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**DOI**
10.1016/j.jclepro.2024.142740

**Publication date**
2024

**Document Version**
Final published version

**Published in**
Journal of Cleaner Production

Journal of Cleaner Production 463 (2024) 142740

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Evaluating the economic viability of near-future wave energy development along the Galician coast using LCoE analysis for multiple wave energy devices

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ARTICLE INFO

Handling Editor: Jin-Kuk Kim

*Keywords:*
Future wave energy resources
Downscaling
SWAN model
Levelized Cost of Energy (LCoE)
Wave energy converter (WEC)
RCP8.5 scenario

ABSTRACT

The economic profitability of future wave energy production along the Galician coast is assessed by analyzing the Levelized Cost of Energy (LCoE) under different Capital Expenditure (CapEx) scenarios and two discounts rates (5% and 10%). Wave resources for the near future under the RCP8.5 scenario are downscaled using SWAN, providing up to 75 m spatial resolution in coastal areas. The study's goal is to enhance the cost-effectiveness by selecting the most suitable wave energy converter (WEC) for each location. Fourteen WECs operating at different depths are considered. This analysis reveals that the Atargis device boasts the lowest LCoE for 64.2% of the coastal area, mainly in deep waters, with an LCoE of 77 €/MWh. In addition, the Oyster and Wave Dragon devices exhibit the lowest LCoE for 12.4% and 15.0% of the coastal area, respectively, excelling in shallow waters and near the coast, with values of 50 €/MWh and 97 €/MWh. These findings demonstrate the profitability of wave energy production along the Galician coast, even when considering a more conservative CapEx of 3 M€/MW, resulting in a cost of 140 €/MWh. This conclusion takes into account the evolving electricity prices in Spain, which reached 0.2068 €/kWh in the second half of 2023.

## 1. Introduction

The European Union (EU) is accelerating its evolution towards sustainability and making substantial investments in renewable energy to achieve the objectives outlined in the European Green Deal (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en). Simultaneously, this effort aims to diminish our reliance on energy imports. The European Members are exposed to varied Seas and resources, such as the Atlantic Ocean, North Sea, Mediterranean Sea, Baltic Sea and Black Sea. Hence providing them with a great potential for harnessing ocean renewable energy through a diverse range of technologies, positioning it as a pivotal element in the transition to clean energy.

Wave and tidal converters, representing ocean energy technologies, play a pivotal role in the EU's 'Blue Economy.' These technologies are rapidly advancing and hold the promise for delivering steady and predictable power generation, thereby playing a crucial role in achieving the European Union's climate and energy objectives. In order to facilitate the contribution of offshore renewable energy to the European Union's ambitious energy and climate objectives for both 2030 and 2050, the Commission released a specialized EU strategy dedicated to offshore renewable energy on November 19, 2020, known as the Offshore Energy Strategy COM(2020)741 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0741). This strategy outlines tangible steps to foster the enduring and eco-friendly growth of this industry. Among its key provisions, the strategy establishes goals for achieving a minimum installed capacity of 1 GW of ocean energy by 2030 and a substantial 40 GW by 2050 (IRENA, 2021).

Over the past decade, the EU member states, in collaboration with the private sector, have committed more than 4 billion of euros to fund research and pilot initiatives focused on oceanic energy. Within the framework of the Strategic Energy Technology (SET) Plan, the EU has established ambitious objectives for cost reduction in ocean energy technologies for the upcoming decade. These objectives aim to bring the

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https://doi.org/10.1016/j.jclepro.2024.142740
Received 22 January 2024; Received in revised form 9 May 2024; Accepted 28 May 2024
Available online 1 June 2024

cost of wave energy down to 0.20 €/kWh by 2025 and further decrease it to 0.15 €/kWh by 2030 (European Commission, https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en).

To ensure the long-term viability of offshore renewable energy, and encourage essential investments, it is imperative to sustain the progression of European energy infrastructure, regulatory systems, market structures, and research and innovation. This entails the incorporation of offshore renewable energy solutions on a regional scale across various European sea basins, as well as in the European Union's remote regions and overseas territories. It also involves setting and upholding ambitious targets within national maritime spatial plans. These regional studies require a very high spatial resolution (at sub 1 km scale) to capture local wave climate changes properly (Lavidas and Venugopal, 2018).

The Atlantic Arc, spanning from 35°N to 60°N and stretching from 0 to 20°W, encompasses the coastal areas of Portugal, Spain, France, England, Ireland, and Scotland. This region boasts the highest ocean energy potential in Europe, primarily owing to its favorable climate conditions for harnessing wind, tidal, and wave energy technologies (Rusu, 2022). It stands as a global hub for marine energy conversion, attracting developers from around the world to test the resilience and viability of their devices in the challenging conditions of the Atlantic Ocean. Within Europe, certain places offer optimal positioning for this purpose, notably along the western coast of the Iberian Peninsula (IP), where the Atlantic Ocean's swells create ideal conditions (Rusu, 2022; Clément et al., 2002). In particular, Spain leads Europe in the establishment of research and development facilities dedicated to floating wind power and various marine energy technologies (IDAE, 2023; MITECO, 2021). One noteworthy example is the experimental zone for marine energy exploration located in Punta Langosteira, situated in Galicia, NW Spain (Fig. 1). This initiative is part of the broader EnergyMare project. Notably, Punta Langosteira boasts the world's second-highest testbed wave energy density, second only to the southern coast of Wales (MITECO, 2021). Thus, Galicia emerges as the leader in terms of wave energy potential, with an impressive range of 40–45 kW per meter (kW/m), followed by the Cantabrian Sea with 30 kW/m and the northern part of the Canary Islands with 20 kW/m (MITECO, 2021).

Previous studies have shown that the current wave resource will change in the future due to the impact of climate change (Ribeiro et al., 2021a; Rusu and Onea, 2018; Majidi et al., 2023). In this sense, Majidi et al. (2023) noticed a decreasing trend in wave energy across the IP, with the most notable reductions being observable in the northwestern region for both near and far future, under the RCP8.5 scenario. They attribute this wave potential decline to a decrease in local wind speeds associated to the projected increase in global warming. Moreover, for the coastal area of the IP, Rusu and Onea, 2018 found that in the near future, under the RCP4.5 scenario, there are no significant differences in

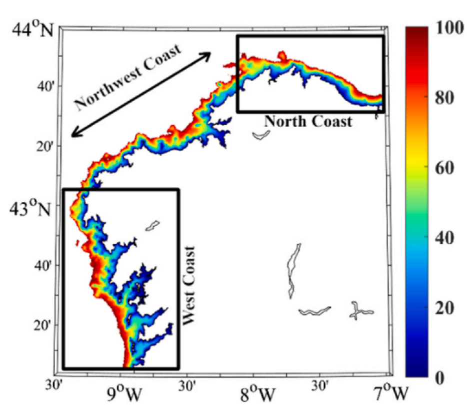


**Fig. 1.** Different parts of the Galician coast: North, Northwest and West, according to their orientation. Colours represent the bathymetry (m). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the wave power fields in terms of maximum values or general patterns during the transition seasons (spring and autumn). Nevertheless, a decrease in resources is expected in the summer season, reducing from 12 kW/m to 9 kW/m. Conversely, the winter season exhibits a maximum value approximately 14 kW/m higher than in recent past. Despite this, Ribeiro et al. (2021a) classify the wave resource along the Atlantic coast of the IP as excellent in both the near future (2026–2045) and far future (2081–2100) under the RCP8.5 scenario although, it has been categorized as exceptional for the historical period (1979–2005). This assessment encompasses the majority of regions, with the Galician coast being the only area retaining an exceptional rating. This remains the case despite the decrease in wave energy and the rise in wave variability and extreme wave conditions across much of the region (Ribeiro et al., 2021a).

Wave energy technology has an advantage and challenge simultaneously due to its wide variety of design concepts. Various technologies employ diverse solutions for harnessing energy from ocean waves, each suited to specific water depths and locations. Despite significant research and development efforts in the wave energy sector, resulting in numerous prototypes, it has not yet transitioned to a mature marketing stage. Conversely, the abundance of distinct technologies prevents the sector from achieving convergence, except for a slight preference towards point absorbers, as highlighted by Lopez et al. (2013). The primary types of Wave Energy Converters (WECs), categorized by their alignment concerning wave direction and operating principle, include the attenuator, point absorber, oscillating wave surge converter, oscillating water column, and overtopping device. Please refer to (Arguilé-Pérez et al., 2022) and the associated references for further details.

The capability of different WECs to harness wave energy was previously analyzed along the western coast of the IP both under current (Silva et al., 2013; Mota and Pinto, 2014; Bento et al., 2018; Rusu, 2019; Arguilé-Pérez et al., 2022) and future (Ribeiro et al., 2020) wave climate conditions by means of parameters such as: power load factor, capture width or efficiency.

Wave energy technologies exhibit significant cost variability due to the wide diversity of existing prototypes, anchoring and fixation systems, as well as energy transport systems. The prevailing metric for evaluating the cost competitiveness of power generation technologies is the Levelized Cost of Electricity (LCoE). What makes LCoE particularly advantageous is its ability to consolidate all direct technology expenses, encompassing construction, fuel, carbon pricing, operations, and maintenance, into a singular metric. Furthermore, LCoE can be effectively employed across a diverse spectrum of technologies, irrespective of their varying technical lifespans. Previous studies on LCoE have been conducted for marine energy with various objectives. These include analyzing the effect of different wave resources in different geographical locations (O'Connor et al., 2012; Dalton et al., 2010), different development strategies (de Andres et al., 2014), and uncertainties in the calculation of resources and revenues (Guanche et al., 2014). Chozas et al. (2014) made efforts to provide a standardized calculation of LCoE in wave energy projects to understand how different designs impact the final energy costs. More recently, de Andres et al. (2017), used the reversed LCoE calculation to define the costs and production potential required for a wave energy project to be economically competitive with other energy sources. The LCoE reported by Soukissian et al. (2017) exhibits a spectrum of values spanning from approximately 120 €/MWh to 500 €/MWh, reflecting the inherent uncertainties associated with factors such as device variations, resource availability, and underlying assumptions. More recently, Lavidas and Blok (2021) explored whether mild wave resources can be cost effectively exploited, by properly attributing a "production-to resource" approach.

