Energy Reports 8 (2022) 6411–6422

Contents lists available at ScienceDirect

Energy Reports

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

Research paper

Inter- and intra-annual variability of wave energy in Northern mainland Portugal: Application to the HiWave-5 project

Kássio Silva [a], Tiago Abreu [a,b,*], Tiago C.A. Oliveira [c]

[a] School of Engineering (ISEP), Polytechnic of Porto, Porto, Portugal
[b] CESAM-Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal
[c] Physics Department & CESAM-Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal

ARTICLE INFO

Article history:
Received 24 January 2022
Received in revised form 21 April 2022
Accepted 3 May 2022
Available online xxxx

Keywords:
CPOWEC
ERA5
HiWave-5
Wave buoys
Wave energy
Wind–wave climate

ABSTRACT

Ocean wave energy capacity has been pointed out as one of the unexplored renewable energy sources to help reach net zero carbon emissions by 2050, contributing to meeting the European Green Deal targets. However, despite the broad range of wave energy converter technologies already developed in a sustainable and economic model, there is still a lack of structured projects with high performance beyond the prototype stage. This paper investigates the potential for large-scale electricity production by the innovative HiWave-5 project in Aguçadoura (on the Northern coast of mainland Portugal). Wind–wave data (1950–2020) from the ERA5 reanalysis model are used to estimate inter- and intra-annual wave energy variability in Aguçadoura. ERA5 data is compared with field wind–wave data recorded between 2012–2019 near the study area. A mean wave power resource of 25.84 kW/m is obtained, for a possible device capture equal to 119.45 kW, despite a considerable intra-annual variability (ranging between 8.03 and 47.57 kW/m) and inter-annual variability (between 18.29 and 35.47 kW/m). Results show that local wave conditions do not substantially compromise the absolute performance of the device, given its survival limitations to adverse conditions. Considering a Levelized Cost of Energy of around €60/MWh, an annual investment of €62 885 is estimated, tending to meet targets for large sustainable electricity generation with the exponential growth expected until 2030, aided by the increase of devices in an energy farm concept. Wave power resources estimated using ERA5 data can underestimate about 7.20% values obtained with the wave buoy data.

1. Introduction

The use of sustainable renewable energy has been increasing in recent years, which is reflected in a projection of its prevalence in the global energy market between 2035 and 2050 (Sandu and Gribincea, 2019). It is expected that ocean energy will make a large contribution with a total installed capacity going from 1 GW in 2013 to 178 GW by 2050, notably thanks to South Korea, China, the United States, Italy, Spain, and Portugal (Jin and Greaves, 2021).

By the end of 2050, it is estimated that 10% of Europe's electricity will be supplied via ocean energy, which would be equivalent to supplying 94 million homes per year, in an annual global market estimated at 53 billion euros. Portugal has been making significant progress in this context, collaborating with the National Energy and Climate Plan 2021–2030, which aims to contain CO_2 emissions (Gomes et al., 2020). This plan envisages meeting the targets of the European Green Deal, which is the most recent set of policy initiatives to make Europe the world's first climate-neutral continent by planning for net-zero carbon emissions by 2050 (Eckert and Kovalevska, 2021; Leonard et al., 2021). In addition, the European Commission is committed to promoting renewable energy solutions and achieving the 2015 Paris Agreement, through the following targets: reduction $\geq$ 55% of greenhouse gas emissions, $\geq$ 32.5% for the share of renewable in the electricity system, and $\geq$ 21.5% of energy efficiency (see *e.g.*, Lavidas and Blok, 2021).

Even at an early stage of development, wave energy has a great potential for the resilience of the energy mix, with the likely highest contribution among different options of renewable energies, offering the possibility of offsetting wind and solar productions (*e.g.*, Kies et al., 2016; Caetano et al., 2020; Jin and Greaves, 2021; Costoya et al., 2022). Portugal has been the implementation site of several projects in this field, starting with the Pico wave power plant in 1992, followed, for example, by Archimedes Waveswing in 2005, Flow and Breakwater in 2005, Pelamis in 2006, Waveroller in 2007, Oscillating Water Column in 2008, WEGA in 2011, CorPower Ocean in 2015 (*e.g.*, Brito-Melo

---

[*] Corresponding author at: School of Engineering (ISEP), Polytechnic of Porto, Porto, Portugal.
E-mail address: taa@isep.ipp.pt (T. Abreu).

https://doi.org/10.1016/j.egyr.2022.05.005

Nomenclature

CDS	Climate Data Store
CO_2	Carbon dioxide
CPOWEC	CorPower Ocean Wave Energy Converter
C_w	Wavefront capture width (m)
ECMWF	European Centre for Medium-range Weather Forecasts
ERA5	Fifth generation ECMWF atmospheric re-analysis of the global climate
g	Gravitational acceleration (9.81 m/s^2)
H_s	Significant wave height (m)
IAV	Inter-Annual Variability
LCOE	Levelized Cost of Energy
MAV	Mean Annual Variability
n	Number of measurements
P	Wave power resource (kW/m)
P_{CPOWEC}	Wave power captured by the CPOWEC prototype (kW)
P_E	Electrical power (kW)
R^2	Determination coefficient
$RMSE$	Root mean square errors
T_e	Wave energy period (s)
T_p	Peak wave period (s)
UTC	Coordinated Universal Time
WEC	Wave Energy Converter
Θ_m	Mean wave direction (°)
α	Wave spectrum
ρ	Sea water density (1025 kg/m^3)
η	Efficiency of the electricity generation (%)
ψ	Bias estimator

et al., 2001; Dalton et al., 2010; Rusu and Guedes Soares, 2013; Castro-Santos et al., 2018).

In a scenario of more than 100 different types of Wave Energy Converter (WEC) prototypes classified according to location, size, and operating system, López et al. (2013) observed that 81.78% of the long-term wave energy projects work with oscillating-body devices (point absorber type). These types of devices can reach an efficiency (η) of about 50% (Falnes, 2002), such as the Wavebob project ($\eta = 51\%$) (Aderinto and Li, 2019), in cases of sea states with peak wave periods close to 12 s in deep waters.

The HiWave-5 project aims to deploy WEC operational devices structured in five stages to reach the pre-commercial phase in 2025 and a future large-scale production based on the wave energy farm concept. Within the HiWave-5 project, the CorPower Ocean Wave Energy Converter (CPOWEC) technology has been working on stage 4 with a single C4 WEC full-scale device, located at Aguçadoura — North of Portugal (41.4306°N, −8.7861°E) in an area of 750 × 500 m^2 at sea depths between 35 and 50 m (CorPower Ocean, 2020). CPOWEC is a relatively small device (9 × 18 m and 60 tons), aiming to produce five times more energy per ton of device than previous technologies (CorPower Ocean, 2020). Furthermore, CPOWEC focused on overcoming usual wave energy project challenges such as complying with environmental and economic issues, operational and maintenance competitiveness, replacing entire units, and the well-known grid connection architecture. The wave motion in CPOWEC is captured by a composite buoy connected to the seabed over a Power Take-Off system and a tensioned mooring line. This prototype uses a WaveSpring phase control and a transparent storm survival mode, which only turns off when the significant wave height exceeds 8 m for peak wave periods above 12 s.

Latitude is known to influence the mean wave power resources. Therefore, high energy values are expected per meter of a wavefront for latitudes between 30° and 60° in both hemispheres (*e.g.*, Angelis-Dimakis et al., 2011). Located at a latitude of 37° to 42°, the Portuguese mainland coast has been considered an energetic wave location based on long-term wave buoy data collected at around 100 m depth (*e.g.*, Oliveira et al., 2018). Placed on the North coast of Portugal, the worldwide relevance of the Aguçadoura region is noteworthy, being a privileged place with long years of experience in receiving related projects, such as Pelamis and Archimedes Waveswing (Mota and Pinto, 2014).

The implementation of any wave energy device requires a prior study of the local environmental conditions. As reported by Mota and Pinto (2014) after studying 7 points off the Portuguese coast, between 1995 and 2010, there is a regional distinction at a depth of 50 m due to the refraction effect on the height and direction of waves as they approach the coast. While the South-western coast of mainland Portugal may have a wave energy potential between 18.81 kW/m and 20.53 kW/m, the North and Center regions present a spatial variation between 24.56 kW/m and 25.91 kW/m. However, considering a recent study by Lavidas and Blok (2021), wave energy development focuses on areas with resources $\geq$ 25 kW/m, with moderate resources often not considered.

For the interpretation of the seasonal variation of the energy potential, the contribution of the inter-annual variability (IAV) and the mean annual variability (MAV) should be emphasized. According to a 30 year data analysis from 1989 to 2018 carried by Rusu and Rusu (2021), who successfully converged ERA5 reanalysis and satellite databases, the South Pacific, Indian Ocean, and Atlantic Ocean regions can achieve the lowest IAV results (below 10%). Concerning the MAV, the greatest annual variations are found in the Northern Hemisphere due to the different wave energies obtained in the summer and winter seasons.

Despite the positive projection for wave energy production in the Portuguese coast, it is worth paying attention to the influence of maritime storms, occurring between December and March (Oliveira et al., 2018), and those of a post-tropical nature that reach the coast between September and October (Oliveira et al., 2020). These storms result in an extremely energetic events, tending to generate instability and damage to the installed devices. For recent examples, recall the severe winter of 2013–2014 (Rusu et al., 2015), the storms Emma and Felix in 2018 and Fabien in 2019 (Mendes and Oliveira, 2021), or the post-tropical storms Ophelia in 2017, Leslie in 2018, and Lorenzo in 2019 (Oliveira et al., 2020).

