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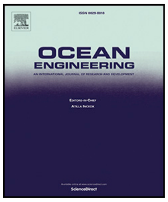

Future electricity production at Mutriku Wave Energy Plant estimated from CMIP6 wave climate projections (2015–2100)

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ABSTRACT

Renewable marine energy sources are rapidly developing worldwide. With numerous operational marine power plants in existence, it is becoming increasingly important to explore their potential. Hence, this study aims to examine the impact of climate change on the future potential of wave energy. The case study was centred on the Mutriku Wave Energy Plant, situated in the Bay of Biscay in the northern region of the Iberian Peninsula.

To accomplish this, this study investigated changes in wave energy from 2015 to 2100 by employing ERA5 data and an ensemble of CSIRO wave projections driven by six distinct models derived from CMIP6 model runs. Two were associated with the SSP1-2.6 pathway while the other four corresponded to the SSP5-8.5 pathway. The unidimensional wave variables were bias-corrected using the Quantile Matching (QM) technique, whereas the bidimensional variables were corrected using the Multivariate Bias Correction N-pdf (MBC N-pdf) technique. Subsequently, a self-organising map (SOM) technique was employed to classify daily sea type frequencies and power. Additionally, the Smirnov test was employed to determine whether the probability density functions derived from different datasets exhibited significant differences at a significance level of 0.05.

The conclusions obtained indicate that energy production in the Bay of Biscay will remain stable in the late 21st Century. The daily frequencies of the sea type and power did not change significantly. This stability ensures consistent power generation, enabling the location to provide a reliable and consistent source of energy both currently and in the future.

1. Introduction

Renewable energy is attracting considerable attention, funding, and technological advancement in an effort to reduce our dependence on oil and fossil fuels and the negative impacts of their use on global warming. Marine energy has recently gained attention as a renewable and sustainable energy source. In addition to its energy potential, marine energy has high industrial and technological potential. According to Ocean Energy Systems from the International Energy Agency (Anon, 1999), the world has the potential to develop 300 GW of wave and tidal energy by 2050. At the European level, The European Commission's "Marine Renewable Energy Strategy" (Anon, 2011) predicts an increase in installed capacity from the current 13 MW to 1 GW by 2030, with the aim of reaching 40 GW by 2050. In Spain, the target set by the National Integrated Energy and Climate Plan 2021–2030 (PNIEC 2021–2030) (Anon, 2019) for renewable energies, including marine energy, is 80 MW by 2030, although this range may vary depending on the technological developments achieved.

With regard to the environmental protection of the marine environment, Spain protects approximately 12% of its marine area; therefore, the government has set a priority target of 30% protected marine areas by 2030, in line with the European Union's Biodiversity Strategy (Anon, 2020). In Spain, the government has an obligation to ensure the integrity and adequate conservation of this space, as well as its orderly and rational use; therefore, the development of renewable energies in the maritime environment must be advanced in accordance with the Planning and Management of Marine Spaces (POEM) (Anon, 2023b).

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List of Abbreviations

AR6	Sixth Assessment Report
CMIP6	Coupled Model Intercomparison Project Phase 6
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EA	EastAtlantic pattern
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ERA5	Latest reanalysis by the ECMWF
GCM	Global Climate Models
IPCC	Intergovernmental Panel of Climate Change
MBC	Multivariate Bias Correction of Climate Model Outputs
MBC N-pdf	Multivariate Bias Correction N-pdf
NAO	North Atlantic Oscillation
OWC	Oscillating Water Column
PDF	Probability Density Function
PNIEC 2021–2030	National Integrated Energy and Climate Plan in Spain 2021–2030
POEM	Planning and Management of Marine Spaces in Spain
PTECC 2021–2024	The Energy Transition and Climate Change Plan 2021–2024 of the Basque Country
QM	Quantile Matching technique
SOM	Self-Organising Map technique
SSPs	Shared Socioeconomic Pathways
WECs	Wave Energy Converters
WES	Wave Energy Scotland

Nomenclature

AP	Annual Power (kW)
Dir_m	Mean wave direction (°)
f_i	Frequency of each sea-type
H_0	Null hypothesis of the test
H_a	Alternative hypothesis of the test
p_i	Power associated to each sea-type (kW)
P1	First future period 2015–2044
P2	Second future period 2045–2074
P3	Third future period 2075–2100
Ref	Reference period 1985–2014
H_s	Significant height of combined wind waves and swell (m)
$T02$	The second turbine of Mutriku's Wave Energy Plant
$T02_{pow}$	Daily mean power generated by the T02 turbine (kW)
T_m	Mean wave period (s)
T_p	Peak wave period (s)
WEF	Wave Energy Flux (kW/m)
WEF_u	Zonal Wave Energy Flux (kW/m)
WEF_v	Meridional Wave Energy Flux (kW/m)

This will therefore consider the compatibility of different uses, as well as the objectives and commitments regarding the protection of the sea and biodiversity.

