https://doi.org/10.52131/jee.2025.0601.0055

*i*RASD Journal of Energy & Environment

Volume 6, Number 1, 2025, Pages 59 - 81

Journal Homepage:
https://journals.internationalrasd.org/index.php/jee

*i*RASD JOURNAL OF ENERGY & ENVIRONMENT

INTERNATIONAL RESEARCH ASSOCIATION FOR SUSTAINABLE DEVELOPMENT

Preliminary Study on Wave Energy Plants for the Leeward Islands of Cabo Verde

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ARTICLE INFO

Article History:

Received:	December	28, 2025
Revised:	May	24, 2025
Accepted:	May	30, 2025
Available Online:	June	05, 2025

Keywords:
Offshore Technologies
Ocean Power
Clean Electricity
Wave Power Plants
Leeward Islands of Cabo Verde
Wave Power Plants for Cabo Verde's Leeward Islands

JEL Classification Codes:
Q2, Q42

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

This study assesses the viability of establishing offshore wave energy plants around the Leeward Islands of Cabo Verde, aiming to diversify the country's energy mix and reduce reliance on fossil fuels. The research focuses on resizing three well-known wave energy converters (AquaBuoy, Wave Dragon, and Pelamis) to determine the scale factor (λ) that maximizes their Capacity Factor (CF) in the region. Key performance indicators, including CF, Levelized Cost of Energy (LCOE), Cost-Benefit ratio (C/B), Total Investment Costs (TC), and Maritime Space Utilization Efficiency (ηut), were analyzed alongside environmental considerations to identify the most suitable technology for wave power plants. The Monte Carlo method was applied to account for uncertainties in technology costs and their effect on LCOE values. The results revealed that the optimal scale factors were λ = 0.3, 0.4, and 0.5, corresponding to the highest CF values for Wave Dragon (71.5%), AquaBuoy (56.8%), and Pelamis (25.6%), respectively. At full scale (λ = 1), AquaBuoy emerged as the most suitable device, offering a CF of 18.8%, an LCOE of 210 $/MWh, and maritime space utilization efficiency (ηut) ranging from 3176.4 MWh/ha to 3563.7 MWh/ha, while occupying less offshore space. However, AquaBuoy also demonstrated the most significant environmental impact, particularly on marine species in the water column. Overall, the Wave Dragon outperformed Pelamis in all evaluation parameters. The study also highlighted that a reduction in interest rates from 12% to 8% would result in a 20% decrease in LCOE values, potentially offering a strong incentive for the government to attract investors in wave energy projects. Considering the uncertainties in technology costs, the most likely LCOE for AquaBuoy, Wave Dragon, and Pelamis were 193 $/MWh, 597 $/MWh, and 600 $/MWh, respectively. Notably, AquaBuoy's LCOE (210 $/MWh) is substantially lower than the current electricity cost in Cabo Verde (330 $/MWh), underscoring its potential as a viable energy source for the country.

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Citation: Monteiro, W. M. L., & Sarmento, A. J. N. de A. (2025). Preliminary Study on Wave Energy Plants for the Leeward Islands of Cabo Verde. *IRASD Journal of Energy & Environment*, *6*(1), 59–81. https://doi.org/10.52131/jee.2025.0601.0054

1. Introduction

The environmental impact of using oil and coal for energy production is severe, as these fossil fuels are significant contributors to the rise in greenhouse gas emissions, which in turn exacerbate global warming. This leads to extreme weather events, including intense rainfall and record-breaking temperatures. Our responsibility is to ensure the planet's sustainable development and guarantee its continuity for future generations. Because of these concerns, many countries signed the Paris Treaty in 2015, which requires all signatory countries to work together to reduce greenhouse gas emissions and control global warming, keeping it below 1.5°C. To achieve this goal, the countries involved must introduce significant changes to their economies and especially to their energy production infrastructures. Unfortunately, not all countries are willing to follow this path. This is why the most recent president of the United States of America, Donald Trump, withdrew his country, which is one of the world's biggest polluters, from the Paris Treaty.

One of the great steps towards a cleaner planet is the commitment to the energy transition, opting for renewable energy sources such as the sun, wind, sea (waves, currents, and tides), and hydropower. A massive investment in renewable energy sources will contribute to reducing CO_2, diversifying the energy matrix, and creating several jobs (Irena, 2020). Ocean waves are one of the energy sources currently competing to produce clean electricity, emitting very low amounts of CO_2 (Nguyen et al., 2020). Furthermore, according to (Sheng, 2019) studies, ocean energy harvesting technologies can produce electricity up to 90% of the time, superior to solar panels or wind turbines that only produce electricity 30% of the time. Therefore, investing in wave energy extraction technologies would certainly be an intelligent way to mitigate the effects of oil and promote sustainable development of the planet.

1.1. Wave Energy: A Historical Evolution

The use of wave energy dates back to the 18th century, more precisely to 1799, when Monsieur Girald and his son patented the first wave energy conversion device (Clément et al., 2002). However, a significant step towards modern systems for harnessing this type of natural resource was taken by Commander Yoshio Masuda with his invention of the wave-powered maritime navigation buoy (Falcão, 2010).

Interest in wave energy grew during the oil crisis of the 1970s, prompting several countries to explore its potential for electricity generation (Kofoed, 2017; Shehata et al., 2017). Stephen Salter's influential 1974 paper in Nature underscored the feasibility of wave energy, driving research and development, particularly in Europe (Salter, 1974). In 1975, the British government launched a wave energy research program, which inspired similar initiatives in Sweden, Norway, Denmark, Portugal, Ireland, Japan, and the United States. However, due to overly optimistic expectations, the program was discontinued in the mid-1980s.

In 1979, Masuda introduced the Kaimei ship, incorporating pneumatic chambers and turbo-generators based on the Oscillating Water Column (OWC) principle (Cruz & Sarmento, 2004). By the late 1980s, Japan had established a 60 kW OWC plant in Sakata Port (Neelamani & Reddy, 2010), while India developed a 125 kW OWC plant in Trivandrum (Ravindran & Koola, 1991). Norway also built two wave energy plants, though one was destroyed in a storm in 1988, and the other remained in experimental operation (Cruz & Sarmento, 2004; Falcão, 2010; Ravindran & Koola, 1991).

In 1991, the European Commission formally included wave energy in its renewable energy program, leading to projects such as the European wave energy atlas and pilot OWC plants on Pico Island (Azores) and in Scotland (LIMPET) (Cruz & Sarmento, 2004; Falcão, 2010). From the 1990s onwards, pilot plants emerged in India, China, Portugal, Italy, and the UK, with European Commission-sponsored conferences held in cities such as Falcão (2010).

Although interest in wave energy declined after the oil crisis, it resurged in the 2000s due to rising demand for alternative energy sources. In 2001, the International Energy Agency established an agreement to promote research and development in wave energy

(Falcão, 2010). Portugal tested the Archimedes Wave Swing (AWS) in 2000 and inaugurated a 2.25 MW wave energy park featuring Pelamis devices in 2008, though the project was later decommissioned.

China began researching wave energy in 1980 through the Guangzhou Institute of Energy Conversion (GIEC). Between 1985 and 2001, significant efforts were made to develop OWC-based systems, resulting in the construction of three onshore OWC devices with capacities of 3 kW, 20 kW, and 100 kW, along with a 5 kW Backward Bent Duct Buoy (BBDB) device.

It is also important to highlight that Asian countries such as China, Indonesia, the Philippines and Taiwan have recognized the potential of wave energy and have therefore made significant efforts to introduce this renewable form of energy into their electricity production scenarios (Burhanuddin et al., 2022). In 2023, Eco Wave Power and I-ke International Ocean Energy signed an agreement to develop a wave energy park with a total installed capacity of 400 MW. The project will be rolled out in phases, starting with a 100 kW power plant and gradually expanding to the full 400 MW capacity.

Since the 1990s, Australia has been actively developing cost-effective wave energy conversion technologies through companies like Energetech Pty Ltd and SeaPower. Energetech created an OWC system with a wave-focusing device designed for operation approximately 40 meters offshore, while SeaPower developed the CETO device.

Europe remains a global leader in wave energy development, with 12 MW of installed capacity since 2010, though only 1.1 MW remains operational (TAPOGLOU et al., 2022). Countries such as Portugal, France, and Sweden continue advancing wave energy technology. Sweden, in particular, has made notable progress through companies like CorPower and Seabased, which have developed efficient point absorber devices (CorPower, 2023; Seabased, 2021). On a global scale, China and the United States now lead in wave energy capacity, actively supporting investors and operators in commercial-scale deployment (Parsons & Gruet, 2018).