Several studies estimated the wave energy distribution in different parts of the world based on numerical models, buoy data, and reanalysis. Table 1 lists some study cases, highlighting that the covered periods vary from 5–6 years (López et al., 2015; Guimarães et al., 2019) to a few decades in general (*e.g.*, Rusu and Onea, 2015; Guillou and Chapalain, 2020). As exception is made by Sierra et al. (2013), who assessed the wave energy resources in Lanzarote (Spain) for 5 decades.

This paper aims to assess the wave resource potential for large-scale electricity production by the innovative HiWave-5 project in the coastal location of Aguçadoura based on seven decades of wave data, also exploring the inter- and intra-annual variability of the wave energy resources. In view of the foregoing, it is crucial to understand the wave resource availability at Aguçadoura for a future contribution to Portugal's general renewable energy market using a mix of different sources. More specifically, it is essential to know when the energy market can rely on wave energy by characterizing its inter- and intra-annual

Table 1
Overview of relevant case studies for wave energy potential.

Case study	Covered period	Reference
Japan	1994–2014 (21 years)	Sasmal et al. (2021)
The North-West Atlantic The Gulf of Mexico The Caribbean Sea	1979–2009 (31 years)	Guillou and Chapalain (2020)
Australia	1980–2017 (38 years)	Cuttler et al. (2020)
Brazil	1979–1983 (5 years)	Guimarães et al. (2019)
Peru	2007– 2012 (6 years)	López et al. (2015)
European seas (Mediterranean Sea, Black Sea and Baltic Sea)	1989–2018 (30 years)	Rusu (2021)
European continental coast	2003–2013 (11 years)	Rusu and Onea (2015)
Lanzarote (Spain)	1958– 2008 (51 years)	Sierra et al. (2013)
Portugal	1979–2012 (34 years)	Silva et al. (2018)

variability. In fact, a sound energy consumption system can be well managed only if the variability of each source of renewable energy is well known. In particular, the following questions are addressed in this paper: (i) what is the inter- and intra-annual variability of the wave energy resources in the Aguçadoura site? (ii) how do wave power estimates based on long-term wind–wave reanalysis model data represent local conditions? (iii) from a commercial perspective, how much would be the annual HiWave-5 project investment, considering a Levelized Cost of Energy?

Wind–wave reanalysis data from the ERA5 model (Hersbach et al., 2018) between 1950 to 2020 are utilized to analyze the inter- and intra-annual variability of the wave energy resources. Model data are compared with field wind–wave data recorded between 2012–2019 near the study area.

This paper is composed of 4 sections. After this introductory section, the methodology is presented in Section 2. Results are presented and discussed in Section 3. Finally, Section 4 summarizes the main findings.

2. Material and methods

Considering the performance of the HiWave-5 project prototypes, aiming at a large-scale deployment, a wave data analysis needs to be taken for the study location. Essentially, the characterization of different sea states can be made through three key wave parameters: the mean wave direction (Θ_m), the significant wave height (H_s) and the peak wave period (T_p). This section presents the collated buoy and ERA5 reanalysis data and how this information is used to estimate the wave power and the Levelized Cost of Energy (LCOE).

2.1. Buoy data

The acquisition of field data through buoys is still of interest for wave climate monitoring. This monitoring is fundamental for the implementation of forecasting models and their validation, for the characterization of extreme conditions and for a more accurate determination of design waves. Here, ERA5 reanalysis data from 2012 to 2019 is compared with Leixões buoy data (tri-hourly records). This wave buoy is located at an offshore distance of 1.6 km from Leixões (northwest coast of mainland Portugal) at coordinates 41.15°N–9.58°W (see Fig. 1 and Table 2). The data is freely available based on the European Union effort to provide access to the observations made by individual organizations in all Member States, mainly through the European Marine Observation and Data Network (EMODnet, www.emodnet.eu) Data were collected by a multi-parametric SEAWATCH Wavescan buoy between 10/01/2012 and 28/12/2019. The Portuguese Hydrographic Institute (IH, www.hidrografico.pt) secures the deployment and maintenance of this wave buoy, which for the analyzed period presented 34% of unregistered data (Mendes and Oliveira, 2021) The unregistered records could be mostly due to the very rough wave conditions during major storms, ship collisions or buoy maintenance periods (Mendes and Oliveira, 2021). Wave parameters are calculated using the spectral method. A 25 min long record of sea-surface elevation with a sampling frequency of 1 Hz is processed internally by the wave buoy. This procedure is repeated every hour, and wave parameters are subsequently sent to the IH office, where data is checked and stored.

Table 2
Definition of study points.

Reference	Latitude/longitude	Analyzed period
Buoy (Leixões offshore)	41.15°N/−9.58°W	10/01/2012–28/12/2019
ERA5 (Leixões offshore)	41.00°N/−9.50°W	10/01/2012–28/12/2019
ERA5 (Aguçadoura)	41.50°N/−9.00°W	01/01/1950–31/12/2020

2.2. ERA5 wind–wave data

ERA5 reanalysis data provided by the European Centre for Medium-range Weather Forecasts (ECMWF) over 71 years (1950 to 2020) is considered in this study. Using an atmospheric resolution of 0.25° × 0.25° and ocean waves of 0.5° × 0.5°, by a temporal coverage via Climate Data Store – CDS of the Copernicus program, this work was carried out with data on single levels (ERA5 Hourly Data on Single Levels), every 3 h from Coordinated Universal Time - UTC (00 UTC, 03 UTC, 06 UTC, …), for every day and month of the studied years. The considered historical data is subdivided into two well-defined datasets:

- 1950–1978: preliminary extension, satisfactory, although all results are considered experimental (Bell et al., 2020);
- 1979–present: updated version (Hersbach et al., 2018).

For the detailed characterization of the area foreseen for energy use in Portugal, considering both latitude and longitude positions, two different ERA5 points listed in Table 2 were chosen. The ERA5 (Leixões offshore) data was selected as the closest point on an 0.5° × 0.5° grid to Leixões wave buoy, making it possible to establish a comparison of the modeled data with real data. The second location, ERA5 (Aguçadoura) was considered by the representativeness of the North region, close to Aguçadoura, being the demonstration site of the HiWave-5 project. The locations of these study points are identified in Fig. 1.

Additionally, the validation of the wave buoy parameters of both buoy and ERA5 data is assessed by computing the respective determination coefficients, R^2, the root mean square errors, *RMSE*, and the percentages of systematic deviation between expected values and the true values, through the bias estimation, ψ, obtained by:

$$R^2 = \left(\frac{\sum_{i=1}^{n} (y_i - \bar{y}) - (x_i - \bar{x})}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2} \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}} \right)^2 \tag{1}$$

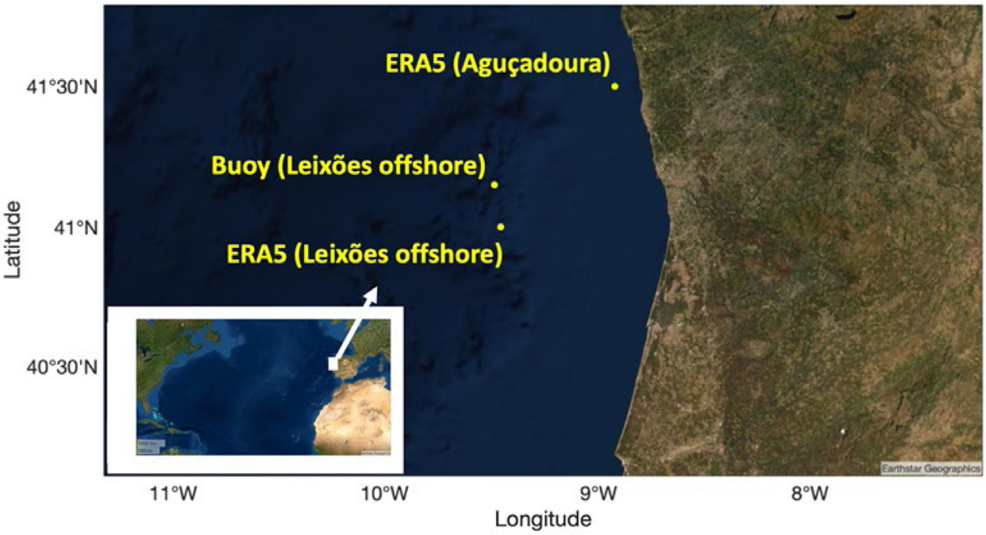


Fig. 1. Location of points analyzed in the study.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{2}$$

$$\psi = 100\frac{\sum_{i=1}^{n}(\frac{x_i}{y_i} - 1)}{n} \tag{3}$$

$$|\psi| = 100\frac{\sum_{i=1}^{n}\left|\frac{x_i}{y_i} - 1\right|}{n}, \tag{4}$$

where x and y denote the observed and modeled values of the studied parameter, respectively. The overbar denotes mean, and n denotes the number of data pairs.