Concerning the Basque Country, a recent strategy, i.e., the Energy Transition and Climate Change Plan 2021–2024 (PTECC 2021–2024) (Anon, 2021b), aims to work on all aspects of climate change. Mitigation involves reducing greenhouse gas emissions, increasing carbon sinks, strengthening the energy strategy, and implementing adaptation measures for the territory and its population. In this sense, the Basque government has three initiatives underway in the field of marine energy: EuropeWave, TurboWave, and a multi-annual support programme to boost investments in the demonstration and validation of marine renewable technologies. EuropeWave (Anon, 2021a) is a consortium that, together with Wave Energy Scotland (WES) and the European Commission, proceeds with the pre-commercial purchase of Wave Energy Converters (WECs). TurboWave (Anon, 2021c) is a project involved with the development of last-generation turbines at the Mutriku Wave Energy Plant site.

The Mutriku Wave Energy Plant was built into a breakwater at the harbour in the village of Mutriku in the Bay of Biscay (Fig. 1 (a)). It contains 16 well-type turbines that use Oscillating Water Column (OWC) technology (Fig. 1 (b)). The plant has a total capacity of 296 kW, which has been supplying electricity to the grid since July 2011 (Torre-Enciso et al., 2009). The Mutriku Wave Energy Plant has been thoroughly analysed by this research group (Ibarra-Berastegi et al., 2018; Serras et al., 2019; Ibarra-Berastegi et al., 2021). The first study (Ibarra-Berastegi et al., 2018) focused on the calculation of electricity generation, capacity factor, and the plant's efficiency index from 2014–2016. The second study (Serras et al., 2019) aimed to forecast 24 h ahead of the electricity generated at the plant using different models and data for the same period (2014–2016). In the latest study (Ibarra-Berastegi et al., 2021), a self-organising map (SOM) was fitted to identify 10 major sea-state types, each with a distinctive electricity generation pattern on a daily scale. This allowed for the reconstruction of the daily electric power that would have been generated if the Mutriku Wave Energy Plant had been operational over the analysed 1979–2019 period; thus, allowing the evaluation of the impact that the observed changes in the wave energy flux (WEF) would have had on the electricity production of the plant.

Examining how climate change will affect the future potential of waves is crucial for informed decisions regarding the planning of marine renewable projects and investments in a country. The Intergovernmental Panel on Climate Change (IPCC) reviews scientific evidence on climate change, its effects, and potential risks while also providing new data and solutions for adaptation and mitigation. The IPCC prepared its latest Sixth Assessment Report (AR6) based on the results provided by climate models integrated into the CMIP6 (Coupled Model Intercomparison Project Phase 6) coordinated effort. The simulations provided by the CMIP6 models used in the AR6 report included historical simulations from 1950 to 2014, which were obtained by running the models and applying estimations of both natural and anthropogenic climate forcing derived from observations. Additionally, the models provide future projections from 2014 to 2100 based on different Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2016). In this study, the following two SSPs were used: SSP1-2.6, which represents a low-forcing sustainability pathway, and SSP5-8.5, which simulates a high-end forcing pathway. In other words, the best and most adverse simulated scenario from the perspective of climate change. Furthermore, SSP5-8.5 and SSP1-2.6 are analogous to the well-known RCP8 and RCP2.6 scenarios in CMIP5, respectively.

Not all models participating in the CMIP6 initiative include ocean-wave models. However, oceanic wave data were required for this study. Therefore, the CSIRO data were used in this study. Meucci et al. (2021) obtained these results by nesting the WaveWatch III (v6.07) model into the atmospheric variables provided by some CMIP6 simulations. The results are freely accessible.

The main objective of this study was to investigate whether electricity production in Mutriku Wave Energy Plants would be affected by future climate change conditions. To achieve this, we examined

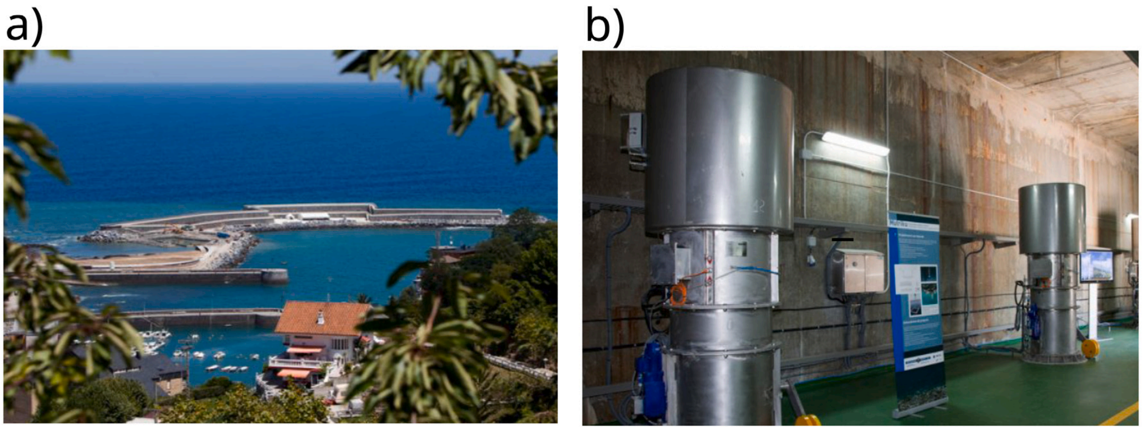

Fig. 1. (a) Aerial photograph of the Mutriku Wave Energy Plant and (b) part of its 16 well-type turbines (Anon, 2023a).

changes in the WEF during the late 21st Century using an ensemble of CSIRO wave projections forced by six different CMIP6 models. To the best of our knowledge, this is the first study to investigate the impact of climate change on a real energy plant made possible by the Mutriku Wave Energy Plant's continuous operation over an extended period.

