



Research paper

Wave-resolved dynamics and power generation at the Mutriku wave farm: Oceanic resonance and evidence of Zipf's law

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ABSTRACT

In this study, Supervisory Control and Data Acquisition (SCADA) records sampled at 0.5 s intervals at the Mutriku wave farm, covering the period from August 2018 to July 2019, were analyzed. The dataset was decomposed into more than 3.2 million individual pressure cycles of varying duration within the air chamber and subsequently examined following their classification into nine daily sea state categories. On this basis, 7353 operating points, relating instantaneous pressure, rotational speed, and generated power, were identified and employed to fit the operational surface of the Mutriku plant.

The relationship between the air-chamber dynamics and oceanic conditions at the nearest ERA5 grid point was also investigated. The results indicate that the air chamber exhibits the characteristics of a resonant cavity, in which the mean wave period and wave amplitude are directly associated with the cycle duration and the pressure developed within the chamber, respectively.

Finally, the adherence of the wave farm records and ERA5 open-ocean variables to Zipf's law was evaluated. This preliminary assessment enabled the identification of variables that comply with Zipf's law and those that do not. This constitutes an initial step toward a systematic investigation of the extent to which oceanic variables follow Zipf's law.

1. Introduction

1.1. Energy from oceans

The global transition toward a decarbonized energy system has accelerated the exploration of marine renewable energy as a key mechanism to mitigate greenhouse gas emissions and meet international climate targets (IRENA, 2023). Ocean renewable energy constitutes a vast and largely untapped resource with significant potential to support the European Union's objective of achieving climate neutrality by 2050 (Lehmann et al., 2017; European Commission, 2020).

The theoretical potential of marine energy is substantial. Global assessments indicate that ocean energy resources could generate between 45,000 and 130,000 TWh per year (IRENA, 2020), exceeding current global electricity demand, estimated at approximately 22,800 TWh/year (Khan et al., 2022). In particular, wave energy is widely recognized as a largely untapped resource, with the global wave resource estimated to be in the range of 1–10 TW (Guo and Ringwood, 2021).

However, despite this high resource availability, the development of marine energy technologies remains markedly asymmetrical. Offshore wind has reached industrial maturity, with reported LCOE values in the range of 68–102 USD/MWh and large-scale deployment at the gigawatt level (Barthelmie et al., 2023). In contrast, wave energy converters (WECs) remain at pre-commercial stages, with installed capacities limited to pilot projects on the order of tens of megawatts and typical LCOE values ranging between 300 and 1000 EUR/MWh depending on location and technology (Ibarra-Berastegui et al., 2023; Guo and Ringwood, 2021; Ezpeleta et al., 2026). Recent analyses based on CMIP6 projections indicate statistically significant, climate-driven modifications in global offshore resources over the coming decades (Martinez and Iglesias, 2024; Casas-Prat et al., 2024; Köhler et al., 2025). In contrast, within nearshore environments suitable for the deployment of wave-energy farms, the projected impacts are spatially limited, with only a relatively small number of areas expected to

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List of abbreviations

A_q	Amplitude of the q th tidal constituent in harmonic analysis
$Cyc\ Len$	Cycle length (s)
ΔP	Maximum pressure variation within the air chamber in each individual cycle (Pa)
$\Delta P(t)$	Time series of ΔP along a period (Pa)
ΔP_0	Mean value of ΔP (Pa)
$\Delta P_{1/3}$	Average of the highest third of ΔP records
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Latest reanalysis by the ECMWF
f_q	frequency of the q th tidal constituent in harmonic analysis
$f(r)$	frequency of occurrence of a word with a specific rank to test Zipf's law compliance
H_s	Significant wave height of combined wind waves and swell (m)
I_{pres}	Instantaneous pressure in the air chamber
I_{pow}	Instantaneous electric power generated by T02
I_{rot}	Instantaneous rotational speed of the Wells group
MAEP	Mean Annual Energy Production
ρ	Exponent (slope) of the Zipf's law
r	Rank of a specific word to test Zipf's law compliance
R^2	Squared correlation coefficient or coefficient of determination
SCADA	Supervisory Control and Data Acquisition
SOM	Self-organizing maps
SS	Sea state types in Mutriku
SW_p	Swell period (s)
T02	The second turbine of Mutriku's wave energy farm
T_m	Mean wave period (s)
t_i	Hourly step in harmonic analysis
u_{10}	Zonal component of the wind speed (m/s)
v_{10}	Meridional component of the wind speed (m/s)
WAM	Wave model incorporated into the ERA5 reanalysis
WEF	Wave Energy Flux (kW/m)
WS	Wind speed (m/s)
WW_p	Wind waves period (s)
ϕ_q	Phase of the q th frequency which determines its temporal shift in harmonic analysis

exhibit changes, and these changes are generally of small magnitude (Ibarra-Berastegui et al., 2023).

1.2. Mutriku wave farm

Mutriku is a breakwater-integrated wave-energy plant situated in the eastern Cantabrian Sea, in Northern Spain (Fig. 1).

It typically generates above 200 MW-h of electricity per year and, on average, operates roughly ten devices out of a total of 14 Oscillating Water Column (OWC) Wells groups (Ibarra-Berastegui et al., 2018). Each group consists of two Wells rotors, each with a diameter of 0.75 m, coupled on both sides of an intermediate electric generator rated at 18.5 kW, with a nominal rotational speed of 3000 rpm (M'zoughi et al., 2024).