2.3. Wave power estimation

Wave generation results from the action of the wind blowing across the surface of the oceans water and wave energy results from the transfer of a portion of the winds kinetic energy to the water below. The wave power resource in deep waters can be obtained through Eq. (5):

$$P = \frac{\rho g^2}{64\pi}H_s^2 T_e \simeq 0.491 H_s^2 T_e, \tag{5}$$

where the wave power resource (P) is measured in kW/m, the sea water density considers $\rho = 1025$ kg/m^3 and the gravitational acceleration $g = 9.81$ m/s^2. Although the energy period (T_e) can be modeled (*e.g.*, Sasmal et al., 2021), in most cases it is hardly accurately indicated and its uncertainties can be considered based on the shape of the wave spectrum (α) of parametric spectrum models (*e.g.*, Pierson–Moskowitz and JONSWAP spectrum) (Ribeiro et al., 2020; Ahn, 2021). Here, T_e is computed based on α and T_p as shown in Eq. (6) (*e.g.*, Sierra et al., 2013).

$$T_e = \alpha T_P \tag{6}$$

The parameter α can vary from 0.86 (considering the adoption of a Pierson–Moskowitz spectrum) and increase towards unity with decreasing spectral width (Cornett, 2008; Pastor and Liu, 2016; Ahn and Neary, 2020). This work adopts a conservative value of α equal to 0.86.

When analyzing the best WEC in terms of efficiency for a specific location, the study of the capture width (C_w) is extremely important. In practical terms, C_w represents the ratio between the device electrical power (P_E) and P (*e.g.*, Ribeiro et al., 2020). The confirmation of a clear relationship between the real results of electrical production through waves, within the scale of months and years, as well as the wave power captured by the CPOWEC prototype (P_{CPOWEC}), took into account the survival mode limitations ($H_s = 8$ m when $T_p > 12$ s), the wavefront capture width ($C_w = 9$ m) and an estimated yield, η, of 51.5% (CorPower Ocean, 2020). This value of η is slightly higher than the maximum of 51% found in the literature for the Wavebob Point Absorber project (Aderinto and Li, 2019). Then, P_{CPOWEC} can be obtained by (*e.g.*, Aderinto and Li, 2019):

$$P_{CPOWEC} = 0.491 H_s^2 T_e \eta C_w, \tag{7}$$

considering $\eta = 0.515$. From a commercial point of view, considering all days and hours in the database, Eq. (8) shows the sum of monthly production (converted into MWh). Therefore, based on a LCOE of around €60/MWh (CorPower Ocean, 2020), Eq. (9) represents the total annual amount to be invested, in EURO.

$$P\ monthly\ amount\ [\mathrm{MWh}] = P_{CPOWEC}(24\ hours)(number\ of\ days) \times \frac{1\ \mathrm{MW}}{1000\ \mathrm{kW}} \tag{8}$$

$$Total\ annual\ investment = 60\sum_{jan}^{dec} P\ monthly\ amount\ [\mathrm{MWh}] \tag{9}$$

Fig. 2 presents a general flowchart of material and methods section, showing the adopted methodology where the wave parameters are collated from buoy and ERA5 reanalysis data and how this information is used to estimate the wave power and the respective CPOWEC annual investment.

3. Results and discussion

This section compares the wave climate analyzing Leixões offshore buoy data (tri-hourly records) and ERA5 reanalysis data acquired near that location, considering the most relevant wave spectral parameters, namely, H_s, T_p, and Θ_m. From this information, the characterization of the LCOE and of the wave energy at Aguçadoura in terms of its inter- and intra-annual variability are made and the results are discussed.

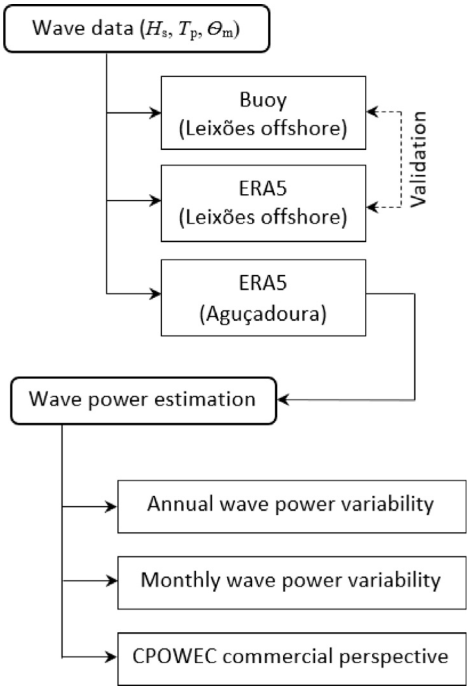


Fig. 2. General flowchart of material and methods.

3.1. Buoy versus ERA5 (Leixões offshore)

The simultaneous comparison of the data available by the buoy limits the coverage period to 8 years (2012 to 2019). However, as mentioned before, it is usual the occurrence of buoy data gaps, some of them caused by the need of station maintenance, and others, by occasional malfunctions. Often, these gaps occur in extreme conditions in winter months and, in particular, during storms. For example, in the year 2013, known for its severe storm conditions (*e.g.*, Mendes and Oliveira, 2021), there are only data records for six months (between March and August). In the other years, even though there may be measurements in all months, there are always data gaps on certain days/hours. During the 8 years analysis, there are 53 074 measurements, n, corresponding to about 24.3% of hourly data gaps. Nevertheless, it is considered that the existing data set allows estimating the robustness of the model to represent a wide range of normal and storm ($H_s > 4.5$ m) wave conditions at Leixões offshore buoy location.

Fig. 3 compares the values of H_s, T_p, Θ_m and P (obtained by Eq. (5)) for the Leixões buoy data and the ERA5 reanalysis data. The color gradation of the scatter plots and respective color bar, ranging from red to blue, reflects a higher and lower point density and represents the number of points in the same bin, being directly associated to histograms that compare occurrence frequencies.

In general, the measured and estimated data follow similar trends for the various parameters.

The comparison of the data for H_s (Fig. 3a) reveals a high value of the determination coefficient ($R^2 \approx 0.95$). This illustrates a very good fit with the observed data. The presented density is associated with the histogram of H_s. The wave regime is essentially characterized by H_s between [1, 2] m, with relative frequencies close to 40% and between [2, 3] m, with relative frequencies of 30%. This regime is characterized by a Rayleigh distribution, as lower H_s show a higher frequency compared to greater H_s. The *RMSE* ($\approx$ 0.32 m) and bias ($\psi \approx -0.78\%$, $|\psi| \approx 9.8\%$) values are low, corroborating the good fit of the estimates. Nevertheless, the ERA5 reanalysis data slightly underestimate the highest values of H_s as evidenced by the linear regression line.

A larger dispersion of the points is observed for T_p (Fig. 3b). This is reflected in a reduction of the determination coefficient value to $R^2 \approx 0.73$, still confirming a good fit of the estimates. The largest percentage of the measurements is in the interval [10, 12] s with relative frequencies of 27%, being followed by the intervals [8, 19] s and [12, 14] s with relative frequencies of about 22%. The values of *RMSE* ($\approx$ 1.5 s) and bias ($\psi \approx 3.4\%$, $|\psi| \approx 9.7\%$) are low, corroborating a good agreement.

Regarding the mean wave direction, Θ_m (Fig. 3c), it is observed, as for T_p, a good determination coefficient value ($R^2 = 0.72$). There is a predominance of wave directions between [315, 360]°, with about 30% of occurrences, followed by the range [292.5, 315]° with about 15%. The good fit of the estimated data is also reflected in both *RMSE* ($\approx$17.5°) and bias ($\psi \approx 0.1\%$, $|\psi| \approx 4.3\%$) values.

The comparison of the wave power resource, P (Fig. 3d), shows a high determination coefficient value ($R^2 \approx 0.91$) and low values of *RMSE* ($\approx$ 19.4 kW/m) and bias ($\psi \approx 4.1\%$, $|\psi| \approx 24.7\%$) due to the high correlation observed for H_s. Although larger P values reach up to 800 kW/m, 80% of both data values stay below 50 kW/m and about 13% in the range [50, 100] kW/m. The dependence of P on H_s also replicates the tendency of the regression line where ERA5 reanalysis data slightly underestimates larger P buoy values. The average power at the buoy is 34.7 kW/m, while the modeled data is 30.3 kW/m, corresponding to a difference of less than 12%. According to the available data, it is also possible to establish a monthly comparison of the mean P values. Fig. 4 shows that the data follow the same seasonal trend. Except for October, where the values are practically identical, a slightly greater energy return is observed every month for Leixões offshore buoy. On average, wave power resources estimated using ERA5 data can underestimate about 7.20% the values obtained with the wave buoy data. At the seasonal level, the energetic winter months between December and March present a difference of 10.24% while for the rest of the months the difference reduces to 5.67%.

Fig. 5 presents scatter diagrams, emphasizing the influence of the various sea states that contribute to the offshore total annual energy for both buoy (Fig. 5a) and ERA5 data (Fig. 5b). Additionally, Fig. 5c presents the scatter diagram at the point absorber location (Aguçadoura) using ERA5's data for the same period, displaying the overall performance. A general offshore good agreement is observed with the highest-energy percentages corresponding to T_p between 11 and 15 s and H_s between 2 and 5 m, which are associated with swells generated in the North Atlantic Ocean. Considering the storm survival mode of the HiWave-5 project prototype that turns off when H_s exceeds 8 m for a T_p above 12 s, it is possible to perceive that these energetic occurrences are residual. This is also confirmed at Aguçadoura location (Fig. 5c), denoting highest energy contributions for $T_p \approx 12$ s and $H_s \approx 2.5$ m.