The remainder of this paper is structured as follows. Section 2 outlines the datasets and methods employed in this study. Section 3 presents the results, and Section 4 discusses the findings. Section 5 presents the conclusions of the study and Section 6 suggests directions for future research.

2. Data and methodology

2.1. Data

Situated in southern Europe, specifically in the Bay of Biscay, the Mutriku Wave Energy Plant (−2.5 °E and 43.5 °N) is the focal point of this study (Fig. 2). Two data sources were used at this location: the ERA5 reanalysis and the ocean wave climate simulation dataset, CSIRO.

2.1.1. ERA5

The ERA5 reanalysis (Hersbach et al., 2015) is the latest reanalysis developed by the European Center for Medium-Range Weather Forecasts (ECMWF). This dataset provides ocean variables in addition to atmospheric variables. The ERA5 wind variables have been successfully validated and used in various studies to obtain positive results (Olauson, 2018; Carreno-Madinabeitia et al., 2021; De Assis Tavares et al., 2020). Additionally, the ERA5 ocean variables have been validated against buoy data from different parts of the world (Silva et al., 2022; Sun et al., 2022; Penalba et al., 2020; Ulazia et al., 2020). Overall, the measurements show a good fit between the observations and reanalysis data. Therefore, we considered the ERA5 ocean wave variables adequate for this study. The following oceanic variables were used in this study:

- Significant height of combined wind waves and swell (H_s)
- Mean wave period (T_m)
- Peak wave period (T_p)
- Mean wave direction (Dir_m)

All variables are available hourly, with a recommended 0.5° × 0.5° spatial resolution for ocean data from 1940 to the present. The WEF per unit wave-crest length in deep water, expressed in kW/m, was obtained using Eq. (1) (Bidlot, 2016; Multon, 2013):

$$WEF = 0.49 \cdot T_m \cdot H_s^2 \tag{1}$$

Then, by combining WEF and Dir_m, the 3-hourly zonal (WEF_u) and meridional (WEF_v) components of the WEF were derived for the grid point nearest the Mutriku Wave Energy Plant [-2.5 °E, 43.5 °N].

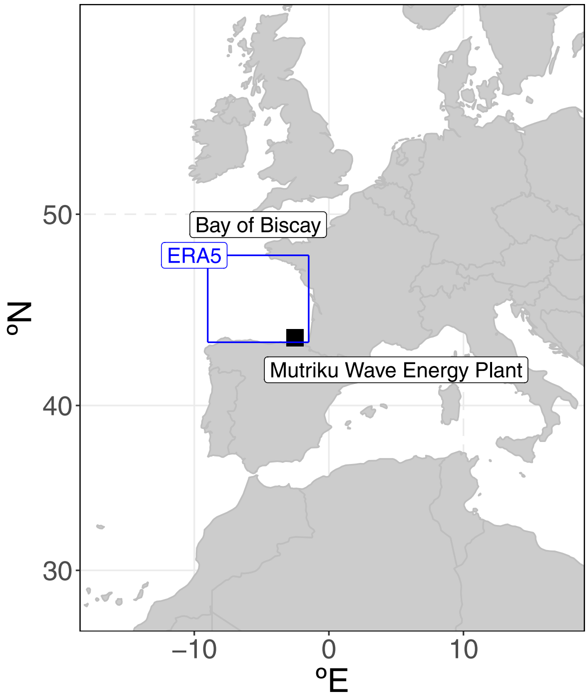

Fig. 2. Mutriku Wave Energy Plant located in the Bay of Biscay. The blue square indicates the ERA5 and SCIRO-WW III data area used in this study.

2.1.2. Wavewatch III integrations at CSIRO

The second data source used in this study was an ocean wave climate simulation dataset developed at CSIRO and made available to the scientific community (Meucci et al., 2021, 2020). The dataset was obtained by forcing the WaveWatch III (v6.07) model (WW III) with surface wind and sea ice concentration fields from the CMIP6 model runs. The CMIP6 model runs corresponded to two IPCC shared socioeconomic pathways (SSP1-2.6 and SSP5-8.5), two models (ACCESS-CM2 and EC-EARTH3), and two values of the CDFAC parameter in WaveWatch III for the SSP5-8.5 scenario (CDFAC1 and CDFAC1.08), and one for the SSP1-2.6 scenario (CDFAC1.08). This parameter is related to the drag coefficient, which affects the total shear stress acting on the atmosphere-ocean interface (Fernández et al., 2021). Therefore, there are six future projections (see Table 1).

This dataset contains 3-hourly outputs at a global 0.5° × 0.5° spatial resolution, corresponding to the period from 1961–2100. For this study, among the variables made available to the scientific community, the following were used:

Table 1
Definition of the six different future projections provided by CSIRO data.

Scenario	Model	Parameterisation
SSP1-2.6	ACCESS-CM2	CDFAC1.08
SSP1-2.6	EC-EARTH3	CDFAC1.08
SSP5-8.5	ACCESS-CM2	CDFAC1
SSP5-8.5	ACCESS-CM2	CDFAC1.08
SSP5-8.5	EC-EARTH3	CDFAC1
SSP5-8.5	EC-EARTH3	CDFAC1.08

- Peak wave period (T_p)
- Wave Energy Flux (WEF)
- Mean wave direction of incoming waves (Dir_m)

Similar to ERA5, combining WEF and Dir_m, the 3-hourly WEF_u and meridional WEF_v components of the WEF were obtained at the [-2.5 °E, 43.5 °N] gridpoint.