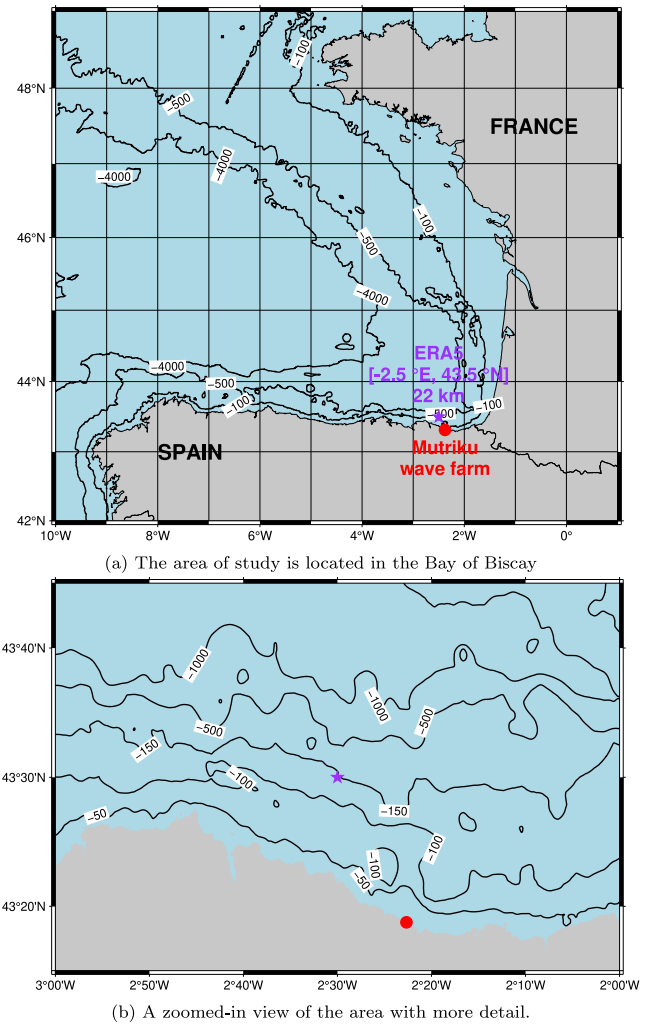


Fig. 1. Location of Mutriku wave farm and reference ERA5 gridpoint.

The turbine assembly is installed above an air chamber with a rectangular cross-section of 4 m × 3.1 m (Lekube et al., 2018) (Fig. 2). This chamber is open to the sea, and the incoming and receding waves produce alternating (direct and reverse) air flows that drive the Wells turbine located above. Remarkably, Mutriku is the only wave farm in the world that has been delivering electricity continuously for more than 15 years, offering an unparalleled record of operational data. Its main operational characteristics have been thoroughly reported in the literature (Ibarra-Berastegui et al., 2018; Lekube et al., 2018; Serras et al., 2019; Torre-Enciso et al., 2009; Casas and Lekube, 2024; Lopez-Mendia et al., 2025).

Systematic data acquisition through Mutriku's SCADA system has also enabled the development of short-term (Serras et al., 2019; Casas and Lekube, 2024) and climate-driven long-term (Carreno-Madinabeitia et al., 2024) electricity-production forecasting models. In addition, using daily-averaged SCADA data and self-organizing maps (SOM) for 1979–2019, the authors identified ten dominant daily electricity-generation patterns, each associated with one of ten sea state (SS) types in the waters off Mutriku (Ibarra-Berastegui et al., 2021).

1.3. Characteristic curves and modeling of OWC systems

The performance of OWC systems has traditionally been analyzed through the coupling between the air chamber dynamics and the

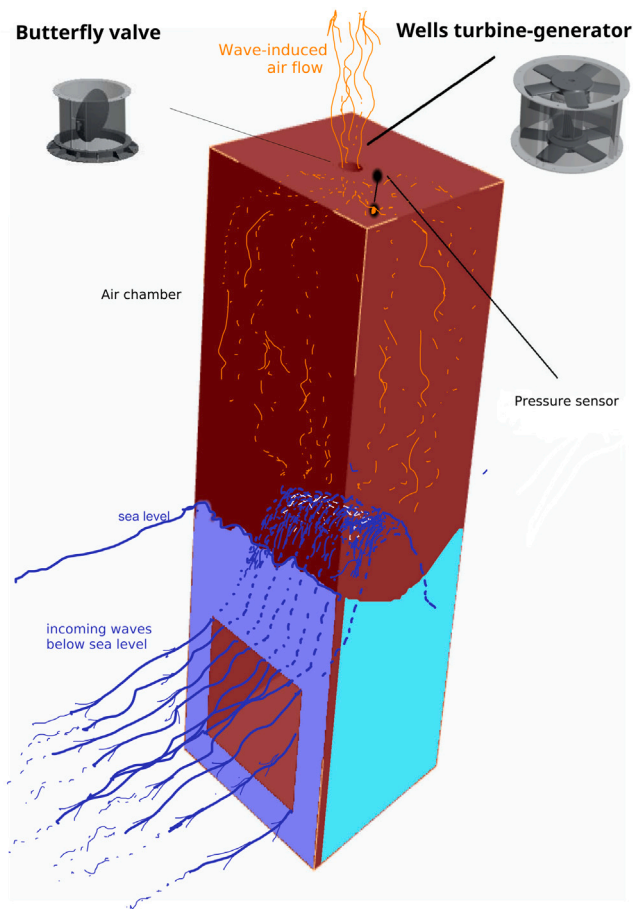


Fig. 2. Mutriku's air chamber and Wells group.

turbine response, which are often represented through characteristic relationships between pressure drop, airflow rate, and turbine efficiency, as widely reported in experimental and numerical studies (Fenu et al., 2024; Ordoñez-Saca et al., 2025; Brito-Melo et al., 2002). In Wells turbine-based systems, these relationships are commonly expressed in terms of dimensionless parameters such as the flow coefficient and other dimensionless performance coefficients related to torque and efficiency, which together define the operational envelope of the turbine under oscillatory flow conditions (Brito-Melo et al., 2002; de O. Falcão, 2010). Numerous authors have underscored the critical role of air-chamber geometry in the design and performance of oscillating water column (OWC) systems (Lopez-Mendia et al., 2025; Falcão and Henriques, 2016; Davidson et al., 2020; Izquierdo et al., 2025). Nevertheless, in the particular context of existing, operational wave farms (such as the Mutriku plant), post-construction modification of the air-chamber dimensions is not practicable, and these geometric characteristics must therefore be regarded as fixed design parameters.

These characteristic relationships play a key role in determining the energy conversion efficiency, as they govern the interaction between the oscillating air flux generated by the waves and the aerodynamic response of the turbine. Experimental and numerical studies have shown that the turbine exhibits an approximately linear relationship between pressure drop and flow rate under normal operating conditions, before the onset of stall phenomena, which introduce significant nonlinear effects at higher flow conditions (Fenu et al., 2024). This transition has been widely identified as one of the main limitations of Wells turbine performance, particularly under irregular sea states where the airflow conditions span a wide operating range.