1.2. Wave Energy Market Challenge

Although interest in wave energy has grown significantly, with numerous studies assessing its resources and potential for energy generation, this renewable source has yet to achieve the technological maturity and commercialization level seen in other renewables, such as wind and solar energy. Several challenges still need to be overcome before wave energy technologies can be considered mature (Aderinto & Li, 2018). These challenges are technical, economic, administrative, and legal. Additionally, it is important to highlight conflicts of interest regarding the use of maritime space required for installing wave energy parks (Cruz & Sarmento, 2004).

Technological challenges include device efficiency, survival under storm conditions, the complexity of components and subsystems, and the need for competitive and market-available solutions. One of the main issues is wave irregularity, which limits efficient energy extraction. Similar to wind energy, wave energy devices operate optimally within a specific power range, reducing their efficiency outside that range.

Other challenges involve the corrosive marine environment, high maintenance costs offshore, and energy production losses caused by interruptions due to difficult access for maintenance, an issue also faced by offshore wind energy (André, 2010). While these technical problems can be resolved, the primary hurdle lies in the costs associated with the necessary solutions (Cruz & Sarmento, 2004).

Administrative and legal challenges primarily concern the licensing of wave energy devices. This includes issues related to maritime space usage, environmental licensing, and grid connection (Cruz & Sarmento, 2004). However, positive developments have been observed in several European countries, such as Portugal, partly due to advancements in offshore wind energy technologies.

The most significant obstacle in the wave energy market is financial. High development costs, the risk of not achieving competitiveness with other renewable energy sources, and the long time-to-market are critical factors. For example, CorPower invested approximately €68 million to reach Technology Readiness Level 5 (TRL 5).

This situation is further complicated by the competitiveness of fixed-platform offshore wind energy, which already offers energy prices close to €50/MWh, and by floating wind energy, which is rapidly advancing and expected to become competitive within 5 to 10 years. These alternatives, offering lower risks, lower development costs, and shorter time-to-market, attract investments that could otherwise support the development of wave energy (Cruz & Sarmento, 2004).

1.3. Recent Advances

Most wave energy devices utilize electromagnetic generators to produce electricity. However, these generators require stable, high-frequency inputs (50–60 Hz) to operate effectively. This reliance limits their efficiency in conditions characterized by low-frequency waves, small amplitudes, irregular patterns, or unpredictable directions. To overcome these limitations, recent advancements have introduced alternative wave energy conversion technologies, including triboelectric, piezoelectric, and electromagnetic systems.

Triboelectric technology has garnered particular interest with the emergence of triboelectric nanogenerators (TENGs), pioneered by Professor Wang Zhonglin. TENGs are especially effective in low-frequency wave environments due to their lightweight design, low cost, simple structure, and environmentally friendly operation. However, their small size restricts large-scale deployment in open-sea conditions. The current challenge is to integrate these generators into larger networks for broader application while also enhancing their energy efficiency to facilitate widespread adoption.

Scaling up TENG systems for more extensive use also presents practical challenges, such as the need for extensive cabling, which can significantly increase costs. Additionally, wear and tear on triboelectric materials in harsh marine environments poses a significant concern, potentially reducing the durability and long-term performance of these systems.

1.4. Wave Energy in Cabo Verde

Cabo Verde is located 500 km off the west coast of Africa and is an archipelago with approximately half a million inhabitants, consisting of nine inhabited islands and one uninhabited island (Figure 1). Economically, it is classified as a developing country, with an energy matrix heavily reliant on the importation of fossil fuels. This dependency makes electricity in Cabo Verde one of the most expensive in Africa (Selenec, 2015). Additionally, this high cost also impacts the price of water, as more than half of the water consumed is desalinated using electrical energy.

Given the socio-economic and environmental impacts of Cabo Verde’s dependence on fossil fuels, transitioning to alternative energy sources is vital. In response, the government has outlined a master plan for the electricity sector, targeting 54% renewable energy by 2030 (DGE, 2009). Solar and wind energy have been prioritized to reduce reliance on fossil fuels in power generation.

Owing to its insular nature, about 90% of Cabo Verde’s economic activities are concentrated along the coast (de Carvalho, 2013), making the surrounding ocean waves a promising renewable energy resource. Studies have shown that the Leeward Islands (Monteiro et al., 2016) and the Windward Islands (Gastelum, 2017) have substantial wave energy potential, considering the stability and size of the waves in these areas.

Cabo Verde's first efforts to harness wave energy began in the 1990s, though they did not lead to tangible outcomes. In 2009, the government of Cabo Verde showed interest in investing in wave energy to produce electricity using the Danish WaveStar device. During this attempt, some preliminary studies were carried out to determine the wave energy potential around Sal Island, where the plant was intended to be installed. Unfortunately, when the project was in its initial phase, there was a change in management at the company that manufactures the Wave Star device. The company's agreement with the government of Cabo Verde lost its effect and the project was interrupted.

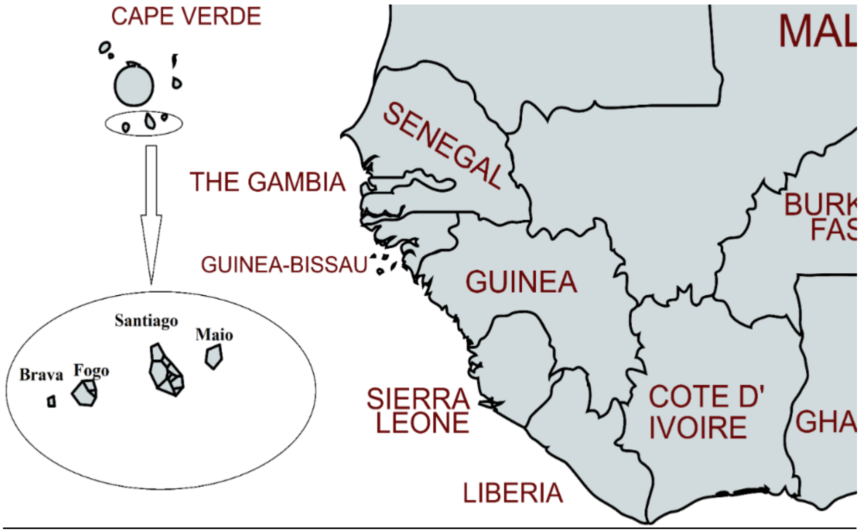

Figure 1: Study Sites: The Leeward Islands

In 2014, the North American company, RME- Resolute Marine Energy, presented a project to use the energy of ocean waves to operate a seawater desalination plant (Wave 2OTM, 2015). Unfortunately, this project never started. A year later, a study proposed utilizing Cabo Verde's natural caves to capture wave energy, suggesting that these formations could lower installation costs and enhance plant durability (Monteiro et al., 2016). The following year, the German company SINN Power announced a project to use wave energy to power fish farming on São Vicente Island, but this initiative also failed to materialize.

In 2017, a study was published assessing the wave energy resource in Cabo Verde (Monteiro et al., 2016). This study showed that the wave energy resource in Cabo Verde is stable with a power variation coefficient ranging from 0.36 to 0.66 and presenting an annual energy flow of 18 kW/m. Later, in 2019, studies carried out by Monteiro et al. (2021) showed that the southern coast of the leeward islands of Cabo Verde presents more favorable conditions for harnessing wave energy. In these locations, approximately 70.52% of the waves are characterized by significant heights of 1 m to 2.6 m and peak periods ranging from 7.8 s to 12.95 s.

Additionally, two years later, Monteiro et al. (2021) proposed the use of maritime natural caves in Cabo Verde to produce clean electricity and subjected the Cidade Velha natural cave to a series of studies to determine its energy potential. This cave exhibited peak available power between 6.9 kW and 10.8 kW, and this parameter was highly influenced by tidal states. In 2022, a study was published on the Cidade Velha natural cave equipped with a Wells turbine, designed and built to develop 1 kW at its shaft (Monteiro et al., 2021). Finally, more recent studies on the Cidade Velha natural cave were published in 2024.

In this most recent study, the cave was subjected to a series of tests using Wells turbines with different rotor blade geometries to identify the turbine that best suits the extreme operating conditions of the cave. The study indicated the turbine with 15° of blade inclination as the one that best suits the operation of the cave during periods of high tide, although it was the turbine that presented the most difficulties in starting and the longest downtime. Finally, in the same work, a set of important challenges related to the first attempt to supply electricity to a house using the studied cave was presented (Monteiro et al., 2021).