Finally, using ERA5 and CSIRO data at this grid point, a previously developed self-organising map (SOM) (Ibarra-Berastegi et al., 2021) was used to classify the local sea types at the Mutriku Wave Energy Plant. This could be readily fed with future WW III estimations of WEF_u, WEF_v, and T_p to identify possible changes in the frequency of the occurrence of local sea state types. In our previous study (Ibarra-Berastegi et al., 2021), the sequence of sea types was used to reconstruct the local evolution of electricity production at Mutriku from 1979–2019. In this study, the estimation of future sea types corresponding to 2015–2100 was used to forecast future electric yields.

2.2. Methodology

2.2.1. Bias correction methodology

Global climate models (GCM) describe climatic responses to large-scale forcings, including those caused by greenhouse gases. In contrast, reanalysis assimilates atmospheric, ocean, and land surface information into a comprehensive coupled data assimilation system. Thus, reanalysis solves a problem strongly related to the initial conditions, also referred to as first-kind predictability (Lorenz, 1975). However, climate simulations, such as those in the CMIP6 repository, run beyond the first-kind predictability limit. Therefore, for climate model runs, the diagnostics must be based on the probability density functions (PDF). Thus, the removal of errors in climate projections are often eliminated using bias-correction techniques. Here, the correction of CSIRO future projections was performed using the ERA5 reanalysis dataset as the reference dataset for the historical period. In this study, different calibration techniques were applied based on the nature of the variables. For one-dimensional variables, such as T_p, we used a Quantile Matching (QM) technique. This technique has been previously applied to studies related to marine energy (Ulazia et al., 2019; Penalba et al., 2018; Ulazia et al., 2017). QM is a technique commonly used in meteorological studies (Carreno-Madinabeitia et al., 2021; Squintu et al., 2019; Donk et al., 2019). QM (Cannon et al., 2015) compares the percentiles of the GCM-derived data to be corrected with those from a reference dataset (ERA5 in our case), adjusting the percentiles of the former to match those in the latter for the entire PDF. This ensured that the corrected data had the same statistical properties as the reference dataset. However, for the two-dimensional WEF variable, which include WEF_u and WEF_v, a Multivariate Bias Correction N-pdf (MBC N-pdf) technique was applied (Cannon, 2018). The goal was to simultaneously correct both dimensions, WEF_u and WEF_v, by considering their original relationship and matching their marginal distributions and inter-variable dependence structure.

To perform the calculations, the multivariate bias correction of the climate model output (MBC) in the R package (https://CRAN.R-project.org/package=MBC) was used. The *QDM()* function, a univariate bias correction via QM, was applied to one-dimensional variables, and the *MBCn()* function, MBC N-pdf, to two-dimensional variables. All data and methodologies used in this study were processed using the R software (R Core Team, 2023; RStudio Team, 2020).

Table 2
Sea-state types, characteristic values, and associated daily power for the 2 × 5 SOM in the Mutriku Wave Energy Plant (Ibarra-Berastegi et al., 2021).

Sea-state type	Hs m	Tm s	WEF kW/m	Tp s	WS m/s	T02 pow.	Freq. %
1	4.8	12.0	142.3	15.1	11.4	7.81	0.6
2	3.7	10.5	78.9	13.2	10.2	8.10	1.1
3	2.1	8.9	20.8	11.1	6.2	5.22	8.4
4	3.6	11.6	75.4	14.4	8.1	9.04	2.3
5	2.0	11.3	22.4	14.1	4.4	5.12	10.5
6	2.8	11.1	43.8	13.7	6.6	7.84	6.2
7	1.0	6.5	4.1	8.9	4.2	0.24	4.8
8	1.2	9.3	7.6	12.4	3.7	1.50	24.1
9	1.0	7.4	4.2	9.8	3.4	0.76	26.8
10	1.0	5.6	3.5	6.7	4.7	0.32	15.3

2.2.2. Daily sea-type classification and power

As mentioned previously, to determine the daily sea type classification and power, the methodology developed in a previous study was used (Ibarra-Berastegi et al., 2021). This study used wave data to classify each day according to the sea state type. To accomplish this, an SOM (Kohonen and Somervuo, 2002; Wehrens and Buydens, 2007) with a 2 × 5 architecture was fitted to identify 10 primary sea-state types, each with a unique pattern of daily electricity generation and the associated electric power that would have been generated by the Mutriku Wave Energy Plant. The data used in the study were obtained from the second turbine of the Mutriku Wave Energy Plant ($T02$). This turbine was selected because of its continuous operation over an extended period, making it the primary source of a greater amount of data, and, therefore, higher data quality. Therefore, in this study, the daily mean power generated by the $T02$ turbine ($T02_{pow}$) for each sea state was required. To categorise the new cases, the adjusted SOM for the Mutriku Wave Energy Plant during the training period [2014–2016] was used. The variables T_p, WEF_u, and WEF_v, described in the data section of six different future projections provided by the CSIRO data, were corrected using the MBC technique to obtain future daily sea type classifications from 1985–2100. Table 2, which corresponds to part of Table 1 of the abovementioned article (Ibarra-Berastegi et al., 2021), lists the 10 sea types and their $T02_{pow}$.

