Technical and economical viability study of a Floating Coaxial Ducted OWC

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Abstract

In the present study, a techno-economical analysis is performed to a new wave energy converter, the Floating Coaxial Ducted OWC equipped with a biradial turbine. A methodology is proposed that can be applied to other devices. This type of assessment is part of the development process of new technologies, by supporting investment decisions that can finance wave farms connected to national energy grids. The methodology proposed comprises five processes. The first one deals with the location, geo-physical and socio-economic characteristics. The second refers to the design of one device considering certain constraints. The third is related to the design of arrays and distribution of devices. The fourth process deals with the financial evaluation of the project, comprising the estimation of well-known indicators, such as the NPV and LCOE, and applying discounted cash flow techniques. Finally, the overall technical and economical assessment of the project is performed, as well as the estimation of cost reduction associated to the sector’s learning process. The methodology was applied to a case study, conceived focusing on cost effectiveness and device performance, applying knowledge obtained from off-shore wind energy. The location chosen for the case study was at the Portuguese Pilot Zone. Arrays with different power outputs were assessed, under assumptions supported by state-of-the-art studies. The financial evaluation was performed using current project assessment methods. Results show the high investment costs needed for the actual devices and the insufficient support tariffs required to make the projects feasible in this early phase of the technology.

Keywords: techno-economical analysis, project assessment, wave energy, oscillating water column, renewable energies

1. Introduction

Earth is an aqueous planet with about 70% of its surface covered by oceans, which retain about 96.5% of all Earth’s water. Oceans are the largest solar collector [1], and a great storage of mechanical energy, due to the action of wind which is another form of solar energy. In order to reduce mankind’s dependence on fossil fuels, mechanisms that can take advantage of this great amount of energy available should be developed. Although, in a long term basis, the aim should be a sustainable market of wave energy, in a short to medium term, the goal can be the integration of wave energy conversion systems in the renewable energy mix.

To achieve this sustainable market, competitive prices for electricity produced by wave energy converters (WEC) must be attained. Hence, techno-economical studies are important in two ways. First, verify if the deployment of the available technology presently or in a near future constitutes a feasible project for investors and, perhaps the most important, delve the existence of new directions in technique and product development always having a cost-effective design in mind.

1.1. State of the art

The first successful attempt to transform the wave oscillations in electrical power was made by Yoshio Masuda (1925-2009), using an air turbine to equip a navigation buoy, system which would later be known as oscillating water column (OWC) [2]. The first theoretical studies on oscillating-body and OWC converters showed that in efficient devices, the frequency of oscillation match the frequency of the incoming waves, i.e. they should operate at near-resonance conditions. This explains the failure of some quasi-static systems, that simply follow the wave surface motion. Control strategies can be applied to establish actions for survivability under extreme conditions, and also to increase the power absorbed by wave energy systems. Control strategies such as rotational speed control and phase control by latching are strategies that are being researched for OWC; however, optimal phase control in real random waves and its practical implemen-
tation in wave energy converters remains an open problem [2].

While in wind energy horizontal-axis turbines early dominated the industry as the most effective technology [1], in wave energy there is a wide variety of different ways to absorb energy from waves and to convert it into electricity. These depend on the conditions of the surroundings, i.e. water depth, location (shoreline, near-shore, offshore).

1.2. Floating Coaxial Ducted OWC

The wave-powered navigation buoys and the Kaimei barge are the first examples of OWC floating-structure. These devices are slack-moored to the sea bed, so the water surface is freer to oscillate than in the previous devices [2].

The device studied is based on the concept of an OWC, having an axisymmetric cross section with reference to its vertical axis (Fig. 1). The heaving motion (i.e. vertical oscillation) of the anti-heave plate is almost null, so that the upper tube moves relatively to the bottom part [3]. This device can be designed to have a cavity or a series of cavities that may be filled with water in order to control the draft, which would allow to adapt the absorbed power of the device, keeping a larger capacity factor in more sea-states without having to switch-off the power generation. The latter may represent an advantage over other types of OWC. Another advantages might be the reduction in buoy motion due to the extra mass, which results in less moorings and cabling movements [4].