1.5. Behavior of Offshore Technologies on Different Wave Climate

Studies carried out by Aderinto and Li (2018) showed that among wave energy harvesting devices, oscillating body kind have the highest hydrodynamic efficiency values while overtopping devices have the lowest values for this performance parameter. The adaptation of wave energy harvesting devices to different wave climates has been extensively studied recently. In this way, Majidi et al. (2021) resized a set of devices to better operate in 62 locations characterized by different sea depths. The study proved that the Oyster device was the most efficient for depths between 4 m and 6 m, with the Wave Dragon and SSG devices having the highest values of power produced for these depths. The same study also revealed that in water depths of 25 m, 50 m, 75 m, and 100 m, the device that had the highest capacity factor values was the Oceantec. The Wave Dragon performed best in 25 m water depths, while the Pantoon performed best in 50 m, 75 m, and 100 m water depths.

Additionally, Bozzi et al. (2018) also resized offshore devices to operate in the Mediterranean Sea. Six of the devices studied achieved capacity factors above 20% in 40% of the locations chosen for the study. In addition, three of the devices studied (AquaBuoy, Wavebob, and Pelamis) exhibited capacity factors above 30% in 8% of the study regions. The same study concluded that in some of the regions studied, the devices at the optimal scale produced values of power between 10 kW and 30 kW.

Lavidas and Blok (2021) studied the relationship between the Levelized Cost of Energy (LCOE) and the Capacity Factor of the wave energy installation. The study showed that the higher the capacity factor, the lower the LCOE. Furthermore, according to this study, the AquaBuoy (250 kW), WaveStar (600 kW), and F2HB (1000 kW) devices that exhibited capacity factor values above 20% revealed LCOE values in the order of 60 Euros/MWh, assuming an interest rate of 5% and low CAPEX (capital expenditure) values.

According to Varol (2022), technical and financial aspects are not the only ones that should be considered when evaluating the best technologies to implement a wave energy plant. Environmental aspects should be considered more relevant when choosing these technologies. After these come the economic aspects, and only lastly the technical aspects.

Our study analyzes different scenarios for supplying electricity to the leeward islands of Cabo Verde using wave power plants consisting of three well-known wave energy devices that are well-studied in academia (AquaBuoy, Wave Dragon, and Pelamis). We compared these plants, taking into account technical aspects (Capacity Factor and efficiency of the maritime space usage) and economic aspects (LCOE, Cost-Benefit ratio, and Investment Cost). As expected, we also compared these plants, considering their environmental effects. Uncertainty and sensitivity analyses were also carried out to determine how fluctuations in technology costs, interest rates, and wave climate could influence the LCOE. Our results showed that the AquaBuoy devices are the most suitable for the wave climate in the study area when based on the technical and financial parameters of the plants. However, in environmental terms, they are the ones that raise the most concerns.

2. Materials and Methods

2.1. Wave Energy Conversion Technologies

As mentioned before, this study used three well-known wave energy converters whose performance under different wave conditions has been extensively investigated (Henderson, 2006; Kofoed, 2017; Weinstein et al., 2004). These devices are AquaBuoy (AB - 250 kW), Pelamis (PL - 750 kW), and Wave Dragon (WD - 7 MW). All of those devices have undergone testing in marine environments. AquaBuoy: is a point absorber designed to operate in water depths between 50 m and 70 m. Pelamis is a terminator device also suited for depths of 50 m to 70 m and Wave Dragon is an overtopping device developed for intermediate depths ranging from 25 m to 40 m. Table 1 summarises the key specifications of these devices that are important for this study.

Table 1
Key characteristics of the devices used in this study (Astariz & Iglesias, 2015)

Devices	Dimensions	Nominal Power	Cost [$/kW]
AB	6 m diameter Buoy	250 kW	800
PL	150 m long and 3.5 m diameter	750 kW	3333
WD	260 m x 150 m	7 MW	2400

2.2. Study Sites and The Power Plant's Locations

This study focuses on the southern coastal regions of the Leeward Islands of Cabo Verde, which include Maio, Santiago, Fogo, and Brava, as highlighted in Figure 1. The findings of Monteiro et al. (2021) indicated that in deep waters near the southern coasts of the Leeward Islands, approximately 70.52% of the waves exhibit H_s values between $1.0\,m$ and $2.6\,m$, with peak periods ranging from $7.8\,s$ and $12.9\,s$. Thus, to simplify the analysis, it was assumed that the wave climate in the study area can be represented, on average, by a significant wave height of $H_s = 2\,m$ and a corresponding peak period of $T_p = 10\,s$.

The power output of each device was calculated for this representative sea state. This involved using the H_s and $T_p$values that characterise the wave conditions in the study area and inputting them into the corresponding power matrix tables of each device, considering different scale factors and then the converted power output for each case was calculated.

As previously mentioned, each technology used in this study has a recommended range of sea depths. For AquaBuoy and Pelamis, the most suitable depth range is between 50 m and 70 m, while for Wave Dragon, the optimal depth values range from 25 m to 40 m. For this study, it was assumed that the plants are located in the southern regions of the islands considered here, where the sea depth values are 30 m for plants composed of Wave Dragon devices and 60 m for plants formed by AquaBuoy or Pelamis devices. Using Google Earth tools, it was possible to accurately locate the plants, respecting the assumed depth values, as shown in the following figure.

Figure 2: The Power Plant Locations

The exact locations of the plants, along with the water depth values at the installation site and the respective distances from the shore of the corresponding islands, are shown in the table below.

2.3. Power Matrices and Dynamic Similarity

The performance of a wave energy conversion technology was evaluated using its power matrix, which is a table that represents the power output of the device based on different combinations of Significant Wave Height (H_s) and Wave Period (T_p) that characterise the wave climate in the target region. The power matrices for the devices above were derived from full-scale sea tests conducted during the later stages of technological development (Technology Readiness Level, TRL 7-8).

Table 2
Main Characteristics of The Power Plants' Locations

Technology	Location	Water depth	Distance from the shore
Maio			
AquaBuoy	15°04'32"N 23°09'21"W	30 m	4.5 km
Wave Dragon	15°04'11"N 23°09'23"W	60 m	5.3 km
Pelamis	15°04'11"N 23°09'23"W	60 m	5.3 km
Santiago			
AquaBuoy	14°53'33"N 23°32'29"W	30 m	1.4 km
Wave Dragon	14°53'26"N 23°32'27"W	60 m	1.6 km
Pelamis	14°53'26"N 23°32'27"W	60m	
Fogo			
AquaBuoy	14°48'17"N 24°22'22"W	30 m	0.83 km
Wave Dragon	14°48'13"N 24°22'22"W	60 m	0.96 km
Pelamis	14°48'13"N 24°22'22"W	60 m	0.96 km
Brava			
AquaBuoy	14°47'46"N 24°42'08"W	30 m	0.77 km
Wave Dragon	14°47'41"N 24°42'17"W	60 m	1.5 km
Pelamis	14°47'41"N 24°42'17"W	60 m	1.5 km

It is important to highlight that the comparison of these devices in this study is valid, as they were analyzed at equivalent stages of development. Tables 5, 6, and 7 (in the Appendix) present the power matrices for the Wave Dragon (7 MW), Pelamis (750 kW), and AquaBuoy (250 kW), respectively, obtained for regions of the North Atlantic.

These power matrices provide a detailed overview of each device's energy production potential under varying sea conditions, allowing for a precise evaluation of their feasibility for wave energy generation in the offshore waters of the Leeward Islands.

It should be noted that these devices were originally designed for operation in the North Atlantic at relatively high latitudes, and their suitability for Cabo Verde's conditions is not guaranteed. To address this, the study applies the principles of dynamic similarity to determine the optimal scaling of each device relative to its original design for Northern Europe, ensuring better adaptation to the study area.

The power output of the offshore devices under different scaling factors was determined using dynamic similarity principles, specifically the Froude Number (Fr). The Froude Number, which characterizes the relationship between inertial and gravitational forces in a fluid flow, is given by Eq. (1), where V is the flow velocity, g represents gravitational acceleration, and l is the characteristic length (Nakayama, 2018).

$$Fr = \frac{V}{\sqrt{gl}} \tag{1}$$

This method ensures that the scaling process preserves the fundamental physical interactions between the devices and wave dynamics, allowing for reliable predictions of their performance under Cabo Verde's typical wave conditions. By implementing this approach, the study adjusts the original power matrices to match the scaled designs and assesses their energy generation potential within the new wave climate scenarios.

