supporting accessories components (EUR/kg)	15.0

2.2. Device: Power Take-Off (PTO) and Generators

The PTO is one of the main components in WECs, and it converts the mechanical power absorbed by the hull from the incoming waves into electricity. There are different types of PTOs, and Têtu and Chozas [28] suggest cost metrics for four types: these cost metrics are proposed in Table 3. The validity of these cost metrics is not limited to a range of power rating, and they are expressed as a fixed value. This is in contrast to what other studies propose (e.g., [31]), and it follows that this analysis needs to be integrated with further works.

Table 3. Summary of the cost metrics for the different type of PTO proposed by [28].

Type of PTO	Cost Metric (EUR/kW)
Hydraulic	800
Linear generator	600
Mechanical	1400
Air turbine	1000

Ref. [31] focuses its attention to the Pelamis wave energy converter, which works with a hydraulic PTO. It proposes cost metrics for such a specific type of PTO, providing values for different power ratings (205, 435, 685, and 1000 kW). The values proposed by [31] are reported in Table 4, after having adopted the mean value for the 2016 conversion rate, equal to 1.2242 EUR/GBP [68]. The values proposed provide evidence that:

- The cost function of a hydraulic PTO follows a logarithmic law;
- The values proposed in [28] and reported in Table 3 refer to PTOs with a power rating of about 295 kW (range between 250 and 350 kW).

Table 4. Summary of the cost metrics for the different power size of hydraulic PTO proposed by [31].

Power Size of the Hydraulic PTO	Cost Metric (EUR/kW)
205 kW	900
435 kW	670
685 kW	645
1000 kW	615

Note that a quadratic form could also fit the value suggested in Table 4, but this kind of formulation has a minimum point. The minimum point would correspond to a power rating value above which the cost function remains constant. This hypothesis is not supported by the cost functions proposed in the literature, which tend to vary in value without reaching a fixed price. This behaviour is better described by the logarithmic form assumed. Moreover, this assumption is supported by the literature on other types of PTOs;

several studies and catalogues show that PTO cost functions follow this logarithmic trend, regardless of the type of PTO considered:

- Mechanical PTO. Fingersh et al. [49] state a logarithmic dependency of the specific cost of the mechanical components (as mechanical PTO) with respect to the machine rating;
- Linear Generator and Air Turbine. Faiz and Nematsaberi [69] and Thomaz and Crooks [46] propose a logarithmic cost trend for different power sizes of the two types of PTO.

It follows that a logarithmic trend is adopted for describing the cost variation of the PTO, and the relationship stated for a hydraulic PTO has been shifted in order to meet the cost metrics reported in [28] at the reference power size (295 kW). All the relationships are reported in Table 5, where P_{PTO} is the power rating of the PTO expressed in kilowatt (kW).

Table 5. Summary of the cost functions (BuA) for the different types of PTO. P_{PTO} stays for the power size of the PTO whose cost has to be estimated.

Type of PTO	Cost Metric Function (EUR/kW)
Hydraulic	$-179.5 \cdot \ln P_{PTO} + 1822$
Linear generator	$-179.5 \cdot \ln P_{PTO} + 1621$
Mechanical	$-179.5 \cdot \ln P_{PTO} + 2421$
Air turbine	$-179.5 \cdot \ln P_{PTO} + 2021$

The cost functions proposed in Table 5 include the cost of the generator. Even though this component has been considered as part of the PTOs, it needs to be analysed in detail. For generators in the range of 125–250 kW, a reliable cost metric for the permanent magnet generator corresponds to EUR 75/kW [31,49], while in the case of the direct drive generator, the correct cost range is EUR 230–350/kW [49,70]. Note that some references provide generator cost functions that neglect information about the type of generators considered. This leads to an apparent discrepancy between the information proposed in the literature and could result in such cost functions not being used properly by WECs developers. The adoption of the cost function of a generator is particularly critical, as the right choice depends on various factors (power rating, type) that can be unjustly neglected in some reference. For this reason, it requires a lot of attention.

2.3. Device: High-Precision Mechanical Components

Several WECs convert energy with mechanical systems that require high-precision machining (shafts, bearing housings, etc.) [31,61,63,65]. In particular, this kind of mechanisms can be adopted for the primary transmission component or/and to vary the angular speed. For the construction of such components, more expensive technological operations are usually needed; hence, proper cost metrics have to be introduced. However, cast iron is also used, which requires cheaper operations. Therefore, different cost functions are provided hereafter for different levels of precision, either low or high, and different material; the final cost of each macro-component is the weighted sum of its various components.

Concerning components that require high-precision processing, such as mechanical brakes, gearboxes, joints, and seals, Fingersh et al. [49] suggest a cost metric equal to EUR 15/kg. This value has been computed taking into account the conversion from dollar to euro and the price index (as explained in the previous subsection). Maciol [71] proposes the costs metric for components in cast iron with different degrees of complexity and compactness. Focusing on the case of mechanical parts with high degrees of complexity and a middle degree of compactness, in [71] a cost metric equal to 14 PLN/kg is suggested, which corresponds to about EUR 3/kg (considering a conversion factor of 1PLN = 0.22 EUR, as reported in [72]). Fingersh et al. [49] propose a cost metric for bearings equal to EUR 27/kg, whereas a cost function equals to EUR 11/kg is proposed for the shafts. However, this last cost metric is introduced for a shaft with a ratio between the diameter and the length equal to 0.3. As highlighted by the price provided in [73], the cost metric linearly increases with the increase of this ratio.

A last aspect concerns the assembly of the mechanical systems and all the correlated operations, such as testing, painting, and handling. Approaching the problem with a BuA methodology, in [31] the cost of mechanisms for wave energy technology is quantified as 35% over the total cost for mechanical components. Then, considering a mechanical component with a weighted cost metric of EUR 10/kg, the cost function for the assembly and all correlated operations correspond to about EUR 3.5/kg. The cost metrics suggested for the mechanical components with different degrees of manufacturing complexity are summarized in Table 6. Note that costs are expressed with respect to the mass of each component.

Table 6. Summary of the cost metrics (BuA) for the mechanical component with different degrees of manufacturing complexity. The unit of measurement corresponds to euros per kilogramme of a single component.

Component/Material	Cost Metric (EUR/kg)
High-precision steel (mechanical brake, gearbox, joints, and seals)	15.0
Low-precision steel	4.5
Cast iron	3.0
Bearings	27.0
Shaft	22.0
Assembly	35%

2.4. Mooring System

The primary function of a mooring system is to guarantee the seakeeping of the floater and its survivability in severe sea-state conditions. It consists of one or more lines, jumpers, and clump weight and is kept steady to the seabed with anchors. Common materials for mooring lines are sections of studlink chains, wire ropes, and/or synthetic materials such as polyester or nylon. Following the design in Figure 2, we can identify the following main components:

- Anchors;
- Mooring lines;
- Connection components: shackle, thimbles, etc.;
- Buoys (or jumpers)

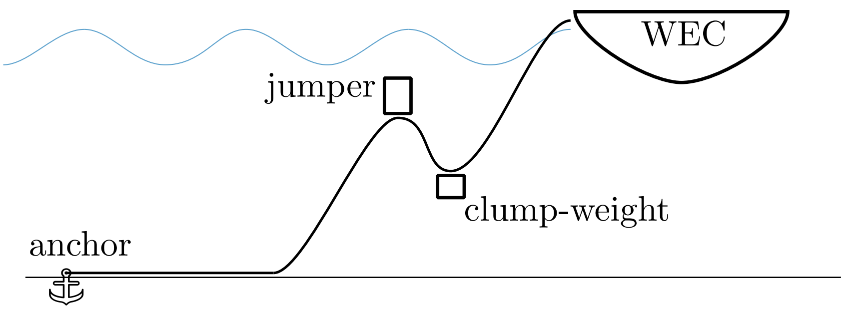

Figure 2. Generic mooring system configuration.

Some researchers have investigated the cost of mooring lines, anchors, and installation with regard to some specific case studies [32,53,74,75]. The aim of this section is to develop a methodology that provides cost functions for elements commonly used for a larger typology of mooring systems for WEC applications.

The new methodology herein proposed is based on a method that derives cost functions by exploiting data sets from scientific publications and open access projects and applying the BUA or aggregation approach technique. The minimum breaking load (MBL) usually characterizes the main mooring components. Despite this, in most cases, cost functions are provided with respect to mass or geometric features (EUR/kg or EUR/m), neglecting the MBL. Therefore, in order to fill this gap, we correlate the item's geometric or mass characteristic to the MBL based on an in-depth analysis of catalogues and public data sets.

2.4.1. Anchor Cost Functions

Drag Embedded

The drag embedded anchor (DEA) is designed to penetrate the seabed, either partly or wholly, and its holding capacity is generated by the resistance of the seabed. The DEA is typically well-suited for resisting large horizontal loads but not for large vertical loads; however, some recent DEAs available on the market can withstand significant vertical loads. The anchor cost has been estimated based on [32,53,59]. In particular, in [32] anchors are characterized with the ratio of the holding capacity (in tons) over their dry mass; in [59], costs are quoted with respect to the dry mass only, leading to results consistent with [32]. Aggregating and homogenizing such information, considering anchors with values of the capacity over dry mass ratio less than 50 (Figure 3), we define a cost metric of EUR 6.5/kg (this cost metric updates the value from [32], considering the increase of steel cost from 2013 to date [76]). Appendix A.2 shows the sizing procedure to extract the correspondent DEA mass in function of the withstood loads.