![Figure 1: Floated Coaxial Ducted OWC scheme. Source: [4]](image)

The device is equipped with a biradial air turbine, an alternative to the self-rectifying axial-flow impulse turbine and to the Wells turbine. Compared with the axial-flow turbines that have dominated the applications in OWC, the biradial air turbine has a compact configuration, especially in the axial direction [5]. The flow into, and out of, the rotor is radial and the turbine is symmetrical with respect to a plane perpendicular to the rotation axis [5]. The numerical tests done with this turbine show a relatively good efficiency (peaking up to 0.83 for certain conditions) over a wide range of flow rates. To maximize turbine efficiency, rotational speed should be controlled [5].

1.3. Economical and Law review

In 2013, the worldwide electricity generation was 22668 TWh, with fossil and nuclear fuels contributing to more than 70% of total electricity generation. Although these are the most pollutant sources of energy, their market price makes them economically appealing, as shown in Table 1. The development of a self-sustainable wave energy market requires technologies that are able to produce electricity at a price that is not more expensive than that of the offshore existing alternatives while having less environmental impact.

<table>
<thead>
<tr>
<th>Technology</th>
<th>€/kWh</th>
<th>g CO₂/kWh</th>
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</thead>
<tbody>
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<td>40</td>
</tr>
<tr>
<td>Photovoltaic PV</td>
<td>0.12</td>
<td>70</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.08</td>
<td>20</td>
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<tr>
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<td>15</td>
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<tr>
<td>Geothermal</td>
<td>0.07</td>
<td>45</td>
</tr>
<tr>
<td>Hydro</td>
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</tr>
<tr>
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<td>0.06</td>
<td>850</td>
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<tr>
<td>Gas</td>
<td>0.05</td>
<td>500</td>
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</table>

Some estimates for the cost of electricity regarding wave energy farms, are between 0.07 and 0.34 €/kWh [7] and between 0.21 and 0.68 €/kWh [8]. Even though, the lack of a fully operating off-shore power plant makes any estimation uncertain.

Since 1995 to 2014, Portugal’s renewable electricity increased almost constantly from 9501 GWh/yr to 32399 GWh/yr, mainly due to hydro and wind energy, being the fourth country in EU with larger incorporation of renewable sources [9].

In 2010, a progressive feed-in tariff (FIT) programme, with a maximum value of 0.26 €/kWh, regulated by the decree DL 5/2008 and the introduction of a Portuguese Pilot Zone (PPZ) started the support system for wave energy in Portugal. Due to the economical crisis and FMI intervention, the FIT system changed with the publication of the Ordinance 202/2015 in July of 2015, regarding a payment of 80 €/MWh, whether in demonstration or pre-commercial phase. To this amount,
20€/MWh are added if the project is recognized by the Portuguese Carbon Fund.

2. Financial analysis background

A valuable investment is one in which the earnings are larger than the investment costs and with bigger gains than in other investments [10]. In order to turn decision-making effective, an assessment of the flows in and out of an entity, during a series of periods (i.e. months or years) is used, the statement of cash-flows.

2.1. Interest rate

The time value of money is a fundamental concept in project assessment. It can be described by the idea that money available at the present time is worth more than the same amount in the future, because the value available at present can be invested in order to earn interest [10]. In a statement of cash flows, future cash flows have to be discounted to present value in order to illustrate its uncertainty. The rate at which future values are discounted to present values or, in contrary, present values are compounded to future values is called interest rate, or also discount rate for the first case. The acceptance of a project depends on a positive value of the NPV, being the project more interesting the higher the value of the NPV [10]. When the NPV is equal to zero, a point of balance between expenses and revenue is achieved, the break-even point (BEP). If the project is accepted, the NPV gives an estimation of the value added.