Despite the cost constraints that avoid the acceleration of the wave energy deployment (Carlsson, 2014; Dalton et al., 2015), a substantial cost reduction is anticipated in the areas of installation, grid connection, and project development, thanks to considerable research going into improvements of the power take-off systems and efficiency in air turbines, to economies of scale and advances in these processes resulting from learning through practice. In 2015, the LCoE for wave energy ranged from 470 €/MWh to 1400 €/MWh, with its value reduced to 560 €/MWh in 2018 with the development of initial demonstrations. In 2020, the LCOE ranged from 280 €/MWh to 520 €/MWh (IRENA, 2020). Estimations by developers with active projects indicated that costs could be lower, although it would be expected to lag five years behind. They estimated that the LCoE can reach 206 €/MWh by 2025, 155 €/MWh by 2030, and 100 €/MWh by 2035 (European Commission, 2016; Magana, 2019; Smart and Noonan, 2018). MITECO (2021) shows similar results (see the cost reduction curve depicted in Fig. 37).

The aim of this study is to analyze the economic profitability of future wave energy along the Galician coast considering the most suitable WEC device for each location. The assessment of future economic profitability is carried out in terms of LCoE calculations based on the methodology outlined in Lavidas and Blok (2021), while considering projections for the near-future wave resource influenced by climate change. The Galician coast is one of the few European regions that remains with an outstanding score, despite the reduction in wind energy attributed to climate change (Ribeiro et al., 2021b). This study seeks to optimize the cost performance by placing the best device at each location. In this sense, fourteen different types of WECs with different operational depths are considered. The methodological approach employed relies on best practices, aiming to minimize assumptions and limiting economic feasibility extrapolations to individual data points. The outcomes offer a comprehensive perspective on what is achievable, as well as identifying the most suitable WEC for deploying at each region.

## 2. Data, models and methods

### 2.1. Data and models

Historical and future wave data (significant wave height, Hs, and peak period, Tp) were retrieved from simulations carried out by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Bureau of Meteorology datasets developed under the Pacific-Australia Climate Change Science and Adaptation Planning Programme (PACCSAP) (https://data-cbr.csiro.au/thredds/catalog/catch_all/CMAR_CAWCR-Wave_archive/Global_wave_projections/catalog.html) using WAVEWATCH III (WWIII) model (Tolman, 2014). Data cover both ocean wave hindcast over a historic period (1979–2005) (Durrant et al., 2013) and wind-wave climate projections from 2026 to 2045 (near future) and from 2081 to 2099 (far future) (Hemer et al., 2015). For hindcast purposes, CSIRO offers 8 different historical realizations forced with 8 different Global Circulation Models (GCMs) and an additional simulation forced with reanalysis winds obtained from the Climate Forecast System Reanalysis (CFSR). The GCMs used to force CSIRO WWIII wind-wave model are summarized in Table 1.

**Table 1**
Global Climate Models (GCMs) used to simulate historical and projected wave fields.

| GCMs | Research Center |
|---|---|
| ACCESS1.0 | Australian Community Climate and Earth System Simulator, Australia |
| BCC-CSM1.1 | Beijing Climate Center, China Meteorological Administration, China |
| CNRM-CM3 | National Center of Meteorological Research, France |
| GFDL-CM3 | NOAA Geophysical Fluid Dynamics Laboratory, USA |
| HadGEM2-ES | Met Office Hadley Center, UK |
| INMCM4 | Institute for Numerical Mathematics, Russia |
| MIROC5 | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan |
| MRI-CGCM3 | Meteorological Research Institute, Japan |

The accuracy of the CSIRO WWIII simulations to reproduce the wave field in the NW coast of the Iberian Peninsula was analyzed in previous research (Arguilé-Pérez et al., 2023; Ribeiro et al., 2020; Ribeiro et al., 2021a; 2021b), showing that BCC-CSM1.1 represents the best climate model to reproduce the extreme wave climate and MIROC5 the best model to reproduce the annual mean wave conditions. Consequently, these will be the models downscaled in the present study over the period 2026 to 2045 under the RCP8.5 greenhouse gas emission scenario (Moss et al., 2010) defined by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013). According to Smith and Myers (2018), this scenario, which posits that radiative forcing will reach 8.5 W/m$^2$ by the end of the 21st century and continue to increase thereafter, currently appears to be the most plausible scenario due to the absence of robust and coordinated global policies aimed at reducing greenhouse gas emissions.

The coarse-resolution ($1^\circ \times 1^\circ$) wave parameters obtained from CSIRO WWIII simulations forced with BCC-CSM1.1 and MIROC GCMs were used as the starting point in the present study following the approach described in deCastro et al. (2024).

Downscaling in the Galician coast (Fig. 1) was carried out with the third-generation SWAN model developed by the Delft University of Technology (Booij et al., 1999; Ris et al., 1999; SWAN, 2024) considering the wave parameters, Hs and Tp, provided by CSIRO WWIII simulations as boundary conditions. SWAN solves the spectral action balance equations being an accurate tool to simulate high-resolution coastal waves. In this particular application, SWAN uses the unstructured mesh described in Carmeáns et al. (2014), with a higher spatial resolution in coastal and estuarine areas —where it can reach 75 m resolution—than offshore. Consequently, high-resolution wave data were obtained for the areas of interest at an affordable computational time. This grid also coincides with the one used the Galician Weather forecast Agency (MeteoGalicia, https://www.meteogalicia.gal) for its operational calculation of local wave fields, which has been used in previous research (Arguilé-Pérez et al., 2022). The only difference between the operational calculation and the present one is that the former uses data from a regional model based on WWIII, whereas the latter involves dynamic downscaling based on projected data, as elaborated in the CSIRO WWIII data description mentioned above. Hs and Tp data are recorded every 3 h for further analysis.

### 2.2. Methods

#### 2.2.1. Wave power resource, electric power and WECs

The wave power (WP) resource is defined as the amount of energy per unit of time and length of the wave front (expressed in kW/m) transmitted in the direction of wave propagation (Mota and Pinto, 2014), that is calculated according to:

$$WP = \frac{\rho g^2}{64\pi} H_S^2 T_e \tag{1}$$

being $\rho$ the seawater density (1025 kg/m$^3$), g the gravitational acceleration and $T_e$ the energy period, which itself depends on the peak period as:

$$T_e = \alpha T_p \tag{2}$$

where $\alpha$ varies with the shape of the wave spectrum. A value of $\alpha = 0.9$ was considered in the present study, which is equivalent to assuming a standard JONSWAP spectrum with a peak enhancement factor of $\gamma = 3.3$ (Ribeiro et al., 2020).

The expected average electric power ($P_E$) that can be extracted with a particular WEC was calculated as

$$P_E = \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} P_{ij} \tag{3}$$

being $P_{ij}$ the electric power obtained from a bin $ij$ of the power matrix of a particular WEC, $p_{ij}$ is the probability of occurrence of a given sea state for this bin, and $n_T$ a and $n_H$ are the number of peak period and significant height bins considered.

The WEC types employed in this study, their operational depth and various technical specifications, such as the maximum value in the power matrix ($P_{max}$), the power-take-off (PTO) system, the length of the device and the mode to extract energy are described in Table 2.

### 2.2.2. SWAN downscaling validation

The accuracy of the downscaling process to reproduce the wave field in the area was investigated by means of an overlap test which consists in calculating the overlap percentage (OP) between two series and has the advantage that the entire data distribution is considered. This method is based on the study of Perkins et al. (2007) and has been used by the authors in previous studies (Ribeiro et al., 2021a; Arguilé-Pérez et al., 2022). The OP can be calculated as

$$OP_j\ (\%) = 100 \cdot \sum_{i=1}^{n} \min\left(f_i\left(x_j^{down}\right), f_i\left(x_j^{oper}\right)\right) \tag{4}$$

where $x$ is the variable of interest to be analyzed (the wave power), $n$ is the number of bins in which series are classified, $j$ represents the grid point and $f_i\left(x_j^{down}\right)$ and $f_i\left(x_j^{oper}\right)$ represent the relative frequency of values in a given bin $i$. The superscripts *down* and *oper* correspond to downscaled values and values obtained from the operational calculation carried out daily by MeteoGalicia, respectively. A number of 20 bins were considered. The closer the $OP_j$ is to 100%, the more similar both data series will be at grid point $j$.

OP calculation is not straightforward, primarily stemming from the disparity between the historical data supplied by the different data sources, namely 1979–2005 for BCC-CSM1.1 and MIROC5 and a short time frame (2014–2022) associated with operational system data provided by MeteoGalicia. This temporal misalignment underscores the potential influence of the specific range of years chosen for comparative analysis on the resulting outcomes. To solve this problem, a Monte Carlo-inspired methodology was carried out. The methodology was executed as follows: Initially, a random selection was made of a set of nine different years within the broader timeframe spanning from 1980 to 2005. It is noteworthy that despite the availability of historical data covering a more extensive temporal range, exclusive attention was accorded to the specific sub-period from 1980 to 2005, primarily due to its proximity to the operational period under scrutiny. The overlap metric between the chosen subset of historical data and the nine years of operational data was computed. Following this, the entire protocol was iterated a total of 10,000 times, with the imposition that a particular subset cannot be considered more than once. Finally, the 10,000 OPs were averaged for each of the 27 points selected for the area. Results for the wave power obtained from both models (BCC-CSM1.1 and MIROC5) are depicted in Fig. 2.

On average, considering the 27 points under analysis, the mean OP was 84.8% for BCC-CSM1.1 and 85.0% for MIROC5. For either of the two models, none of the points exhibit an OP lower than 80%. Furthermore, OP values are higher near coast than those in offshore areas, with the highest values being observed on the northern coast of Galicia.

The approach undertaken in this study to assess the future wave energy resources at a regional level closely follows the methodology described by deCastro et al. (2024). This study reviews methodologies from existing literature regarding future wave energy resources and their exploitation. These includes assessing optimal future atmospheric models to drive wave models, the different downscaling techniques for high-resolution resource evaluation in large regions, and analyzing future energy resources variability and potential exploitation in specific regions with different types of devices.