Dynamic similarity is achieved when the Froude Numbers of both the full-scale (prototype) and reduced-scale (model) configurations are equal. For clarity, this study refers to the full-scale version as the prototype and the reduced-scale version as the model. The scale factor is defined as $= l_{model}/l_{prototype}$. As established by Hughes (1993) and Payne (2008), the relationships governing Power Output, Significant Wave Height, and Peak Period as functions of the scale factor λ are given by Eqs. (2), (3), and (4) below.

$$\frac{P_{model}}{P_{prototype}} = \lambda^{7}/_{2} \tag{2}$$

$$\frac{H_{s\,model}}{H_{s\,prototype}} = \lambda \tag{3}$$

$$\frac{T_{p\,model}}{T_{p\,prototype}} = \lambda^{1}/_{2} \tag{4}$$

The performance of the wave energy conversion devices was evaluated in terms of their respective Capacity Factor (CF) values, as defined by Eq. (5). This parameter was calculated through the following mathematical equation that represents the ratio between the power produced by a particular wave energy converter ($P_e[kW]$) under specific wave conditions and the correspondent nominal power ($P_{nominal}[kW]$) (Vannucchi & Cappietti, 2016).

$$CF = \frac{P_e\,[kW]}{P_{nominal}[kW]} \tag{5}$$

The CF values were calculated from the power matrices of each device at a real scale and resized. Thus, assuming that the waves in the study regions are characterized by Hs = 2 m and Tp = 10 s and introducing this information in each of the matrices, it was then possible to calculate the power produced by the devices at different scales. Thus, CF was calculated by dividing the power produced by the corresponding maximum values of this parameter in each matrix. Finally, the scale factor for which CF is maximum was identified for each device.

2.4. Levelized Cost of Energy - LCOE

The Levelized Cost of Energy, abbreviated as LCOE, is a financial parameter widely used to assess the economic viability of an energy production infrastructure. It is calculated by dividing the sum of the investment cost and the total cost, including the maintenance cost of the plant throughout its useful life, by the total energy produced by the plant during its useful life. Considering that the maintenance costs of the plant and the annual energy produced by it are constant, the LCOE can be calculated by the following equation (Sic Ocean, 2014).

$$LCOE = \frac{(SCI+SLD)}{8760\,CF}\frac{i(1+i)^{v}}{[(1+i)^{v}-1]} + \frac{OM}{8760CF} \tag{6}$$

In Eq. (6) LCOE is expressed in $/kWh, SCI [$/kW] is the Specific Levelized Investment Cost and SLD [$/kW] represents the Specific Decommissioning Cost given by:

$$SLD = \frac{SDC}{((1+i)^{v})} \tag{7}$$

Where SDC [$/kW] is the Specific Decommissioning Cost at the end of the plant's useful life. The parameters v [years], i and OM [$/kW] represent, respectively, the plant's useful life, the interest rate and the plant's annual maintenance cost.

The $LCOE$ should be as low as possible. However, the system with the lowest $LCOE$ does not always represent the most suitable choice for establishing a wave energy production plant. The $LCOE$ metric, while valuable, does not account for critical aspects of the conversion technology, such as its market robustness, the risks of the technology becoming obsolete or the supplier ceasing operations and potentially jeopardizing the continuity of spare parts supply for maintenance.

Additionally, environmental impacts of energy conversion technologies are increasingly significant considerations in energy projects, and these factors are not included in the $LCOE$ parameter.

Therefore, in comparative terms, a wave energy plant based on a certain technology might achieve a lower $LCOE$ but still may not be the most viable option when taking into account the aforementioned aspects or other factors that may emerge as important in the technology selection process (Varol, 2022).

2.5. The Cost-Benefit Ratio

According to Dantas (2015), the relationship between the cost and benefit (C/B) associated with a given wave energy conversion device is expressed by Eq. (8):

$$\frac{C}{B} = SM + \left(I \times i + \frac{(I - RV)\times i}{(1+i)^{v/CF} - 1}\right) \times \frac{1}{P_{nominal} \times CF \times 8760} \quad (8)$$

In the equation above, the parameter C/B is expressed in $[\$/kWh]$. The term SM $[\$/kWh]$ represents the specific cost associated with Operation and Maintenance (O&M), $RV[\$]$ is the residual value of the devices (the monetary value of the devices after their useful life), I [$]is the capital cost, CF is the Capacity Factor (Eq. (5)), $v[years]$ is the plant's lifetime, $P_{nominal}$ $[kW]$ is the installed power, and i is the interest rate.

One of the major challenges associated with offshore devices relates to their residual values (RV). The International Maritime Organization (IMO) requires that these devices be completely removed from the sea after the plant's operational life has ended. As a result, the residual value of these energy conversion technologies is considered to be zero ($RV = 0$) (Beserra, 2007). The nominal power $P_{nominal}$ of a given plant, expressed in kW, is calculated using Eq. (5).

2.6. The Maritime Space Utilization Efficiency

This parameter evaluates the ability of a wave energy plant, using a specific conversion technology, to generate energy per unit area occupied in the sea (Veigas et al., 2015). Mathematically, it is defined as the ratio between the power converted by the plant, $E_e[MWh]$, and the area, A [ha], occupied by the plant, as follows:

$$\eta_{ut} = \frac{E_e[MWh]}{A\,[\mathrm{ha}]} \quad (9)$$

The annual energy produced by the plants was calculated by multiplying the electrical power required for each island by the number of annual operating hours of the plants ($8760 \times CF$ hours).

The total area occupied by an offshore wave power plant was calculated based on the size of the devices that comprise it and the spacing between these devices that must be ensured to eliminate operating interference that may exist between them (Frederick, 2014). Table 3 shows the values of these geometric parameters that were used to determine both the areas occupied by devices in a plant and the total area occupied by the plant. It is important to note that, for calculating the total areas occupied by the plants, it was assumed that the devices were arranged in a single line.

Table 3
Spacing between the devices within the Power Plants

Technology	Range of spacing between the devices	Spacing values considered
AquaBuoy	50 m to 100 m	75 m
Pelamis	300 m to 500 m	400 m
Wave Dragon	500 to 1000 m	750 m

This parameter is crucial because it provides a realistic understanding of the total area occupied by the plant at sea. It allows for relating this information to maritime zones designated for ship traffic, recreation, and marine species preservation. In a context like that of Cabo Verde, composed of islands relatively close to each other, understanding the total area that a plant may occupy at sea is essential to avoid possible interference with areas already reserved for other specific purposes.

2.7. The Total Cost of the Plant

The estimative of the total cost of the plant, using any of the technologies considered in this study, was calculated through the following equation, where the subscripts i refers to the technology used in the plant (AquaBuoy-AB, Pelamis-PL, and Wave Dragon-WD) and j the correspondent island (Santiago, Maio, Fogo, and Brava), respectively:

$$TC_{ij} = C_i P_j \tag{10}$$

In the above equation: $TC_{ij}[\$]$ represents the total cost of the plant using technology i installed in the sea for island j, $C_i[\$/kW]$ is the cost coefficient associated with technology i and $P_j\ [kW]$ is the nominal power of the plant intended for island j.

According to Waveplam (2009b), the total capital cost of a wave power plant can be broken down into the individual cost percentages of the conversion devices, as presented in the following table (Table 4). According to the same source, the total capital cost is about 252% of the cost of the devices.

Table 4
The Breakdown Cost of Wave Power Plants

Capital Cost	% Device Cost
Device	100
Replacement Cost	100
Installing and Mooring Costs	33
Cabling	10
Network Connection Cost	5
Licensing and Location Costs	2
Component Replacement Cost	2

According to the same source, the logistics cost is 4.5% of the capital cost and the maintenance cost represents about 3% of that same capital cost. Furthermore, Têtu (2020) suggested the decommissioning cost to be 70% of the installation cost, while Cyprien et al. (2015) suggested the installation cost to be 13% of the capital cost.