2.4. Internal rate of return

The internal rate of return (IRR) is the value of the interest rate at which the net present value is zero [10],

\[
IRR = \sum_{t=0}^{n} \frac{R_t - C_t}{(1 + k)^t} = 0. \tag{3}
\]

To solve this equation, a trial and error method is needed: guess a value for the interest rate, calculate the NPV, and repeat the procedure until a guess is made which satisfies the equation [10]. The decision criteria inherent to the IRR is based in the implementation of the project when the IRR is larger than a reference interest rate [10]. The main advantage of the IRR is in comparing projects, but this can lead to some conflicts with other techniques, namely NPV [10].

2.5. Levelised cost of energy

The Levelised Cost of Energy (LCOE) is a commonly used indicator to assess energy projects, and it represents a cost per kWh estimated by dividing all the expenses of the project by the electrical energy generated to the grid throughout the project’s lifetime, all terms discounted to present value [7, 11]. The expenses of the project can be divided in two phases, Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). CAPEX are the expenditures that incur prior to commissioning, like manufacture costs, deployment and installation costs and also the decommissioning costs. On the other hand, OPEX are the sum of the expenses during the useful life of the project, and can be broken in annual O&M costs, insurance, seabed lease rates and transmission charges [7].

\[
LCOE = \frac{\text{CAPEX} + \sum_{t=1}^{n} \text{OPEX}}{\sum_{t=1}^{n} \text{Annual Energy Production}_{t}} \cdot \frac{1}{(1 + k)^t}. \tag{4}
\]

2.6. Weighted average cost of capital

The techniques used are very sensitive to the value of the interest rate, and thus its definition is an important stage in project assessment [10].

A method used often in large organisations to choose the interest rate is the weighted average cost of capital (WACC), which relates the risk of a project with the financial cost of the capital invested, giving an estimate on its opportunity cost.
It is the combination of the equity that owners initially put into the company and the debt that the company raises weighted by their relative contribution to the company’s total capital [10].

\[
WACC = \left( \frac{E}{E+D} \right) R_E + \left( \frac{D}{E+D} \right) R_D, \tag{5}
\]

where \( E \) is the amount of equity, \( D \) is the amount of debt, \( R_E \) is the cost of equity, and \( R_D \) is the after-tax cost of debt.

3. Techno-economical Methodology

The methodology used in the present work, was developed based on several wave energy techno-economical studies [12, 13, 14], is outlined in the following figure, where five processes and the major outputs can be identified.

3.1. Location

The first step of this method is to define the location of the project, from which the data of the wave climate is taken. The raw data (wave height, period and direction) of the waves in the location, preferably in a large range of time, can be statistically analysed in order to define a wave climate model. The support provided by the government of the country where the project is applied should be taken into account also in this part. The geophysical characteristics of the site should be accounted: bathymetry, distance to shore, seabed composition, potential conflicts with other oceanographic activities (e.g. the fishing activities of local populations) or local fauna and flora.

3.2. Device design

For a device size to be chosen, it is necessary that the assumptions related with the performance of the device are combined with the wave climate model of the site. The depth of the site is also important, with some devices being not applicable where the depth is shorter or vice versa. With the optimum geometry for the wave climate, it is possible to know the power output of a single device, which is necessary to the next section. Also the materials and equipments applied in the devices are defined in this step.

3.3. Array design

In this part, the available wave power is assumed to be known, and using the power output of the devices from the previous section, an array can be designed. The array should be optimized in order to promote constructive wave interaction and mooring and cabling costs reduction, promoting the cost-effectiveness of the project. Knowing the capacity factor and the availability, the rated power of the devices can be calculated and, therefore, the amount of energy produced by the plant.