As mentioned above, the authors previously developed a methodology to obtain daily sea-type classification and power (Ibarra-Berastegi et al., 2021). In that research, in addition to developing a method to obtain these variables, the author also validated and analysed the trend of the data for the period 1979–2019. The conclusion is that the WEF variable has increased significantly by 0.146 kW/m per decade, but this increase has not affected the energy production.

2.2.3. Sea-type frequency and annual power calculation

In the Mutriku Wave Energy Plant, the daily sea type is available for both ERA5 and CSIRO- WW III future projections. Based on these data, the frequency of each sea type (f_i where $i = 1, 2, \ldots, 10$) for periods of 30 years was calculated, including a study of the seasonal evolution during those 30 years. The World Meteorological Organization recommends the use of 30-year periods to minimise uncertainties caused by climate variability (Stopa et al., 2019; Anon, 2017). Specifically, the frequencies of the projections for each scenario (SSP1-2.6 and SSP5-8.5) and the model runs (see Table 1) were computed.

Daily sea-type frequency information in combination with the daily mean power associated with each sea type (p_i) (Table 2) was used to obtain the Annual Power (AP) (Eq. (2)):

$$AP = \sum_{i=1}^{10} f_i p_i \text{ where } i = 1, 2, \ldots, 10 \tag{2}$$

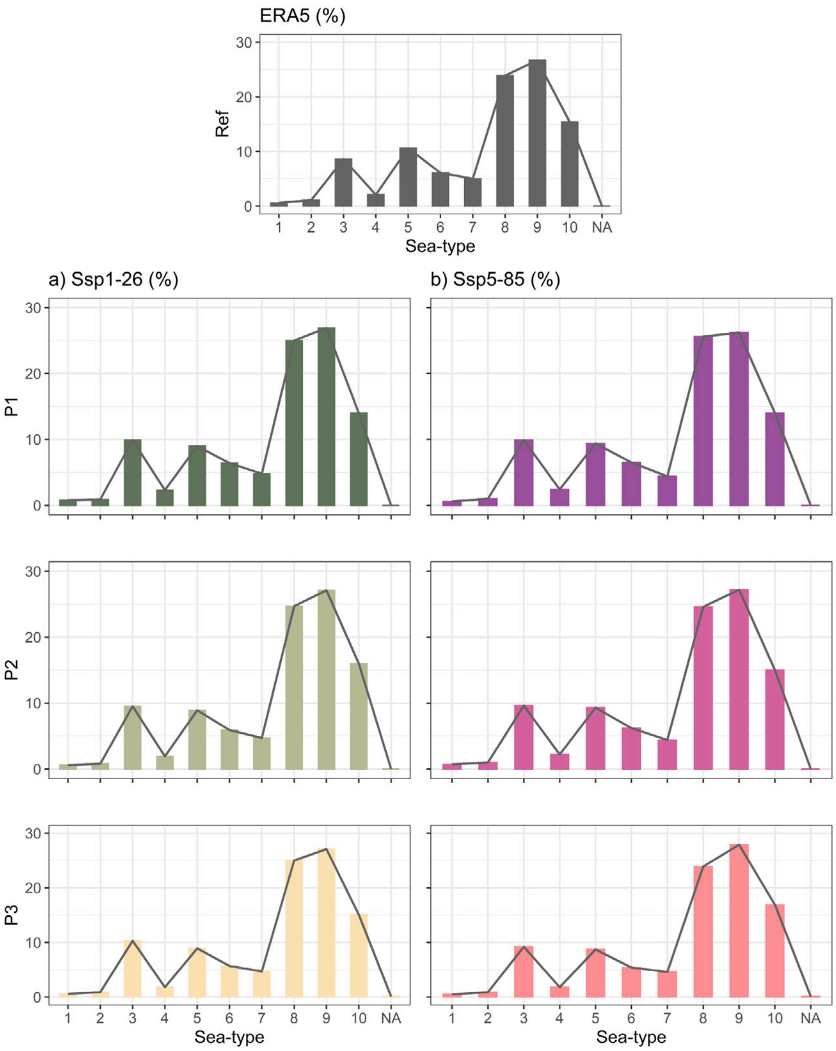

Fig. 3. Sea-type frequencies in the Mutriku Wave Energy Plant in the reference period (Ref) in the three climate projections periods (P1, P2 and P3) and scenarios (a) SSP1-2.6 and (b) SSP5-8.5.

The typical Annual Energy Production (AEP) parameter characterises energy production and is therefore proportional to AP, considering the annual amount of hours: $AEP = AP \times 365 \times 24$ in kWh.

Data are available from 1985–2100, which was divided into four 30-year periods. The first is the reference period (Ref), which covers 1985–2014. Three future projection periods were defined as P1, P2, and P3, covering–2015–2044,2045–2074, and 2075–2100 years, respectively.

2.2.4. *Smirnov test*

The Smirnov test is a nonparametric statistical test used to calculate the goodness of fit of two probability distributions (Conover, 1999; Berger and Zhou, 2014). The test was formulated as follows:

H_0 : Both datasets originate from the same distribution (Null hypothesis)

H_a : Both datasets did not originate from the same distribution (Alternative hypothesis)

If the obtained *p*-value is small, the null hypothesis (H_0) is rejected in favour of the alternative hypothesis (H_a), indicating that the PDFs derived from the two datasets are significantly different.