### 2.2.3. Economic analysis

In addition to the significance of a region's wave energy potential, the analysis of wave energy profitability in terms of LCoE hinges on two main factors: the cost of the device and the revenue capacity. In terms of the device cost, the capital expenditure (CapEx) and the maintenance, or

**Table 2**
Characteristics of WECs used in the analysis including WEC types, the operational depth and some technical specifications, such as the maximum value in the power matrix ($P_{max}$), the power-take-off (PTO) system, the length of the device and the mode to extract energy.

| WEC | Type | Depth range (m) | $P_{max}$ (kW) | PTO System | L (m) | Energy mode | References |
|---|---|---|---|---|---|---|---|
| Aqua Buoy | Point Absorber | Deep (50–100) | 250 | Hydro turbine | 6 | Heave | Bozzi et al. (2014), Ahmed et al. (2020) |
| Atargis | Terminator | Nearshore and Deep (40–100) | 2530 | Hydro turbine | 60 | Heave and Surge | Atargis Energy Corporation webpage, Ahmed et al. (2020) |
| Ceto | Point Absorber | Nearshore (20–30) | 260 | Hydro turbine | 7 | Heave | Babarit et al. (2012), Ahmed et al. (2020) |
| Langlee | Oscillating Surge | Nearshore and Deep (40–100) | 1665 | Hydraulic motor | 25 | Surge | Babarit et al. (2012), Bozzi et al. (2018) |
| OE Buoy | Oscillating water column | Deep (50–100) | 2880 | Pneumatic air turbine | 24 | Oscillating pressure differences | Babarit et al. (2012), Ahmed et al. (2020) |
| Oceantec | Attenuator | Nearshore (20–60) | 500 | Pneumatic air turbine | 7.5 | Pitch | Lavidas and Blok (2021), Tethys webpage, Ahmed et al. (2020) |
| Oyster | Oscillating Surge | Shallow (10–20) | 290 | Hydro turbine | 18 | Surge | Silva et al. (2013), Ahmed et al. (2020) |
| Pelamis | Attenuator | Deep (50–100) | 750 | Hydraulic motor | 150 | Heave and sway | Bozzi et al. (2014) |
| Pontoon | Point absorber | Deep (50–100) | 3619 | Hydro turbine | 80 | Heave | Babarit et al. (2012), Ahmed et al. (2020) |
| RM5 | Oscillating Surge | Deep (50–100) | 360 | Hydraulic motor | 25 | Surge | Yu et al. (2015) |
| SeaPower | Attenuator | Deep (50–100) | 3587 | Hydraulic motor | 16.75 | Heave | Rusu and Onea (2018), Sea Power webpage |
| Wave Bob | Point Absorber | Deep (50–100) | 1000 | Hydraulic motor | 20 | Heave | Babarit et al. (2012), Ahmed et al. (2020) |
| Wave Dragon | Overtopping | Nearshore (25–50) | 7000 | Hydro turbine | 260 | Overtopping | Bozzi et al. (2014), Kofoed et al. (2006) Ahmed et al. (2020) |
| Wave Roller Type | Oscillating Surge | Shallow (8–20) | 3332 | Hydraulic motor | 26 | Surge | Babarit et al. (2012) |

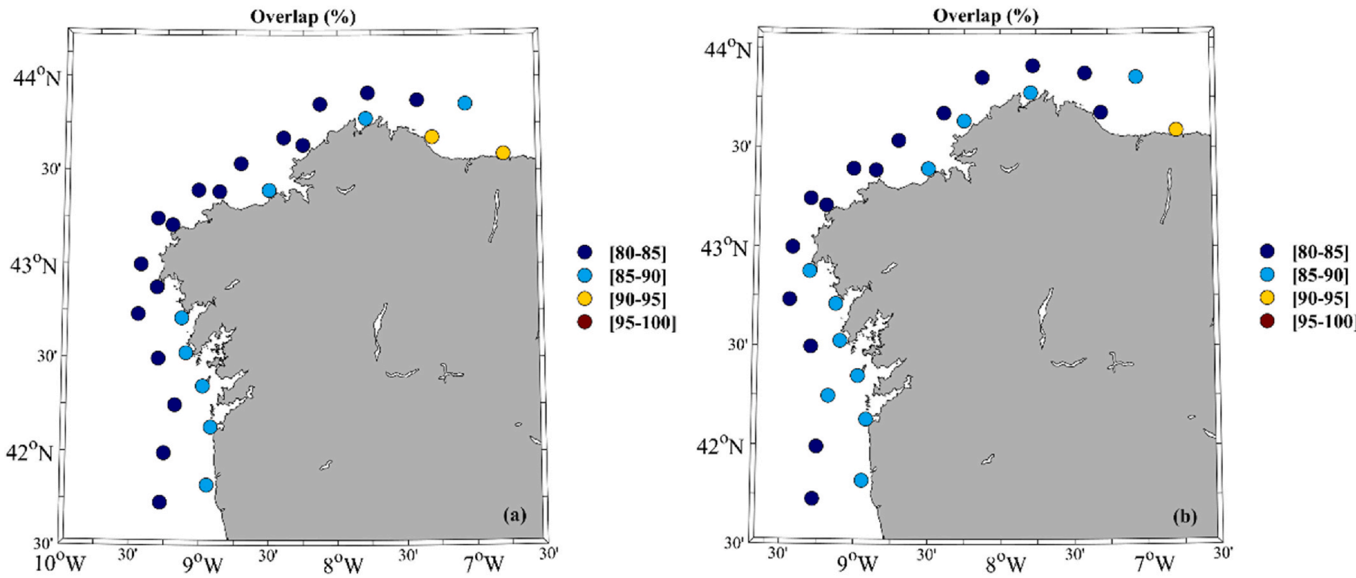


**Fig. 2.** Wave power (WP) overlap percentage between operational data (2014–2022) and historical data (1980–2005) for BCC-CSM1.1 (a) and MIROC5 (b) models.

operational expenditure, (OpEx) are the major economic aspects considered. Due to the variety of devices utilized, discrepancies in capital (CapEx) and operational (OpEx) costs are anticipated. To account for potential cost reductions, sensitivity costing was proactively integrated, considering CapEx values ranging from 1.5 M€/MW to 5 M€/MW at increments of 500 k€. This approach was adopted due to the lower Technology Readiness Level (TRL) of wave farm installations, following the methodology outlined in Lavidas and Blok (2021). In the realm of OpEx considerations, a fixed annual cost for maintenance was assigned as a percentage of CapEx following Babarit et al. (2017) and Lavidas and Blok (2021), instead of modelling unforeseen expenses. Thus, an OpEX of 10%, which can be perceived as representative of the sector, was considered in alignment with previous studies (MacGillivray et al., 2014; Astariz et al., 2015, de Andres et al., 2017) which estimate that it can vary between 8 and 15% depending on the technology.

LCoE serves as a commonly used metric encompassing both the lifetime costs (CapEx and OpEx) and the energy production of an installation. This metric enables the assessment of the economic performance of various technologies, expressed as the expected unit cost per electricity, usually in €/MWh or €/kWh. The formula for calculating LCoE is as follows:

$$LCOE = \frac{PV[(CapEx + OpEx)]}{AEP} \tag{5}$$

where *PV* represents the Present Value of expenses or benefits over the considered lifetime, which is typically 20 years. *AEP* denotes the annual energy production, calculated as AEP = $P_E \times \Delta t$, with $\Delta t$ equal to 24 h multiplied by 365 days.

In our calculations, we have applied a social discount rate (r) set at 5%, which is typically employed for projects with considerable social benefits, such as environmental protection, local employment, and enhancements to the quality of life. Additionally, we have considered a conventional to high-risk investment r of 10% (pessimistic) for situations where societal benefits are marginal.

The totality of these economic considerations is described in Table 3.

**Table 3**
Characteristics of the economic analysis of the future profitability of wave energy.

| CapEx | 1.5 M€/MW –5 M€/MW (0.5 M€/incr.) |
|---|---|
| OpEx | 10% |
| Discount rate (r) | 5% (social) & 10% (high risk) |
| Projected lifetime | 20 years |

The size of each device can also significantly influence the estimation of the packing factor for WECs within a 1 km$^2$ spatial area. The spacing between devices and their arrangement order can have adverse effects on array performance, depending on the type of WEC (Gunn and Stock-Williams, 2012; Veigas et al., 2014; Bozzi et al., 2017; Rodriguez-Delgado et al., 2019). In this study, when evaluating the feasibility of a wave farm, a practical packing density of 10 MW/km$^2$ was assumed, in line with Lavidas and Blok (2021). Consequently, the economic analysis considered a 10 MW wave farm as feasible for each grid cell.

The methodological procedure employed in this study is outlined in the following workflow diagram (Fig. 3).

## 3. Results

Our main focus is to analyze the future economic profitability of wave energy along the Galician coast considering the most suitable WEC device for each location. Firstly, the mean wave power resource was calculated for the near future period (2026–2045) under the RCP8.5 (Fig. 4).

The Galician coastline will exhibit varying levels of wave power values in the near future, ranging from less than 10 kW/m in the inner sections of the estuaries to approximately 60 kW/m in the offshore regions. Future projections of wave power resource closely resemble the current conditions (refer to Fig. 3 in Arguilé- Pérez et al., 2022), albeit with a slight reduction in intensity. Similar to the present situation, the future wave power resource will remain the highest along the northwestern coast and the lowest along the northern coast. This wave power spatial distribution follows the predominant direction of the waves coming from the North Atlantic, heading directly towards the northwest coast, with the north coast being leeward of the waves due to its morphology. This pattern arises due to the powerful impact of low-pressure systems originating in the mid-Atlantic Ocean and the recurring storms that amplify sea conditions along the Galician coast. Consequently, the northwestern coast of Galicia boasts the highest wave energy levels in Spain (Iglesias et al., 2009; Veigas et al., 2015) and ranks among the top in Europe (Gleizon et al., 2017). This region therefore represents a good testing ground for analyzing the profitability of wave energy in the near future (Arguilé-Pérez et al., 2022, 2023).

The LCoE analysis for the WECs outlined in Table 2 is presented in Fig. 5, considering a CapEx of 1.5 M€/MW and a discount rate of 5%.