3.2. Wave power characterization at Aguçadoura

The comparative study between the two databases supports the assumption that the modeled data are suitable for assessing the wave energy in this area. As a result of this reliability, a seasonal and long-term study using the complete ERA5 reanalysis data between the years 1950 and 2020 is carried out for the Aguçadoura study site to obtain, respectively, the intra- and inter-annual variabilities.

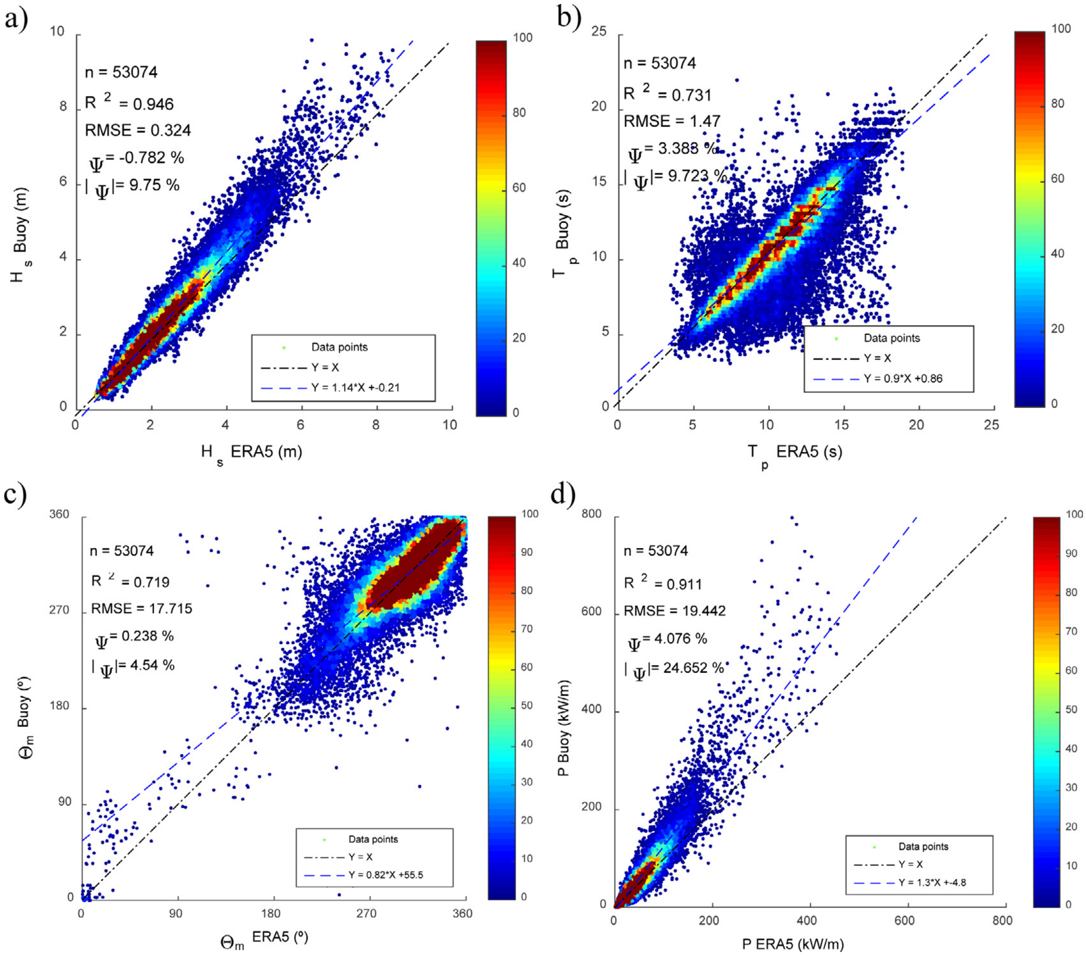


Fig. 3. Comparison between buoy and ERA5 (Leixões offshore) data for (a) H_s, (b) T_p, (c) Θ_m and (d) P. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

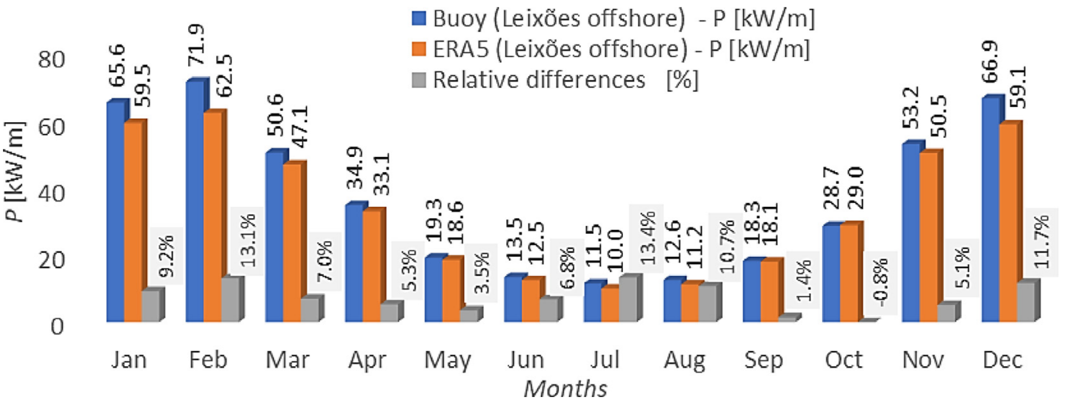
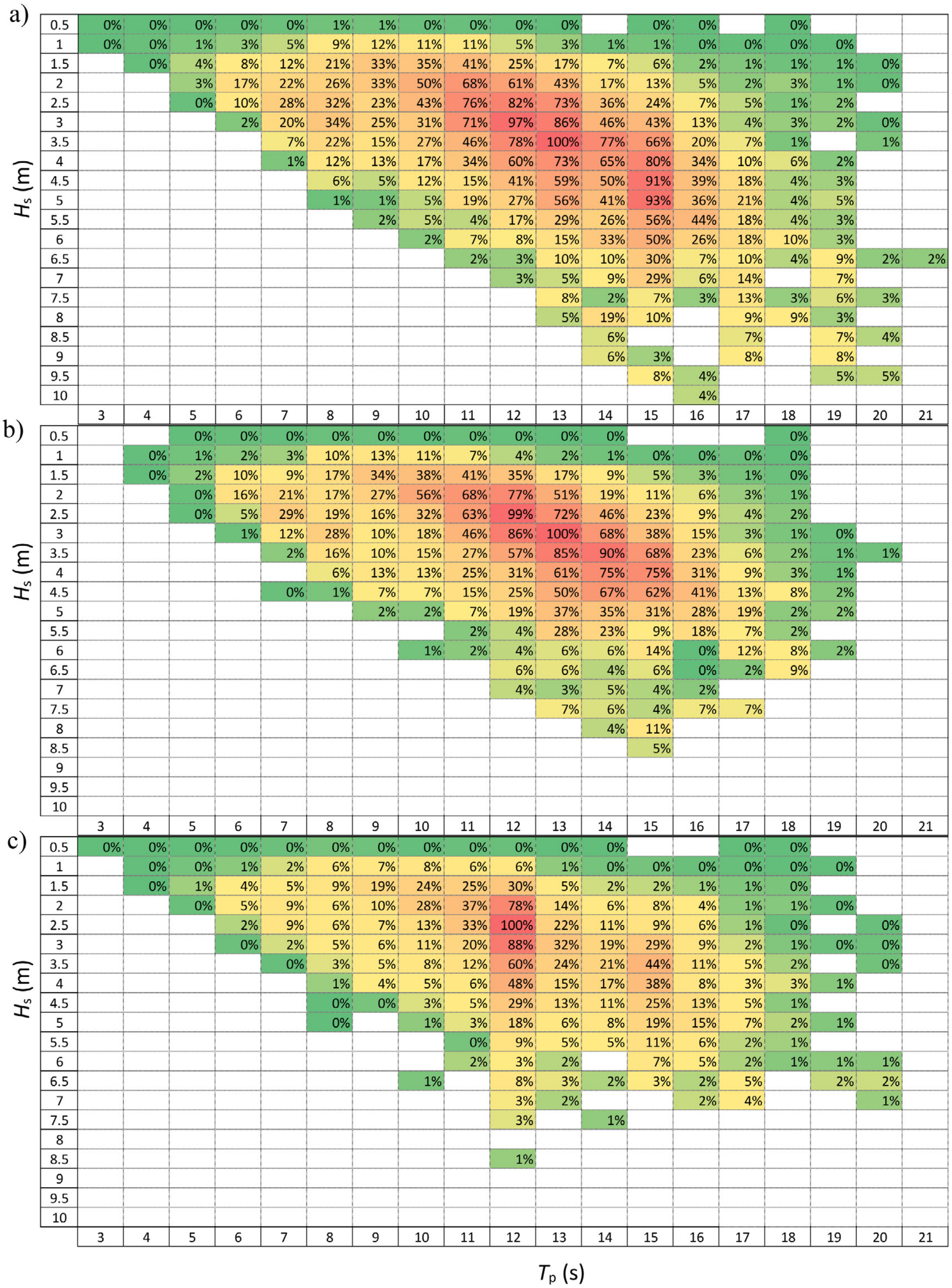


Fig. 4. Monthly comparison of wave power estimated by Buoy and ERA5 at Leixões offshore and respective relative monthly differences (%)

3.2.1. Annual wave power variability

Initially, the wave direction was studied in the Aguçadoura region. The mean value of Θ_m was equal to 300.88°N, with an average standard deviation of 36.82°. This value is important for confirming the origin of the natural resource. However, it is noted that this factor is of relative relevance, as CPOWEC is of the point absorber type, which manages to extract energy from all directions.