3.4. Financial evaluation

In order to calculate the cash flows necessary to apply the financial indicators of the last step, the costs and economical assumptions should be defined. The interest rate should be calculated using the WACC method, having in mind the risks and the budgeting of the project. With the revenues produced by selling the electricity, yearly cashflows can be made, which, discounted to present value, can be applied in the next process.

3.5. Project assessment

The purpose of this part of the analysis, besides understanding the viability of the OWC, is to evaluate the need for government’s financing for this kind of wave energy projects. From a policy maker perspective, it is important to know exactly how much support is needed for a new technology to give its first steps. Following the conclusions of Connor et al. [12], which is one of the most recent studies to date, only with larger FIT a wave energy project using Pelamis P1 and Wavestar can be economically viable. In the current economical scenario, an increase in government expenses may not be an option but, if a slight increase in financing can provide the impulse that wave energy needs to become competitive, some choices have to be considered.

From a developers point of view, this kind of studies are mandatory to determine the economic feasibility of a wave energy project. And can also be useful by making comparisons between different materials and sizes with a cost-effectiveness orientation. This kind of benchmarking approach may create new solutions for the industry that can make some devices or arrays viable.

From both perspectives, this techno economical assessment represents an useful method of analysis of the viability of promising technologies and also a tool to find breakthroughs due to the cost effectiveness approach.
4. Case Study

Three distinct rated power wave farms are assessed: 5, 20 and 100 MW. These plants can be constituted by three different size buoys, with 10, 12 and 16 m of diameter. The nine resultant combinations will share the most cost-effective arrangement and collection system configuration. Different construction materials are assessed while the location is the Portuguese Pilot Zone, in depths and distances from coast according with the devices used.

4.1. Location

The project should be deployed in the Portuguese pilot zone (PPZ) (Figure 3), which was set between Figueira da Foz and Nazaré, with an area of 320 km$^2$ [15].

![Figure 3: Portuguese pilot zone. Source: [15]](image)

This site’s seabed is constituted by sand and gravel with a smooth and steady slope to west, which is favourable to the application of electrical cabling without additional metal coatings, thus reducing costs [15]. In this study, a total tariff of 100 €/MWh is assumed, following Decree DL 202/2015.

The PPZ has a predominant swell from NW (71.3%) and W (18.8%) with a medium height of 2.2 m and medium period of 7.2 s. Wave heights minor than 3 m occur in all months of the year during more than 60% of the time. Per year there are about 20 days of storm, with wave heights larger than 4.5 m. 16% of the storms reach more than 7 m of maximum wave height [15].

To characterise the wave climate, a set of 14 sea states defined by a spectral distribution and a frequency of occurrence is considered, taken from Gomes et al. [16].

4.2. Device design

The devices used (Table 2) are made of steel sheet with a thickness between 1.5 and 2.5 cm, with concrete in the anti-heave plate and upper ballast, a price of 2.5 k€ was assumed for manufactured and painted steel sheet [17].

The cost of one isolated device should account for the power take-off system (generator and birradial turbine), the construction of the marine structure, the control systems and water pump and the transport from factory to the sea-site.

In order to reduce initial costs in the project some alternative materials are investigated, such as precast concrete and polymer composites. The first is applied in wind turbine towers having a cost of 957 €/ton [18]. Although structural analysis is needed to verify the suitability of this material to the device structure, analysis assuming an increase of approximately 285% in device weight are made [18]. Other type of composite materials are the fiber-reinforced polymers, that use a polymer-based resin as matrix, and a variety of fibres such as glass, carbon and aramid as the reinforcement. With the evolution of composites techniques, the production costs are becoming lower, which makes them a possibility for wave energy devices. For axisymmetric structures, the process of filament winding can be used [19], consisting in the winding of fibre tows (previously bathed in resin) in various orientations, which are controlled by the fibre feeding mechanism. For this process, material costs starting in 250 k€ per device, for the smaller OWC, plus 50 k€ and 100 k€ for the others. The construction costs considered are 50 k€ per device [19].