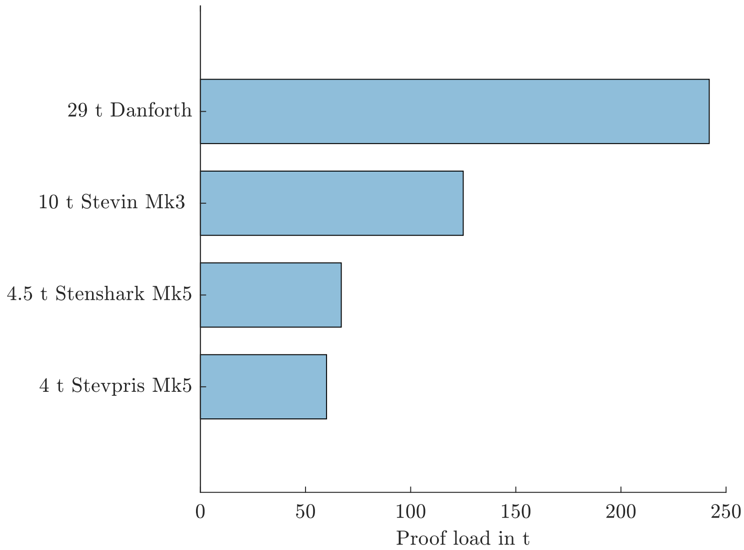

Figure 3. Proof load of drag embedded anchor [77].

Pile Anchor

Pile anchors are well-established technologies for offshore energy systems, typically divided into two main categories: *driven pile* and *suction*.

- Driven pile anchors (Figure 4a) are versatile and can be installed in soil profiles ranging from soft clay to soft rock [78]. They can also resist any load orientation, making them suitable for any mooring system: catenary, taut, or vertical tethers [55].
- Suction caissons (Figure 4b) are installed partially by self-weight penetration and partially by pumping from the interior chamber of the caisson to induce 'suction'. While installation requires relatively little equipment, caissons are bulky, so relatively large transport vessels and repeated vessel trips are needed, increasing the total cost. Their holding capacity is generated by combining the seabed layers' friction along the suction anchor interface and lateral soil resistance.

In the case of suction anchors analyzing installation times, in [57,58], it is considered that the suction installation time is 50% greater than the time needed for an equivalent drag embedded system. Therefore, the cost of the material varies around EUR 10/kg, as reported by [54,58,59], considering anchors with a total mass of 140 and 150 t and a holding capacity of about 700 t. Appendix A.2 shows the sizing procedure to compute the required pile anchor mass.

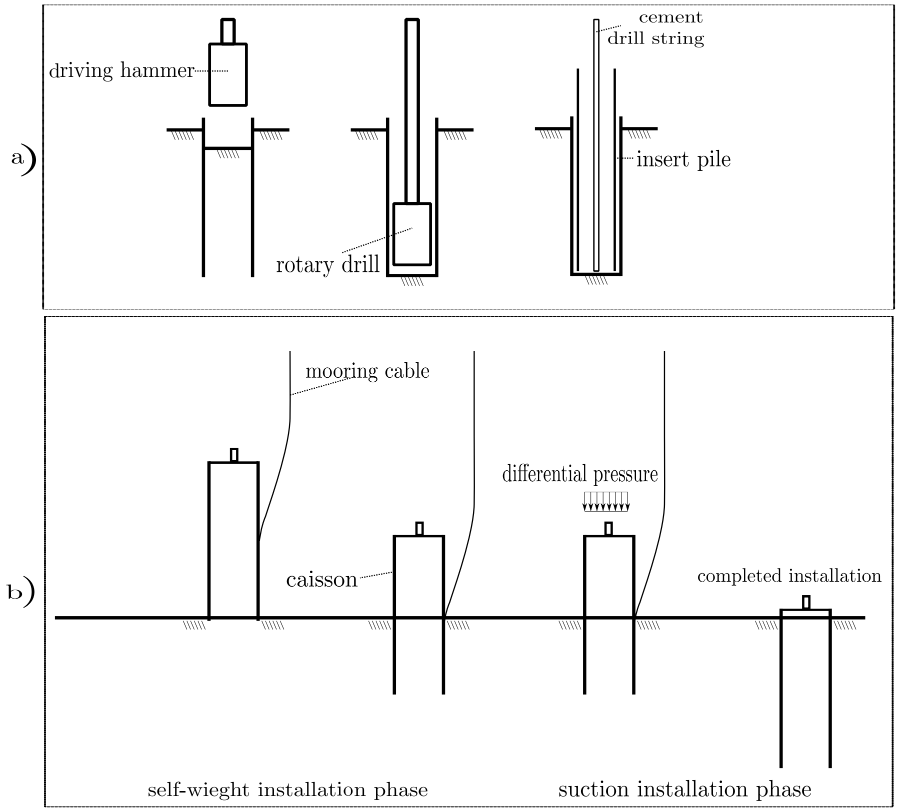

Figure 4. (**a**) Driven pile anchor; (**b**) suction pile anchor illustrations.

Dead Weight Anchor (DWA)

The dead weight is one of the oldest anchors in existence. The holding capacity of the gravity anchors is generated by the weight of the material and partly by the friction between the dead weight and the seabed. Common materials in use today for dead weights are steel and concrete. This anchor is well adapted to sandy bottoms and compact sediments. A preliminary anchor design is made based on [79]: the required submerged weight $mass_{DWA}$ is calculated as

$$mass_{DWA} = \frac{H_D}{tan(\phi - 5)} - V_D \quad (2)$$

where H_D is the horizontal component of the anchoring loading, ϕ is the angle of the internal friction of the sediment, and V_D is the vertical component of anchor loading (kg). The cost of gravity anchors is estimated by considering [42]. Indeed, we mediate between the cost of concrete and reinforced concrete, obtaining EUR 0.15/kg, where we consider the dry mass computed in Equation (2).

Suction Embedded Plate Anchor (SEPLA)

The SEPLA system uses a suction follower (similar to a suction anchor) to embed a plate anchor deeply in the soil. The suction follower is retracted once the plate anchor is brought to design soil depth and can be used repeatedly to install additional plate anchors. The equivalent mass in that case is not directly taken from an empirical equation like DEAs and suction anchors. Indeed, as reported in [80], their mass is assumed to be 25% of the suction pile anchors; however, in [57], it is described that the value of the installation cost is approximate to that of DEA. According to [81], the cost metric is assumed to be 50% of the equivalent suction anchor, therefore equal to EUR 5/kg. This cost metric is given for an anchor of 24 t, and the proposed cost metric can be considered valid around a range of 15–35 tons.

Vertical Load Anchor (VLA)

The vertical load anchor is installed like a conventional DEA but with higher penetration into the seabed. After the installation phase, this type of anchor can withstand both horizontal and vertical loads [82,83]. Usage of VLAs is restricted to soft clay soil seabeds. As reported in [58,59], the cost of the VLA was estimated at EUR 5.2/kg The proposed cost metric can be considered valid around a range of 10–40 tons. Appendix A.2 shows the sizing procedure to compute the VLA anchor mass required to obtain a desired load.

Chain Line

The most common product used for mooring lines is chain [84], which is available in different diameters and grades of quality (in terms of mechanics properties). Chains have been used for a long time for mooring applications. They can be studlink or studless. Studlink chains are heavier, have a higher drag coefficient, and resist fatigue better. Two different projects [29,32] and papers [53,74] were considered to identify the price of chains, which converge on similar values, averaged at EUR 1.5/kg. As reported in the DNV regulation [85], a direct correlation between the catenary nominal diameter and its linear density (ρ_{chain}) exists. This relationship is valid for a wide diameter range, particularly from values around 40 mm up to more than 200 mm:

$$\rho_{chain}\left(\frac{kg}{m}\right) = 0.0219 \cdot D^2(mm) \tag{3}$$

Synthetic Fiber Mooring Line

Fiber ropes can be a valid alternative of mooring materials for WEC or offshore wind technology. They are typically made of nylon (polyamide), polyester (polyethylene terephthalate), aramid (para-aramid), or HMPE (high modulus polyethylene). Fiber ropes are significantly lighter than other materials and can therefore be used to reduce the weight of moorings on the floating structure. First, the cost function of polyester ropes is analyzed: in [32,53], the cost metric is quoted at EUR 11.0/kg, referring to a rope with a linear density of 10.6 kg/m and a diameter of 125 mm. Following comparisons with other studies, such as [57], it can be concluded that the proposed relationship can be considered valid up to 15 kg/m of linear density. If the linear density is higher than 15 kg/m, the polyester cost metric increases to a value of EUR 22/kg.

The polyester rope mass can be calculated considering the regression between its linear density and MBL extracted from a catalogue [86]:

$$\rho_1\left(\frac{kg}{m}\right) = (Load_{rope} \cdot c_1) + c_2 \tag{4}$$

where $Load_{rope}$ is the respective MBL polyester rope limit, and c_1 and c_2 are the regressions coefficients (Table 8). In the case of nylon ropes, the cost function proposed by [57,75] has been adopted. The metric cost was obtained with eight-spiral-strands type nylon rope. In particular, [57] considers a cable with a diameter of 115 mm, an MBL of 450 t, and a linear density of 11.35 kg/m. Then, merging and homogenizing the quotations from both papers, the cost metric herein suggested is EUR 18.0/kg.

The computation of the cost of nylon ropes follows the same methodology as polyester. In fact, in [86] a catalogue was used as the data set to obtain the regression law, which computes the equivalent weight value of elastic fibre line as

$$\rho_2\left(\frac{kg}{m}\right) = (Load_{rope} \cdot d_1) + d_2 \quad (5)$$

where $Load_{rope}$ is the respective MBL limit of the nylon rope, and d_1 and d_2 are the regression coefficients (Table 8).

2.4.2. Subsea Buoy (or Jumper) Cost

Typically, jumpers are used in order to vary the stiffness characteristics of the mooring line or to avoid long mooring lines to lie on the seabed (Figure 2).

In [32], a cost function of EUR 20/kg for the jumpers is proposed, referring to the net mass of the device. The cost of EUR 20/kg is scaled up based on the ratio of volumetric efficiencies and normalised on the net buoyancy load (NBL) provided by the jumper, reported in [56]. The final value of 1.025 $\frac{€}{kg_{NBL}}$ has therefore been defined. This value is considered valid for jumpers capable of providing a theoretical net buoyancy load ranging from 3000 to 20,000 kg, with a ratio between net thrust and volume of about 650 $\frac{kg_{NBL}}{m^3}$ [56].