To accomplish this, the *ks.test()* function in R Cran was used. In this study, the ERA5 data from 1985–2014 were compared to the other samples using a significance level of 0.05.

3. Results

3.1. *Climate sea-type frequency projections*

The distributions of sea-type frequencies between Ref, derived from ERA5 reanalysis, were compared with sea-type frequency projections in the future (P1, P2 and P3 periods) for both scenarios, i.e., SSP1-2.6 and SSP5-8.5 (Fig. 3).

This comparison was performed by applying the Smirnov test to two samples at a significance level of 0.05. The result is that in all cases, H_0 is accepted; therefore, there were no significant changes in the mentioned distributions.

Fig. 3 illustrates that the most common sea-type frequencies in the Mutriku Wave Energy Plant were the 9th and 8th, respectively. These sea-types have an associated low power at $T02$ of 1.5 and 0.76 kW (Table 2). The least common sea-types are the 1st, 2nd, and 4th, which have high associated power (7.81, 8.10, and 9.04 kW, respectively). The last sea type, the 4th, generates the highest power.

In addition to the overall analysis, sea type frequencies were calculated by season. The seasons were winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and autumn (September, November, and October). The projected sea type frequencies for each season were compared by scenario and period against the reference ERA5 data. The results of the Smirnov

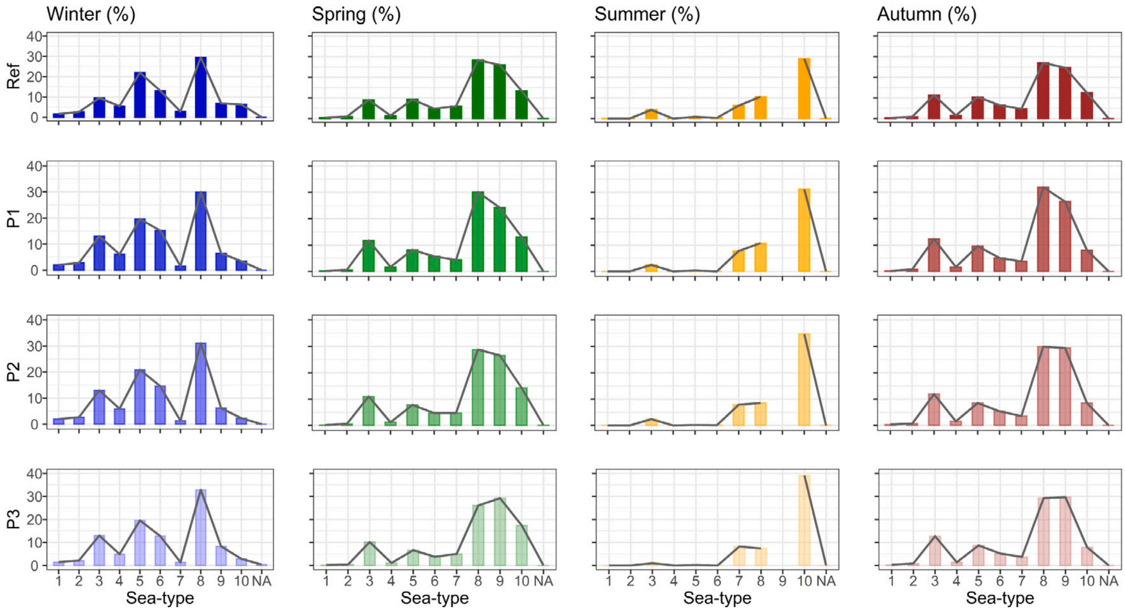

Fig. 4. Sea-type frequencies for the SSP5-8.5 scenario by season (winter, spring, summer, and autumn) in the reference (Ref) period and future climate projections periods (P1, P2, and P3).

test indicated that there were no significant differences between them at a significance level of 0.05. Fig. 4 shows the sea-type frequencies of the climatic projections corresponding to the SSP8-58 scenario for each season in the periods analysed in this study (Ref, P1, P2, and P3).

Fig. 4 shows that sea types 9th and 8th remain most frequent during spring and autumn. Sea types 1st, 2nd, 4th, and 6th, which have lower frequencies, but higher $T02_{pow}$ values, occur more often in winter than in other seasons. In summer, the 10th sea-type is the most frequent, but it is associated with a low power generation of 0.32 kW at $T02$ (Table 2). This figure also indicates that, in the Mutriku Wave Energy Plant, winter is the season with more power, whereas summer is the season with less power. The same results were also obtained for the SSP1-2.6 scenario (not displayed).

3.2. Climate annual power projections

The AP produced by the Mutriku Wave Energy Plant was also analysed to determine whether there were changes under different climatic scenarios. This analysis was performed by comparing the AP production PDF obtained from Ref to the same PDF for each of the three future climate projections (P1, P2, and P3) using the Smirnov test with a 0.05 significance level. The resulting distribution functions are presented in Fig. 5. Therefore, we concluded that no changes were expected in the AP generated by the $T02$ turbine analysed in the different scenarios during the study period. In all options, the annual production range was from 2.36 to 5.96 kW, with an average of approximately 4.2 kW per year.