A large portion of the existing literature has focused on modeling and optimizing these characteristic relationships through Computational Fluid Dynamics (CFD), laboratory experiments, and simplified analytical approaches. In particular, several studies have highlighted the importance of the interaction between chamber geometry, internal airflow dynamics, and turbine performance in determining the overall system efficiency, especially when the coupling between the pneumatic chamber and turbine response is explicitly considered (Ordoñez-Saca et al., 2025; Brito-Melo et al., 2002). These works demonstrate that optimal performance is achieved when the turbine damping is properly matched to the hydrodynamic response of the OWC chamber, enabling resonance conditions that maximize energy extraction (Lopez-Mendia et al., 2025; Falcão and Henriques, 2016; Davidson et al., 2020; Izquierdo et al., 2025; de O. Falcão, 2010).

Although Mutriku represents the most extensive operational case with long-term data availability, being one of the first commercial OWC wave power plants to provide continuous operational data over several years (Ibarra-Berastegi et al., 2018, 2021), earlier OWC systems employing Wells turbines have provided key insights into coupled chamber–turbine dynamic and are direct technological precursors to later systems such as Mutriku (de O. Falcão, 2010).

Despite these advances, most existing studies are based on controlled experiments or numerical modeling (de O. Falcão, 2010), with limited validation under real operating conditions. While previous OWC installations such as LIMPET, Pico, and Sakata provided fundamental insight into chamber–turbine coupling and characteristic relationship behavior, the availability of long-term operational data under realistic and highly variable sea conditions remains limited.

Recent studies note that experiments are often performed under simplified or non-representative conditions, which may not reflect OWC behavior in real sea states (Licheri et al., 2025). Yet characterization using long-term, high-frequency operational data remains scarce, especially under real conditions like Mutriku. Improving marine-energy resource assessments therefore requires systematic validation with high-frequency operational measurements to better represent in situ energy conversion.

1.4. Objectives

In this context, the objectives of this paper are as follows:

1. Reconstruct the operational envelope of the Mutriku wave power plant on a cycle-by-cycle basis through detailed performance analysis.
2. Investigate the manner in which the local oceanographic conditions in the vicinity of Mutriku are manifested within the plant's air chamber.
3. Assess the extent to which Zipf's law is satisfied by (i) the internal variables characterizing the air chamber dynamics and (ii) the relevant oceanographic variables associated with wave energy, as derived from the ERA5/WAM reanalysis.

The remainder of this paper is structured as follows. The data employed and the methodological approach adopted are described in the next section. Subsequently, the results are presented, followed by a discussion, conclusions, and an outlook on potential directions for future research.

2. Data and methodology

In this section the data used and the methodology employed will be explained

2.1. Data

In Mutriku, the SCADA system records, at 0.5 s intervals, measurements of:

1. air-chamber pressure located below the turbine,
2. turbine rotational speed, and
3. electrical power produced by the generator driven by the Wells turbine.

In this study, 0.5 s records covering the period from August 2018 to July 2019 corresponding to one Wells group (Turbine #2, T02) were used. First, after data cleaning, the records were synchronized and aligned to the UTC reference timeline to allow comparison with hourly ERA5 data at the nearest grid point [-2.5° E, 43.5° N] from Mutriku (22 km of distance). In the absence of in situ measurements for the waters surrounding Mutriku and following the approach adopted in previous studies (Ibarra-Berastegi et al., 2021), this work assumes that ERA5 — despite some aspects discussed below in Section 4. Discussion — oceanographic data at the nearest grid point provide a sufficiently accurate approximation of the local marine conditions.

When a new wave enters the air chamber, the pressure begins to rise, and as the wave recedes, a suction effect occurs (Fig. 2). Consequently, the passage of each individual wave through the chamber can be followed via the air pressure signal, which clearly describes a pressure cycle beginning as the wave enters and ending as it exits. Based on this, in a second step, for all records, pairs of successive local minima in the chamber air pressure were identified so that the data could be analyzed on a cycle-by-cycle basis.

Consequently, between August 2018 and July 2019, more than 3.2 million cycles (3,206,806) with durations ranging from 1.5 s to 20 s were analyzed. For each individual cycle, measurements acquired at 0.5 s intervals enabled a joint characterization of the temporal evolution of the air-chamber pressure as a function of sea state. Fig. 3 presents, for the various sea states, the mean pressure profile inside the air chamber, computed from a total of 232,021 cycles of 5 s duration. The overall profile exhibits a predominantly parabolic shape; however, for the sea states associated with the highest significant wave heights H_s (Table 1), such as $SS04$, $SS02$, and $SS06$, the pressure oscillations are more pronounced. This behavior is consistent with, and suggests, a relationship between wave height and pressure intensity within the air chamber.

To characterize each cycle, the following three variables were considered:

1. Cycle length in seconds, $CycLen$
2. The maximum pressure variation recorded within each cycle (Pa), ΔP
3. If there is such a relationship between incoming wave heights and pressure, the hourly average of the highest third of ΔP records, $\Delta P_{1/3}$, can also be expected to be related to the significant wave height H_s and for this reason, was also computed

Besides, instantaneous pressure $Ipres$, rotational speed $Irot$ and electric power $Ipow$ at the Wells group were available from the SCADA records, thereby enabling a complete energetic characterization of each individual cycle at a temporal resolution of 0.5 s.

Finally, hourly ERA5 data from [-2.5° E, 43.5° N] for the following variables were retrieved from ECMWF and, in certain cases, further derived:

1. Mean wave energy period (s), T_m
2. Significant wave height (m), H_s
3. The wave energy flux, WEF (kW/m), computed by combining the two previous variables using Eq. (1) (Bidlot, 2016; Multon, 2013):

$$WEF = 0.49 \cdot T_m \cdot H_s^2 \quad (1)$$

Mean pressure in the air chamber every 0.5 s
Cycles of 5 s for the different SS

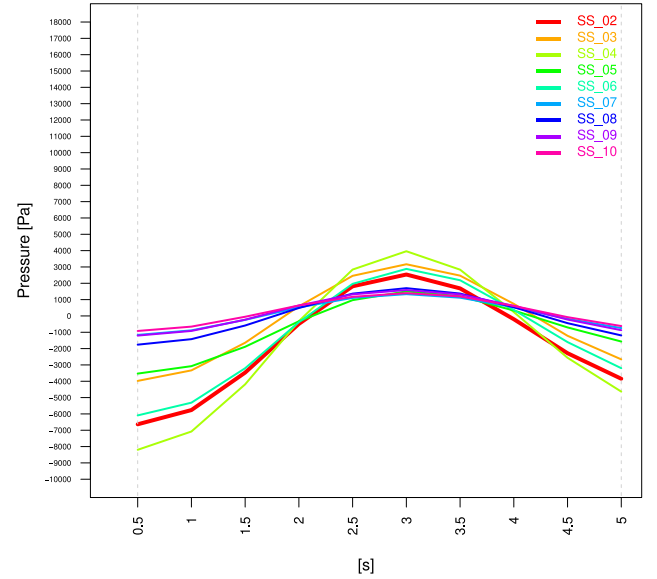


Fig. 3. Mean pressure evolution in the air chamber for cycles of 5 s by SS .