2.4.3. Wire Rope Cost

For wire rope, the value proposed by [32] of EUR 5.5/kg has been adopted. Note that this value is valid for linear density values of 22.0–25.0 kg/m, with rope diameters around 70–90 mm, so the equivalent cost per meter of rope length is EUR 125/m.

2.4.4. Connection Elements

The most common connection elements in a standard mooring system are shackles and tri-plates. They serve to connect two lengths of mooring, independently of the material.

For triangle plate connectors (Figure 5), a quoted value on the mass and one on the MBL, equal to 5.5 $\frac{€}{kg}$ and 8.0 $\frac{€}{kg_{SWL}}$, respectively, is proposed. The cost metric has been calculated for applications with a payload of 1500 kN. These assumptions are valid for a wide range. Indeed, [55] proposes the metric as constant value. Appendix A.2 performs the regression between mass and MBL value shown in Table A6. It is therefore possible to evaluate the connection element mass based on [87]:

$$mass_{con} = (MBL_{con}^2 \cdot g_1) + \ (MBL_{con} \cdot g_2) + g_3 \quad (6)$$

where MBL_{conn} is the limit load (in tons) of the connection element, and $g_{1,2,3}$ are the regression coefficients obtained from the regression between mass and its MBL value (Table 8).

Instead, the value of shackles is derived from the work [32]. It is to be distinguished, however, that in this work, economic analysis seems to be hinged on the D-type anchor shackles.

D-type anchor shackles are characterized by different manufacturing procedures than the standard one used for connections between chains or other mooring elements. So, as suggested in [32] we used the function quoted on the MBL, extrapolated from a linearization in 23 case studies. The equation expressing the relationship between cost on the payload (y, in $\left(\frac{€}{kg_{SWL}}\right)$) and the MBL, is equal to

$$y\left(\frac{€}{t_{MBL}}\right) = 0.02 \cdot MBL(t_{MBL}) + (1.8 \cdot f) \quad (7)$$

where $f = 1.22$ is the conversion factor GBP to EUR

$$C_{sh} = MBL(t_{MBL}) \cdot y\left(\frac{€}{t_{MBL}}\right) \tag{8}$$

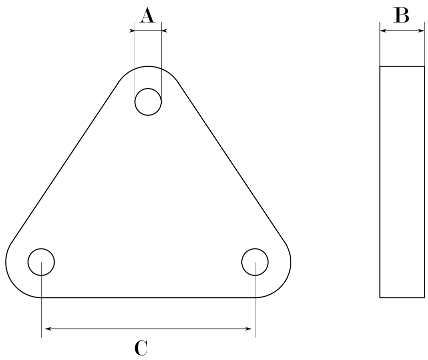

Figure 5. Triangle plates connector [88]. A is the diameter of the through-holes, B is the width dimension, and C is the inter-axial distance among two of them.

Standard Shackles

The cost for standard shackles is determined with regression law based on the mass, the working load limit (WLL = 1:6 of MBL), and the correspondent mass obtained from a datasheet of catalogues [89,90].

$$mass_{sh} = (MBL_{sh}^2 \cdot f_1) + (MBL_{sh} \cdot f_2) + f_3 \tag{9}$$

then from the paper [32], we obtain the cost per kg as

$$C_{sh} = 5.4 \frac{£}{kg} \cdot f \cdot mass_{sh}(kg) \tag{10}$$

2.4.5. Clump Weight

Clump weights are specially designed to reduce the vertical forces acting on the anchor. Thus, they restrict the movements of the floating structure by contributing to the restoring forces. They can be incorporated with a lighter mooring line to achieve beneficial stiffness properties for the relevant top-end offset [53]; they can also reduce the amplitude of tension peaks on mooring lines in shallow waters.

The cost of clump weights is estimated by considering [42], averaging between the costs of concrete and reinforced concrete. Considering that the mass of the concrete constitutes 60% of the total for each clump weight, a final cost function value ofEUR 0.15/kg is reached.

2.4.6. Total Mooring System Costs

Summarizing all the cost metrics for the mooring system into a single formulation, we obtain:

$$C_{tot} = (C_{ML} \cdot n_{ML}) + (C_{SC} \cdot n_{SC}) + (C_{CW} \cdot n_{CW}) + (C_{anc} \cdot n_{anc}) + (C_J \cdot n_J) \tag{11}$$

where C_{ML} is the cost of mooring line, C_{SC} refers to shackle connector, and C_{CW} corresponds to clumps weight cost. C_J refers to the jumper cost. The overall function costs are summarized in Table 7, while the necessary coefficients of transformation laws are summarized in Table 8.

Table 7. Summary of cost functions (BuA) for a mooring system.

	Components Name	Inputs	Transformation Law	Metric Cost	Cost Function (EUR)
C_{anc}	Anchor drag embedded (DEA)	$UHC(t)$	$W(kg) = \left(\frac{UHC}{a_1}\right)^{\frac{1}{a_2}}$	$6.5\ \frac{€}{kg}$	$C_{DEA} = W \cdot 6.5$
	Anchor pile		$L, T, D(m) = b_1 \cdot UHC^{b_2}$	$10\ \frac{€}{kg_{NBL}}$	$C_{suction} = \rho_{steel} \cdot Vol_{anch} \cdot 10$
	Anchor VLA		$A_F(m^2) = e_1 \cdot UHC) + e_2$	$5.2\ \frac{€}{kg}$	$C_{VLA} = mass_{VLA} \cdot 5.2$
C_{ML}	Elastic fiber line (polyester)	$Load_{rope}(t)$	$\rho_1\left(\frac{kg}{m}\right) = (Load_{rope} \cdot c_1) + c_2$	11 or 22 $\frac{€}{kg}$	$C_{polyester} = L_{rope} \cdot \rho_1 \cdot (11 \text{ or } 22)$
	Elastic fiber line (Nylon)		$\rho_2\left(\frac{kg}{m}\right) = (Load_{rope} \cdot d_1) + d_2$	$18\ \frac{€}{kg}$	$C_{Nylon} = L_{rope} \cdot \rho_2 \cdot 18$
	Chain line	L, D (m)	$\rho_{chain}\left(\frac{kg}{m}\right) = 0.0219 \cdot D^2 mm^2$	$1.5\ \frac{€}{kg}$	$C_{chain} = L \cdot \rho_{chain} \cdot 1.5$
C_J	Jumper	NBL (kg)	-	$1.025\ \frac{€}{kg_{NBL}}$	$C_{ju} = NBL \cdot 1.025$
C_{SC}	Standard shackles	$MBL_{Sh}(t)$	$mass_{sh}(kg) = (MBL_{sh}^2 \cdot f_1) + (MBL_{sh} \cdot f_2) + f_3$	-	$C_{sh} = 5.4\frac{£}{kg} \cdot f \cdot mass_{sh}$
	D-type anchor shackles		$y(\frac{€}{t_{MBL}}) = 0.02 \cdot MBL + (1.8 \cdot f)$	-	$C_{sh} = MBL \cdot y$
	Tri-plates connector	$MBL_{con}(t)$	$mass_{con} = (MBL_{con}^2 \cdot g_1) + (g_2 \cdot MBL_{con}) + g_3$	$5.5\ \frac{€}{kg}$	$C_{con} = mass_{con}$
C_{CW}	Clumps weight	$mass_{CW}(kg)$	-	$0.15\ \frac{€}{kg}$	$C_{CW} = mass_{CW} \cdot 0.15$

Table 8. Summary of Coefficients.

Coeff.	Value
a_1	From Table A3
a_2	From Table A3
b_1	From Tables A1 and A2
b_2	From Tables A1 and A2
c_1	0.004305
c_2	−0.33852
d_1	0.0043222
d_2	0.5305
e_1	From Table A4
e_2	From Table A4
f_1	0.003595
f_2	0.4818
f_3	−0.8472
g_1	0.00287
g_2	1.7932
g_3	−54.17

2.5. Marine Power Cable

The submarine cable represents the largest cost factor of the power transmission system. In this paper, we ignore the cost of less expensive components, such as transformers, bending stiffeners, junction box, connector, etc.). Submarine cables are an established technology for the offshore power market, and there is abundant evidence on cost metrics and characteristics. Submarine power cables consist of an inner copper cable insulated with a layer of cross-linked polyethylene (XLPE). Compared to data for power cables used in the oil and gas industry or offshore wind sector, less information is available or readily accessible for ocean energy. The main difference between the submarine cables used in these two application areas is the size (voltages, CSA), which depends on the electrical power to be delivered. The most commonly used cables for ocean energy applications have a typical voltage range of 400 V to 10 kV [91].

The cost function proposed in this paper depends on the voltage and cross section of the submarine cable, starting from a model proposed in [48] for offshore wind applications. Indeed, the proposed Equation (12) consists of:

- C_{ref} and n_{CSA}, the reference cost (200 $\frac{€}{m}$) and the coefficients for normalisation based on CSA, proposed in [48];
- n_V, the coefficients for voltage normalisation, adjusted to rescale the formula from offshore wind application (12) to marine energy application.

$$Cost_{cost} = C_{ref} \cdot n_{CSA} \cdot n_V \tag{12}$$

Table 9 shows the normalized value of linear density based on the 10 kW corresponding value. Table 10 shows the result of the normalized cost based on the CSA.

The installation cost functions for submerged marine cable can be derived from [28], and the value suggested are summarized in Table 11.

Table 9. Coefficients for normalization based on cables' linear density.

Cables Voltage (V)	n_V
400	0.637
900	0.657
3000	0.764
6000	0.901
10,000	1

Table 10. Coefficients for normalization based on CSA. Source: [48].

CSAs (mm)	n_{CSA}
25	0.74
35	0.78
50	0.82
70	0.9
95	1
120	1.1
150	1.2
185	1.3
240	1.5

Table 11. Range of cable installation costs (BuA) proposed by [28].