4. Discussion

Global studies utilising ensemble projections from CMIP5 (Morim et al., 2020) models for wind power variables (H_s and T_p) have demonstrated a general trend of decreasing values in the Northern Hemisphere and increasing values in the Tropical and Southern Hemisphere by the end of the 21st century (2081–2099) (Patra et al., 2021). Specifically, these studies (Lemos et al., 2019; Odériz et al., 2022) highlighted significant decreases in the WEF variable in the Atlantic area: the first in the 2031–2060 period and the second from 2081–2099, particularly during the winter season. However, such a significant decrease was not observed in the northern part of the Iberian Peninsula.

In line with the decrease in the WEF in the Northern Hemisphere, recent investigations based on CMIP6 (Shen et al., 2022; Deng et al., 2021) indicated a decline in both land and ocean surface wind speeds. These results suggest that the decrease is linked to the rise in temperature caused by greenhouse gas emissions, which will likely have an impact on the future wave climate. Research conducted in the European region, particularly in the North Atlantic and the Bay of Biscay, showed different results. Carvalho et al. (2021) concluded that there would be a decrease in wind in Europe with large intra-annual variability, especially in the Iberian Peninsula and Ukraine. This intra-annual change could explain why Fernández-Alvarez et al. (2023) observed a significant increase in wind in the Iberian Peninsula region, particularly in summer. As a result, changes in wind tendencies could occur in the North Atlantic and the Bay of Biscay. However, based on the results of this study, this change did not affect the generation of wave energy in the study area. In fact, it seems that these changes will occur in summer, when the Mutriku Wave Energy Plant generates less energy.

We previously examined wave energy trends in the Bay of Biscay (Ulazia et al., 2019, 2017). Two periods of 40 and 110 years were analysed using reanalysis data; we concluded that the WEF increased in the Atlantic area, but this increase was lower on the Basque coast, where the Mutriku Wave Energy Plant is located. This global study (Wu et al., 2018) also confirmed the results in this area of interest. We conducted a third study (Ibarra-Berastegi et al., 2021), which found that at the Mutriku Wave Energy Plant, the WEF has increased by 0.146 kW/m per decade, but this does not significantly affect electricity production. These are the first approximations obtained from CMIP6 first climate projection models and it is known that these results have uncertainty (Lobeto et al., 2023). Therefore, based on this research, energy production is expected to remain stable in the future.

When identifying the most convenient locations for WECs, it is important to consider not only the areas with the highest wave energy resources, but also additional factors such as intermittency or capacity, especially to determine the economic viability of the devices. In this sense, the results obtained by some studies (Portilla et al., 2013; Coe et al., 2021) show that regions or places that have traditionally not been considered prime wave energy locations can be promising future locations because of their less energetic, but more regular conditions. Considering all of these parameters, some studies have created an interactive wave power map focused on the variability of wave

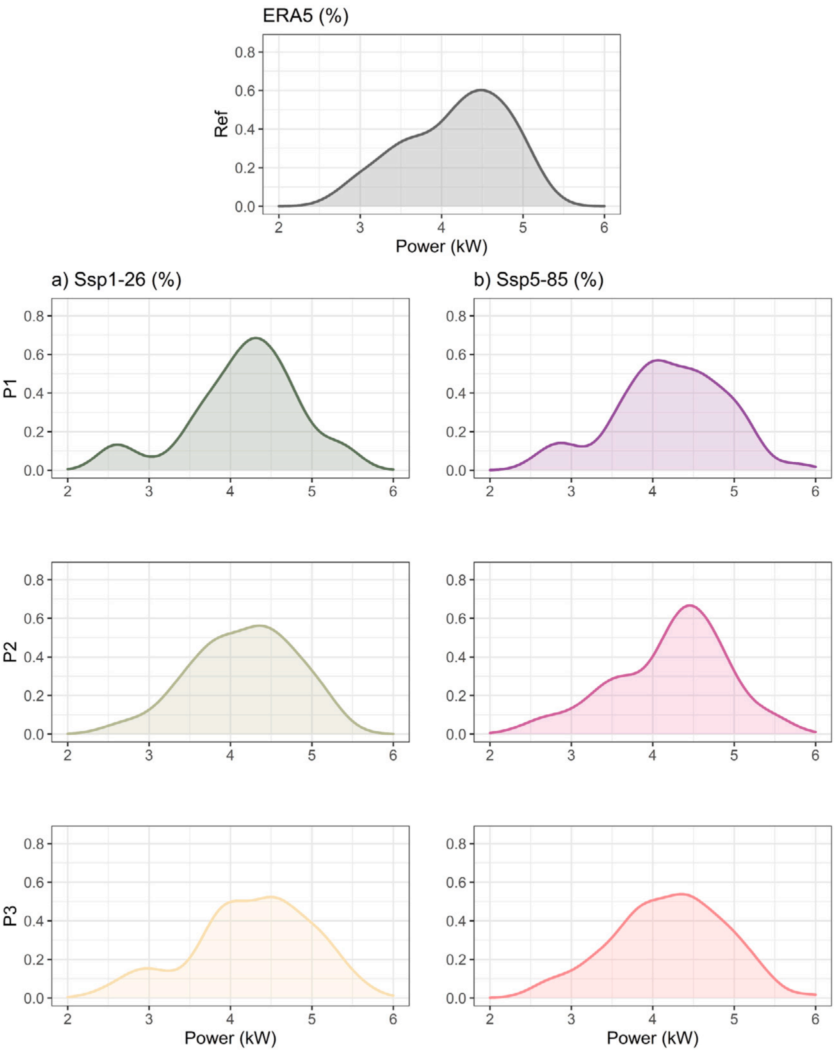

Fig. 5. The annual power (AP) by period (Ref, P1, P2, and P3) in the Mutriku Wave Energy Plant for the two different climate projections scenarios of (a) SSP1-2.6 and (b) SSP5-8.5.