4. Wind wave period (s), WW_p
5. Swell period (s), SW_p
6. Zonal wind speed component (m/s), u_{10}
7. Meridional wind speed component (m/s), v_{10}
8. Wind speed, WS derived from u_{10} and v_{10} as the square root of the sum of squares.

The authors had previously developed, for the Mutriku facility, a classification methodology based on Self-Organized Maps (SOM) of sea state types (Ibarra-Berastegi et al., 2021), SS , with a focus on energy generation at a daily temporal scale using the aforementioned ERA5 variables. This approach enabled now the classification of each of the 365 days within the analyzed period into distinct sea state types, SS .

For each of the 365 days in the August 2018–July 2019 period categorized by SS , 24 hourly ERA5 variables were available. For every hour, a varying number of cycles, between 10,000 and 14,000, were recorded, each with an average duration of about 8 s. For each cycle, ΔP values were computed, and rotational speed and instantaneous power were obtained from the SCADA records.

All these variables were merged and synchronized onto a single time axis. ΔP is obtained within each cycle of varying length $CycLen$. At the 0.5-second resolution, $Ipres$, $Ipow$, $Irot$ are available, while $\Delta P_{1/3}$ and the ERA5 variables are piecewise constant over each hour and apply to all cycles occurring within that hour. The SS classification is defined at the daily level, remaining unchanged throughout the day, whereas ERA5 variables vary hourly and covers all cycles executed on that particular day.

The averages by SS for the analyzed period are presented in Table 1. The sea state $SS01$ corresponds to an extreme and infrequent condition which, although reported in the original (Ibarra-Berastegi et al., 2021) and further studies (Carreno-Madinabeitia et al., 2024), does not occur within the August 2018–July 2019 interval considered here. Nevertheless, $SS01$ is retained in the tables to maintain consistency with the established classification.

2.2. Methodology

2.2.1. Operational surface

To extract meaningful information from the large volume of measurements, the cycles were analyzed as a function of SS and cycle

Table 1
Averages by sea state types. August 2018–July 2019.

SS	[%] occurrence					Air chamber			ERA5 [−2.5° E, 43.5° N] ≈ 22 km from Mutriku					
	Total	Winter	Spring	Summer	Autumn	ΔP [Pa]	$\Delta P_{1/3}$ [Pa]	Mean cycle length [s]	T_m [s]	H_s [m]	WEF[kW/m]	WS[m/s]	$W W_p$ [s]	$S W_p$ [s]
SS01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SS02	0.6	100.0	–	–	–	16 824.4	31 329.5	8.8	8.8	3.8	75.7	13.4	5.9	9.3
SS03	5.2	39.4	39.5	5.5	15.5	10 582.1	17 994.6	8.8	9.4	2.3	24.9	6.9	3.3	9.1
SS04	2.2	13.7	86.3	–	–	19 108.6	32 098.4	8.2	10.9	3.9	82.3	10.7	5.1	11.5
SS05	9.7	28.9	42.1	29.0	–	9 295.3	16 362.5	9.7	11.7	2.1	25.1	5.4	2.7	10.5
SS06	6.0	29.6	47.3	23.1	–	14 667.9	24 954.5	8.9	11.5	2.8	46.3	6.8	3.2	10.8
SS07	5.2	21.2	20.6	33.4	24.7	3855.1	6946.4	7.4	6.7	1.1	5.7	4.7	2.6	5.9
SS08	25.1	32.7	26.1	6.6	34.6	4884.5	8696.7	9.5	9.7	1.3	8.8	4.6	2.5	8.3
SS09	28.4	22.6	16.4	40.4	20.7	3895.1	6870.1	8.5	7.7	1.1	5.1	4.3	2.4	6.7
SS10	17.6	24.9	6.9	61.3	6.9	2444.6	4345.3	7.4	5.5	1.0	3.4	2.0	2.8	5.4

length. For instance, the most frequent sea state is *SS09* (28.4% occurrence, Table 1), and within this sea state the most common cycle duration is 5 s. All cycles of this length (a total amount of 60498 pressure cycles between two individual waves) occurring under *SS09* were averaged, yielding a joint characteristic profile of rotational speed, air-chamber pressure, and instantaneous power over the ten 0.5 s time steps defining the 5 s cycle (Fig. 4). These ten points define the actual operating conditions of the T02 turbine. In all cases, the records exhibit minimal dispersion around these points, forming a unimodal distribution with a narrow spread.

Fig. 4 illustrates the behavior of turbine T02 during each cycle and clearly depicts the interaction between the airflow to and from the air chamber and how the instantaneous regulation algorithms influence the resulting rotational speed and electrical power. This behavior can be generalized to the remaining cycles and *SS*, which follow a similar pattern. Typically, each cycle begins with negative pressure, reaches peak rotational speed and electrical power at an intermediate stage, and concludes with a reduction in pressure, speed, and power.

Fig. 4 depicts the temporal relationship between chamber pressure, turbine rotational speed, and electrical power output during a representative 5-second averaged cycle under Sea State 09 conditions. This figure extends the analysis presented in Fig. 3, which illustrates the mean pressure evolution within the chamber for the averaged 5-second cycles corresponding to the different sea-state categories. Specifically, Fig. 4 combines the averaged pressure profile with the corresponding variations in rotational speed and generated power over the course of the cycle. Thus, it provides an integrated representation of the system response by summarizing the mean temporal evolution of chamber pressure, turbine rotational speed, and power output at 0.5-second intervals throughout a 5-second cycle under *SS09*. This visualization facilitates the interpretation of the coupling between the hydrodynamic forcing induced by wave motion and the resulting electromechanical performance of the energy conversion system.

An interactive 3D HTML representation of this static plot (Fig. 4) is available in **Supplementary Material section.10.1** and can further aid in understanding this general behavior.

Across all *SS* conditions and operating cycles, qualitatively similar characteristic curves were obtained. Taken together, the centroids associated with the individual time steps of these curves constitute a set of 7353 operating points in the corresponding state space. The final step consisted of fitting a continuous surface through these 7353 representative points. The progression from 3.2 million individual waves, to 7353 representative points, and finally to the fitted surface constitutes an effort to condense the vast amount of operational information contained in the SCADA records into a concise and interpretable description of the wave-to-electricity conversion process at the Mutriku wave farm.