2.8. Uncertainty and Sensitivity Analysis

By applying the Monte Carlo method, with a uniform probability distribution, it was possible to determine how uncertainties in the estimation of unitary costs of the technologies can affect the LCOE and with this, we calculated the most likely values of this financial parameter of the plant. To carry out the uncertainty analysis, a range of unitary cost variation for Pelamis and Wave Dragon was assumed from \$1,500/kW to \$2,500/kW and from \$400/kW to \$1,000/kW for AquaBuoy (De Oliveira et al., 2021). Also through sensitivity analysis, we determined how the LCOE can be influenced by variations in the interest rate i and the wave climate conditions (through variations in the significant wave height). To carry out the sensitivity analysis, the interest rate values of 12%, 10% and 8% and the significant wave height of 1.0 m, 1.5 m, 2.0 m and 2.5 m were considered.

3. Results and Discussion

3.1. The Power Matrices Analysis

An in-depth analysis of the power matrices for the offshore devices considered in this study reveals that there are specific wave conditions where these devices cannot produce energy (Tables 5 to 7). Generally, energy generation begins when the Significant Wave Height and Period exceed 1 m and 5 s for the Wave Dragon (Table 5), 1 m and 6 s for the Pelamis (Table 6), and 1 m and 7 s for the AquaBuoy (Table 7). On the other hand, the devices stop generating energy when the wave height and period reach their maximum thresholds: 7 m and 17 s for the Wave Dragon (Table 5), 10.5 m and 13 s for the Pelamis (Table 6), and 5.5 m and 17 s for the AquaBuoy (Table 7).

These results show the limitations of these devices in wave climates. This information is important as it helps to identify the devices that are best suited to wave climates. Thus, since the Wave Dragon and Pelamis operate in the wider ranges of H_s and T_p, they are better suited for more energetic wave climates. Additionally, since the AquaBuoy operates in tighter H_s and T_p values, they are better suited for less energetic wave climates.

3.2. The Best Scaling Factor of the Devices

To evaluate the performance of the devices chosen for this study, their power matrices were resized by applying Eqs. (2–4). Through this procedure, it was possible to identify the optimal scale factors that maximize the Capacity Factor of the plants in the study areas. These maximum CF values were compared with those exhibited by the full-scale devices, for the same wave climate conditions. The results are shown in Table 8.

Table 8
Values of the Key Parameters of the Wave Dragon Device Downscaling

λ	Nominal Power [kW]	Output Power [kW]	CF [%]
1.0	7000.0	1190.0	17.0
0.9	4841.1	1042.8	21.5
0.8	3205.6	872.4	27.2
0.7	2008.8	752.0	37.4
0.6	1171.2	510.3	43.6
0.5	618.7	326.0	52.7
0.4	283.3	160.0	56.5
0.3	103.5	74.0	71.5
0.25	54.7	19.0	34.7

Table 9
Values of the key parameters of the AquaBuoy device downscaling

λ	Nominal Power [kW]	Output Power [kW]	CF [%]
1.0	250.0	47.0	18.8
0.9	172.9	38.0	22.0
0.8	114.5	29.0	25.3
0.7	71.7	22.0	30.7
0.6	41.8	14.0	33.5
0.5	22.1	10.0	45.3
0.4	10.1	5.8	56.8
0.35	6.3	2.3	36.0

Table 10
Values of the key parameters of the Pelamis device downscaling

λ	Nominal Power [kW]	Output Power [kW]	CF [%]
1.0	750.0	116.0	15.5
0.9	518.7	93.0	17.9
0.8	343.5	66,0	19.2
0.7	215.2	48.0	22.3
0.6	125.5	30.0	23.9
0.5	66.3	17.0	25.6
0.4	30.4	5.0	16.5

According to the results, the CF increased as the scale factor (λ) decreased, reaching a peak before beginning to decline. This indicates that each device has an optimal scale factor that maximizes energy production. Specifically, the Wave Dragon, at a scale of λ = 0.3 with a CF of 71.5%, demonstrated the highest efficiency for the study area's wave climate. It was followed by AquaBuoy (λ = 0.4, CF = 56.8%) and Pelamis (λ = 0.5, CF = 25.64%). However, when considering the original design scale for Northern Europe (λ = 1), AquaBuoy emerged as the most effective device (CF = 18.8%), followed by Wave Dragon (CF = 17%) and Pelamis (CF = 15.5%).

Based on these CF values, Pelamis appears to be the least suitable device for the wave climate in the study region.

Another important aspect related to the devices under study concerns the power output values, both at the optimised scale and at the real scale. As indicated in Tables 8, 9, and 10, the Wave Dragon device showed the highest power output values (74 kW for λ=0.3 and 1190 kW for λ=1), followed by the Pelamis (17 kW for λ=0.5 and 116 kW for λ=1). Additionally, the AquaBuoy device exhibited the lowest power output values, both under optimal conditions (λ=0.4 and 5.8 kW) and at the natural scale (λ=1 and 47 kW).

3.3. The Cost Analysis

Cost estimation is a critical factor in evaluating the feasibility of wave energy plants. This study focused on calculating the costs for wave energy installations capable of meeting the electricity demands of Fogo (13.8 GWh/year), Brava (2.8 GWh/year), and Maio (3.6 GWh/year), which have relatively low energy consumption levels, as reported by Electra, Cabo Verde's electricity provider (Electra, 2019). Santiago Island, on the other hand, has a much higher electricity demand of 238.8 GWh/year due to its size and population. Meeting this demand would require a large-scale wave energy plant and significant investment. To address this challenge, the analysis considered a plant designed to supply 15% of Santiago's total electricity demand, equivalent to 35.82 GWh/year.

Table 11
Annual Power Production on the Leeward Islands [kWh] (Electra, 2019)

Islands	Thermal Power Plant	Wind Power Plant	Solar PV Power Plant
Santiago	196,866,524	35,977,521	5,948,842
Maio	3,599,512	0	0
Fogo	13,767,217	0	0
Brava	2,795,426	0	0

Table 11 indicates that Santiago Island already has renewable energy plants, including solar and wind installations, which contribute to the island's clean electricity generation. Using the previously calculated Capacity Factor (CF) values and applying Equation (5), we estimated the installed power required for each offshore technology, along with the number of devices necessary to meet this power. These findings are summarized in Table 12, which details the installed power for each device and the corresponding number of units needed to satisfy the electricity demand of the target islands. The reference installed power for each island is based on the smallest integer value greater than the highest nominal power calculated for each device, as shown in the final column of Table 12. As a result, the actual number of devices required may be slightly higher than indicated. For Santiago Island, supplying 15% of its electricity demand would necessitate 22 Wave Dragon (WD) units, 574 AquaBuoy (AB) units, or 232 Pelamis (PL) units. In contrast, Maio and Brava Islands would require a plant consisting of 2 WD units, 64 AB units, or 31 PL units. Fogo Island, having a higher demand, would need an installation of 11 WD units, 209 AB units, or 94 PL units to meet its full electricity requirements.

Table 12
The Power Plants Nominal Powers ($P_{nominal}[MW]$) and the Number of Devices

Islands	WD	No. WD	AB	No. AB	PL	No. PL	Reference Power $P_{nominal}$
Santiago	24.05	20	21.75	463	26.38	227	27
Maio	2.42	2	2.19	47	2.65	23	3
Fogo	9.25	8	9.36	178	10.14	87	11
Brava	1.88	2	1.70	36	2.06	18	3

As mentioned earlier, the cost components of a wave power plant consist of several key elements. Capital costs make up 252% of the device costs, while logistics costs account for 4.5% of the capital costs. Operation and Maintenance (O&M) costs are estimated at 3% of the capital costs, and decommissioning costs are calculated as 70% of the installation costs, which represents 13% of the capital costs.

Using this information, we calculated the primary cost components for the wave power plant needed to meet the electricity demand of each island included in this study. The resulting figures can be found in Table 13.

Table 13
The Mmain Cost Components for the Three Technologies Under This Study

	WD	PL	AB
Capital Cost [$/$kW$]	6,048	8,399	2,016
Logistics [$/$kW$]	272	378	91
Decommission Cost [$/$kW$]	550	764	184
O&M[$/$kW$]	3,629	5,040	1,210
SM [$/kWh]	0.122	0.186	0.037
Total Cost [$/kW]	10,499	14,581	3,501

In Table 13, the Specific Maintenance Costs (SM [$/kWh]), were calculated from the corresponding O&M [$/kW] costs, replacing 1kW by the correspondent annual energy produced that was obtained by multiplying 1kW of power by effective time operation of the devices. To do this, we assumed a plant lifetime of 20 years and calculated the annual energy produced as 1kW × 8,760 × 20 × CF (where CF is the Capacity Factor). Therefore, the SM, expressed in $/kWh, was obtained by dividing the O&M cost values shown in Table 12 by the factor 8,760 × 20 × CF.