Kind of Required Operation	Cost Metric (EUR/m)
Cable laying trenched	282
Cable laying untrenched	100
Cable coverage (rock coverage)	939

Lastly, the installation cost of submarine cable is evaluated as in Equation (13).

$$Cost_{cost} = C_{LT} \cdot L_{LT} + C_{LU} \cdot L_{LU} + C_C \cdot L_C \quad (13)$$

where C_{LT} corresponds to cable laying trenched, C_{LU} represents cable laying untrenched, and C_C is the cost of cable coverage, each multiplied by the respective cable length (L_{LT}, L_{LU}, and L_C).

2.6. Installation

The cost metrics for the installation phases have been evaluated based on the time required for the corresponding procedures. The equations related to the time and cost of positioning the mooring lines (with the anchors and dead weights) have been analysed in particular detail, as this is the most time-consuming phase. Note that the information available in the literature usually relates to specific case studies. As an example, [34] considers the installation of a point absorber and provides the time needed for the different phases of the installation, as well as the cost of the required means (workers and boat); the proposed information is reported in Tables 12 and 13. Hereafter, we aggregate information from the literature to produce an operative list of cost functions applicable to the vast majority of WEC type and installation sites. In the evaluation of the installation process's timing, we assumed that the downtime period's impact could be disregarded. This clarification is extensively elaborated upon in the Discussions section.

Table 12. Summary of the time values needed for the installation of a point absorber reported in [34].

Operation id	Operation	Time (h)
A	WEC preparation	1
B	WEC submersion	0.5
C	Buoy preparation	1
D	Buoy connection	3
E	Cable connection	0.5
F	Monitoring	0.5

Table 13. Summary of the cost metric for the installation phases of a point absorber reported in [34].

Operation Cost id	Item	Cost (EUR/h)
C1	P_{diver}	90
C2	P_{worker}	50
C3	P_{boat} (support boat)	120

A final relationship is proposed in order to suggest an equation useful to compute a preliminary cost of the installation, starting from the number and the type of elements which compose the mooring system and have to be installed (Table 14). Starting the analysis from the anchors, the time necessary for the installation depends on the type of anchor considered; Myhr et al. [58] report that drag embedded anchors require eight working hours, with good sea-state conditions (Beaufort number lower than three). In contrast, suction and screw anchors require 12 working hours (because of the time demanded by the sink). The catenary can be arranged with a maximum speed of 0.15 m/s [92]. Ref. [34] suggests the value of 3 h as the time needed to connect components, such as buoys. This value has been assumed to be valid for the jumpers as they have a comparable mass and volume to the buoys. The same study estimates 30 min as the time required to connect components, such as the jumpers, to the mooring line and to connect each mooring line to the device. Concerning what was reported in [34], each main component or connection that needs to be inspected after its positioning requires a diver for half an hour. The positioning of the device can be performed towing it to the installation site from the port of departure; [93] indicates a speed range for this operation equal to 0.5–1.5 m/s. All the components that have to be installed, such as the device that have to be towed must also be allocated on the vessel or in the sea. This kind of operation has to be carried out with a specific crane, requiring in average of about one working hour on land per each main component allocated.

Table 14. Summary of the time values needed for the installation.

Expense Item	Symbol	Time
Anchoring (drag embedded)	$T_{A,de}$	8 h
Anchoring (screw, suction)	$T_{A,s}$	12 h
Catenary positioning	T_{ch}	0.15 m/s
Positioning of the dead weights	T_{dw}	30 min each
Positioning of the jumpers	T_j	3 h each
Connection of the main element (device, sublines of the mooring system)	T_{con}	30 min each
Inspection	T_i	30 min per each inspected component
WEC tracking	T_{wec}	0.5–1.5 m/s
Component preparation at land	T_{land}	1 h per each component arranged

All the reported data refer to devices with a maximum length dimension in the range of 15–25 m and a weight in the range of 100–250 t. If any ROV is used in the described procedures, the inspection requires two diver operators, a support coat, and three working operators on land for the preparation procedure. The installation of the mooring lines can be brought on in parallel.

Moving to the cost metrics related to the installation, [34] suggests costs for the great majority of expense items, which have been reported in Table 13. In order to estimate the cost of hiring the vessel, six types of vessels were considered, which can be grouped under two possible functions: vessels typically used to lay the mooring lines on the seabed (cost parameter C4) and vessels typically used to tow the WEC from the port to the installation site (cost parameter C5). To install a WEC, at least one vessel per function is required. The choice of vessel depends on typical weather conditions, availability in port near the installation site and depth at the installation site. Ref. [33] proposes the cost functions for such vessels, whose output is the daily cost of the rented device (EUR/day). These functions, which match the costs proposed in [28], were adopted in this work and reported in Table 15. Note that the cost functions must be entered with different technical parameters:

- For crane vessels, independently of the specific typology, the cost functions have to be entered with the crane lift capacity (CL) expressed in tonnes;
- For the AHTS and Tug, the functions have to be entered with the bollard pull (BP) expressed in tonnes;
- For the multicat, the cost function must be entered with the length overall (LOA), expressed in meters.

Table 15. Daily costs (BuA) for the boats reported in [33]. Note that "x" stands for the "Cost input parameter" corresponding to each boat.

Vessel Type—Cost id	Cost Input Parameter	Validity Domain	Cost Metric (EUR/day)
Jack up vessel—C4	CL (t)	$50 \leq x \leq 755$	$P_{JuV} = 64.71x + 21448.41$
Non-propelled crane vessel—C4	CL (t)	$4 \leq x \leq 3300$	$P_{nPCV} = -5.44 \cdot 10^{-3}x^2 + 64.41x - 6974.10$
Propelled crane vessel—C4	CL (t)	$4 \leq x \leq 500$	$P_{PCV} = 26.15x + 5842.59$
AHTS—C4	BP (t)	$70 \leq x \leq 338$	$P_{AHTS} = -0.0083x^2 + 114.90x - 261.87$
Multicat—C5	LOA (m)	$35 \leq x \leq 42$	$P_{multicast}$= 10000
Tug—C5	BP (t)	$13 \leq x \leq 25$ $25 \leq x \leq 70$ $70 \leq x \leq 80$	$P_{TUG1} = 151.34x - 467.47$ $P_{TUG2} = 2.18x + 3261.61$ $P_{TUG3} = 508.57x - 32186$

Aggregating the information provided in this paragraph, Tables 16 and 17 propose the different expense items that have to be considered and summed up for the estimation of the total installation cost.

Table 16. Installation cost metrics (BuA) summary. Focus on device installation phases.

Specific Phase	Expense Item Analyzed	Cost Metric Formula
Towing	Cost for the preparation of the device into the sea (workers)	$T_{land} \cdot 3 \cdot C2(\frac{€}{h})$
Towing	Cost for the boat rent	$\frac{D(m)}{T_{wec}(m/s)} \cdot \frac{1}{8760}\left(\frac{day}{s}\right) \cdot C5(\frac{€}{day})$
Towing	Support boat	$\frac{D(m)}{T_{wec}(m/s)} \cdot \frac{1}{3600}\left(\frac{h}{s}\right) \cdot C3(\frac{€}{h})$
Towing	3 workers are assumed to be on the multicat e 2 on the supporting boat	$\frac{D(m)}{T_{wec}(m/s)} \cdot \frac{1}{3600}\left(\frac{h}{s}\right) \cdot (3+2) \cdot C2(\frac{€}{h})$

Table 17. Installation cost metrics (BuA) summary. Focus on mooring system installation phases.

Specific Phase	Expense Item Analyzed	Cost Metric Formula
Transportation	Preparation of the N_{co} components on the AHTS (chain line, jumpers, dead weights, connection components)—Workers cost	$T_{land} \cdot N_{co} \cdot \left((C2(\frac{€}{h}) \cdot 6) + (\frac{1}{24}(\frac{day}{h}) \cdot C4(\frac{€}{day}))\right)$
Transportation	Cost for the boat rental	$\frac{D(m)}{T_{wec}(m/s)} \cdot \frac{1}{86400}(\frac{day}{s}) \cdot C4(\frac{€}{day})$
Transportation	Support boat	$\frac{D(m)}{T_{wec}(m/s)} \cdot \frac{1}{3600}(\frac{h}{s}) \cdot C5(\frac{€}{h})$
Transportation	Three workers are assumed to be on the AHTS and two on the supporting boat	$\frac{D(m)}{T_{wec}(m/s)} \cdot \frac{1}{3600}(\frac{h}{s}) \cdot (3+2) \cdot C2(\frac{€}{h})$
Positioning of the anchors	N_{screw} is the number of screw anchor per line, N_{drag} is the number of drag embedded anchor per line—Cost for renting the boats and the workers	$N_{line} \cdot [N_{screw} \cdot T_{A,s}(s) + N_{de} \cdot T_{A,de}(s)] \cdot [\frac{1}{86400}(\frac{day}{s}) \cdot C4(\frac{€}{day}) + \frac{1}{3600}(\frac{h}{s}) \cdot C3(\frac{€}{h}) + \frac{1}{3600}\left(\frac{h}{s}\right) \cdot (3+2) \cdot C2(\frac{€}{h})]$
Arrangement of the catenary	N_{line} is the number of mooring line, $L_{line}(m)$ is the length of the catenary—Cost for renting the boats and the workers	$N_{line} \cdot \frac{L_{line}(m)}{T_{ch}(m/s)}(s) \cdot [\frac{1}{86400}(\frac{day}{s}) \cdot C4(\frac{€}{day}) + \frac{1}{3600}(\frac{h}{s}) \cdot C3(\frac{€}{h}) + \frac{1}{3600}\left(\frac{h}{s}\right) \cdot (3+2) \cdot C2(\frac{€}{h})]$
Arrangement of jumpers, dead weights, and connection of the main elements	N_{ju} is the number of jumper per mooring line, N_{dw} is the number of dead weights, N_{con} is the number of main connections—Cost for renting the boats and the workers	$N_{line} \cdot (N_{ju} \cdot T_j(s) + N_{dw} \cdot T_{dw}(s) + N_{con} \cdot T_{con}(s)) \cdot [\frac{1}{86400}(\frac{day}{s}) \cdot C4(\frac{€}{day}) + \frac{1}{3600}(\frac{h}{s}) \cdot C3(\frac{€}{h}) + \frac{1}{3600}(\frac{h}{s}) \cdot (3+2) \cdot C2(\frac{€}{h})]$
Monitoring	Number of elements to be monitor N_i	$N_{line} \cdot (N_i \cdot T_i(s)) \cdot [\frac{1}{86400} day/s \cdot C4(\frac{€}{day}) + 2 \cdot \frac{1}{3600}(\frac{h}{s}) \cdot C3(\frac{€}{h}) + \frac{1}{3600}(\frac{h}{s}) \cdot (3+2+2) \cdot C2(\frac{€}{h}) + 2 \cdot \frac{1}{3600}(\frac{h}{s}) \cdot C1(\frac{€}{h})]$

2.7. Cost Functions Based on a TdA

In this paper, the cost computed with the BuA has been compared with both the one estimated with a TdA approach and a HyA. For the former case, percentages proposed by [17,28] have been adopted, shown in Table 18.