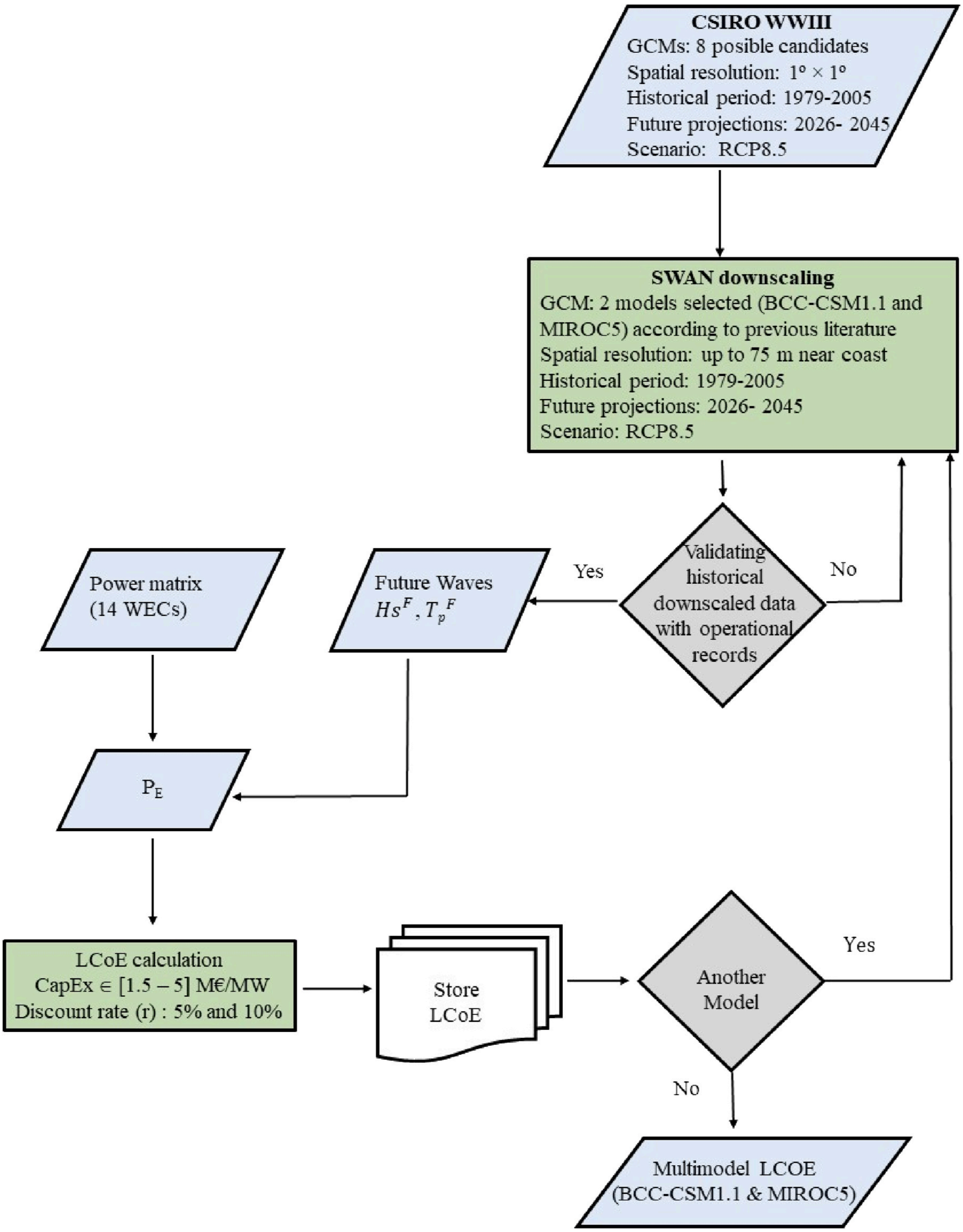


**Fig. 3.** Workflow of the methodological procedure employed.

The LCoE calculations were performed individually for each device and GCM (BCC-CSM1.1and MIROC5) at locations where the WEC is operable based on their depth requirements. Then, a multimodel LCoE mean was considered by averaging the cost calculated for every model (BCC-CSM1.1 and MIROC5), reducing the uncertainties associated with the different scenarios and establishing more realistic cost expectations for the future. The LCoE values exceeding 1000 €/MWh were dismissed from consideration due to their lack of feasibility.

The near future LCoE follows the same pattern along the Galician coast regardless of the device (Fig. 5). It reaches the lowest values in the region between 43 and 44°N and 8–9°W, where the wave energy potential will be higher, increases south of 43°N, and reaches its maximum value on the northern coast where the wave energy potential will be at its lowest value. This underscores the high influence of regional wave energy potential (Fig. 4) on the LCoE. Among the assortment of devices examined, Atargis and RM5 stand out as the most profitable options across the entire coastal region. They achieve the most favorable LCoE in areas with greater wave energy potential with rates of 77 €/MWh and 89 €/MWh, respectively. As we move south of 43°N, the LCoE begins to rise, reaching its peak on the northern coast of Galicia at 130 €/MWh for

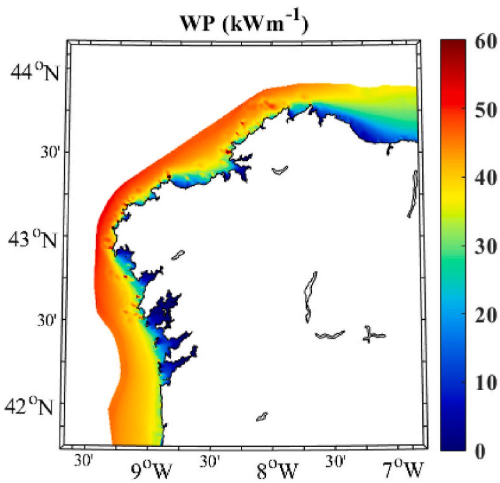


**Fig. 4.** Multimodel mean of wave power (WP, kW/m) along the Galician coast for the near future period (2026–2045) under the RCP8.5.

Atargis and 140 €/MWh for RM5. The following device with the most cost-effectiveness would be the Aquaboy, with an LCoE ranging from 130 €/MWh to 250 €/MWh. However, since these three devices operate at similar depths, the most profitable one for these locations will be the Atargis. The rest of devices that operate at deep locations will be less competitive than the previous ones. Looking to those devices that operates nearshore the most profitable options will be Wave Dragon and OceanTech with LCoE values ranging from 97 €/MWh and 140 €/MWh to 450 €/MWh and more than 500 €/MWh, respectively. Finally, the most profitable options for shallow waters will be Oyster and Wave Roller Type with LCoE values ranging from 50 €/MWh and 119 €/MWh to 350 €/MWh and more than 700 €/MWh, respectively. The same LCoE calculations were carried out for a discount rate of 10% (see Fig. A1. in appendix).

The profitability of WECs throughout the study region for the near future is shown in Tables 4 and 5 through the average and minimum values of LCoE considering all CapEx ranging from 1.5 M€/MW to 5 M€/MW with an increment of 0.5 M€ and discount rates of 5% and 10%.

The most profitable WEC in the near future, in terms of LCoE, was calculated for every location as shown in Fig. 6 (a) for the entire coastal area and in Fig. 6(b-d) for the western, northwestern and north coast of Galicia, respectively. Those devices that did not provided the lowest LCoE at any location were not displayed. It is worth mentioning that the most profitable WEC for a particular location remains unchanged, no matter the discount rate or CapEx (Tables 4 and 5).

Atargis is positioned to achieve the highest level of profitability in deep water environments (50–100 m) in the near future, whereas Wave Dragon stands out in nearshore areas (25–50 m) and Oyster demonstrates its strength in shallow water conditions (10–20 m). Table 6 shows the percentage of occupation of the most profitable devices along the Galician coast.

LCoE analysis for the most profitable WECs considering CapEx values of 3 M€/MW and 5 M€/MW is shown in Figs. A2 and A.3. in appendix.

Previous investigation (Arguilé-Pérez et al., 2022) thoroughly assessed the performance of various WECs – namely, Atargis, Oyster, Aqua Buoy, and Pelamis – for wave energy extraction along the Galician coast within the timeframe of 2014–2021. This evaluation centered on key parameters such as the power load factor and efficiency. Notably, Atargis emerged as the optimal choice for deployment along the Galician coast due to its exceptional power load factor, efficiency, robust electric energy power output, submerged positioning beneath the sea surface, and operational water depth, which strategically avoids ecologically sensitive areas (Arguilé-Pérez et al., 2022).

Additionally, the suitability of specific WECs, including Atargis, Aqua Buoy, RM5, and a Wave Roller-Type device (WRTD), for

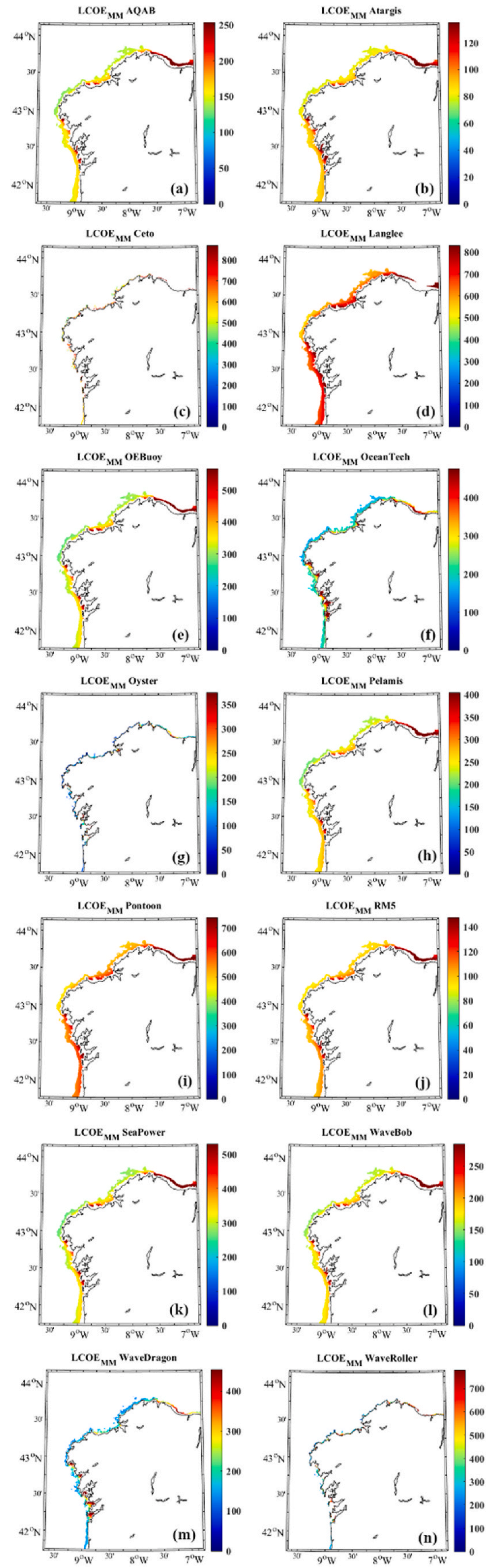


**Fig. 5.** Near future multimodel LCoE (€/MWh) for the WECs depicted in Table 2 considering a discount rate of 5% and a CapEx of 1.5 M€/MW.