Table 14 presents the total costs of wave energy plants, calculated using Eq. (10), as well as the most cost-effective configurations for their implementation around the islands analyzed in this study.

Table 14
The Total Costs and the Composition of the Power Plant

Islands	Reference Power [MW]	AB	WD	PL
Santiago	27	$95 Million	$284 Million	$394 Million
	The lowest cost option: 574 AB a $95 Million			
Fogo	11	$38.5 Million	$115.5 Million	$160.4 Million
	The lowest cost option: is 234 AB a $38.5 Million			
Maio and Brava	3	$10.5 Million	$31.5 Million	$43.7 Million
	The lowest cost option: 64 AB a $10.5 Million			

The analysis in Table 14 indicates that a wave energy plant capable of supplying 15% of Santiago Island's electricity demand can be constructed using only AquaBuoy (AB) devices at a total cost of $95 million. Alternatively, a plant made entirely of Wave Dragon (WD) devices would cost $284 million, while one composed solely of Pelamis (PL) devices would amount to $394 million. These findings clearly show that the most cost-effective solution for Santiago Island is the plant utilizing AB devices.

For any island targeted by this study, the best option for implementing wave power plants continues to use AquaBuoy devices. Thus, to meet 15% of the electricity demand on Santiago Island, the best choice would be a plant with 574 AB devices, which would have a total cost around of US$95 million. For Fogo Island, the optimal plant would be one consisting of 234 AB devices, for US$38.5 million. To fully meet the electricity needs of Maio and Brava Islands, a plant with 64 AB devices, at a minimum cost of US$10.5 million, would be the ideal solution from a financial point of view. Furthermore, as can be seen in Table 14, the plants consisting of Pelamis devices are the most expensive.

3.4. The LCOE parameter, the C/B Ratio and the Maritime Space Usage Efficiency

Generally, the most important parameters through which the economic viability of a wave power plant is assessed are the Cost-Benefit ratio and the Levelized Cost of Energy (LCOE). For an interest rate of 12%, the useful life of the plants of 20 years, and assuming a residual value RV=0 as recommended for offshore plants, the values of LCOE and the C/B ratio were calculated using the data shown in Table 13. Table 15 shows the values of LCOE, C/B and CF of the different proposed wave power plants.

Table 15
Economic and Performance Parameters of the Proposed Wave Energy Centrals

Devices	**Nominal Power** $[kW]$	$LCOE[\$/MWh]$	$C/B[\$/MWh]$	$CF[\%]$
AquaBuoy	250	210	190	18.8
Wave Dragon	7000	700	630	17.0
Pelamis	750	1060	960	15.5

The AquaBuoy device stood out as the best option for building wave power plants in the study area, with the lowest values of LCOE = $210/MWh and C/B = $190/MWh. Wave power plants composed of Wave Dragon were the second best option, with an LCOE of $700/MWh and a C/B ratio of $630/MWh. The plants formed by Pelamis were identified as the least suitable, exhibiting the highest values of LCOE = $1,060/MWh and C/B = $960/MWh. Additionally, comparing the CF, LCOE and C/B values shown in Table 15, we conclude that all of them pointed to AquaBuoy as the best device, followed by Wave Dragon. Pelamis was the least reliable option for building plants around the Leeward Islands of Cabo Verde.

We can also note that the LCOE and C/B values shown in Table 15 are quite close. The small difference between them is because the C/B ratio uses the effective useful life, as suggested by Carvalho (2013). The effective lifetime is determined by dividing the plant's lifespan (v) by its Capacity Factor (CF). This approach is justified by the understanding that a plant's lifespan increases inversely with its CF. As CF decreases, wear on components diminishes (de Carvalho, 2013).

Based on our analysis, the AquaBuoy device emerges as the most economically viable option due to its lower costs compared to other devices. The total implementation cost for power plants utilizing AquaBuoy devices is approximately three times less than that of plants using Wave Dragon technology and about four times cheaper than those employing Pelamis devices. However, since AquaBuoy generates the least power, a significantly greater number of units is required to meet the electricity demands of each plant.

Currently, the electricity price in Cabo Verde is around $330/MWh, making it one of the highest in Africa. When we compare this with the data in Table 15, it's clear that the cost of electricity generated by AquaBuoy plants is lower than the existing electricity prices in Cabo Verde. Conversely, the generation costs for Wave Dragon and Pelamis devices are roughly two and three times higher, respectively, than the current electricity price in the country. This suggests that these devices still produce electricity at a higher cost than what is currently generated by diesel power plants.

The subsequent table illustrates the total area occupied by the conversion devices in each plant, including the overall area needed for adequate spacing between devices. The Wave Dragon devices require the largest area due to their wave-focusing system, followed by Pelamis and AquaBuoy devices. Notably, plants using Pelamis devices demand significantly more space compared to those using Wave Dragon or AquaBuoy devices, which occupy much less land.

These observations are consistent with research conducted by Veigas et al. (2015), which analyzed the spatial requirements of wave energy plants utilizing Pelamis, Wave

Dragon, and Archimedes Wave Swing devices. Their findings also indicated that plants employing Pelamis technology occupy considerably larger areas compared to those using the other two types of devices.

Table 16
Total Area of the Devices within the Power Plants and Total Area of the Power Plants

	Area occupied by the devices within the power plant [ha]				Total area of the Power Plant [ha]			
Technology	**Maio**	**Santiago**	**Fogo**	Brava	**Maio**	**Santiago**	**Fogo**	**Brava**
AquaBuoy	0.181	1.622	0.590	0.181	1.542	14.0	5.1	1.5
Pelamis	1.622	12.8	4.93	1.628	181.6	1398.2	562.9	181.6
Wave Dragon	7.8	85.8	42.9	7.8	19.1	322.1	155.4	19.1

Table 17 presents, for each island, the total areas occupied by the plants, the annual energy produced by these plants, and the efficiency in maritime space utilisation. The first point to highlight is that the energy produced by the proposed plants meets the electricity needs of each island analysed in this study.

The annual energy needs of the Maio and Brava islands are 3.9 GWh/year and 2.8 GWh/year, respectively, while the proposed plants produce 4.07 GWh/year (Maio island) and 4.95 GWh/year (Brava island). In the Santiago and Fogo islands, whose electricity demands are 35.2 GWh/year (15% of total electricity needs) and 13.8 GWh/year, respectively, the proposed plants generate between 36.6 GWh/year and 44.4 GWh/year (Santiago island) and between 14.9 GWh/year and 18.1 GWh/year (Fogo island).

Furthermore, the table shows that plants composed of AquaBuoy devices are significantly more efficient in maritime space utilisation compared to plants formed by Pelamis or Wave Dragon devices. The efficiency of AquaBuoy plants is approximately 14, 25, 34, and 14 times greater than that of Wave Dragon plants in the Maio, Santiago, Fogo, and Brava islands, respectively. Compared to Pelamis plants, the efficiency values of AquaBuoy plants are about 143, 121, 134, and 141 times higher for the same islands (Maio, Santiago, Fogo and Brava, respectively).

Thus, plants formed by Pelamis devices are considerably less efficient in maritime space utilization for energy production compared to both Wave Dragon and AquaBuoy plants, with the latter being the most efficient.

Table 17
The Annual Energy Produced and the Efficiency of the Space Utilisation

Technology	Area of the Power Plant $A[ha]$	Annual Energy Produced by the power plant $E_e[MWh]$	Efficiency, $\eta_{ut}[MWh/ha]$
Maio			
AquaBuoy	1.5	4940.6	3204.7
Wave Dragon	19.1	4467.6	234.5
Pelamis	181.6	4073.4	22.4
Santiago			
AquaBuoy	14.0	44465.8	3176.4
Wave Dragon	322.1	40208.4	124.9
Pelamis	1398.2	36660.6	26.2
Fogo			
AquaBuoy	5.1	18115.7	3563.7
Wave Dragon	155.4	16381.2	105.4
Pelamis	562.9	14935.8	26.5
Brava			
AquaBuoy	1.5	4940.6	3204.7
Wave Dragon	19.1	4467.6	234.5
Pelamis	181.6	4073.4	22.4

It is worth noting that these results align with those obtained by Veigas et al. (2015), who demonstrated that plants formed by Wave Dragon devices are approximately 33 times more efficient in maritime space utilization than the ones composed of Pelamis devices. These researchers analysed the efficiency of three types of offshore plants and concluded that plants composed of Pelamis devices are the least efficient in terms of maritime space utilization.