Fig. 6a illustrates a comparison between the annual average variation of both H_s and T_p over the studied years. Table 3 also lists these wave parameters, including minimum, maximum, mean and standard deviation values per decade, helping to interpret Fig. 6. Special concern is also given regarding the limitation and disconnection of the device in adverse situations (T_p > 12 s and H_s > 8 m) by including the limits of CPOWEC (referred to as «CPOWEC limited H_s»), but it can be seen these constraints are practically non-existent. During the 71 year period, the restriction of energy production would be for very short periods of time, in particular, three days in 1959 (30/11, 01/12 and 07/12), one day in 1973 (17/01), one day in 1978 (11/12), two days in 1979 (13 and 14/02), two days in 1986 (16 and 17/02), one day in 2001 (28/01), one day in 2011 (17/02) and one day in 2013 (19/01).



a)

H_s (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0.5	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%		0%	0%		0%			
1	0%	0%	1%	3%	5%	9%	12%	11%	11%	5%	3%	1%	1%	0%	0%	0%	0%		
1.5		0%	4%	8%	12%	21%	33%	35%	41%	25%	17%	7%	6%	2%	1%	1%	1%	0%	
2			3%	17%	22%	26%	33%	50%	68%	61%	43%	17%	13%	5%	2%	3%	1%	0%	
2.5			0%	10%	28%	32%	23%	43%	76%	82%	73%	36%	24%	7%	5%	1%	2%		
3				2%	20%	34%	25%	31%	71%	97%	86%	46%	43%	13%	4%	3%	2%	0%	
3.5					7%	22%	15%	27%	46%	78%	100%	77%	66%	20%	7%	1%		1%	
4					1%	12%	13%	17%	34%	60%	73%	65%	80%	34%	10%	6%	2%		
4.5						6%	5%	12%	15%	41%	59%	50%	91%	39%	18%	4%	3%		
5						1%	1%	5%	19%	27%	56%	41%	93%	36%	21%	4%	5%		
5.5							2%	5%	4%	17%	29%	26%	56%	44%	18%	4%	3%		
6								2%	7%	8%	15%	33%	50%	26%	18%	10%	3%		
6.5									2%	3%	10%	10%	30%	7%	10%	4%	9%	2%	2%
7										3%	5%	9%	29%	6%	14%		7%		
7.5											8%	2%	7%	3%	13%	3%	6%	3%	
8											5%	19%	10%		9%	9%	3%		
8.5												6%			7%		7%	4%	
9												6%	3%		8%		8%		
9.5													8%	4%			5%	5%	
10														4%					

b)

H_s (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0.5			0%	0%	0%	0%	0%	0%	0%	0%	0%	0%				0%			
1		0%	1%	2%	3%	10%	13%	11%	7%	4%	2%	1%	0%	0%	0%	0%			
1.5		0%	2%	10%	9%	17%	34%	38%	41%	35%	17%	9%	5%	3%	1%	0%			
2			0%	16%	21%	17%	27%	56%	68%	77%	51%	19%	11%	6%	3%	1%			
2.5			0%	5%	29%	19%	16%	32%	63%	99%	72%	46%	23%	9%	4%	2%			
3				1%	12%	28%	10%	18%	46%	86%	100%	68%	38%	15%	3%	1%	0%		
3.5					2%	16%	10%	15%	27%	57%	85%	90%	68%	23%	6%	2%	1%	1%	
4						6%	13%	13%	25%	31%	61%	75%	75%	31%	9%	3%	1%		
4.5					0%	1%	7%	7%	15%	25%	50%	67%	62%	41%	13%	8%	2%		
5							2%	2%	7%	19%	37%	35%	31%	28%	19%	2%	2%		
5.5									2%	4%	28%	23%	9%	18%	7%	2%			
6								1%	2%	4%	6%	6%	14%	0%	12%	8%	2%		
6.5										6%	6%	4%	6%	0%	2%	9%			
7										4%	3%	5%	4%	2%					
7.5											7%	6%	4%	7%	7%				
8												4%	11%						
8.5													5%						
9																			
9.5																			
10																			

c)

H_s (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%			0%	0%			
1		0%	0%	1%	2%	6%	7%	8%	6%	6%	1%	0%	0%	0%	0%	0%	0%		
1.5		0%	1%	4%	5%	9%	19%	24%	25%	30%	5%	2%	2%	1%	1%	0%			
2			0%	5%	9%	6%	10%	28%	37%	78%	14%	6%	8%	4%	1%	1%	0%		
2.5				2%	9%	6%	7%	13%	33%	100%	22%	11%	9%	6%	1%	0%		0%	
3				0%	2%	5%	6%	11%	20%	88%	32%	19%	29%	9%	2%	1%	0%	0%	
3.5					0%	3%	5%	8%	12%	60%	24%	21%	44%	11%	5%	2%		0%	
4						1%	4%	5%	6%	48%	15%	17%	38%	8%	3%	3%	1%		
4.5						0%	0%	3%	5%	29%	13%	11%	25%	13%	5%	1%			
5						0%		1%	3%	18%	6%	8%	19%	15%	7%	2%	1%		
5.5									0%	9%	5%	5%	11%	6%	2%	1%			
6									2%	3%	2%		7%	5%	2%	1%	1%	1%	
6.5								1%		8%	3%	2%	3%	2%	5%		2%	2%	
7										3%	2%			2%	4%			1%	
7.5										3%		1%							
8																			
8.5										1%									
9																			
9.5																			
10																			

Fig. 5. Scatter diagrams showing the contribution percentage of the total annual energy for various sea states of (a) Leixões Buoy, (b) ERA5 data (offshore) and (c) ERA5 data (Aguçadoura).

It was noted that the maximum value of H_s reached was 9.85 m, which corresponded to a value of $T_p = 16.41$ s, for the year 1986. For this reason, the mean and standard deviation values in Table 3 that consider the limits of CPOWEC are practically identical to the observed wind–wave climate values.

It is possible to observe that between 1950 and 2020 the mean annual H_s values in Fig. 6a ranged between 1.77 m (1973) and 2.29 m (2002), and T_p between 10.22 s (1973) and 11.38 s (2018). Based on Fig. 6b, P ranged between 18.29 kW/m (1953) and 35.47 kW/m (2014), which is also directly reflected in P_{CPOWEC} values varying between 84.8 kW and 164.4 kW. This 70-year data analysis leads to an IAV of 14%, which is slightly higher when compared to the Atlantic Ocean values obtained by Rusu and Rusu (2021) in the 30-year data analysis (below 10%).

On average, in Northern Portugal between 1950 to 2020, ERA5 data leads to $P = 25.84$ kW/m. This result corroborates the value proposed by Lavidas and Blok (2021), for a solid resource development ($\geq$ 25 kW/m) and the values presented by Mota and

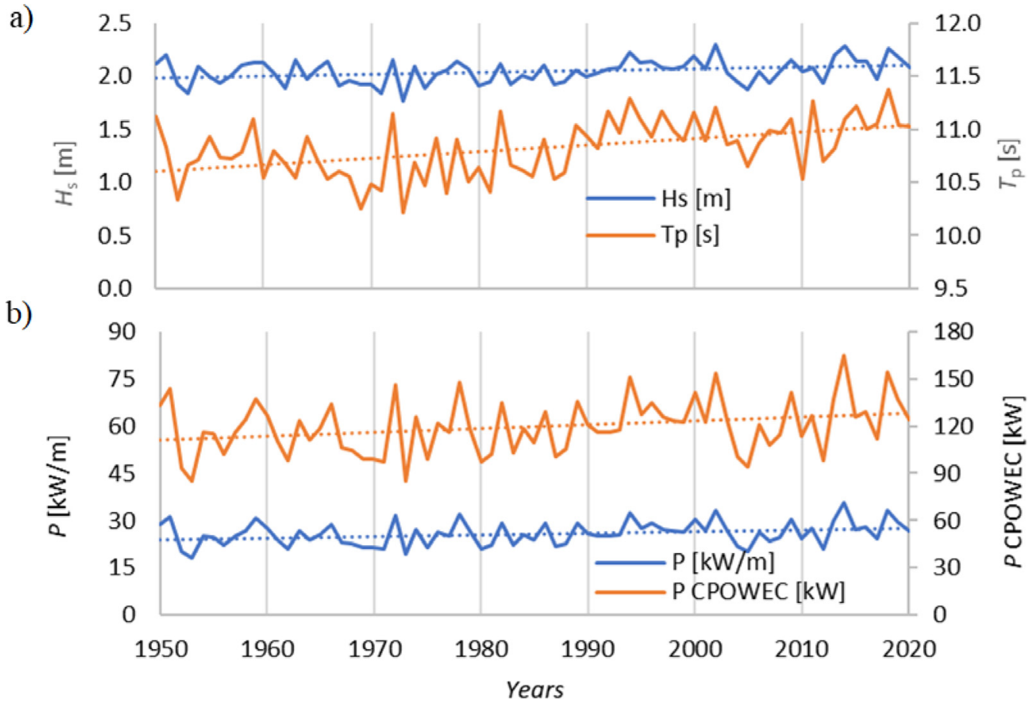


Fig. 6. Annual means (solid lines) and respective linear trends (dotted lines) from 1950 to 2020 at Aguçadoura of (a) H_s and T_p, (b) P and P_{CPOWEC}.