Table 18. Summary of the percentage weights (TdA) of the different parts of the system proposed in [17,28].

Subpart of the System	Percentage of the Total Cost
Device	45–50%
Balance of the plant (PTO incl.)	30–40%
Mooring system	15–35%
PTO	15–20%
Installation	15–20%

Referring to Table 18, note that:

- As defined in [17], the balance of the plant is defined as the PTO, the mooring system, and all the electrical installation necessary to connect the farm to the grid;
- A range has been suggested for each cost item, where the choice of actual value depends on the specific case study. In Section 4.3, an example of how the values in such a value range can be chosen is given;
- The sum of the percentage costs of the mooring system and the PTO is lower than 40% of the total costs. It follows that the two components cannot both reach the maximum percentage allowed, otherwise 55% would be obtained.

2.8. Cost Functions Based on HyA

In a HyA, some item costs are estimated using a BuA (potentially adopted in a reduced form, as defined in [22]), while the remaining items are given using a percentage pie distribution (TdA). A BuA can be applied in a complete form (as defined in Section 2) or in a reduced form, as defined hereafter. A reduced form of a BuA differs from the definition of the BuA (see Section 1 and Figure 1) because:

- The cost metric does not depend on the technological parameters that affect the manufacturing costs. For example, [28] proposes a foundation cost metric function expressed in euros per megawatt (EUR/ MW).
- The cost metrics are not limited by a range of validity, or they remain fixed regardless of the dimension of the component. For example, [28] proposes a fixed cost metric per PTOs, without any validity limit.
- The definition of cost metrics may be approximate due to the lack of a thorough investigation of the underlying elements that build up to the cost metric, leading to either
  - Duplication (e.g., the generator may be explicitly included as an individual item, but also as a hidden implicit part of the PTO);
  - Gaps (e.g., assembly or marinisation of the hull).

It follows that the reduced-BuA could lead to unreliable cost estimations.

In order to highlight differences between the BuA, the TdA, and the HyA, the same components considered in Sections 2 and 2.7 are evaluated with a HyA as follows:

- Installation cost is given as a TdA, and the cost functions given in Section 2.7 are assumed (15–20% over the total cost);
- Marine cable is quoted as a BuA, and the cost functions proposed in Section 2.5 are assumed;
- Hull materials, PTO, mechanical components, and the mooring system are quoted with a reduced-BuA form:
  - Steel and concrete costs have been defined ignoring marinisation costs;
  - Mooring cost has been identified using a cost function that depends on the MBL and total length, ignoring specific components used along the mooring line;
  - PTO has been considered as a cost metric that does not depend on nominal power.

The approach adopted for each of the subcomponents is summarised in Table 19, and the cost metrics adopted as a “reduced” BuA follow in the next paragraph.

Table 19. Summary of the approaches used to calculate the cost metrics in the application of the HyA.

Subcomponent	Approach Adopted for the Cost Computation of the Subcomponents in HyA
Installation	TdA
Marine cable	BuA
Hull materials	“reduced” BuA
PTO	
Mechanical components	
Mooring system	

Garcia-Teruel et al. [51] propose cost metrics for the mild steel and reinforced concrete. For steel, two different values are proposed for rolled and welded steel. The paper clarifies that the proposed cost metrics include assembly costs, but no details are provided for marinisation. In a HyA, this is a sufficient level of detail, but a BuA would require further investigation. In the case of a pure BuA, this missing information should be investigated, including whether an extra cost should be considered. Likewise, Ref. [28] proposes a cost function for low-precision steel, that is suggested to be adopted for the hull and the lowly worked components. This cost function does not vary with the dimension of the device

(LBD), as well as the cost function developed with BuA and presented in Section 2.1. While in a HyA this level of detail is sufficient, in a BuA, it would not be. The proposed value is then used as a cost metric for the hull and lowly worked components. All the resulting cost metrics for a HyA are summarized in Table 20.

Table 20. Summary of the cost metrics (HyA) for the construction of the hull and the mechanical components proposed in [28,51] and assumed for the estimation of the costs adopting a top-down approach.

Material	Cost Metric
Low-precision steel (EUR/kg)	4.50
Rolled milled steel (EUR/kg)	13.56
Welded mild steel (EUR/kg)	19.21
Reinforced concrete (EUR/kg)	0.63

Têtu and Chozas [28] suggest cost metrics for four types of PTOs listed in Table 3. These values are fixed and do not depend on the power ratings, even though the literature shows a significant variation. While in a BuA the proposed fixed values for PTOs would not have been acceptable, they are suitable for the level of detail required by a HyA.

Beiter et al. [52] and Castillo [94] propose cost functions for mooring systems that do not consider the components of the line, but only the MBL and the length. Such an approximation consists of another typical difference between the pure and the reduced BuA. For this reason, the cost functions proposed by these studies are adopted as an example for the reduced BuA and then for the HyA. The cost functions follow.

$$Cost_{chain} = \left(0.05236\frac{€}{m \cdot kN} \cdot MBL(kN) - 79.69\frac{€}{m}\right) \cdot L_{section}(m) \quad (14)$$

$$Cost_{polyester} = \left(0.0138\frac{€}{m \cdot kN} \cdot MBL(kN) + 11.281\frac{€}{m}\right) \cdot L_{section}(m) \quad (15)$$

$$Cost_{Nylon} = \left(0.0122\frac{€}{m \cdot kN} \cdot MBL(kN) + 12.116\frac{€}{m}\right) \cdot L_{section}(m) \quad (16)$$

$$Cost_{anchor} = 9.0358\frac{€}{kN} \cdot MBL(kN) \quad (17)$$

where the mooring chains are costed in euros (this value has been computed taking into account the conversion from dollar to euro and the the price index [67]) by providing the mooring line length ($L_{section}$) in meters and MBL of the chain in kilonewtons.

In summary, it can be argued that although convenient, a HyA can be unreliable due to the inherent need for simplification (mix of a reduced BuA and TdA), which justifies the difference in results between different approaches.

3. Pewec Case Study in Pantelleria

The PeWEC device designed for the site of Pantelleria Island (Sicily, Italy) is the case study adopted to compare the three cost assessment methodologies (BuA, HyA, and TdA). According to [95], the peculiarity of the PeWEC lies in the exploitation of the oscillating motion of a pendulum for the generation of electricity. For the physical description of the device, Ref. [95] uses a two-dimensional mathematical model, and this hypothesis is supported by the fact that the pendulum does not exchange forces along the third axis. This type of device is characterised by the property of self-alignment with respect to the dominant wave direction, thanks to a weatherproof mooring system.

The pendulum generates mechanical energy through its oscillations, which is converted into electricity by means of a power take-off (PTO) . In terms of manufacture, it consists of a mass with a central block (the disc) and a rod. The outer shell of the pendulum is made of thin steel sheets, while inside, it is reinforced with rods (Figure 6) [95]. At the opposite end of the bar, in relation to the central mass, it is attached to the PTO shaft. It follows that the shaft of the generator is directly connected to the pendulum. An encoder installed on the engine enables the position and speed of the shaft to be controlled. The parameters of the device are listed in the Table 21 [96]. The pendulum mass consists of 80% cast iron, 10% low-precision steel, and 10% high-precision steel. The basement mass consists of 45% cast iron, 55% low-precision steel, and 5% high-precision steel.

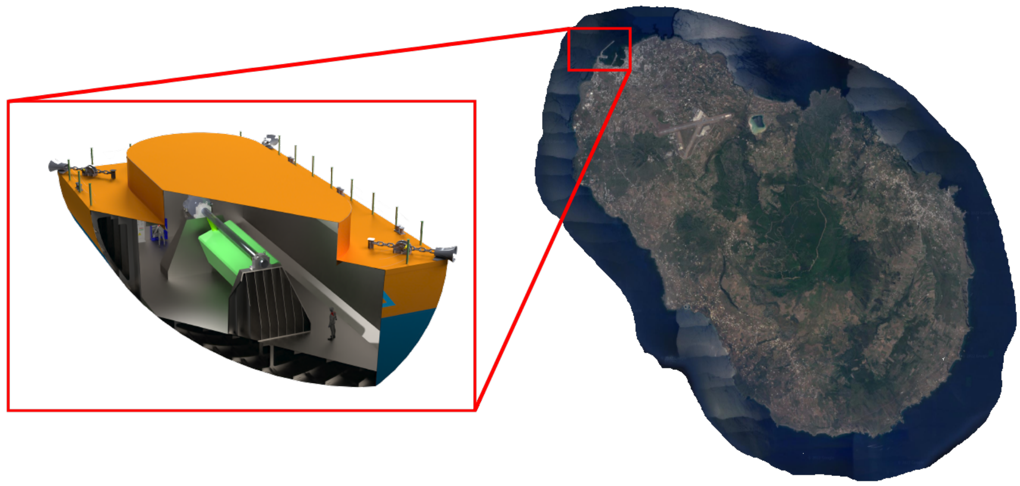

Figure 6. PeWEC design and deployment site illustration (Pantelleria Island).