**Table 4**
Near future mean LCoE (€/MWh) for different CapEx and devices using discounts rates of 5% and 10%, respectively. Locations where LCoE values exceeded 1000 €/MWh were discarded.

| | CapEx (M€/MW) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 |
| Aqua Buoy | 179/218 | 238/288 | 295/355 | 350/420 | 405/480 | 455/538 | 503/594 | 550/647 |
| Atargis | 101/122 | 133/162 | 166/202 | 199/242 | 232/281 | 264/319 | 296/357 | 327/394 |
| Ceto | 630/714 | 763/860 | 874/926 | 920/956 | 949/— | 961/— | −/− | −/− |
| Langlee | 684/801 | 863/942 | 953/— | −/− | −/− | −/− | −/− | −/− |
| OEBuoy | 385/455 | 491/576 | 589/688 | 680/805 | 776/902 | 866/952 | 926/992 | 960/– |
| OceanTech | 276/323 | 347/404 | 412/478 | 473/548 | 531/613 | 586/672 | 637/730 | 685/786 |
| Oyster | 181/209 | 223/255 | 258/292 | 289/338 | 328/376 | 359/411 | 390/443 | 417/473 |
| Pelamis | 286/346 | 377/453 | 463/547 | 540/635 | 614/720 | 683/810 | 754/886 | 829/917 |
| Pontoon | 586/691 | 745/880 | 897/962 | 958/— | −/− | −/− | −/− | −/− |
| RM5 | 113/138 | 151/184 | 189/230 | 226/275 | 264/321 | 302/366 | 339/410 | 375/453 |
| Sea Power | 365/434 | 468/552 | 564/659 | 652/766 | 738/870 | 828/932 | 899/970 | 940/— |
| Wave Bob | 202/246 | 269/325 | 333/402 | 396/472 | 455/538 | 510/602 | 564/661 | 615/721 |
| Wave Dragon | 240/281 | 302/348 | 354/409 | 405/461 | 450/507 | 487/554 | 526/596 | 564/636 |
| Wave Roller Type | 424/463 | 490/543 | 552/617 | 611/671 | 665/737 | 709/793 | 760/847 | 806/873 |

**Table 5**
Near future minimum LCoE (€/MWh) for different CapEx and devices using discounts rates of 5% and 10%, respectively. Locations where LCoE values exceeded 1000 €/MWh were discarded.

| | CapEx (M€/MW) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 |
| Aqua Buoy | 129/157 | 172/210 | 215/262 | 258/315 | 302/367 | 345/420 | 388/472 | 431/524 |
| Atargis | 77/94 | 103/125 | 129/157 | 154/188 | 180/219 | 206/250 | 231/282 | 257/313 |
| Ceto | 360/439 | 481/585 | 601/731 | 721/878 | 841/ | 961/ | −/− | −/− |
| Langlee | 521/634 | 694/846 | 868/ | −/− | −/− | −/− | −/− | −/− |
| OEBouy | 268/326 | 357/435 | 447/544 | 536/653 | 625/761 | 715/870 | 804/979 | 893/— |
| OceanTech | 140/170 | 186/227 | 233/284 | 280/340 | 326/397 | 373/454 | 419/511 | 466/567 |
| Oyster | 50/61 | 67/81 | 83/101 | 100/122 | 117/142 | 133/162 | 150/182 | 166/203 |
| Pelamis | 196/239 | 262/319 | 327/398 | 393/478 | 458/558 | 523/637 | 589/717 | 654/797 |
| Pontoon | 449/547 | 599/729 | 749/911 | 898/— | −/− | −/− | −/− | −/− |
| RM5 | 89/109 | 119/145 | 149/181 | 179/217 | 208/254 | 238/290 | 268/326 | 298/362 |
| Sea Power | 253/308 | 338/411 | 422/514 | 507/617 | 591/719 | 675/822 | 760/925 | 844/– |
| Wave Bob | 145/177 | 193/235 | 242/284 | 290/353 | 338/412 | 387/471 | 435/530 | 483/588 |
| Wave Dragon | 97/118 | 130/158 | 162/197 | 194/237 | 227/276 | 259/316 | 292/355 | 324/395 |
| Wave Roller Type | 119/145 | 158/193 | 198/241 | 237/289 | 277/337 | 317/385 | 356/434 | 396/482 |

harnessing wave energy was examined (Arguilé-Pérez et al., 2023) during the winter season in the period spanning from 2026 to 2045. This study employed three parameters: the power load factor, normalized capture width, and operational duration. Based on these three suitability parameters, the research proposes a combination of Atargis and WRTDs as the most fitting choice for the prospective establishment of wave energy farms along the northwestern coast of Spain (Arguilé-Pérez et al., 2023).

Finally, the minimum LCoE at every location was calculated by considering the best WEC for each location, different CapEx values and two discount rates, as shown in Fig. 7. As expected, the cost increases with both the CapEx and the discount rate. Additionally, there is a rising trend in LCoE from ocean to coast, with the highest LCoE at the northern coast where the wave power is at its lowest.

## 4. Discussion

The future potential for wave energy resources in the northwest corner of the Iberian Peninsula, specifically in Galicia, remains outstanding, despite a reduction in wave energy due to increased wind variability and extreme wave conditions (Ribeiro et al., 2021a). This high wave energy resource is due to the powerful impact of low-pressure systems originating in the mid-Atlantic Ocean and the recurring storms that amplify sea conditions along the Galician coast. Additionally, this coast is characterized by a narrow platform transitioning from shallow depths near coast to depths exceeding 100 m within a short distance of few kilometers from the coast.

The analysis of the future economic profitability of wave energy along the Galician coast encompass an analysis of the LCoE behavior under different CapEX scenarios. It is widely recognized that energy production is the most crucial factor when estimating the behavior of the LCoE (Lavidas and Blok, 2021; Martinez and Iglesias, 2022). However, given the absence of a single, most efficient technology for wave energy converters, it becomes essential to evaluate which device is the most suitable each location along the narrow coastal shelf of Galician coast.

The minimum LCoE analysis shows that the Atargis device has the lowest LCoE for 64.2% of the coastal area, corresponding to deep waters, with a value of 77 €/MWh. Furthermore, Oyster and Wave Dragon are the two devices that provide the lowest LCoE for 12.4% and 15.0% of the coastal area, in shallow waters and near coast, respectively, with minimum LCOE values of 50 €/MWh and 97 €/MWh. Thus, considering the percentage of coastal area in which each of the aforementioned devices operates and the minimum LCoE achieved for each of them, we could assert that the average LCoE of a future wave energy farm in Galicia would be 70 €/MWh, considering the most efficient device at each location.

Castro-Santos et al. (2024) also analyzed the viability of present and future wave farms on the Atlantic coast by calculating NPV and LCoE. They found that the minimum LCoE calculated with an r = 8% (10%), using an Aquabuoy device under real future wave resources, will be 568.77 €/MWh (609.47 €/MWh). Their LCoE is much higher compared to the LCoE of 85.37 €/MWh obtained in this study for an r of 10% considering the most suitable device for each location, taking into account the depth at which the device operates. The significant difference

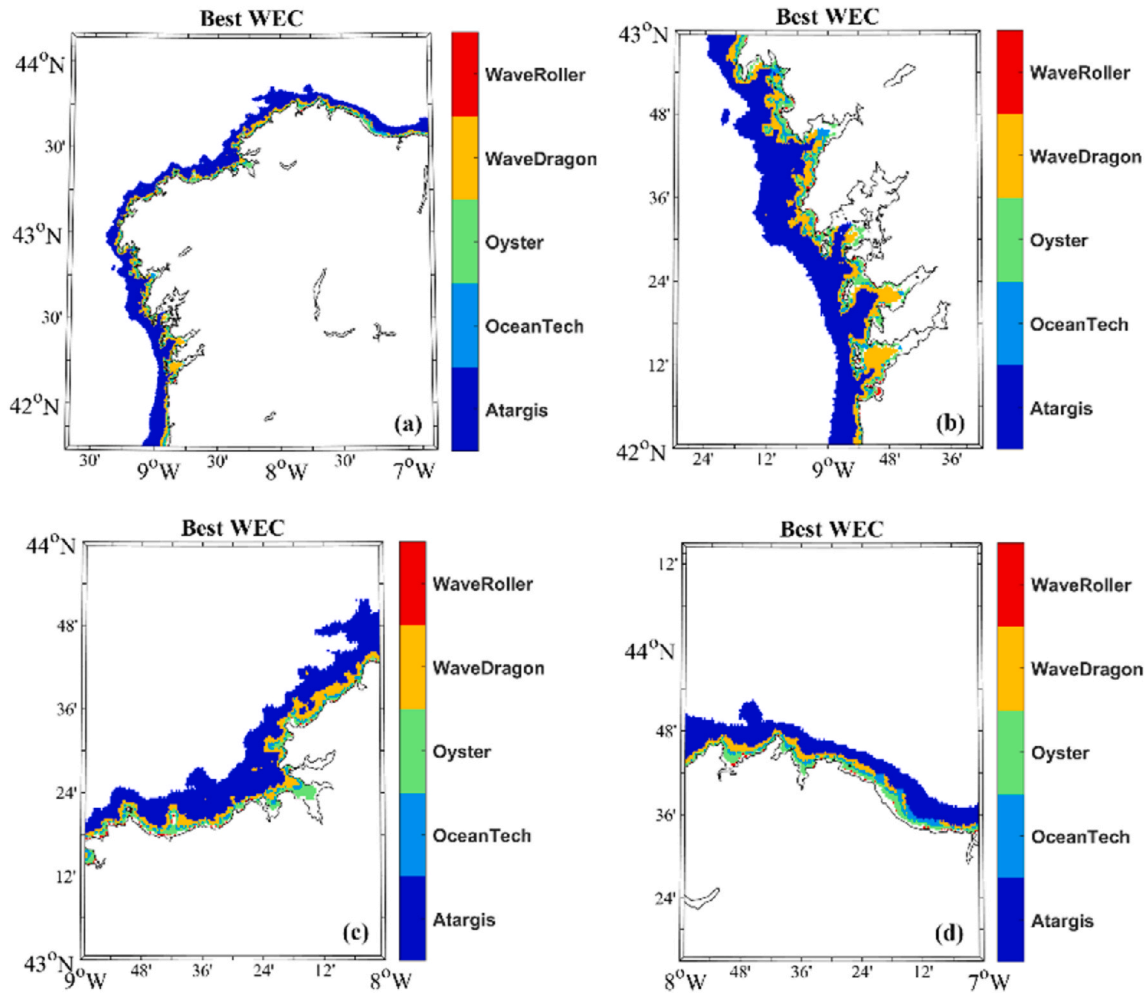


**Fig. 6.** The most profitable WEC for every location in the near future considering a CapEx = 1.5 M€/MW and r = 5% **(a)** for the entire coastal area, **(b)** for the western coast, **(c)** for the northwestern coast and **(d)** for the northern coast of Galicia.