Table 3
Approximate values for H_s, CPOWEC limited H_s and T_p at Aguçadoura.

Years	Variables	Min. value	Max. value	Mean	Standard deviation
1950–2020	H_s [m]	0.37	9.85	2.04	0.98
	CPOWEC limited H_s [m]	0.00	8.00	2.04	0.97
	T_p [s]	2.70	23.92	10.74	2.42
1950–1959	H_s [m]	0.37	8.89	2.04	0.95
	CPOWEC limited H_s [m]	0.00	8.00	2.03	0.95
	T_p [s]	3.46	23.92	10.70	2.47
1960–1969	H_s [m]	0.39	7.72	2.02	0.95
	CPOWEC limited H_s [m]	0.39	7.72	2.02	0.95
	T_p [s]	3.49	20.39	10.55	2.41
1970–1979	H_s [m]	0.40	9.27	1.99	1.02
	CPOWEC limited H_s [m]	0.00	7.86	1.99	1.01
	T_p [s]	2.97	19.73	10.56	2.44
1980–1989	H_s [m]	0.38	9.85	1.99	0.97
	CPOWEC limited H_s [m]	0.00	7.94	1.99	0.97
	T_p [s]	3.02	20.64	10.63	2.42
1990–1999	H_s [m]	0.39	7.88	1.99	0.96
	CPOWEC limited H_s [m]	0.39	7.88	1.99	0.96
	T_p [s]	3.54	20.89	10.63	2.41
2000–2009	H_s [m]	0.41	8.28	2.06	0.97
	CPOWEC limited H_s [m]	0.00	7.84	2.06	0.97
	T_p [s]	3.04	20.15	10.88	2.38
2010–2019	H_s [m]	0.37	8.40	2.12	1.00
	CPOWEC limited H_s [m]	0.00	8,00	2.12	1.00
	T_p [s]	2.70	20.03	10.92	2.41

Pinto (2014), regarding the study of 7 points off the coast of Portugal, between 1995 and 2010, at a depth of 50 m. These authors presented values for the North and Center regions (ranging from 24.56 kW/m to 25.91 kW/m), which shows the value found for Aguçadoura region is in accordance with the data extracted from the ERA5 model. Therefore, the historic variation shown in Fig. 6b results in an average value of $P_{CPOWEC} = 119.45$ kW for the wave power extracted from the CorPower Ocean device.

Fig. 6a reveals that the mean H_s values over the 7 decades remain fairly constant. However, a recent slight increase in T_p values is perceptible, as can be seen from the respective trend line. Without intending to explore the reasons that are associated with this possible change (*e.g.*, climate change), it is pertinent to study the values dividing them by decades as represented in Fig. 6b. On average, an increase in T_p values led to a power increase in the last three decades and, particularly, the last 10 years present the highest energy return, with an average of $P_{CPOWEC} = 129.64$ kW. Despite this tendency, it is noticed the resulting wave power estimates are proportional to T_p and to the square of the H_s. Therefore, variations in the period are less significant than variations in wave height for wave power computations (*e.g.*, Cornett, 2008).

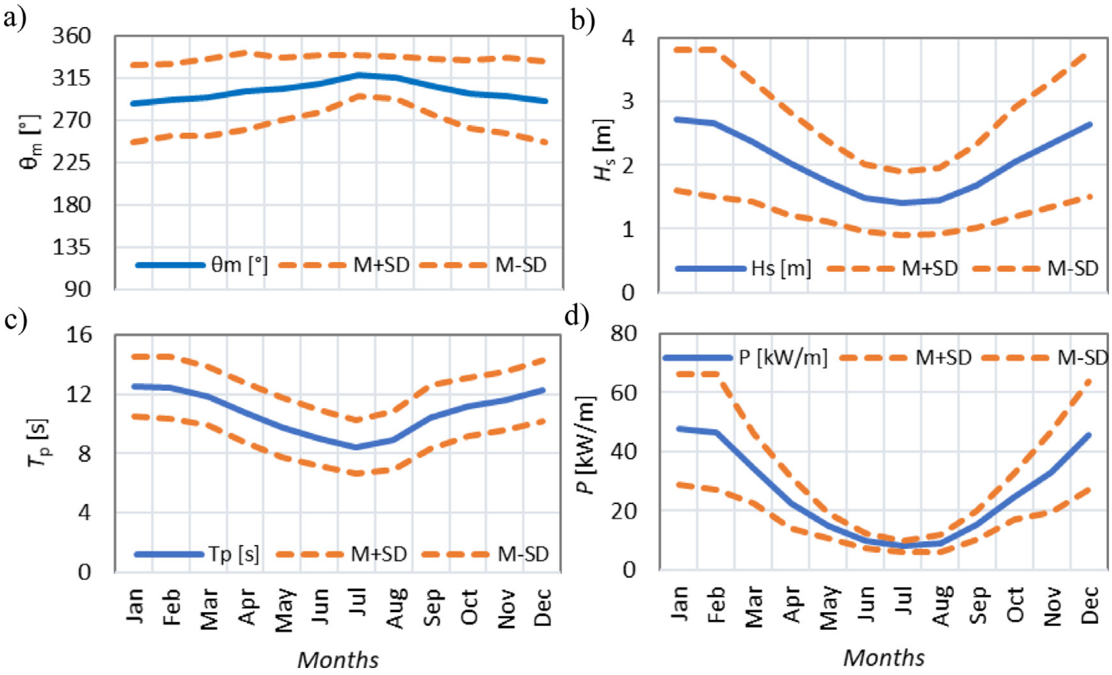


Fig. 7. Monthly variation of (a) Θ_m, (b) H_s, (c) T_p and (d) P at Aguçadoura. Solid lines represent average values. Dashed lines add and subtract the standard deviation.

3.2.2. Monthly wave power variability

To explore the seasonal variability a study per month was also carried out for Θ_m, H_s, T_p and P concerning ERA5's data (see Fig. 7). It is observed that there is a small seasonal variability in the recorded data of Θ_m compared to the other parameters. Fig. 7a shows that in the months of July and August, in high summer, the wave direction presents values fairly constant between 317.83°N and 315.21°N, respectively. Calculations of the standard deviation allow the conclusion that, in the seven decades of data, it is also in the summer that there is a smaller standard deviation of Θ_m. The other months present higher variations of Θ_m and, in average the values decrease to about 291°N between December and March. The history of atmospheric oscillations in Portugal is confirmed, due to more frequent depressions during the winter (December to March), which lead to reporting averages of H_s and T_p with variations that are also distinct from the summer values (also in line with what is pointed by Rusu and Rusu, 2021 concerning the MAV for the Northern Hemisphere).

Figs. 7b and 7c reflect the seasonal behavior of these variables, presenting the average values and the corresponding fluctuations regarding the standard deviation around the average. It is well known that the Northern Hemisphere presents between December and March greater wave energy associated with greater values of both H_s and T_p variables. Fig. 7d shows the corresponding wave power resource at Aguçadoura. January is the month with the highest power return, with an average of $P = 47.57$ kW/m. It is also verified that this value is practically six times lower in the month of July (8.03 kW/m), which highlights a large monthly variability of P throughout the year.

In view of a future risk analysis concerning the consideration of a monthly inter-annual variability of P, a filtering of the 71 year data for some maritime winter months (December to March) is shown in Fig. 8. Except for March (Fig. 8d), where the range between maximum and minimum values over the years can vary less than 50 kW/m (*e.g.*, max = 62.14 kW/m in 1978 and min = 13.68 kW/m in 2000), it is denoted a large variability for the other months with range differences greater than 80 kW/m. Considering January (Fig. 8b), the minimum value occurred in 1953 (18.05 kW/m) and the maximum value in 1996 (102.96 kW/m). These different orders of magnitude are also observed for December and February, and they are expected due to greater monthly standard deviation values of Fig. 7d.

3.3. CPOWEC commercial perspective

When considering P average values, it is possible to show the difference for the resource obtained by the CPOWEC prototype, already in kW (Fig. 9a). As expected, the maximum value is obtained in January ($P_{\text{CPOWEC}} = 219.5$ kW). From a commercial perspective, considering all days and hours of the database, a possible annual production is obtained totaling 1048.1 MWh at Aguçadoura (Fig. 9b). An inter-annual comparison (Fig. 10) shows that the annual production for the seven decades can range between 742.5 MWh and 1440.2 MWh.

Considering a Levelized Cost of Energy (LCOE) of around €60/MWh with a mean annual production of 1048.1 MWh and using Eq. (9), this would result in approximately €62 885 of annual investment. The LCOE is an economic indicator that translates the cost of the energy generation system, including all expenses over its useful life, such as the initial investment, operation and maintenance, fuel cost and capital invested costs. Therefore, the achieved value represents a measure used to evaluate and compare the cost of producing electricity from alternative sources.