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Height</th>
<th>Total mass</th>
<th>Steel mass</th>
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<tbody>
<tr>
<td>[m]</td>
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<td>33</td>
<td>359</td>
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<tr>
<td>16</td>
<td>62</td>
<td>1122</td>
<td>862</td>
</tr>
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</table>

4.3. Array design

The connection of WEC in an array using common export cables and shared moorings is a way of reducing the costs per device, against the installation of singular devices [20].

Following Astariz and Iglesias [21], moorings and electrical connection lines constitute each about 10% of the WEC cost. In this study, different options of moorings are compared and the catenary system is considered the best solution in terms of costs and effectiveness. This system is commonly known as CALM (catenary anchor leg mooring), allows the movement of the structure in any one of the six degrees of freedom, with chain lines until
depths of 250–300 m and with 60 to 120 mm of diameter. Although with some counterparts (greater length and weight), other factors, e.g., easy installation, lower cost, or the fact that it is less affected by the corrosion, make it the best option in most cases. The cost calculation is based on diameter and length to achieve the weight of the chain through eq. (6), where \( P_{\text{Chain}} \) is the total weight of the chain (in N), \( L \) is the length (m) which is 2.5 to 3 times the depth (h) of the site, \( d \) its diameter (mm), and \( K \) is a constant with a value 0.02\( \text{kg} \left( \text{mm}^2 \right)^{-1} \) for studless chain and 0.0219\( \text{kg} \left( \text{mm}^2 \right)^{-1} \) for stud-link chain.

\[
P_{\text{Chain}} = 9.81Ld^2K.
\] (6)

Then, its weight is obtained and a cost per unit weight (0.265 \( \text{€} \)/N) is applied. The installation costs are 50 \( \text{€} \)/day [21]. One characteristic of the catenary system is to subject the anchor point only to horizontal forces, making possible to use gravity anchors.

Electrical cabling is another important part of the costs of a wave farm. In order to define them, it is necessary to define first the type of current used (i.e. direct or alternate). Medium voltage AC current is the best option for the transportation of electricity nowadays for distances lower than 80-100 km [21].

The collection grid is the system responsible for the retraction of the electricity produced in the devices and deliverance to the collection point. There are various configurations used in offshore wind energy that can be adapted to wave energy arrays: radial design, single-sided ring design, double sided ring design and star design [22]. The last one does not need cables with capacity as high as the double-sided ring configuration and offers a good level of security, with any cable faults affecting only one device, being the most effective [23]. The array cables system used is the 3-core [22], due to the lower installation costs and minor current interactions (creating different impedances between phases).

The procurement prices of cables were taken from Connor et al. [12], but, in addition, installation cost has to be considered specially for the underwater cable, about 50 \( \text{€} \)/km, which includes the cost of vessel and installation [21]. Apart from the costs of the cable, it is necessary to take into account the other elements of the electrical installation. The most relevant are the offshore substation and grid interface, an onshore substation where electricity characteristics are harmonized. The costs of this devices vary with the tension elevation required to deliver electricity to the network. Following Limpo [23], for small distances of energy transport and plants with rated power below 200 MW, which is always verified in this case study, the best option is the small AC layout. This configuration does not require offshore substation, using the same cables that retract energy from the devices to transmit it to the onshore station.

Applying the small AC radial configuration, with 33 kV of medium voltage, the array pictured in Fig. 4 presented the lower initial costs per MW. The capacity factor, ratio between the average annual energy and the theoretical maximum energy, of WEC has been studied by some authors. A value of 40% is reported by Astariz and Igleias [21]. In Dalton et al. [13] a capacity factor of 20% is used for Pelamis, and in O’Connor et al. [12] a value around 25% is used for various rated power devices in the Portuguese coast. In this study, this value is adopted, which makes the average annual energy one quarter of the generator rated power.