In this study, we assessed three wave energy conversion devices by evaluating a range of performance parameters. Additionally, we deemed it important to explore the environmental impacts of each device. Several studies have analyzed the environmental effects over the lifecycle of these devices. For instance, Banerjee et al. (2013); Parker et al. (2007); Thomson et al. (2019); Thomson et al. (2011); Uihlein (2016) focused on CO_2 emissions from the Pelamis device, reporting values around 23 gCO_2/kWh, 30 gCO_2/kWh, 20 gCO_2/kWh, 44 gCO_2/kWh, and 35 gCO_2/kWh, respectively.

Regarding the Wave Dragon device, emissions were reported by Banerjee et al. (2013) at approximately 13 gCO_2/kWh and 28 gCO_2/kWh. Although specific data for AquaBuoy is unavailable, it can be inferred from research on point absorbers, which AquaBuoy belongs to. Studies by Dahlsten (2009); Uihlein (2016), and Gastelum (2017) reported CO_2 emissions between 39 gCO_2/kWh to 126 gCO_2/kWh, 105 gCO_2/kWh, and 30 gCO_2/kWh to 80 gCO_2/kWh, respectively. These variations likely stem from differences in the conditions under which these studies were conducted. However, it's clear that Wave Dragon generally produces the lowest CO_2 emissions, followed by Pelamis and, lastly, AquaBuoy.

Beyond CO_2 emissions, the impact on maritime navigation and offshore fishing is another crucial factor. Margheritini et al. (2012) pointed out that all devices significantly affect these areas, with AquaBuoy having a larger impact on species living in the water column compared to the other devices. Wave Dragon's impact in this respect was deemed moderate. Therefore, although plants formed by AquaBuoy devices are the best from the performance and economic parameters point of view, they tend to raise greater concerns from an environmental point of view than plants formed by any of the other two technologies considered here.

3.5. The Uncertainty and Sensitivity Analysis

By applying the Monte Carlo Method using the aforementioned ranges of the unit costs of the Wave Dragon, Pelamis and AquaBuoy technologies, to simulate the uniform distribution of cost probabilities, it was possible to determine the most probable values of Levelized Cost of Energy (LCOE) and how the inaccuracy in technology unit cost estimation can affect the LCOE. These most probable LCOE values are those associated with higher frequencies of occurrence for the range of cost values considered. The following graphs show the frequency distribution histograms of the LCOE values for the AquaBuoy device (Figure 3), Wave Dragon (Figure 4) and Pelamis (Figure 5). Analyzing these histograms allowed us to identify the most probable LCOE values, those linked to the highest frequencies of occurrence.

Based on these analyses, the most likely LCOE values for the technologies assessed in this study are $193 per MWh for AquaBuoy, $597 per MWh for Wave Dragon, and $600 per MWh for Pelamis. As anticipated, AquaBuoy emerged as the most appropriate choice for the wave climate surrounding the leeward islands of Cabo Verde, followed closely by Wave Dragon and Pelamis. However, it is worth noting that the difference in LCOE values between Wave Dragon and Pelamis is minimal.

A crucial factor for investors in wave energy projects is the presence of government incentives that can stimulate investments in technologies aimed at harnessing this renewable resource. One particularly attractive incentive is the reduction of interest rates on bank loans for financing wave energy initiatives. This study conducts a sensitivity analysis of LCOE values to assess how changes in interest rates affect costs. The analysis examines three different interest rate scenarios: 12%, 10%, and 8%. The results are summarized in Table 18. Our results showed that a reduction in the interest rate from 12% to 10% caused the LCOE values to fall by 10% for all proposed plants. Furthermore, if the interest rate were to fall from 12%

to 8%, this would result in a substantial reduction in the LCOE values of 20%. Thus, it is clear that reducing interest rates can be an attractive initiative for future investors in the area of harnessing wave energy to produce clean electricity.

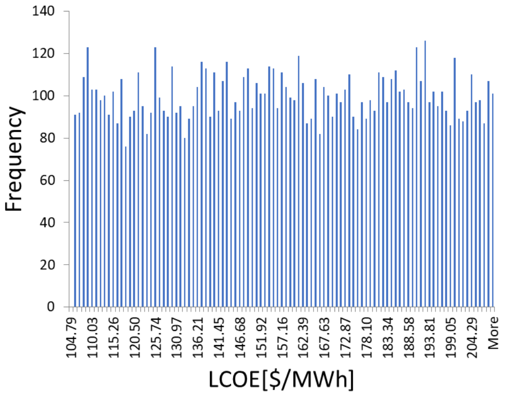

Figure 3: AquaBuoys histogram

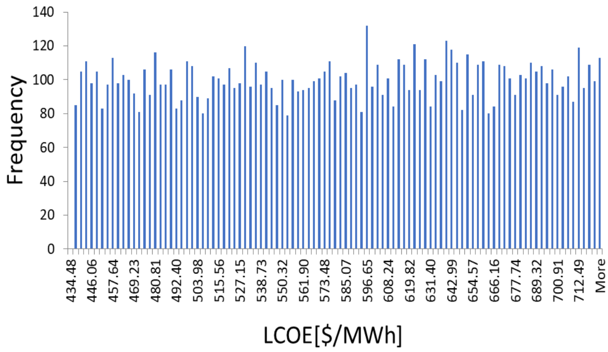

Figure 4: Wave Dragons histogram

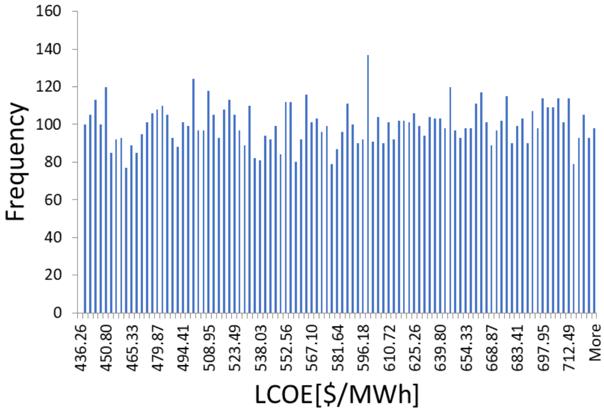

Figure 5: Pelamis Histogram

Table 18
Sensitivity Analysis of LCOE from the Perspective of Interest Rate

i [%]	LCOE [$/MWh]		
	AquaBuoy	Wave Dragon	Pelamis
12	210	700	1060
10	200	630	1010
8	180	560	900

Changes in Hs and Tp values will directly reflect on CF values. This analysis focuses on how variations in CF, driven by changes in wave height while maintaining a fixed wave period of 10 seconds, influence the Levelized Cost of Energy. The wave heights considered range from 1 m to 2.5 m in 0.5 m increments. Using the power matrices for the devices in question, we calculated the corresponding capacity factors and LCOE values, which are presented in the table below.

Table 19
Sensitivity Analysis of LCOE Sensitivity Analysis from the Perspective of Wave Climate Variation.

Hs	AquaBuoy Power [kW]	CF	LCOE [$/MWh]	Wave Dragon Power [kW]	CF	LCOE [$/MWh]	Pelamis Power [kW]	CF	LCOE [$/MWh]
1.0	11	4.4	952	360	5.1	2297	29	3.9	4515
1.5	26	10.4	403	775	11.1	1067	65	8.7	2014
2.0	47	18.8	220	1190	17.0	700	116	15.5	1060
2.5	73	29.2	144	1105	27.2	434	181	24.1	723

However, as shown in Table 19, LCOE values decrease as CF values increase, due to the rise in the significant wave height. It is important to note that this reduction in LCOE is more pronounced for lower CF values but decreases in intensity as it approaches higher CF values. This indicates that LCOE is highly sensitive to variations in wave conditions, especially in regions where the wave climate is less energetic. Additionally, this sensitivity gradually decays as the significant wave heights become higher.

4. Conclusion

The wave resource in Cabo Verde is characterized by stability and moderate energy flux, which implies that devices designed for more energetic wave conditions may not perform as effectively in the region's wave climate. To address this, the study resized three wave energy conversion devices that have undergone sea testing: AquaBuoy (250 kW), Wave Dragon (7 MW), and Pelamis (750 kW). The goal was to determine the scale factors that would maximize the Capacity Factor (CF) for optimal performance in the Leeward Islands, the study's target region. These scale factors were compared with those of the full-scale devices (λ=1). The study explored the feasibility of implementing wave energy plants to meet the electricity demands of Fogo, Maio, and Brava islands fully, while partially addressing Santiago's energy needs (15% of its demand). The analysis considered key parameters such as Capacity Factor, Levelized Cost of Energy (LCOE), Cost-Benefit ratio (C/B), Total Investment Cost (TC), and efficiency in maritime space utilization (η_{ut}).