**Table 6**
Percentage of occupation of the most profitability WECs along the Galician coast in the near future.

| WEC | % |
|---|---|
| Atargis | 64.2 |
| Ocean Tech | 5.3 |
| Oyster | 12.4 |
| Wave Dragon | 15.0 |
| Wave Roller Type | 3.0 |

between the minimum LCoE values obtained in both studies can be primarily attributed to the exclusive utilization of AquaBuoy as the sole wave energy capture device by Castro-Santos et al. (2024) across the entire region, no matter the depth of the zone. Previous research conducted in the same area (Arguilé-Pérez et al., 2022, 2023) had already identified Atargis and oscillating surge devices as the most suitable options for deep and shallow waters, respectively, considering parameters such as efficiency, power load factor and, capture width both currently as under winter season spanning from 2026 to 2045. Therefore, calculating the LCoE of these two devices may be an appropriate starting point when planning future wave energy farms.

Lavidas and Blok (2021), following a comparable approach for LCoE calculation, but in this case for moderate wave resources in the Northern Sea, reported a lowest present LCoE values ranging from 110 €/MWh to 140 €/MWh for most of the analyzed area. For specific coastal regions, LCoE values were observed to fall within the range of 50 €/MWh to 90 €/MWh, and in the southwestern part of their study domain, they extended from 170 €/MWh to 200 €/MWh, as illustrated in their Figure 13. When comparing their findings to ours, we observe that, for most of their region, their lowest LCoE is still higher, even with their thorough amortization analysis that incorporates feed-in premium (FIP) tariffs and reductions in $CO_2$ emissions taxes. The Lavidas and Blok (2021) study underscores that the most influential factor in the LCoE behavior is the energy resource, as analyzed Martinez and Iglesias (2022).

The competitiveness of wave energy depends on its relative performance against offshore wind energy which is already at commercial stage with some farms providing electric power to the grid. In this context, it is essential a comparison between the minimum LCoE values determined for future offshore wind farms and our findings. In a study conducted by Castro-Santos et al. (2021), the authors assessed the future viability of offshore wind farms along the Atlantic coast of the Iberian Peninsula under the RCP8.5 scenario. Their investigation yielded appealing LCoE values for the Galician area, with a minimum LCoE of 74.12 €/MWh which is lower than the present lowest LCoE (~95 €/MWh) obtained by Martinez and Iglesias (2022), in those European Atlantic coasts where the wind resource is most abundant: off Great Britain and Ireland, in the North Sea, and off NW Spain. The LCoE obtained for future offshore wind energy in Galicia is comparable to the LCoE obtained in the present analysis for wave energy in which the most suitable energy capture device is chosen for the operating depth.

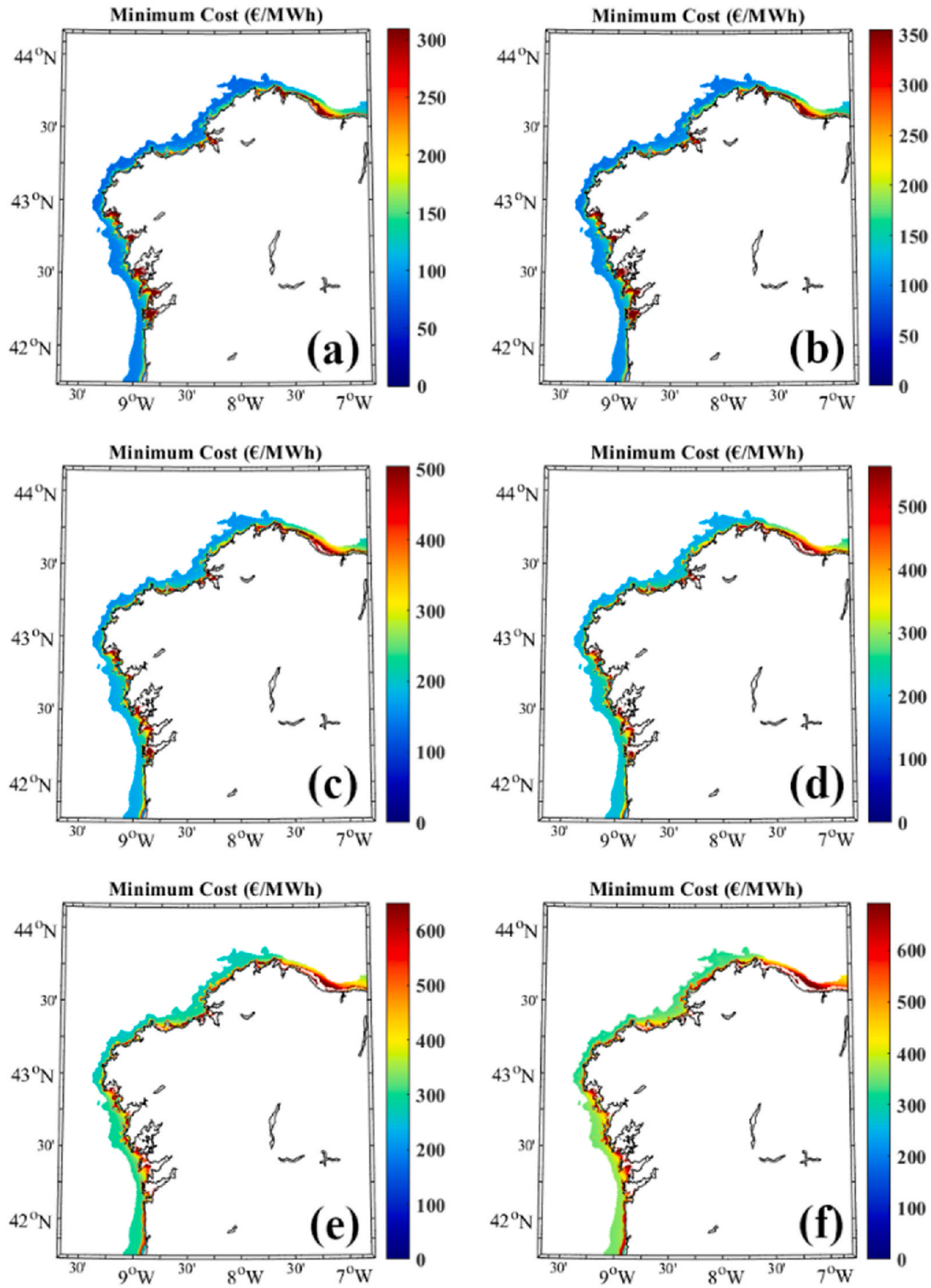


**Fig. 7.** Minimum LCoE at every location for the near future calculated for a discount rate of 5% (a, c, e) and 10% (b, d, f) for different CapEx (from up to down, 1.5 M€/MW, 3.0 M€/MW and 5.0 M€/MW).

Previous studies, such as those conducted by Astariz et al. (2015) and Soukissian et al. (2017) had already compared the LCoE of various marine energy sources, specifically, offshore wind, tidal and wave energy. Astariz et al. (2015) conducted LCoE calculations, taking into account costs associated with the construction of these offshore energy farms and the operation and maintenance tasks throughout their operational lifetimes. Their findings indicate an LCoE of 165 €/MWh for offshore wind energy, 190 €/MWh for tidal energy and 325 €/MWh for wave energy. In addition to these findings, Allan et al. (2011) compared LCoE values for tidal (93 €/MWh) and wave energy (218 €/MWh) in the UK. Concerning LCoE estimations for wave energy, some of these studies suggest that the cost of the WECs falls within the range of 2.5 M€/MW to 6 M€/MW. In the same sense, Lavidas and Blok (2021) indicate that the most probable CapEx requirements for Technology Readiness Level 6–7 devices in high-energy environments range between 2 M€/MW and 3.5 M€/MW for social discount rates to ensure survivability in light of the likely increase in extreme conditions in the future. For the purposes of comparison, the minimum LCoE obtained in this study for a CapEx of 3 M€/MW is 140 €/MWh, significantly lower than the values mentioned above. However, it is important to note that none of these studies considered the future wave resource or the most suitable device for harnessing energy resources in the specific area. Furthermore, the LCoE was calculated in each case considering the cost prevailing at the time of the respective studies.

Electricity prices in Spain are ranked among the top ten in Europe, ranging from 132.6 €/MWh in the first half of 2019 to 206.8 €/MWh in the second half of 2023, with a peak of 296.6 €/MWh in the second half of 2022, excluding taxes and fees (https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204/default/table?lang=en). The results obtained in this study, even when considering not the lowest LCoE achieved (70 €/MWh) but the one derived with a CapEx of 3 M€/MW (140 €/MWh), deemed as the most likely to ensure survivability under the projected increase in extreme wave conditions in this high energetic environments in the future, indicate profitability due the electricity prices in Spain.