To evaluate the error introduced by this information compression process, the MAEP (Mean Annual Energy Production) has been used. MAEP is an energy performance indicator that measures annual electricity generation and is commonly employed for marine energy plants, Kofoed and Folley (2016) making it a suitable metric for assessing this type of installation. It is assumed that the MAEP calculated from the contributions of the 3.2 million cycles and recorded in the SCADA system represents the actual annual electricity production at Mutriku.

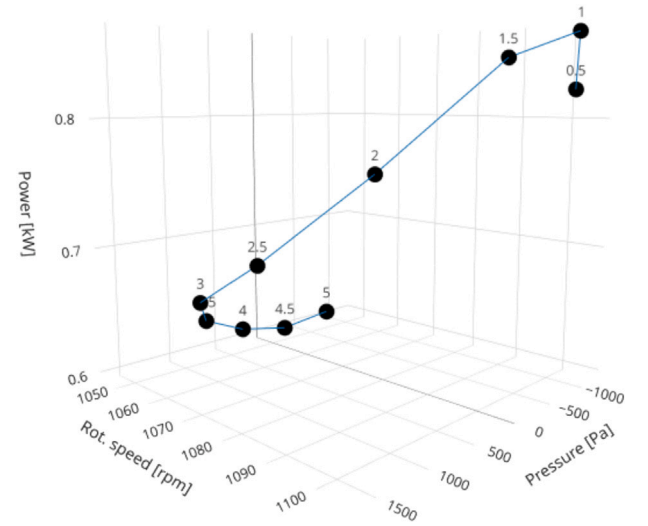


Fig. 4. Average generation cycle of 5 s at 0.5 s time steps under *SS09*.

The MAEP values obtained will first be evaluated using the 7353 representative points and subsequently using the surface fitted from those points.

2.2.2. Cycles in the air chamber

Since one of the objectives was to examine how oceanic variables correlate with the measurements at Mutriku's air chamber, three initial assumptions were made:

1. the duration of each individual wave cycle in the air chamber was correlated with the wave periods recorded at the Mutriku breakwater.
2. the pressure variation, ΔP , recorded for each wave within the air chamber was associated with the corresponding wave heights at the breakwater. More specifically, an analogy can be drawn with the conventional definition of the significant wave height, such that the hourly mean of the highest one-third values of ΔP (denoted as $\Delta P_{1/3}$) can be expected to exhibit a correlation with H_s .
3. for comparative analysis, hourly ERA5 oceanic data at the closest grid point ([−2.5° E, 43.5° N] ≈ 22 km from Mutriku), were available. Consequently, the comparison had also to be performed at an hourly temporal resolution.

However, it must be noted that mainly ΔP can be affected by the evolution of sea level along the year due to the tides. To evaluate this, a harmonic analysis was carried out on the 8760 hourly means of ΔP averaged from the 3,206,806 cycles corresponding to the period analyzed.

Table 2

Major tidal constituents with their periods and magnitude ratios.

Tidal constituent	Frequency (cycles/hour)	Period (h)	Magnitude ratio
M2 (principal lunar)	$f_1 = 0.0805$	12.4	1.000
K1 (luni-solar)	$f_2 = 0.0418$	23.9	0.584
S2 (principal solar)	$f_3 = 0.0833$	12.0	0.465
O1 (principal lunar)	$f_4 = 0.0387$	25.8	0.415
P1 (principal solar)	$f_5 = 0.0416$	24.1	0.193
N2 (larger lunar elliptic)	$f_6 = 0.0790$	12.7	0.192
MF (lunar fortnightly)	$f_7 = 0.0031$	324.4	0.172
MM (lunar monthly)	$f_8 = 0.0015$	673.8	0.091

2.2.3. Harmonic analysis

Because tidal sea level variations are driven by the periodic gravitational forcing of the Moon and the Sun, harmonic analysis has long been regarded as an appropriate and effective method for characterizing tidal evolution ((Thomson and Emery, 2024) and references therein).

The primary impacts of lunar and solar gravitational forces on sea level (Thomson and Emery, 2024) are summarized in Table 2. The magnitude ratio indicates the relative influence of each tidal constituent — named following commonly accepted conventions — compared to the dominant one (M2):

Although harmonic analysis has traditionally been applied to sea level representation, in the present context, the target is a completely different variable like ΔP , that is, the pressure variation of an air chamber exposed to sea waves. Nevertheless, the method can still be applied with confidence to estimate the impact of the combined harmonic tidal constituents mentioned above (Table 2) on ΔP .

Accordingly, the temporal evolution of $\Delta P(t)$ within the harmonic analysis framework can be expressed as shown in Eq. (2).

$$\Delta P(t_i) = \Delta P_0 + \sum_{q=1}^8 A_q \cos(2\pi f_q t_i + \phi_q) \quad (2)$$

where ΔP_0 represents the mean value of ΔP along the whole period, and the summation accounts for the harmonic tidal constituents in Table 2, corresponding to the eight leading frequencies. t_i denotes the 8760 hourly time steps that span the analyzed period (August 2018–July 2019). Each harmonic component is defined by an amplitude A_q , describing its contribution to the overall signal, and a phase ϕ_q , which determines its temporal shift. The parameter f_q is the frequency associated with each of the 8 tidal components considered above.

This formulation provides a decomposition of the signal into a superposition of cosine functions with distinct amplitudes and phases. A comprehensive description of the theoretical background and practical implementation of harmonic analysis can be found in Foreman and Henry (1989), Boon and Kiley (1978), Pawlowicz et al. (2002), Jiao et al. (2026).

After fitting Eq. (2) and the subsequent estimation of the associated amplitudes and phases, the hourly ΔP time series was reconstructed using the eight frequencies corresponding to the principal tidal constituents enumerated in Table 2.

Obviously the hourly ΔP time series is not a purely harmonic signal but a fraction of its variability can be expected to be driven by the harmonic tidal constituents that influence sea level changes. This could be affecting the air-filled volumes in the chamber and may also influence on the pressure generated within it.

The proportion of variance in the observed ΔP series accounted for by Eq. (2) is interpreted as the contribution of tidal forcing to the hourly variability of ΔP . This contribution is quantified by the squared correlation coefficient (R^2), also referred to as the coefficient of determination.