4.4. Financial evaluation

The initial costs considered are related with the procurement and installation of the devices, which can be described as material costs. To calculate this costs, an isolated device approach is firstly used and then the costs of the array are accounted. These are depreciated, i.e. the capital cost of assets is divided over the years of its economic life, at a rate of 8% per year [23].

A part of the initial costs is considered contingencies, possible expenses that could appear in the construction or installation, about 7% of the material costs and the decommissioning costs are considered to be 50 \( \text{€} \)/MW [14, 21].

The expenses incurred during the lifetime of the projects are divided in three major sub headings such as annual O&M costs, insurance and sea bed lease rates. The OPEX is defined as 5% of the CAPEX per year [13, 14] and, in the middle of the life, a major overhaul is considered with larger costs than the regular maintenance [12].

4.5. Project assessment

The main objective of this section is to assess the feasibility of the projects proposed. Consequently, the nine combinations of arrays and devices will be evaluated in terms of NPV and LCOE. Conclusions should be taken about the causes of the economical performance of each one. If the projects are
not economically attractive, the price of electricity necessary to achieve the break-even point is investigated (POEb).

5. Learning curves

Learning curves, also known as experience curves or progress functions, are an empirical method for analysis of the effect of learning on technical change, measuring technical change as cost (or an input factor) improvement of a product or technology as a result of learning [24].

The learning curve is based on a doubling of production, that is, when production doubles, the decrease in cost per unit affects the rate of the learning curve.

In wave power technologies, there are various mechanisms that may produce cost reduction in the sector. These are scale/volume, experience and innovation [8]. The novelty of the technologies presented by wave energy converters offers a high cost reduction potential, while not sharing the technical principles of other sectors as tidal, wind or hydro [11]. In this study, calculations were made for an average learning rate (LR) of 8% [8] and 17% [11], assuming a cumulative power deployed of 200 MW. Reductions in initial costs of approximately 50% and 74% were obtained, respectively.

6. Results

The value of NPV for all scenarios is negative, proving that, from an investor point of view, none of the projects is feasible (Table 3). This indicator follows an increasing tendency in absolute value for larger devices and larger arrays. For all plants, the massive amounts invested in CAPEX relative to the power installed are not compensated during the life of the project. The income from electricity production is not enough to surpass the yearly expenditures, generating losses in all periods. The only exception is the 100 MW plant with 10 m diameter devices where positive cash-flows of around 250 k€ were generated during the life of the project. However, this amount was not sufficient to turn the NPV positive. The LCOE follows an inverse tendency from the NPV in the array dimension, but the same in the device size.

The large initial investment in wave farms constituted by the WEC assessed is confirmed. Analysis for a single device scheme displayed approximately a doubling in initial costs per MW when comparing with the correspondent array configurations. For all the farms studied, the increase in the rated power for the same device diameter presents a slight decrease in initial costs. However, with the increase in diameter, initial costs raise more than 0.5 M€, between 10 m and 12 m, and almost 1 M€ between the latter and 16 m. This suggests the major impact that costs in the marine structure have, even using fewer WEC for the same array rated power.

A preliminary conclusion about the reasons for the non-feasibility of this projects is related with the large costs per MW installed, at best, 60% higher than off-shore wind. Limpo [23] suggests 3 M€ of CAPEX per MW of power installed. This can be explained by the power produced per device in this power plants, which makes necessary the installation of a large number of devices comparatively with wind energy.

Calculations for the POEb shown the same tendency of LCOE, although slightly larger in all cases (about 15%). The LCOE is an approximation to the cost of the electricity produced, but not accounting the interest, some administrative expenses and taxes (which do not apply to the cases studied).

The sensitivity analysis of the NPV with the FIT shown approximately the same variation for the same power arrays (20 MW). However, for different power arrays there is an increase in sensitivity, larger slope, with increasing rated power. The price at which electricity is paid has a larger influence with increasing rated power plants, even if the annual expenditures are almost proportional to the plant capacity.