4. Conclusions

This work uses ERA5 reanalysis data to obtain wind–wave climate characteristics, between 1950 to 2020, aiming to estimate inter- and intra-annual variability of wave energy in Aguçadoura region, located in Northern mainland Portugal. The objective was to evaluate the wave potential energy where the HiWave-5 project has been installed. The ERA5 data is validated with Leixões buoy data records obtained between 2012–2019. The comparison between the two databases for different wave parameters (mean wave direction, significant wave height, and peak wave period) reveal a good agreement, supporting the assumption that the modeled data are suitable for assessing the wave energy in this

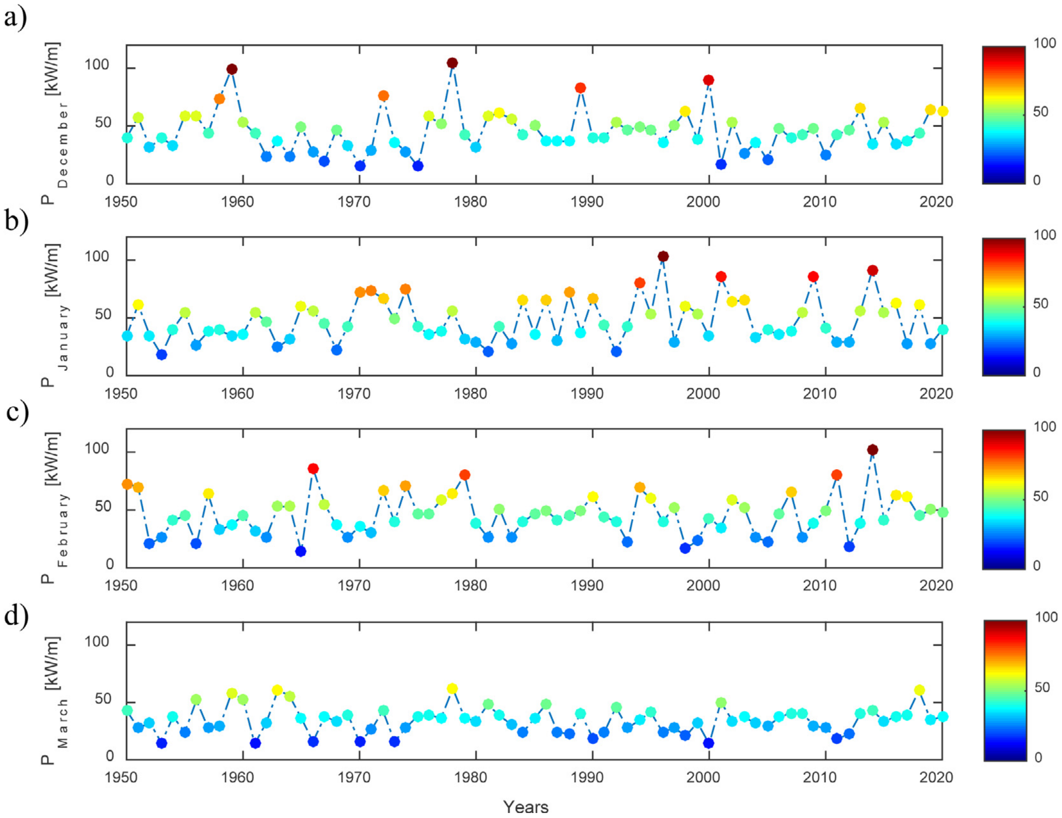


Fig. 8. Monthly means of *P* between 1950 to 2020 at Aguçadoura for: (a) December, (b) January, (c) February and (d) March.

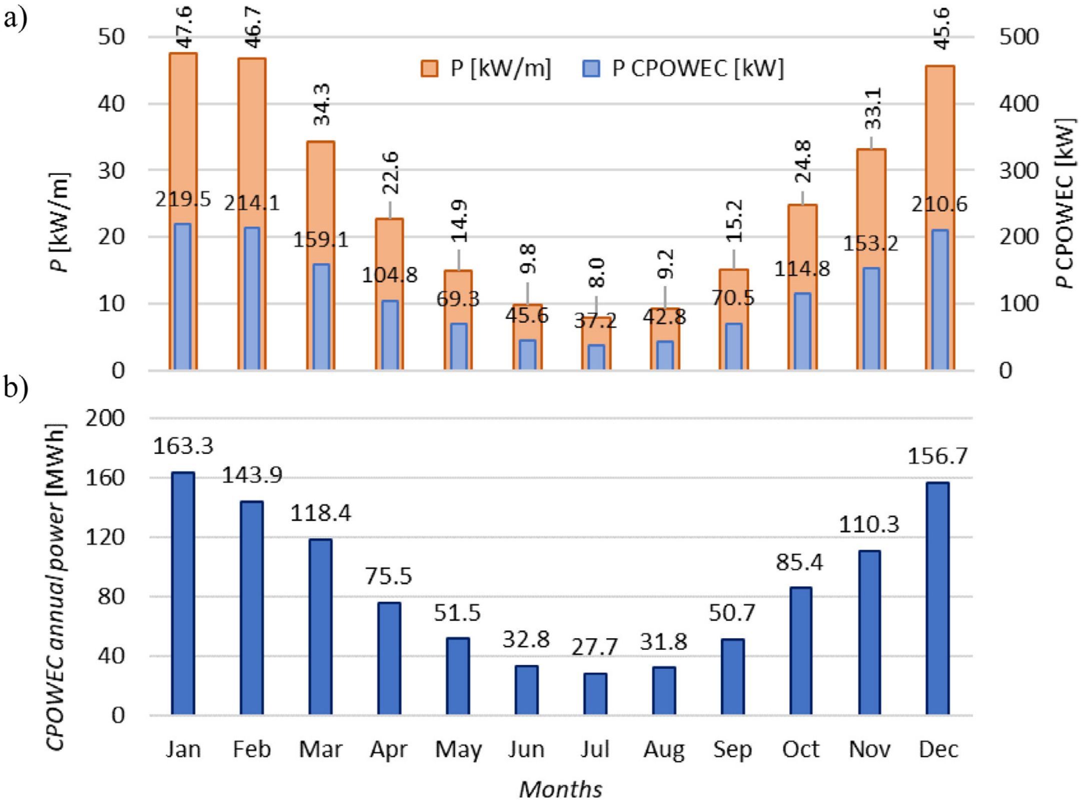


Fig. 9. Comparison between the wave power resource and the CPOWEC device (a) and a commercial perspective of the CPOWEC power value (b), over the months at Aguçadoura.

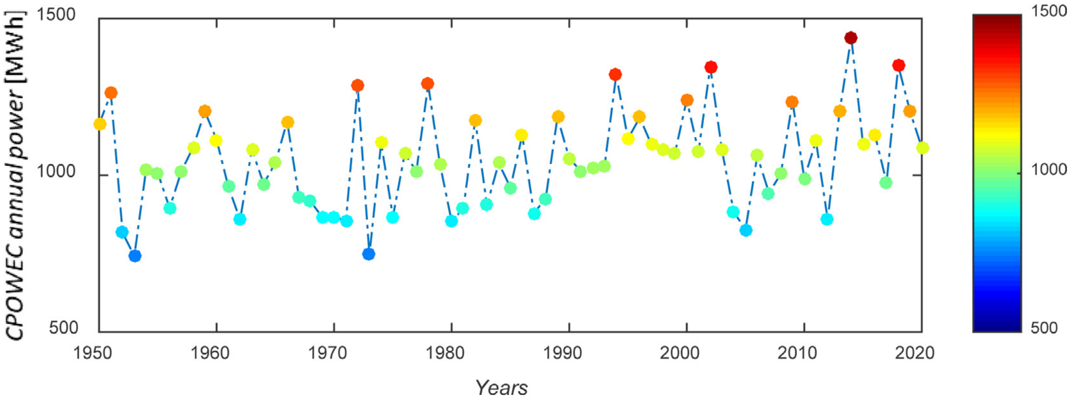


Fig. 10. CPOWEC annual power between 1950 and 2020 at Aguçadoura.

area. In general, the ERA5 reanalysis tends to slightly underestimate the wave power estimations of about 7.20%, resulting, on average and at the seasonal level, in a difference of 10.24% between December and March, and 5.67% for the rest of the months.

The data analysis from the seven decades show that the values of significant wave height and peak wave period, for the North of Portugal, do not significantly compromise the absolute performance of CPOWEC, in survival mode to adverse conditions. Given the limitations of the device, it is seen they are only reached very occasionally. It is also to be noted that this type of technology does not depend on wave propagation directions.

In terms of the annual resources assessment, a mean wave power of 25.84 kW/m was obtained at Aguçadoura, corresponding to a proposed prototype capture of about 119.45 kW. A strong inter-annual variability is observed with values ranging between 18.29 and 35.47 kW/m. The last decades tend to exhibit a slight increase in the wave energy potential, due to an apparent increase in the peak wave period. Concerning the intra-annual variability, a monthly assessment indicates a significant seasonal variability with average values ranging between 8.03 and 47.57 kW/m, respectively, in July and January. The months of the winter season present the highest energy returns, but they also have large standard deviations. For example, for January, a minimum value is observed in 1953 (18.05 kW/m) and a maximum value in 1996 (102.96 kW/m), evidencing a large variability along the seven decades.