To that purpose, the coefficient of determination between the observed ΔP and the reconstructed series based on the tidal harmonics

ΔP values in Mutriku's air chamber
Harmonic fraction attributable to tidal forcing

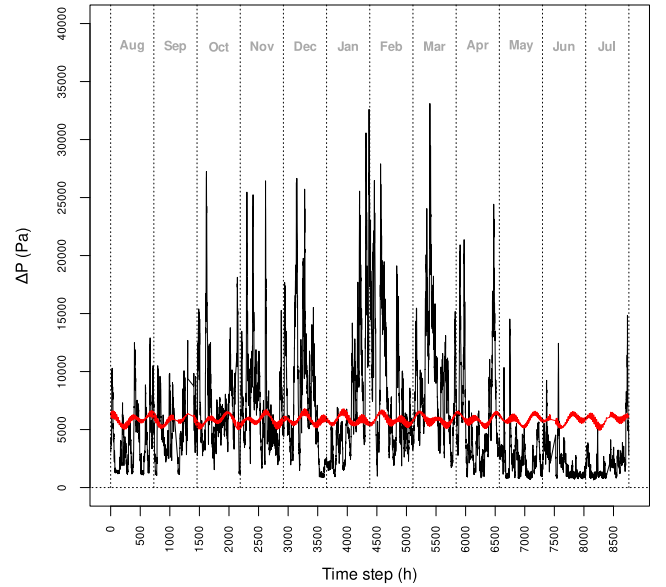


Fig. 5. Hourly values of ΔP and the harmonic fraction (red) attributable to the tidal constituents of Table 2. August 2018–July 2019.

according to Eq. (2) was computed. The results indicated that the 95% confidence interval of R^2 —calculated using bootstrap resampling—was [0.00424, 0.00716 (median), 0.01092].

While this value is statistically different from zero, it represents a very small effect, implying that tidal influences account for only about 0.72% of the total variance in the air chamber pressure.

A graphical representation of the magnitude of this tidal forcing can be seen in Fig. 5.

Given this negligible contribution, further analyses were therefore manageable and concentrated on comparing the observations in the Mutriku air chamber with ERA5 ocean variables, which are unaffected by tidal variability.

2.2.4. Comparison with ERA5 nearest gridpoint

As previously explained, cycle lengths were treated as a direct estimate of wave periods. For each SS , the distribution of cycle lengths was considered potentially related to the various ERA5 wave periods obtained at a distance of 22 km (mean wave period T_m , wind wave period WW_p , and swell period SW_p).

In addition, ΔP was expected to show a correlation with wave heights. The ERA5 reference variable used was the significant wave height, which is defined as the mean of the highest one-third of individual wave height measurements and typically follows a Rayleigh distribution (Bidlot, 2016). Assuming that ΔP can act as a proxy for H_s , in this study, for each SS the mean of the uppermost one-third of the ΔP values ($\Delta P_{1/3}$) was likewise calculated. In a second step, $\Delta P_{1/3}$ was compared with the H_s values from the nearest ERA5 grid point.

2.2.5. Linguistic characterization of observations. Zipf's law

Zipf's law was originally formulated within the field of linguistics (Zipf, 2013). It characterizes the empirical relationship between the frequency of lexical items in a language corpus and their rank when all distinct words are ordered in descending order of occurrence. This regularity has been observed across a wide range of human languages (Mehri and Lashkari, 2016) and has been shown to provide a robust mathematical framework for analyzing not only natural languages, but also artificial and extinct languages (Stanisz et al., 2024) as well as undeciphered texts, including the Voynich manuscript (Montemurro

and Zanette, 2013). Zipf's law appears to extend to certain forms of non-human communication, including the vocalizations of some species such as the songs of humpback whales (Arnon et al., 2025).

Beyond linguistics, Zipf's law has been applied in various other domains and has proven useful for characterizing the fractal or scale-invariant properties of some geophysical variables (De Marzo et al., 2021; Newman, 2005), in fields like geology (Merriam et al., 2004) and hydrology (Pelletier, 1999).

The more general mathematical formulation of Zipf's law is as follows:

$$f(r) = c \cdot r^\rho \quad (3)$$

where r denotes the rank of occurrence of a specific word and $f(r)$ represents its corresponding frequency of occurrence

By applying a logarithmic transformation to Eq. (3), Zipf's law can be reformulated as a linear regression model, whose goodness of fit may be assessed through the coefficient of determination R^2 . Within this framework, the exponent ρ corresponds to the slope of the regression line — typically adopting negative values — in Eq. (4):

$$\log f(r) = \log c + \rho \log r \quad (4)$$

In this context, it is pertinent to highlight the study by (Primo et al., 2007), who applied Zipf's law to hourly precipitation records on a global scale. For each station, they partitioned the full range of precipitation into four intervals and assigned a distinct letter to each interval. Subsequently, for each week, the authors constructed a “word” composed of seven “letters” associated with the daily averages observed. Once these words had been constructed, their frequencies of occurrence over the analyzed period were evaluated for conformity with Zipf's law. The authors found that locations classified within the same Köppen climatic type tended to exhibit similar values of the slope ρ .

Given that the dataset available in the present work is considerably smaller, this methodology was adapted accordingly. Here, a letter was assigned to every 6-hour mean value of all variables, depending on the interval into which it fell: “A” for the first interval, “B” for the second, and “C” and “D” for the remaining two intervals. In all cases, the interval boundaries were defined by the 25%, 50%, and 75% percentiles computed from the full sample of observations. Thus, each day was divided into four 6-hour periods, and the corresponding four symbols (“A”, “B”, “C”, “D”) were concatenated to form a single four-letter daily “word”. In this formulation, each letter encodes the mean magnitude of the variable within one of these four sub-daily periods. This procedure yielded one daily word among the $4^4 \equiv 256$ possible combinations of the letters “A”, “B”, “C”, and “D”.

In this study, all previously introduced variables (Table 1) were examined for adherence to Zipf's law by applying a uniform methodological framework, which involved constructing daily four-letter word sequences.

Across all variables considered, for the August 2018–July 2019 period, this method produced a total of 365 daily four-letter words with an order of occurrence for each of the recorded words. Eq. (4) was then applied to evaluate their compliance with Zipf's law.

To the best of authors' knowledge, Zipf's law has never been tested in the context of wave farms or oceanic variables. For this reason, and despite the rather small amount of data available, it was decided to carry out this investigation, understood as a first step that in the light of its results, could provide some insight on how to proceed further to start developing a methodological framework to test Zipf's law in this context.