It is also pertinent to underscore that estuarine regions, particularly along the western coastline, are characterized by a notably limited energy resource, rendering the prospect of energy production therein economically unviable, particularly in the context of commercial energy generation. Nonetheless, these regions exhibit considerable prominence in the domain of aquaculture activities. Consequently, the incorporation of renewable wave energy into these undertakings represents a propitious and sustainable remedy for energizing diverse facets of aquaculture operations. This is especially salient in the context of energizing aeration systems, facilitating water circulation and feeding mechanisms, providing illumination, and sustaining monitoring and control systems.

A following step forward in this study could be to consider all public support of the country in the analysis of the LCoE behavior. This could include, for example: feed-in tariffs (FIT), FIP, national environmental discounts rates and/or reduction of $CO_2$ emissions taxes (Emissions Trading Scheme, ETS).

In particular Spain, in 1998, took the pioneering initiative to introduce the concept of FIP within the European landscape. This novel endeavor marked a significant development in the realm of Renewable Energy Sources (RES). Under this pioneering scheme, RES operators could opt for a guaranteed FIT, which ensured a predetermined rate for the electricity they generated or to select a guaranteed FIP, which was provided in addition to the prevailing wholesale electricity price. Renewable energy facilities are covered by the special regime only if their installed capacity does not exceed 100 MW (50 MW for hydro facilities). Up to 50 MW, operators can choose between receiving a FIT price, or a FIP on top of the market electricity price. The regulatory framework governing these arrangements was further refined through the enactment of Royal Decree 661/2007. This decree introduced a pivotal element by establishing both maximum and minimum thresholds (referred to as cap and floor, respectively) for the overall remuneration level applicable to each RES technology. Within this defined range, the RES producer would receive the reference FIP. However, should the remuneration level surpass or fall below these established boundaries, the FIP would correspondingly decrease or increase, thereby ensuring that the overall remuneration consistently adhered to the prescribed maximum and minimum limits (iea.org).

The Spanish's Law 7/2021, of May 20th, on climate change and energy transition, established the institutional framework, as well as the regulatory and economic signals that provide stability and set the course towards climate neutrality in Spain. This regulation strongly promotes the development of renewable energies by introducing renewable penetration targets into the legislative framework. It also provides a predictable framework for their deployment through the organization of auctions, in which the bidding variable is the remuneration price for the generated energy.

More recently, the Spanish Council of Ministers by Royal Decree released a Maritime Spatial Planning (MSP) in February 2023 (https://www.miteco.gob.es/es/costas/temas/proteccion-medio-marino/ordenacion-del-espacio-maritimo.html) to establish plans for each of the five Spanish marine subdivisions: North Atlantic, South Atlantic, Gibraltar Strait and Alboran, Levantine- Balearic and Canary Islands. This development signals a well-established and defined legal framework for offshore wind and marine energy in Spain. It is worth emphasizing that the formulation of a MSP represents a pivotal instrument in facilitating the authorization and progression of offshore wind and marine energy projects. Consequently, numerous coastal European countries have established their own MSPs, a practice that has been adopted widely, as reported by WindEurope in 2022.

Regarding ETS, it forms part of a long-term initiative grounded in a capped policy that promotes environmentally friendly solutions by steadily escalating emissions market prices. This is achieved through the annual imposition of emission restrictions, which progressively reduce the permissible emissions. Following Lavidas and Blok (2021), since 2018, there has been a significant uptick in $CO_2$ prices, surging from 5 €/allowance (Tn) $CO_2$ (2013 price) to nearly 25 €/Tn $CO_2$, marking a fivefold increase. Projections anticipate that the threshold of 35 €/Tn $CO_2$ will soon be surpassed, and future values for 2030 are expected to range between 60 and 80 €/Tn $CO_2$.

All these measures, particularly when they are of long lasting nature, will diminish the resulting LCoE and contribute to the realization of the sought-after technological advancements, rendering marine energy financially viable and elevating its share in the energy portfolio. Therefore, from this analysis it is obvious that wave energy is a type of technology that can contribute in the decarbonization of the Spanish energy grid. Future wave resources do not expect too much of a change, and the LCoE from WECs can attain cost competitive levels ($\leq$100 €/MWh), if technologies are matched to the expected region properly.

Conducting this kind of economic analysis of the profitability of wave energy based on long-term projections of future wave resources offers several key advantages in energy policies such as: Informed Decision-Making: providing valuable insights into the potential viability and profitability of wave energy projects, enabling policymakers and investors to make well-informed decision; Risk Mitigation: assessing profitability over an extended period makes easier to identify and mitigate risks associated with wave energy projects, helping to ensure the long-term success and sustainability of the industry; Policy Planning: long-term projections can guide the development of energy policies, helping governments and regulatory bodies set appropriate targets, incentives, and regulations to support the wave energy sector; Investor Confidence: reliable long-term projections enhance investor confidence, making it more likely that private and public funding will be allocated to wave energy projects, thereby fostering industry growth; Resource Optimization: policymakers and project developers can optimize the deployment of wave energy devices and infrastructure with a clear understanding of future wave resources, ensuring the most efficient use of resources; Environmental Impact Assessment: the facilitation of comprehensive assessments of the environmental impact of wave energy projects allows for the implementation of mitigation measures and sustainable practices; Energy Security: wave energy can contribute to a nation's energy security, and long-term projections help assess the potential role of this renewable energy source in reducing dependence on fossil fuels; Technological Advancements: long-term analysis encourages research and development efforts, driving technological advancements that can increase wave energy's profitability and competitiveness over time and, Economic Growth: a thriving wave energy sector can stimulate economic growth by creating jobs and fostering innovation. Long-term projections support the planning of such growth.

Finally, the integration of long-term projections of future wave resources into economic analyses of wave energy profitability offers valuable insights but it also presents certain limitations and prompts consideration of future directions. One limitation is the inherent uncertainty associated with long-term climate and oceanographic modeling, which can affect the accuracy of wave resource projections and subsequently impact economic assessments. Addressing this challenge requires ongoing refinement and validation of modeling techniques, as well as robust sensitivity analyses to assess the impact of uncertainty on profitability estimates. Additionally, economic analyses may overlook non-market factors such as environmental impacts, social acceptance, and policy dynamics, which are essential for comprehensive decision-making. Future directions in this area involve incorporating these non-market factors into economic models, enhancing the integration of multi-disciplinary research approaches, and fostering collaboration between researchers, policymakers, industry stakeholders, and local communities to develop more holistic and nuanced assessments of wave energy profitability. Moreover, ongoing advancements in technology, data collection, and modeling capabilities offer opportunities to enhance the accuracy and applicability of economic analyses, thereby supporting informed decision-making and facilitating the sustainable development of wave energy resources.

## 5. Conclusion

The Galician coast continues to be recognized as an outstanding area for wave energy resources in the near future, despite the projected decrease in wave energy due to climate change impact. Additionally, the presence of diverse energy capture device technologies, often seen as a drawback in commercial implementation, can also be viewed as an asset. Having multiple devices that can operate at any specific site allows us to choose the one that best adapts to the local conditions in terms of efficiency. This aspect is particularly important for the region under study due to the narrow coastal platform and the wide range of depths within a few kilometers from the coast.

In particular, for the Galician coast, Atargis achieved the highest level of profitability in deep water environments, accounting for 64.2% of the domain, while both Wave Dragon and Oyster demonstrate their strengths in near shore (15% of the domain) and shallow water conditions (12.4%), respectively.

The minimum LCoE for the near future wave energy production averaged along the Galician coast, considering the most efficient device at each location, will be 70 €/MWh. This is comparable to other marine renewable energies such as offshore wind (~74 €/MWh). The LCoE value could potentially increase to 140 €/MWh if a CapEx of 3 M€/MW were to be considered. This CapEx value is deemed the most likely to ensure the survivability in the face of projected increases in extreme wave conditions in high-energy environments in the future. However, even under this condition, wave energy production considering the most suitable device at each location along the Galician coast in the near future would still be profitable, especially when taking into account electricity prices in Spain over the last six years, which ranged between approximately 200 €/MWh and 153 €/MWh.

Robust economic analyses informed by long-term wave resource projections play a crucial role in shaping policy, guiding industry investments, and driving continued progress in wave energy research and development. Policymakers rely on such analyses to inform decision-making regarding energy policies, incentives, and regulatory frameworks, ensuring alignment with long-term sustainability goals and economic objectives. For industry stakeholders, including developers and investors, incorporating accurate long-term wave resource projections enhances project planning, risk assessment, and investment decisions, fostering confidence in the viability and profitability of wave energy ventures. Additionally, integrating these projections into economic analyses can drive further research and innovation in wave energy technology, optimization strategies, and resource assessment methodologies, ultimately advancing the development and deployment of reliable and cost-effective wave energy solutions.

## CRediT authorship contribution statement

**M. deCastro:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **G. Lavidas:** Writing – review & editing, Methodology, Formal analysis. **B. Arguilé- Pérez:** Writing – review & editing, Visualization. **P. Carracedo:** Writing – review & editing, Resources, Data curation. **N.G. deCastro:** Writing – review & editing, Visualization, Validation. **X. Costoya:** Writing – review & editing, Formal analysis. **M. Gómez-Gesteira:** Supervision, Software, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data used can be freely downloaded.

## Acknowledgments

The authors would like to acknowledge funding from the Xunta de Galicia under project ED431C 2021/44 (Grupos de Referencia Competitiva) and the Ministry of Science and Innovation of the Government of Spain under the project SURVIWEC PID2020-113245RB-I00. This work was partially supported by Project TED2021-129479A-100 (SAFE project) funded by MCIN/AEI/10.13039/501100011033 and the "European Union NextGenerationEU/PRTR". Moreover, this study forms part of the Marine Science programme (ThinkInAzul) supported by Ministerio de Ciencia e Innovación and Xunta de Galicia with funding from European Union NextGenerationEU (PRTR-C17.I1) and European Maritime and Fisheries Fund. X. Costoya is supported by Grant IJC2020-043745-I/MCIN/AEI/10.13039/501100011033 by MCIN/AEI/10.13039/501100011033 and, by "European Union NextGenerationEU/PRTR" and B. Arguilé-Pérez has been supported by PRE2021-097580 grant funded by MCIN/AEI/10.13039/501100011033 and by "ESF Investing in your future". The present study is also part of the project "WECAnet: A pan-European network for Marine Renewable Energy" (CA17105), which received funding from the HORIZON2020 Framework Programme by COST (European Cooperation in Science and Technology), a funding agency for research and innovation networks.

Funding for open access charge: Universidade de Vigo/CISUG.