power (Ringwood and Brandle, 2015). Similarly, (Iglesias and Carballo, 2010) analysed the special features of the Bay of Biscay, detecting specific points (hot spots) with a high concentration of wave energy, which constitute nearshore areas with the highest potential for the location of wave farms. Some of these points include the coast between Suances and Santander, as well as the coastal stretches from Cape de Ajo to Bilbao and from Cape Machichaco to Getaria. The Mutriku Wave Energy Plant is located between Cape Machichaco and Getaria.

5. Conclusions

Considering the SSP1-2.6 (low-forcing sustainability) and SSP5-8.5 (high-end forcing simulated) pathways, the frequencies of the sea types in the Bay of Biscay are not expected to change over the next 80 years.

This study represents the first exploration of the potential impact of climate change on a wave energy plant operating over a long period. The results indicate that the $T02$ turbine installed at the Mutriku Wave Energy Plant will generate a similar amount of annual power from 2015–2100. If the same set of maintenance protocols and operational turbines are kept constant (Ibarra-Berastegi et al., 2018; Serras et al., 2019), the Mutriku Wave Energy Plant will provide the same amount of yearly production in the coming decades. This ensures stability in power generation, thereby enabling the location to provide a consistent source of energy.

The importance of this study lies in ensuring the sustainability of stable wave energy production and analysing the long-term variations in wave power. This is crucial for the viability of renewable energy plans in the region and country, as well as for determining the future role of marine energy.

Based on the preliminary findings from the CMIP6 projections, the future evolution of wind variables remains uncertain over time. In Europe, a study conducted by Carvalho et al. (2021) indicated that under the SSP5-8.5 scenario, there is a projected decrease in wind resources for almost all of Europe by 2100. However, under SSP2-4.5, some areas may experience slight increases. We note that these potential changes were unlikely to have a significant impact on wave energy generation in the study area. This turning point, compared with historically positive wave and wind energy trends (Ulazia et al., 2017; Carreno-Madinabeitia et al., 2021) is consistent with the effect of global stilling identified in recent studies (Zeng et al., 2019).

6. Future outlook

Future studies should analyse the physical mechanisms underlying the changes in wave energy at a regional scale. This analysis can explore the possible influences of relevant climate variability models, such as the North Atlantic Oscillation (NAO) (Dupuis et al., 2006), East Atlantic pattern (EA) (Cozannet et al., 2011), and the El Niño-Southern Oscillation (ENSO), amongst other potential candidates. In the next few decades, the climatic change signature is expected to be found in changes in the swell component (Lemos et al., 2021).

A recent study suggested that the observed trends in the North Atlantic of Hs over the last few decades can be mainly attributed to natural variability and not anthropogenic forcing (Hochet et al., 2023). These Hs trends in the internal area of the Bay of Biscay are small (Hochet et al., 2023) and can be attributed to changes in swell (Bahareh et al., 2022), which agrees with more local studies developed by previous studies (Ibarra-Berastegi et al., 2021).

Furthermore, from a techno-economic perspective, the relationship between the sea states and energy production of the Mutriku OWC technology, in combination with future projections of wave parameters, can be used to optimise this technology according to its optimal design and sizing (Simonetti and Cappietti, 2023; Ulazia et al., 2020). Future variations in the wave period are relevant for this techno-economic efficiency, because period deviations from the optimum resonance point of the device as a function of the width of the main OWC chamber would significantly affect its performance (Ulazia et al., 2023).

However, we note that, in the context of this part of the Bay of Biscay, the WEF trends seem to exhibit a turning point during this decade, coming from an upward trend (Ibarra-Berastegi et al., 2021) to a constant value in the next few decades, as the results of this study suggest. If the Mutriku Wave Energy Plant has so far shown constant electricity production in the context of increasing WEF values, it can also be expected to continue generating electricity at the same rate if, as shown in this study, the WEF values stabilise in the forthcoming decades. Unlike other contexts (Simonetti and Cappietti, 2023), this implies a constant performance of existing OWC devices designed to maximise production under current day conditions; therefore, no change in the OWC dimensions is required.

Additionally, if, after testing the new turbines within the framework of the TurboWave project, it is decided to implement this new technology at the Mutriku Wave Energy Plant and the operating data are made public, the projections and predictions of electricity generation for this plant will be more accurate. Moreover, if not all turbines are replaced, we will have the opportunity to compare the differences in the operation and performance of both types of turbines.

CRediT authorship contribution statement

Sheila Carreno-Madinabeitia: Conceptualization, Data curation, Formal analysis, Investigation,Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Paula Serras:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Gabriel Ibarra-Berastegui:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jon Sáenz:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Alain Ulazia:** Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

Data availability

The authors do not have permission to share data.

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