3. Results

To enable the joint analysis of variables defined on different temporal scales, averages were computed to match a common time scale across all variables involved.

Table 3

Electricity Generated by Turbine 02 (Aug 2018–Jul 2019).

Method	Electricity [kW-h]	Error [kW-h]	Error [%]
SCADA (Actual Production)	20,998.60	–	–
7353 points	21,375.58	376.98	1.80
Fitted Surface	21,842.29	843.69	4.01

3.1. Operational surface

The analysis by individual cycles and their subsequent calculation of their average performance when applied to all the sea states and cycle lengths, has led to the cloud of 7353 centroids for turbine T02 as shown in Fig. 6(a). A more visual and intuitive 3D HTML version of Fig. 6(a) can be downloaded from the **Supplementary Material section.10.1**

In Fig. 6(b), the 7353 mean operating points, or centers of gravity, for each *SS* are depicted. As shown in Table 1, the three most energetic sea states (i.e., those exhibiting the highest *WEF* values) are, in descending order, *SS04*, *SS02*, and *SS06*. Consequently, these states are located in the upper region of Fig. 6(b), corresponding to higher rotational speeds and greater generated power. Conversely, *SS10*, *SS09*, and *SS07* — the sea states with the lowest *WEF* values — are positioned in the region associated with the lowest power output and rotational speed.

The symmetry of Figs. 6(a) and (b) about the zero-pressure axis reflects the ability of the Wells group to operate effectively under both direct (overpressure) and reverse (negative pressure) airflow conditions, while essentially delivering the same electrical power output in each case.

In this work, the cloud of 7353 operational points has been fitted to a surface using a fourth-order polynomial equation (Eq. (5)) where the instantaneous electric power (I_{pow}) can be expressed as a function of instantaneous pressure in the air chamber (I_{pres}) and rotational speed of the Wells group (I_{rot})

$$I_{pow} = \sum_{i=0}^4 \sum_{j=0}^{4-i} a_{ij} I_{pres}^i I_{rot}^j \quad (5)$$

The agreement obtained between the cloud of points and the fitted surface has been $R^2 = 0.94$. The 95% interval for the residuals was $[-2.08, -0.0653 \text{ (median), } 1.95]$.

Similarly, an 3D interactive visualization and the agreement between the original cloud of 7353 points and adjusted surface, as well as the coefficients fitted can be found in **Supplementary Material section.10.2** for further examination.

To quantify the error introduced during the information-condensation process, from the original SCADA data (3.2M individual cycles) to the 7353 representative points and subsequently to the fitted surface, the total electricity generated (MAEP) between August 2018 and July 2019 at each stage was calculated. Considering that the temporal resolution of the dataset is 0.5 s, each instantaneous power value was multiplied by 0.5 s to obtain the corresponding energy contribution, which was then aggregated to determine the total electricity generation (kW-h) over the study period of one year (August 2018 to July 2019). The results can be seen in Table 3

The results presented in (Table 3) show that MAEP errors grow as the level of data compression increases. Moreover, electricity generation is not consistent across all sea states or wave-period ranges. As illustrated in Fig. 7, the SCADA data indicate that *SS09* together with wave periods of approximately 12–13 s is the combination that makes the largest contribution to total annual electricity generation (20,998.60 kW-h).

The distribution of MAEP errors reported in Table 3 is illustrated by sea state and cycle length in Fig. 8 (for the 7353 data points) and in Fig. 9 (for the fitted surface).

Combining the results shown in Table 3 and Figs. 8 and 9 above, it can be observed that, when moving directly from the SCADA records

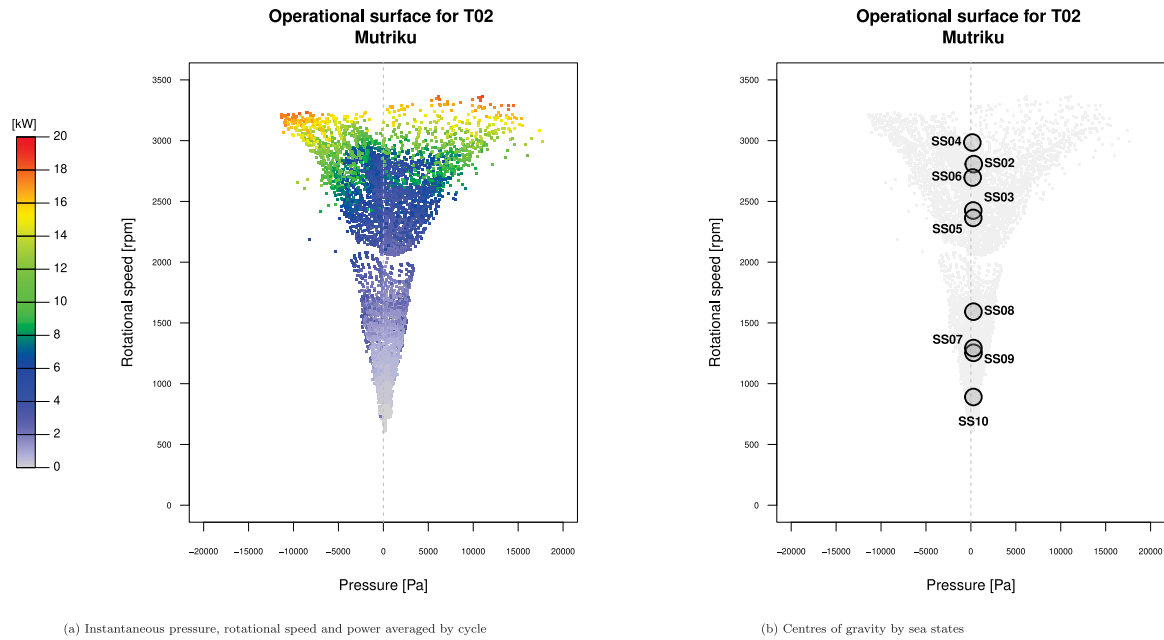


Fig. 6. Operational surface for T02 turbine.