Table 21. PeWEC device configuration detail.

Item	Values
Length	14.8 m
Beam	22.5 m
Draft	4.81 m
Volume	1601 m^3
Pendulum mass	93 t
Generator rated power	523 kW
Ballast mass on the hull	803 t
Hull mass	222 t

The case study is located near the island of Pantelleria, as described in [97,98] and shown in Figure 6. The details are reported in Table 22.

Table 22. Site of deployment.

Variables	Value
Water depth	40 m
Distance from shore	560 m
Average wave power	6.8 $\frac{kW}{m}$

The mooring layout consists of four mooring lines fixed with DEA anchors, steel chains, concrete ballast elements, and jumpers (see Figure 7). In Table 23, the most important items of the mooring system are listed, which form the basis for the cost calculation. In Figure 8, the distribution of the mooring system mass is proposed. The electrical system consists of a 560 m submarine cable divided into two segments: L_{LT} = 500 m and L_C = 60 m. The cable has a cross section of 150 mm and a voltage capacity of 6 kV.

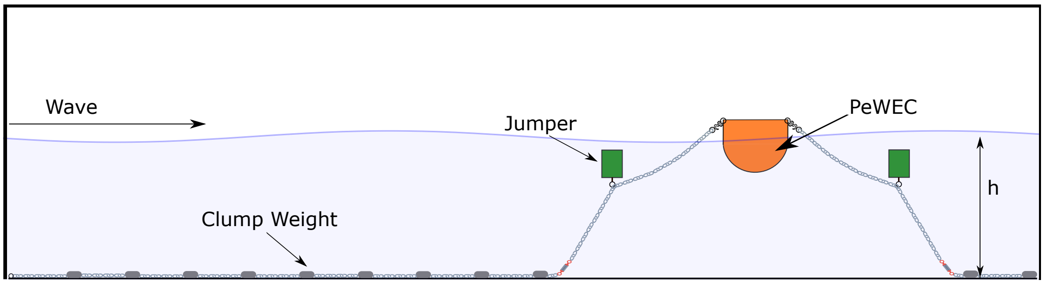

Figure 7. PeWEC's mooring layout illustration [95].

Table 23. Components and dimensions of the mooring system.

Element Name	n° per Line	Dimension	Value
Chain	1	Length	121.5 m
DEA anchors	1	MBL	9800 kN
Clumps weight	9	Mass (for single clump weight)	16,285 kg
Shackles	11	MBL	8000 kN
Tri-plate connector	1	MBL	8000 kN
Jumper	1	Net buoyancy force	18,561 kg
Ballast	1	Mass	12,857 kg

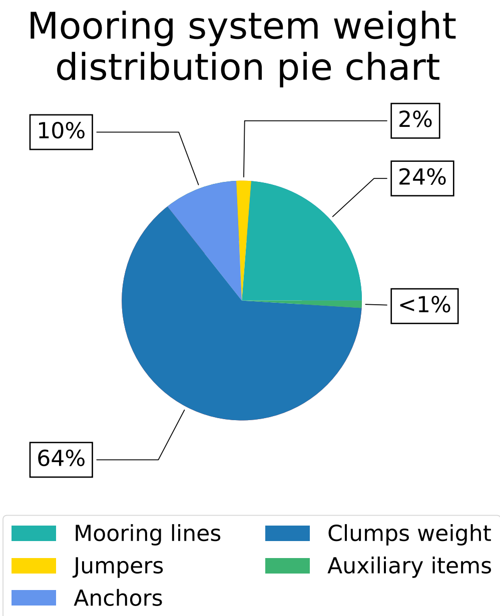

Figure 8. Breakdown of mooring system mass.

4. Case Study Results

The following section shows the calculation results when applying the cost function with the BuA and the HyA to the above case study. The final comparison between the three methods is critical and aims to highlight the main limitations of the three approaches.

4.1. BuA Applied on PeWEC

The data presented in Tables 21, 23 and 24 have been used to input the cost functions proposed in Section 2. The results of the cost estimation for the PeWEC case study using the BuA are given in Table 25.

Table 24. Mass breakdown of mooring system.

Component	Total Weight (kg)
Anchors	99,600
Chain	239,476
Ballast	51,429
Tri-plates	461
Shackles	5766
Buoy (jumper)	20,800
Clump weight	586,260
Grand Total Weight	**1,003,794**

Table 25. Bill of material for the PeWEC projectaccording to the BuA.

System Part	Component	Input	Cost Metric	Cost
Hull	Structural mass (steel)	177,600 kg	4.10 €/kg	728,160.00 €
	Ballast	803,000 kg	0.07 €/kg	56,210.00 €
	Accessories components	44,400 kg	15 €/kg	666,000.00 €
Mechanical component for power extraction	Pendulum	68,400 kg	4.35 €/kg	297,540.00 €
	Basement	19,950 kg	4.57 €/kg	91,271.00 €
	Shaft	2325 kg	22 €/kg	51,150.00 €
	Joints, seals etc	2325 kg	27 €/kg	62,775.00 €
	Assembly		35% of C_{MC}	175,957.00 €
PTO	Electric generator electronic components	523 [kW]		678,542.00 €
	Grand Total Device			**2,807,607.00 €**
Mooring System	Anchors	MBL = 9800 kN	5.2 €/kg	404,521.00 €
	Chain	D = 150 mm	1.50 €/kg	359,200.00 €
	Ballast	51,428 kg	0.15 €/kg	7713.00 €
	Tri-plates	MBL = 8000 kN	5.5 €/kg	2538 €
	Shackles	MBL = 8000 kN	6 €/Te_{SWL}	38,032.00 €
	Buoy	NBL = 18,000 kg	1.025 €/kg	76,700.00 €
	Clump weight	586,260 kg	0.15 €/kg	87,939.00 €
	Grand Total Mooring System			**976,169.00 €**
Marine cable	Manufacturing	560 m	234 €/m	131,214.00 €
	Grand Total System			**3,915,00.00 €**

Tables 26 and 27 summarise the cost functions for the installation procedure of the device and the mooring system. For the installation of the device, we have rounded up the numerical time factors included in the cost functions described in Table 16.

The installation of the mooring system requires more time and a more expensive vessel. The costs are summarised in Table 27, which analyses the duration of each main phase with reference to the specific cost metric associated with the activity. It is assumed that an AHTS is used with a cargo capacity equal to the weight of the mooring system, increased by a safety margin of 20%. This cargo capacity corresponds to a BP of 218 t [99,100], which costs EUR 24,250 per day according to the equation proposed in Table 15. We also estimate two days to rent the AHTS, considering only the travel time from the nearest port that can accommodate such vessels. Considering also the installation time, the rental period amounts to four days per line.

Table 26. Installation device cost. Focus on device installation phases.

Main Component to Be Installed	Specific Phase	Expense Item Analyzed	Cost
Device	Towing	Cost for the preparation of the device into the sea (workers)	EUR 150.00
Device	Towing	Cost for the boat rent	EUR 10,000.00
Device	Towing	Support boat	EUR 120.00
Device	Towing	Three workers are assumed to be involved in preparation; two on the support boat	EUR 240.00
		Grand Total Installation Device	**EUR 10,520.00**

Table 27. Installation of mooring system cost using BuA.

Specific Phase	C1 [h]	C2 [h]	C3 [h]	C4 [day]
Transportation	-	33	0.207	0.46
Positioning	-	40	8	0.33
Arrangement of anchor	-	1.12	0.224	0.009325
Arrangement of connection elements	-	30	6	0.25
Monitoring	7	24.5	7	0.1458
Cost per line	EUR 630.00	EUR 6431.02	EUR 2571.00	EUR 109,302.00
Grand Total Installation Mooring Per Line			**EUR 118,935.00**	

The overall cost for the installation of mooring system is EUR 475,738.00, namely 4 times the total installation cost per line, as in Table 27. The cost of marine cable installation is EUR 197,160.00 using the proper Equation (13), The resulting final grand total installation cost of the entire system accounts to EUR 683,418.00. Considering all cost items, the overall cost is equal to EUR 4,598,422.00. Figure 9 summarizes the breakdown percentage distribution of all system costs.

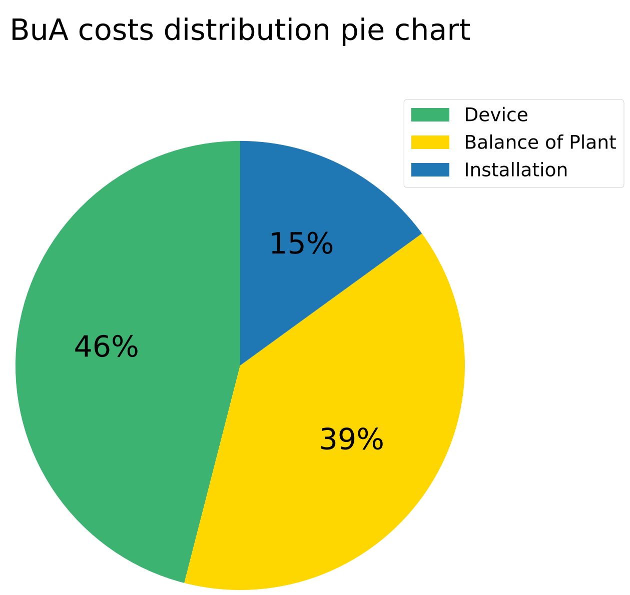

Figure 9. Breakdown percentage cost using the BuA.