For an array with 10 m devices, feasibility of projects is achievable for a FIT of 0.50 €/kWh, having, in this case, profitability indexes around 25% and IRR of 12.3%. The 20 MW and 100 MW farms present better results than the 5 MW. For other devices, these FIT produces positive NPV for 12 m arrays but with profitability index around 12%, which, for the size of the investment, does not make a feasible project, and for 16 m devices, the projects show negative NPV.

The size of this devices makes the construction of the marine structure an important part of the initial costs as it can be seen in Fig. 5. Therefore, changes in the price of manufactured steel, the most relevant expenditure in device construction, have an

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important impact in the viability of a project. The impact of the price of steel is larger for 16 MW arrays than for smaller power plants. Learning by experience can be an important breakthrough in the construction of large arrays.

Although many studies are needed to perform correctly this comparison, an analysis of the viability of the arrays with devices constituted by alternative materials is shown in Fig. 6, using the same FIT of 0.46 \(\text{€/kWh}\).

Due to the different loads supported by an OWC marine structure, a distinct increase in material weight (150\%) was also assessed in the third group of columns of Fig. 6.

The increase in material weight of 285\% per device does not compensate the reduction in the price per tonne, as it was stated for wind towers [18]. Although, the costs used in this analysis are an optimistic estimative and that similar size comparisons like in precast concrete case are not available in the sources consulted.

As it was noticed before, the low output power of this wave energy converter is one of the main causes for the non-feasibility of the investments. A sensitivity analysis of NPV (presented in M€) comparing various capacity factors (\(C_f\) from 15\% to 45\%) against different FIT is presented (Table 4).

The projects with different power presented the same pattern of results, due to the almost proportional increase in expenses with plant power. Assuming a capacity factor of 45\%, the previous maximum FIT value results in positive NPV projects. Still, the profitability index of 11.90\% obtained for the largest array of 100 MW with 10 m devices may not be enough to compensate an investment of this size (CAPEX of 481.56 M€).

Sensitivity analysis to capacity factor show that, like in FIT, the higher power array presents a larger sensibility to the capacity factor variations. Further, for the same value of plant power, varying device diameters, the 10 m device array shows smaller sensitivity, while the others show almost the same.

On the other hand, arrays equipped with larger devices perform worse in this analysis, having positive NPV values only for tariffs above 0.26 \(\text{€/kWh}\).

The experience gained with the installation of future arrays can reduce the investment costs, turning coming investments more cost-effective. In this analysis, various plants are assessed assuming 200 MW of cumulative power deployed globally, using the learning rates suggested by Carbon Trust (2006) [8], shown in table 5.

For the current maximum FIT, 0.10 \(\text{€/kWh}\), the projects are still disadvantageous, presenting negative NPV values. However, with the initial costs per

Table 4: NPV in M€ for different FIT and capacity factors, for a 20 MW array with 10 m devices

<table>
<thead>
<tr>
<th>(C_f)</th>
<th>0.10</th>
<th>0.21</th>
<th>0.26</th>
<th>0.40</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>-118.43</td>
<td>-92.28</td>
<td>-80.39</td>
<td>-49.09</td>
<td>-31.53</td>
</tr>
<tr>
<td>25</td>
<td>-102.59</td>
<td>-59.27</td>
<td>-45.51</td>
<td>-3.68</td>
<td>22.67</td>
</tr>
<tr>
<td>35</td>
<td>-86.73</td>
<td>-33.21</td>
<td>-13.71</td>
<td>38.97</td>
<td>77.03</td>
</tr>
<tr>
<td>45</td>
<td>-70.88</td>
<td>-9.79</td>
<td>13.98</td>
<td>82.46</td>
<td>131.36</td>
</tr>
</tbody>
</table>
Table 5: Assessment of plants with 10 m device assuming 200 MW of cumulative power deployed, with an average 8% LR.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-8.82</td>
<td>0.180</td>
<td>0.213</td>
</tr>
<tr>
<td>20</td>
<td>-33.82</td>
<td>0.178</td>
<td>0.212</td>
</tr>
<tr>
<td>100</td>
<td>-152.34</td>
<td>0.171</td>
<td>0.207</td>
</tr>
</tbody>
</table>

MW installed being halved, the previous maximum FIT would allow feasible projects.