During the preparation of this work the authors used ChatGPT-3.5 in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Appendix

Near future multimodel LCoE (€/MWh) for different WECS considering a discount rate of 10% and a CapEx of 1.5 M€.

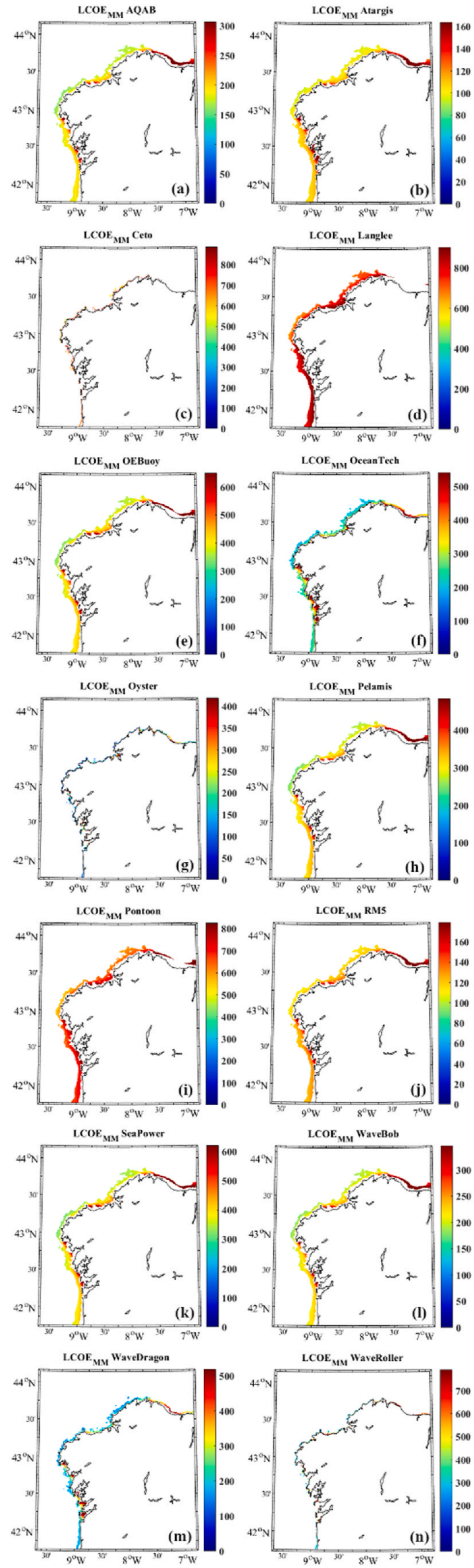

**Fig. A.1.** Near future multimodel LCoE (€/MWh) for different WECS considering a discount rate of 10% and a CapEx of 1.5 M€.
LCoE analysis for a CapEx of 3 M€ and the most profitable WECs (Atargis, Ocean Tech, Oyster, Wave Dragon and Wave Roller Type).

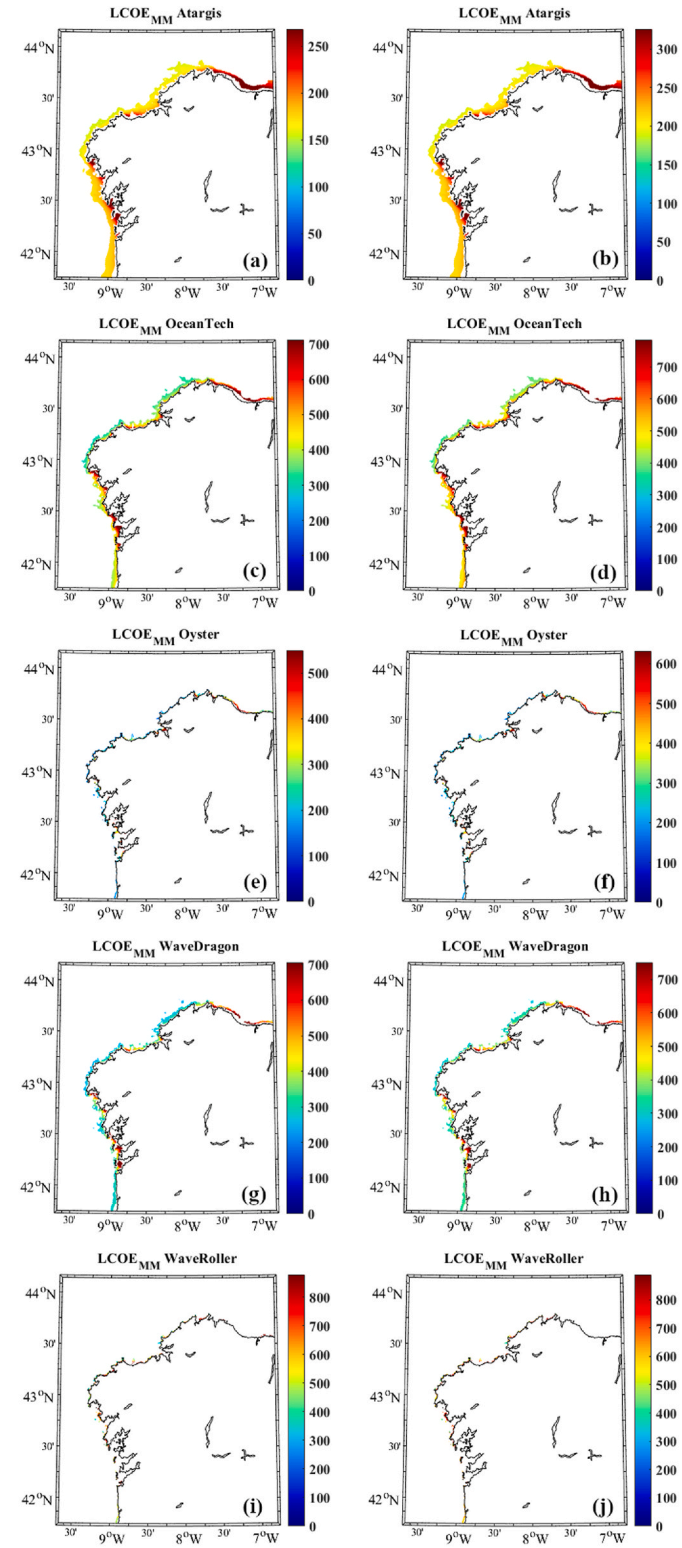


**Fig. A.2.** LCoEs (€/MWh) for the most profitable WECS and a CapEx of 3 M€. Discount rates of 5% (left column) and 10% (right column) were considered LCoE analysis for a CapEx of 5 M€ and the most profitable WECs (Atargis, Ocean Tech, Oyster, Wave Dragon and Wave Roller Type).

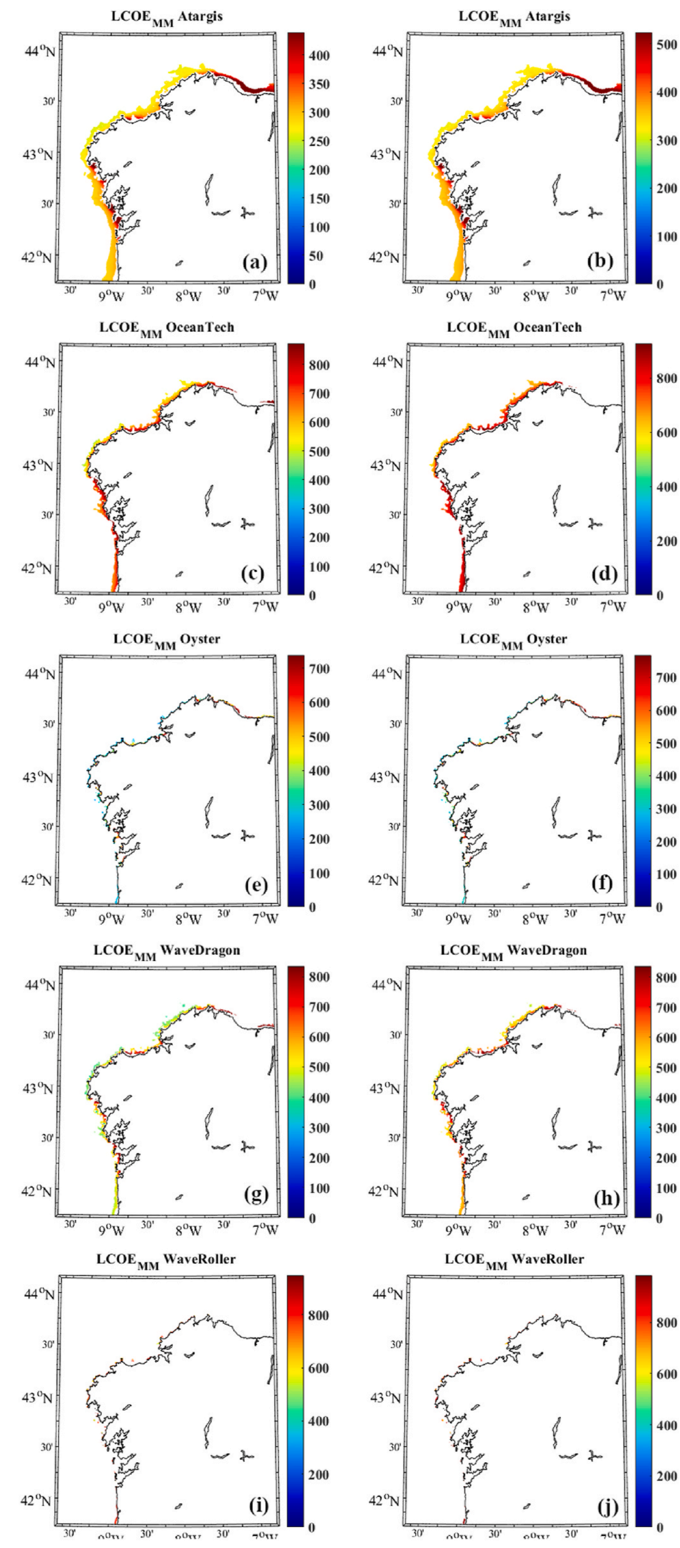


**Fig. A.3.** LCoEs (€/MWh) for the most profitable WECS and a CapEx of 5 M€. Discount rates of 5% (left column) and 10% (right column) were considered.

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