Finally, despite these inter- and intra-annual variability with very low energy productions during the summer season, this location consolidates its wave energy potential, given the accumulated annual value of 1048.09 MWh with this CPOWEC device. To produce this accumulated annual value, an annual investment of €62 885 is required, tending to meet targets for large sustainable electricity generation with the exponential growth expected until 2030, aided by the increase of devices, in the farm concept. The implementation of a hybrid production using wave energy farms integrated with an offshore wind farm can also boost the Portuguese energy scenario. This kind of future research that identifies the variability of different renewable sources will contribute to the knowledge and resilience of the energy mix.

CRediT authorship contribution statement

Kássio Silva: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Tiago Abreu:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Tiago C.A. Oliveira:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition.

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.

Acknowledgments

The second and third authors thank FCT/MCTES for the financial support to CESAM, Portugal (UIDP/50017/2020+UIDB/50017/2020+ LA/P/0094/2020), through national funds. The authors also want to thank the anonymous reviewers for their useful comments and suggestions.

References

Aderinto, T., Li, H., 2019. Review on power performance and efficiency of wave energy converters. Energies 12 (22), 4329.

Ahn, S., 2021. Modeling mean relation between peak period and energy period of ocean surface wave systems. Ocean Eng. 228, 108937.

Ahn, S., Neary, V.S., 2020. Non-stationary historical trends in wave energy climate for coastal waters of the United States. Ocean Eng. 216, 108044.

Angelis-Dimakis, A., Biberacher, M., Dominguez, J., Fiorese, G., Gadocha, S., Gnansounou, E., Guariso, G., Kartalidis, A., Panichelli, L., Pinedo, I., Robba, M., 2011. Methods and tools to evaluate the availability of renewable energy sources. Renew. Sustain. Energy Rev. 15 (2), 1182–1200.

Bell, B., Hersbach, H., Berrisford, P., Dahlgren, P., Horányi, A., Sabater, J. Muñoz, Nicolas, J., Radu, R., Schepers, D., Simmons, A., Soci, C., Thépaut, J.-N., 2020. ERA5 hourly data on single levels from 1950 to 1978 (preliminary version). Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://cds.climate.copernicus-climate.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-preliminary-back-extension?tab=overview (Accessed on 25 May 2021).

Brito-Melo, A., Hofmann, T., Sarmento, A.J.N.A., Clément, A.H., Delhommeau, G., 2001. Numerical modelling of OWC-shoreline devices including the effect of surrounding coastline and non-flat bottom. Int. J. Offshore Polar Eng. 11 (02).

Caetano, N.S., Felgueiras, C., Salvini, C., Giovannelli, A., 2020. ICEER2020—Driving energy and environment in 2020 towards a sustainable future. Energy Rep. 6, 1–10.

Castro-Santos, L., Silva, D., Bento, A.R., Salvação, N., Soares, C. Guedes, 2018. Economic feasibility of wave energy farms in Portugal. Energies 11 (11), 3149.

Cornett, A.M., 2008. A global wave energy resource assessment. In: The Eighteenth International Offshore and Polar Engineering Conference. OnePetro.

CorPower Ocean, 2020. Dropbox - press kit - CorPower ocean. https://www.dropbox.com/sh/gfqsg5o682v68rt/AADuEgQAG0ZRikekO42f18PLa?dl=0>. (Accessed on 28 Jul 2021).

Costoya, X., deCastro, M., Carvalho, D., Arguilé-Pérez, B., Gómez-Gesteira, M., 2022. Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: A case study on the western Iberian Peninsula. Renew. Sustain. Energy Rev. 157, 112037.

Cuttler, M.V., Hansen, J.E., Lowe, R.J., 2020. Seasonal and interannual variability of the wave climate at a wave energy hotspot off the southwestern coast of Australia. Renew. Energy 146, 2337–2350.

Dalton, G.J., Alcorn, R., Lewis, T., 2010. Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. Renew. Energy 35 (2), 443–455.

Eckert, E., Kovalevska, O, 2021. Sustainability in the European union: Analyzing the discourse of the European green deal. J. Risk Financial Manag. 14 (2), 80.

Falnes, J., 2002. Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction, 52. (100), Cambridge University Press, pp. 75–83.

Gomes, J.G., Pinto, J.M., Xu, H., Zhao, C., Hashim, H., 2020. Modeling and planning of the electricity energy system with a high share of renewable supply for Portugal. Energy 211, 118713.

Guillou, N., Chapalain, G., 2020. Assessment of wave power variability and exploitation with a long-term hindcast database. Renew. Energy 154, 1272–1282.

Guimarães, R.C., Oleinik, P.H., Kirinus, E.P., Lopes, B.V., Trombetta, T.B., Marques, W.C., 2019. An overview of the Brazilian continental shelf wave energy potential. Reg. Stud. Mar. Sci. 25 (100446), 2352–4855.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Hersbach, H. Horá, Bell, B., Berrisford, P., Biavati, G., Horányi, A., Sabater, J. Muñoz, Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N., 2018 ERA5 hourly data on single levels from 1979 to present. In: Copernicus Climate Change Service (C3S) Climate Data Store (CDS). http://dx.doi.org/10.24381/cds.adbb2d47, (Accessed on 27 May 2021).

Jin, S., Greaves, D., 2021. Wave energy in the UK: Status review and future perspectives. Renew. Sustain. Energy Rev. 143, 110932.

Kies, A., Schyska, B.U., Bremen, L. von, 2016. The optimal share of wave power in a highly renewable power system on the Iberian Peninsula. Energy Rep. 2, 221–228.

Lavidas, G., Blok, K., 2021. Shifting wave energy perceptions: The case for wave energy converter (WEC) feasibility at milder resources. Renew. Energy 170, 1143–1155.

Leonard, M., Pisani-Ferry, J., Shapiro, J., Tagliapietra, S., Wolff, G.B., 2021. The geopolitics of the European green deal (No. 2021/04). In: Bruegel Policy Contribution.

López, I., Andreu, J., Ceballos, S., De Alegría, I.M., Kortabarria, I., 2013. Review of wave energy technologies and the necessary power-equipment. Renew. Sustain. Energy Rev. 27, 413–434.

López, M., Veigas, M., Iglesias, G., 2015. On the wave energy resource of Peru. Energy Convers. Manage. 90, 34–40.

Mendes, D., Oliveira, T.C., 2021. Deep-water spectral wave steepness offshore mainland Portugal. Ocean Eng. 236, 109548.

Mota, P., Pinto, J.P., 2014. Wave energy potential along the western Portuguese coast. Renew. Energy 71, 8–17.

Oliveira, T.C., Cagnin, E., Silva, P.A., 2020. Wind-waves in the coast of mainland Portugal induced by post-tropical storms. Ocean Eng. 217, 108020.

Oliveira, T.C., Neves, M.G., Fidalgo, R., Esteves, R., 2018. Variability of wave parameters and Hmax/Hs relationship under storm conditions offshore the Portuguese continental coast. Ocean Eng. 153, 10–22.

Pastor, J., Liu, Y., 2016. Wave climate resource analysis based on a revised gamma spectrum for wave energy conversion technology. Sustainability 8 (12), 1321.

Ribeiro, A.S., deCastro, M., Rusu, L., Bernardino, M., Dias, J.M., Gomez-Gesteira, M., 2020. Evaluating the future efficiency of wave energy converters along the NW coast of the Iberian Peninsula. Energies 13 (14), 3563.

Rusu, L., 2021. An assessment of the wave energy in the European seas based on ERA5 reanalysis dataset. In: Developments in Maritime Technology and Engineering: Celebrating 40 years of teaching in Naval Architecture and Ocean Engineering in Portugal and the 25th anniversary of CENTEC, vol. 64, CRC Press, pp. 7–652.

Rusu, L., De León, S.P., Soares, C.G., 2015. Numerical modelling of the North Atlantic storms affecting the West Iberian coast. Marit. Technol. Eng. 1365–1370.

Rusu, E., Guedes Soares, C., 2013. Coastal impact induced by a Pelamis wave farm operating in the Portuguese nearshore. Renew. Energy 58, 34–49.

Rusu, L., Onea, F., 2015. Assessment of the performances of various wave energy converters along the European continental coasts. Energy 82, 889–904.

Rusu, L., Rusu, E., 2021. Evaluation of the worldwide wave energy distribution based on ERA5 data and altimeter measurements. Energies 14 (2), 394.

Sandu, M., Gribincea, A., 2019. Trends on the global energy market. J. Res. Trade Manag. Econ. Dev. 11 (1), 119–129.

Sasmal, K., Waseda, T., Webb, A., Miyajima, S., Nakano, K., 2021. Assessment of wave energy resources and their associated uncertainties for two coastal areas in Japan. J. Mar. Sci. Technol. 26 (3), 917–930.

Sierra, J.P., González-Marco, D., Sospedra, J., Gironella, X., Mösso, C., Sánchez-Arcilla, A., 2013. Wave energy resource assessment in Lanzarote (Spain). Renew. Energy 55, 480–489.

Silva, D., Martinho, P., Soares, C.G., 2018. Wave energy distribution along the Portuguese continental coast based on a thirty three years hindcast. Renew. Energy 127, 1064–1075.