4.2. HyA Applied on PeWEC

The results of the cost estimation for the PeWEC case study using the HyA are given in Table 28. Concerning the device components, Table 20 is the reference for the cost metric. In particular, it was assumed that the hull structural mass, pendulum, and basement are in low-precision steel, while the hull ballast is in reinforced concrete. Shaft and joints are made of rolled milled steel and welded milled steel, respectively. The PTO is mechanical, whose cost metric is shown in Table 3. The mooring cost for the HyA is composed of anchors and mooring line item costs. The relative design inputs of the cost metrics are extracted from [101]. The capital submarine cable cost is evaluated with a BuA, except for its installation cost; the installation cost, estimated with a TdA, is assumed to be 15% of the total "Grand Total System" cost, hence equal to EUR 617,134.00. Figure 10 summarizes the breaking down percentage distribution of system cost and the grand total cost, which is equal to EUR 4,114,230.00.

Table 28. Bill of material for the PeWEC project, according to the HyA.

System Part	Component	Input	Cost Metric	Cost
Hull	Structural mass (steel)	222,000 kg	EUR 4.50/kg	EUR 999,000.00
	Ballast	803,000 kg	EUR 0.63/kg	EUR 505,890.00
Mechanical component for power extraction	Pendulum	72,000 kg	EUR 4.5/kg	EUR 324,000.00
	Basement	19,950 kg	EUR 4.5/kg	EUR 89,775.00
	Shaft	2325 kg	EUR 13.56/kg	EUR 31,527.00
	Joints, seals etc	6975 kg	EUR 19.21/kg	EUR 133,989.00
PTO	Electric generator electronic components	523 kW	EUR 1400/kW	EUR 732,200.00
		Grand Total Device		**EUR 2,816,382.00**
Mooring System	Anchors	MBL = 9345 kN	EUR 2.60/kg	EUR 209,783.00
	Chain	MBL = 8000 kN		EUR 339,716.00
		Grand Total Mooring System		**EUR 549,363.00**
Marine cable	Manufacturing	560 m	EUR 234/m	EUR 131,214.00
		Grand Total System		**EUR 3.497,095.00**

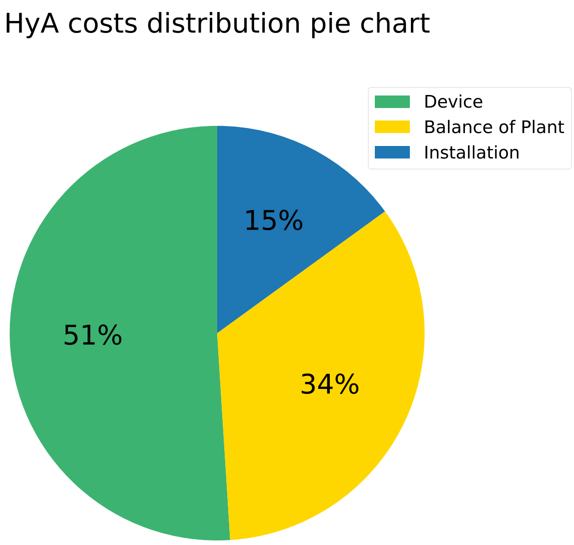

Figure 10. Breakdown percentage cost using the Hybrid approach.

4.3. TdA Applied on PeWEC

The purpose of this section is to show the result of applying the pure top-down approach to the case study. It is assumed that the installation costs represent 15% of the total costs, the PeWEC does not require a complex operation for installation, and the lowest value in the range proposed in Table 18 has been chosen. The PeWEC uses a direct drive system and typically has high torques; this requires a PTO with high power rating and therefore the maximum value of 20% in the range cost has been chosen. In addition, the anchoring system is particularly heavy in relation to the device. It follows that the percentage cost of the balance of the plan is the maximum of the cost range proposed in Table 18, that is 40%. It follows that the cost associated with the device represents 45% of the total cost. Figure 11 summarises the percentage breakdown of system costs.

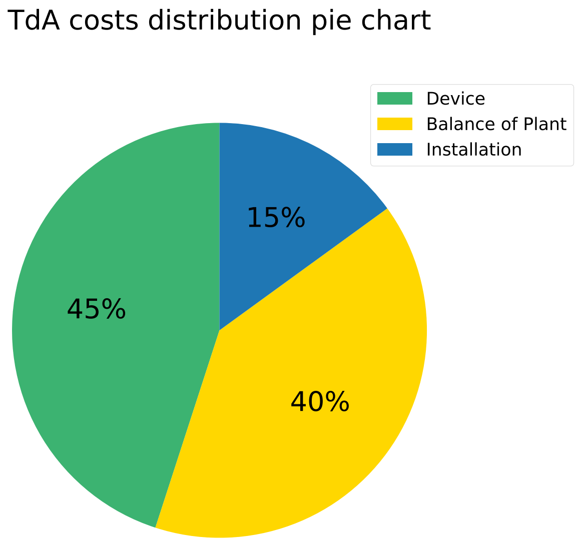

Figure 11. Breakdown percentage cost using a TdA.

4.4. Economic Assessment and CoP Computation

To compare the result obtained, we evaluate them using the capital expenditure (CapEx). The CapEx is evaluated using the following equation:

$$CapEx = C_{Device} + C_{BP} + C_{EC} + C_{Installation} \quad (18)$$

where C_{Device} corresponds to the item cost of the material needed for the hull's manufacturing. C_{BP}, namely the balance of the plan cost, which is the sum of the cost of procurement of overall electrical export cable, mooring system elements, and the item costs of a WEC device, namely the PTO and its mechanical component for power extraction. Indeed, $C_{Installation}$ is equal to the overall cost of the installation activities. Table 29 shows the economic result for the BuA and the HyA scenario.

Table 29. Comparison of BuA and HyA in terms of CapEx.

	BuA	**HyA**
CapEx (EUR)	4,598,422.00	4,114,123.00

5. Discussion

A BuA was adopted to develop cost functions for the common components adopted in a widespread WEC field. The BuArequired the adoption of 20 cost functions, 9 more than the ones adopted in the hybrid approach, while the pure the TdA subdivides the costs into 4 macro-groups. To assess the extent to which the use of the BuA can improve the accuracy of cost assessment in WEC projects, the percentage cost distribution for the three approaches (BuA, TdA, and HyA) is compared in Figure 12. The bar chart shows that the cost functions developed in Section 2 result in total costs that are consistent with the cost breakdown usually proposed in the TdA. Note that for the specific case study to which the cost functions have been applied, BuA is more consistent with the TdA than the HyA.

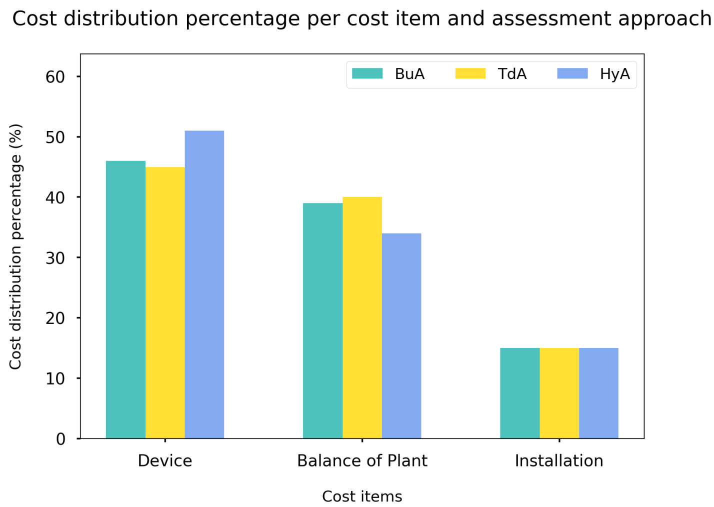

Figure 12. Cost percentages distribution per different type of assessment cost (BuA, TdA, and HyA) and item cost (device, balance of plant, and installation).

A pure TdA cannot be used to obtain final costs, and for this reason, only a HyA and a BuA were compared in terms of absolute costs (in Table 30). The results in the table show that although CapEx differs by only 11%, the cost distribution of each macro group is very different. In particular, the estimated costs of the device are the same, while the balance of plant and installation differ by 14% and 22%, which are the item cost typologies with:

- The highest dependency in relation to the specific location of the case study;
- Less accurate BuA cost functions with broad applicability that are widespread in the literature.

It follows that the BuA intrinsically brings a more distributed, representative, and physics-based cost allocation, which can support an economic optimization process based on multi-criteria analysis. As mentioned in Sections 2.1–2.6, the cost functions proposed in this paper have been compared with the corresponding cost ranges from the literature, which confirms the consistency of the proposed functions.

Table 30. Comparison of costs computed with the BuA and the HyA.

	BuA	HyA	Percentage Difference (%)
Device	EUR 2.1 M	EUR 2.1 M	0%
Balance of Plant	EUR 1.8 M	EUR 1.4 M	−22%
Installation	EUR 0.7 M	EUR 0.6 M	−14%
CapEx	EUR 4.6 M	EUR 4.1 M	−11%

Several item cost metrics utilized in this study are derived from the more established offshore wind sector. The mooring and electrical subsystems, which are common to both the wave and wind sectors, were evaluated using a cross selection of data sets from both sectors. However, the wind sector was given more preference due to its high technology readiness level (TRL) and reliability. Additionally, the cost metrics for ballast and mechanical components were obtained from studies conducted in the wind sector.

One final point concerning installation needs to be discussed. Although the percentage of installation costs to CapEx is consistent between the three approaches, this paper ignores how weather conditions affect the number of days needed to complete the installation. As explained in [102], the time required for installation can vary from the minimum required time of 30% to 210%, depending on the month (and thus weather conditions) in which the installation is carried out. This percentage varies greatly with the months, location, and type of technology. In this sense, the BuA should be applied to assess all parameters that may increase the time required for installation and to understand if these impacts can be described in one or more closed formulas, as is the case with the cost assessment presented in this study. As the focus of this work is to propose a BuA for cost assessment only, the impact of weather conditions on the time required for installation has not been estimated but should be further investigated to complete a full BuA assessment in the cost analysis. The identification of another constraint is related to the expenses incurred during power cable installation. We extracted a preliminary estimate of the cost metric for the primary installation stages from the study [28] (refer to Table 11). Furthermore, the size diameter does not affect the installation assessment of the power cable. Indeed, the most crucial factor that affects the installation procedures is the weight of the cable. The weight is related to the CSA. Furthermore, the typical WEC range amplitude of CSA is narrower compared to the range of offshore wind. For this reason, the authors have supposed that the power cable size does not influence the installation.