The results indicated that the optimal scale factors for AquaBuoy, Wave Dragon, and Pelamis were λ = 0.4 (CF = 56.8%), λ = 0.3 (CF = 71.5%), and λ = 0.5 (CF = 25.6%), respectively. Wave Dragon proved to be the most suitable for the region's wave conditions, with the highest power output (74 kW), followed by Pelamis (17.0 kW) and AquaBuoy (5.8 kW). At full scale (λ=1), AquaBuoy offered the best performance in terms of suitability, with a CF of 18.8% and power output of 47 kW, while Wave Dragon (CF = 17.0%, power output = 1190 kW) and Pelamis (CF = 15.5%, power output = 116 kW) performed less favorably. Despite AquaBuoy's higher CF, its overall power generation was lower than the other two devices.

Our study showed that the Aquabuoy device is the most suitable for implementing wave energy plants in the study region, presenting more attractive values of LCOE = $210/MWh, C/B = $190/MWh, and the highest efficiency of the maritime space utilization varying between 3204.7 MWh/ha and 3563.7 MWh/ha, occupying less space on the high seas. Although the plants composed of these devices outperform all the others, they are the ones that raise the greatest concerns from the environmental point of view. The most environmentally friendly plants are those formed by Wave Dragon devices. These plants presented, after those formed by Aquabuoy, the best values of the performance indicators (CF = 17% and the efficiency of the maritime space usage ranging from 105.4 MWh/ha to 234.5 MWh/ha) and financial (LCOE = $700/MWh, C/B = $630/MWh).

Furthermore, all performance and financial parameters indicated that the plants formed by Pelamis devices were the least suitable for our wave climate, with LCOE = $1060/MWh, C/B = $960/MWh, and significantly lower efficiency of the maritime space utilization, between 22.4 MWh/ha and 26.5 MWh/ha. The lowest investment costs were obtained by opting for Aquabuoy devices to form wave energy plants around the leeward islands of Cabo Verde. In this context, to fully meet the electricity needs of Fogo, Maio, and Brava islands, investments of around US$30.5 million (on Fogo Island) and US$10.5 million for both Maio and Brava will be required. A plant that contributes 15% of the entire electricity needs of Santiago island will cost around US$95 million.

The intervention of the Cabo Verdean government to reduce the interest rate on bank loans is undoubtedly an attractive initiative for investors since a reduction of this parameter from 12% to 8% causes the LCOE to fall by around 20%. The LCOE is quite sensitive to variations in wave climate, which directly affects the capacity factor of the facilities, especially in low-energy wave climates. Variations in wave climate that increase the capacity factor will cause the LCOE to decrease. Finally, we recommend future studies aimed at more accurately assessing the wave energy resources at the proposed installation site, using real measurements through wave climate monitoring buoys. It is also important to conduct an in-depth study on the environmental impacts of these plants in those locations.

Acknowledgements
First, I would like to thank the University of Cabo Verde for its support and, second, Professor António Carlos Mendes from the University of Beira Interior for encouraging me to work in the area of ocean wave energy conversion.

Authors Contribution
Wilson Madaleno Léger Monteiro: conceptualization, methodology, data analysis, visualization, and write-up.
António José Nunes de Almeida Sarmento: conceptualization, data interpretation, critical revision, incorporation of intellectual content, and final editing.

Conflict of Interests/Disclosures
The authors declared no potential conflicts of interest w.r.t. the research, authorship and/or publication of this article.

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Appendix

Table 5

The Wave Dragon-7000 kW Power Matrix (Kofoed, 2017)

Hs [m]	Tp[s]												
	5.0	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**12.0**	**13.0**	**14.0**	**15.0**	**16.0**	**17.0**
1.0	160.0	250.0	360.0	360.0	360.0	360.0	360.0	360.0	320.0	280.0	250.0	220.0	180.0
2.0	640.0	700.0	840.0	900.0	1190.0	1190.0	1190.0	1190.0	1070.0	950.0	830.0	710.0	590.0
3.0	0.0	1450.0	1610.0	1750.0	2000.0	2620.0	2620.0	2620.0	2360.0	2100.0	1840.0	1570.0	1310.0
4.0	0.0	0.0	2840.0	3220.0	3710.0	4200.0	5320.0	5320.0	4430.0	3930.0	3440.0	2950.0	2460.0
5.0	0.0	0.0	0.0	4610.0	5320.0	6020.0	7000.0	7000.0	6790.0	6090.0	5250.0	3950.0	3300.0
6.0	0.0	0.0	0.0	0.0	6720.0	7000.0	7000.0	7000.0	7000.0	7000.0	6860.0	5110.0	4200.0
7.0	0.0	0.0	0.0	0.0	0.0	7000.0	7000.0	7000.0	7000.0	7000.0	7000.0	6650.0	5740.0

Table 6

The Pelamis-750 kW Power Matrix (Weinstein et al., 2004)

Tp [s] **Hs [m]**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**12.0**	**13.0**
0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0	0.0	0.0	0.0	0.0	0.0	29.0	37.0	38.0	35.0	29.0	23.0	0.0	0.0
1.5	0.0	0.0	0.0	0.0	32.0	65.0	83.0	86.0	78.0	65.0	53.0	42.0	33.0
2.0	0.0	0.0	0.0	0.0	57.0	115.0	148.0	152.0	138.0	116.0	93.0	74.0	59.0
2.5	0.0	0.0	0.0	0.0	89.0	180.0	231.0	238.0	216.0	181.0	146.0	116.0	92.0
3.0	0.0	0.0	0.0	0.0	129.0	260.0	332.0	332.0	292.0	240.0	210.0	167.0	132.0
3.5	0.0	0.0	0.0	0.0	0.0	354.0	438.0	424.0	377.0	326.0	260.0	215.0	180.0
4.0	0.0	0.0	0.0	0.0	0.0	462.0	540.0	530.0	475.0	384.0	339.0	267.0	213.0
4.5	0.0	0.0	0.0	0.0	0.0	544.0	642.0	628.0	562.0	473.0	382.0	338.0	266.0
5.0	0.0	0.0	0.0	0.0	0.0	0.0	726.0	707.0	670.0	557.0	472.0	369.0	328.0
5.5	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	737.0	658.0	530.0	446.0	355.0
6.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0	711.0	619.0	512.0	415.0
6.5	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0	750.0	658.0	579.0	481.0
7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0	750.0	613.0	525.0
7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0	750.0	686.0	593.0
8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0	750.0	625.0
8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0	750.0
9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0	750.0
9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0	750.0
10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	750.0
10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7

The AquaBuoy-250 kW Power Matrix (Henderson, 2006)

Hs [m]	**Tp [s]** **5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**12.0**	**13.0**	**14.0**	**15.0**	**16.0**	**17.0**
1.0	0.0	0.0	8.0	11.0	12.0	11.0	10.0	8.0	7.0	0.0	0.0	0.0	0.0
1.5	0.0	13.0	17.0	25.0	27.0	26.0	23.0	19.0	15.0	12.0	12.0	12.0	7.0
2.0	0.0	24.0	30.0	44.0	49.0	47.0	41.0	34.0	28.0	23.0	23.0	23.0	12.0
2.5	0.0	37.0	47.0	69.0	77.0	73.0	64.0	54.0	43.0	36.0	36.0	36.0	19.0
3.0	0.0	54.0	68.0	99.0	111.0	106.0	92.0	77.0	63.0	51.0	51.0	51.0	27.0
3.5	0.0	0.0	93.0	135.0	152.0	144.0	126.0	105.0	86.0	70.0	70.0	70.0	38.0
4.0	0.0	0.0	0.0	122.0	176.0	198.0	188.0	164.0	137.0	112.0	91.0	91.0	49.0
4.5	0.0	0.0	0.0	223.0	250.0	239.0	208.0	173.0	142.0	115.0	115.0	115.0	62.0
5.0	0.0	0.0	0.0	250.0	250.0	250.0	250.0	214.0	175.0	142.0	142.0	142.0	77.0
5.5	0.0	0.0	0.0	250.0	250.0	250.0	250.0	250.0	211.0	172.0	172.0	172.0	92.0