The results shown in Table 6 present feasible projects, with LCOE in the range of a fully commercial technology. The initial cost reduction provided by this experience factor, around 74%, gives assessments that position this wave parks among current utilities technologies. This can be considered a too optimistic approach, taking into account that 200 MW is the value of cumulative power installed assumed. One explanation is the starting point used by Chozas [11], that is with technologies in an earlier phase of development, i.e. with higher costs than estimated for the present case.

The NPV values obtained encourage, in a policy maker perspective, the progressive FIT scheme. The negative results obtained when the learning effect is not accounted, reveal that the FIT is not sufficient for early arrays. On the other hand, the large profits made when assuming a 17% learning rate, show that the tariff is too high. However, in an advanced phase, the price paid for electricity should be the market price.

7. Conclusions

The present dissertation was set out to perform a techno-economical assessment of a Floated Coaxial Ducted OWC in the Portuguese Pilot Zone. To achieve this main objective, a method of analysis is defined. In this methodology, the main guidelines for a feasibility analysis are defined.

The large Portuguese exclusive economic zone located in the Atlantic ocean, makes Portugal one of the countries with the best wave energy resources. The existent PPZ is a stimulus for the implementation of renewable technologies related with the ocean.

Applying the current FIT, the projects were found to be unfeasible, with yearly losses in the majority of cases. The costs per MW installed were found to be in the range of the early arrays of wave energy, as the LCOE. Results showed that only with FIT larger than 0.50 €/kWh the projects would turn viable; which can be considered unaffordable for the current economy. Consequently, better capacity factors, increased rated power or devices with lower initial costs should be found.

Nonetheless, analysis with variable capacity factors showed that even for values considered high by most studies, the current FIT is insufficient. To reinforce this affirmation, analysis accounting for the learning effect, with CAPEX halved, still gave negative results with the current FIT. Assuming larger learning rates, which cause reductions in costs that seem exaggerated for the present case study, projects become feasible. However, as it was stated before, these scenarios are for a fully developed technology.

Research on interactions between the Portuguese socio-economic context and a possible wave energy sector should be made clearer in order to understand the potential for its establishment. When focusing in the Portuguese industry, these studies could allow the construction of a database with real and up-to-date costs of materials that could assist techno-economical analysis. On the other hand, life-cycle studies to appraise the environmental impact of WEC fabrication, installation, use and disposal, as well as more detailed structural studies to assess the utilization of alternative materials are also proposed.

The current low prices of fossil fuels have delayed the investment in further renewable technologies, even more with the diminution of the FIT after the suspension period in the last three years. Nonetheless, while being still in an economy recovery scenario, Portugal’s support to wave energy should be increased in order to achieve the strategic goals in terms of ocean energy. The previous tariff scheme provided a higher price for early technology power plants, that could allow larger developments gaining experience in situ. Initial arrays that could allow the progress needed to acquire the knowledge necessary to produce worthwhile utilities WEC projects.

Table 6: Assessment of plants with 10 m device assuming 200 MW of cumulative power deployed, with an average 17% LR.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.16</td>
<td>0.050</td>
<td>0.058</td>
</tr>
<tr>
<td>20</td>
<td>11.49</td>
<td>0.051</td>
<td>0.058</td>
</tr>
<tr>
<td>100</td>
<td>61.80</td>
<td>0.046</td>
<td>0.207</td>
</tr>
</tbody>
</table>

References