6. Conclusions

This paper first points out that the cost information available in the literature for wave energy converters is sparse and often too specific, which limits its applicability. This brings WEC developers in the early design phase to adopt the cost functions developed with the TdA and the HyA for techno-economic optimisation. The results presented in this paper have shown that:

- Cost functions for WECs can also be developed for early stage projects and that the literature gap can be filled by critically analysing the technological parameters that influence manufacturing costs;
- In the case study analysed in this paper, the application of the BuA has resulted in a cost distribution among the various macro groups that differs by up to 22% from a HyA;
- The BuA is generally more representative and has a transparent relationship between the characteristics of each component and their cost. Therefore, it is well-suited for optimisation and cost reduction. In contrast, the TdA works like a black box and is only useful for evaluation, albeit with low accuracy. A specific case study also quantified the difference between the costs estimated with the BuA, the HyA, and the TdA.

This paper also proposed an aggregated list of representative cost functions for the most common components of WECs. It can allow the adoption of more representative cost functions at an early stage of the design, thus enabling more effective cost optimisation. Ultimately, the suitability of the list allows for a more accurate comparison of different solutions in terms of required costs and a first understanding of whether a solution can lead to economic savings and a first estimate of these savings. This paper aims to support WEC developers at an early design stage, and any real cost metrics should be preferred to proposed functions, when available. If more detailed information is available, such as the coordinates of a specific installation site or the definition of a manufacturing process for a specific group of components, it would be possible to further adapt the proposed cost function to the analysed case study.

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Appendix A

Appendix A.1. Device Hull

Equation (1) has a validity for LBD in the range 20,000 m^3 and 100,000 m^3, and it leads to a steel average price of EUR 2.5–3/kg. The equation includes in its formulation the term $LBD^{-0.015}$, and this term varies from 0.32 to 0.27 (in the range of validity of the equation): considering the small variation, the mean value of 0.285 can be considered.

The typical dimensions of WEC LBD might be outside the validity range of Equation (1), and a correction factor to the cost metric of EUR 2.5–3/kg needs to be applied. Assuming that the total hull price varies only as a function of LBD and that the complexity factors do not change their influence on the final cost moving to smaller hulls [63,65], a scaling factor (H_{sf}) can be calculated as follows:

$$H_{sf} = \frac{LBD^{-0.115}}{0.285} \tag{A1}$$

Assuming that LBD for WECs is in the range 1600 m^3 $< LBD <$ 2500 m^3 [103], and applying the correction factor to the cost EUR 2.75/kg (the mean value of the EUR 2.5–3/kg cost range proposed in [64]), the scaled cost of EUR 3.6–4.1 is calculated. This cost metric is consistent with the values proposed in the literature by other works [28], and for this reason, the cost function of the hull (C_{hull}) proposed in (A2) is adopted in the validity range of 1600 m^3 $< LBD <$ 2500 m^3 (for which the resulting cost values have been compared and validated with those proposed in other studies).

$$C_{Hull} = \frac{LBD^{-0.115}}{0.285} \cdot 2.75€/kg \tag{A2}$$

Appendix A.2. Mooring Elements

Appendix A.2.1. DEA

Observing several anchor manufacturers' catalogues [77] and the work [104], it is possible to obtain the inputs needed to compute the anchor cost. Starting from its mass which is computed with the following equation

$$W = \left(\frac{UHC}{a_1}\right)^{\frac{1}{a_2}} \tag{A3}$$

where the UHC is the ultimate holding capacity in (kN). Then, by choosing one of the three kinds of seabed scenarios, the value of a_1 and a_2 are extracted from Table A3.

Appendix A.2.2. Pile Anchor

These anchors are always regarded as cylindrical and with a very low construction complexity. As expressed in [104], the anchoring capacity can be characterized uniquely by its geometric dimensions (Tables A1 and A2), mainly its length and diameter, and the conditions of the seabed where it will operate (either clay or sand). Kim [104] relates each of the characteristic dimensions to the anchoring capacity by the following equation:

$$L, T, D = b_1 \cdot (C_{anc})^{b_2} \tag{A4}$$

where *L*, *T*, *D* correspond, respectively, to length, thickness, and diameter of the pile anchor, and C_{anc} is the anchoring holding capacity. At the same time, b_1 and b_2 are the factors dependent on the type of seabed's soil composition. Then, it is possible to extract the volume of the cylinder of the anchor as

$$Vol_{anch} = \pi \cdot L \left[\left(\frac{D}{2} \right)^2 - \left(\frac{D - 2T}{2} \right)^2 \right] \tag{A5}$$

assuming that its main components are made of steel ($\rho_{steel} = 7800 \frac{kg}{m^3}$), we obtain the mass value as

$$mass_{anch} = \rho_{steel} \cdot Vol_{anch} \tag{A6}$$

Table A1. Coefficients for sizing driven pile anchor [104].

Soil Consistency	L		D		T	
	b_1	b_2	b_1	b_2	b_1	b_2
Very Soft Clay	2.1697	0.3447	0.1049	0.3016	0.6722	0.4694
Medium Clay	1.2976	0.3733	0.0529	0.3452	1.0531	0.4042
Sand and Hard Clay	2.5296	0.2907	0.0219	0.3700	1.1185	0.3889

Table A2. Coefficients for dimensioning suction pile anchor [104].

Soil Consistency	L		D		T	
	b_1	b_2	b_1	b_2	b_1	b_2
Very Soft Clay	1.1161	0.3442	0.3095	0.2798	2.0580	0.2803
Medium Clay	0.5166	0.3995	0.1260	0.3561	0.8398	0.3561

Table A3. Coefficients DEA [104].

Vryhof Anchor	Soil	a_1	a_2
Stevin MK3	Very Soft Clay	161.23	0.92
	Medium Clay	229.19	0.92
	Sand and Hard Clay	324.42	0.90
Stevpris Mk5	Very Soft Clay	392.28	0.92
	Medium Clay	552.53	0.92
	Sand and Hard Clay	686.49	0.93
Stevpris MK6	Very Soft Clay	509.96	0.93
	Medium Clay	701.49	0.93
	Sand and Hard Clay	904.21	0.93

Appendix A.2.3. VLA

Its mass is estimated by a relationship given by the manual of Vyrhof anchors detailed in Table A4, where the area is computed as

$$A = e_1 \cdot UHC + e_2 \tag{A7}$$

where UHC is ultimate holding capacity of the anchor value estimated in kN, A is the required fluke area in square metres (m^2) with a range between 5 and 28 m^2.

The UHC of the anchors should be related to the break-load of the mooring line interface. Ref. [77] proposes estimating the UHC of the anchor to be equal to 50% of the MBL of the attached mooring line. Under this assumption, it is possible to extract the fluke's area from Equation (A7). Then, we suppose to discretize the anchor volume from design in Figure A1, assuming from the computed fluke's area the correspondent geometric anchor dimension from Table A5.

Table A4. Sizing coefficient for computing the admissible fluke area [104].

Soil Quotient Undrained Shear Strength ($\frac{kPa}{m}$)	e_1	e_2
1.25 (very soft)	0.003581	−0.1094
1.75 (very soft)	0.002461	−0.2847
2.25 (medium)	0.001857	−0.3259
2.75 (medium)	0.001489	−0.3176

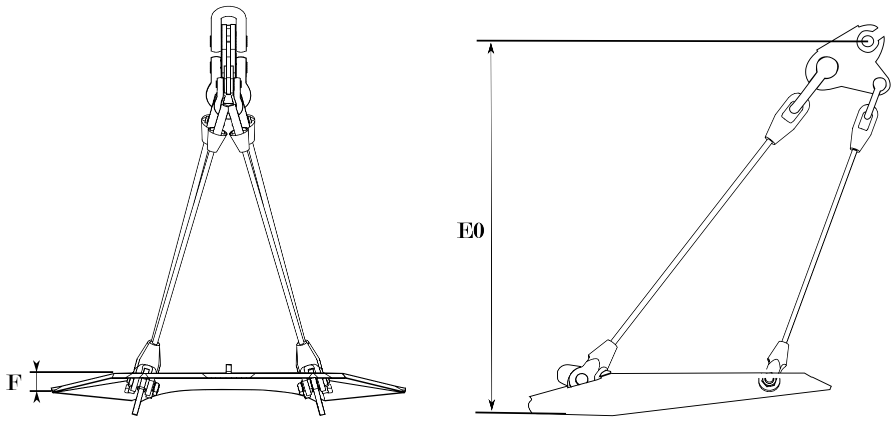

Figure A1. Technical VLA design [77].

Table A5. Main geometric dimension Stevmanta VLA [77].

Area (m^2)	5	8	10	12	15	17	20
F (mm)	172	217	243	266	298	317	344
E0 (mm)	3075	3890	4349	4764	5326	5670	6150

The overall mass of the VLA anchor is obtained from the following equation:

$$mass_{VLA} = \left(\rho_{steel} \cdot A_f \cdot \frac{F}{2}\right) + \left(4 \cdot \rho_{chain} \frac{E0}{sen(\alpha)}\right) \quad \text{(A8)}$$

where $\frac{F}{3}$ is assumed to be the fluke's thickness extracted from Table A5, α can be assumed to be 30° that is the average value of chain cords inclination, and ρ_{chain} is the linear density of chain which is supposed to be the same used in the quotation of the mooring line.

Appendix A.2.4. Triangle Plate Connection

Table A6. Triangle plates catalogue technical characteristics [88].

MBL	A (m)	B (m)	C (m)	Weight (kg)
125	55	50	140	9.4
175	60	60	150	13.2
275	75	80	180	26.4
425	90	90	220	43.6
600	105	110	240	46.8
675	115	130	260	94.6
875	115	140	290	114.7
1000	140	150	380	198.0
1250	150	170	450	289.8

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