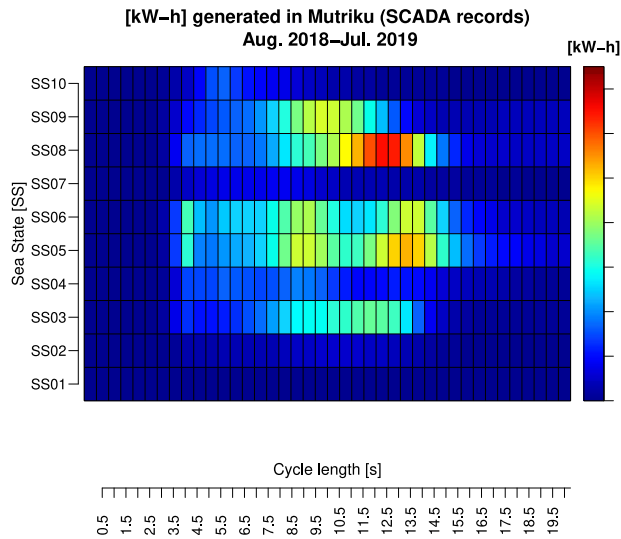


Fig. 7. Contribution by sea-state and cycle length to the 20998,6 kW-h (MAEP) generated in Mutriku by 3.2M cycles as recorded by the SCADA. August 2018–July 2019.

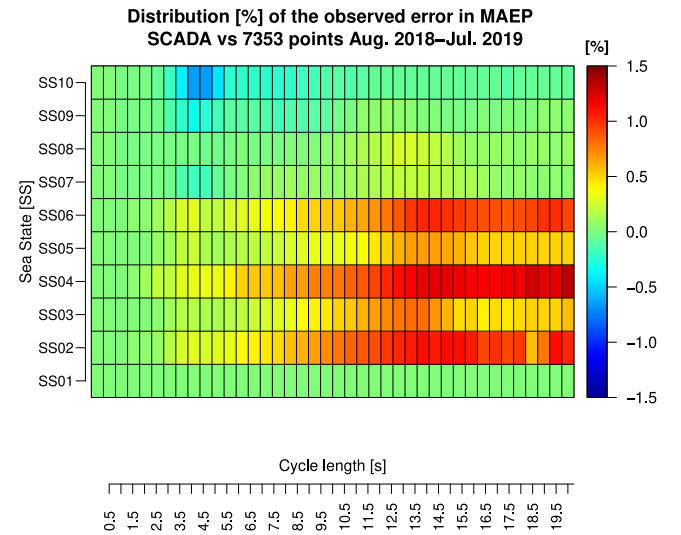


Fig. 8. Contribution by sea state and cycle length, expressed as percentages, to the MAEP difference (376.98 kW-h, Table 3) obtained using SCADA records and the 7353 centroids.

to the operational surface, the annual electricity production is overestimated by approximately 4.0% and tends to be concentrated within a relatively small number of sea states and cycle lengths. In contrast, the intermediate representation based on the 7353 averaged points results in a smaller overestimation of approximately 1.8% and distributed more uniformly across the full range of sea states and cycle lengths.

These results suggest that the fitted surface preserves the main characteristics of the turbine response while providing a substantial reduction in data complexity, at the cost of a relatively modest increase in error.

3.2. Oceanic resonance

In the following section, results are presented that support the interpretation of Mutriku's air chamber as a resonant cavity that is dynamically coupled to the prevailing surrounding oceanic conditions.

3.2.1. Mean wave period

Observed wave fields typically consist of a superposition of waves generated by local or regional winds (the so-called wind sea) and waves generated in remote oceanic regions that propagate over long distances (swell). These two wave systems exhibit distinct characteristics: wind sea waves commonly have characteristic periods of approximately 5 s, whereas swell periods are typically appearing from 8–10 s onwards, with some locations being in some occasions exposed to more than one swell (Holthuijsen, 2010). Depending on the sea state, the apportion of both elements may vary and as mentioned above, the cycle length *CycleLen* inside Mutriku's air chamber was considered to be directly connected with the wave period of the more than 3.2M individual waves hitting Mutriku and analyzed during the period of study. In Fig. 10, it can be seen the histograms of occurrence of *CycLen* by sea state.

The ERA5 ocean data at the grid point nearest to Mutriku, situated around 22 km offshore, cannot be regarded as an exact depiction of

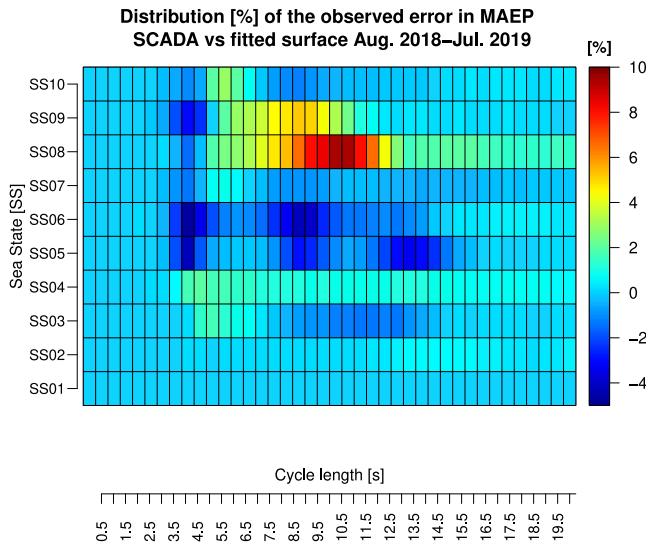


Fig. 9. Contribution by sea state and cycle length, expressed as percentages, to the MAEP difference (843,69 kW-h, Table 3) obtained using SCADA records and the fitted surface.

the wave conditions that eventually reach Mutriku's air chamber and contribute to electricity production. Nevertheless, a significant correspondence between both datasets can be expected, as demonstrated by previous studies, mainly in the casual relationship between sea state types and electricity generation patterns established by authors (Ibarra-Berastegui et al., 2021). Therefore, ERA5 data provide a sound basis for the joint analysis conducted in this section.

In Fig. 10, all sea states exhibit a distinct peak around 5 s, which is clearly associated with locally generated wind-sea waves. A second peak is observed near 10 s, corresponding to the dominant swell component, while a second swell peak appears in some cases at approximately 12 s. A close agreement can be identified between these observations and the ERA5 mean values reported in Table 1 for WW_p and SW_p .

As shown in Fig. 10, sea states SS07 and SS10 are primarily governed by wind-sea conditions with no distinctive peak around 10 s. These two sea states predominantly occur during spring and summer and are characterized by the lowest average values of T_m . They also present reduced WEF , H_s , and wind speed magnitudes. As reported by authors (Ibarra-Berastegui et al., 2021), Mutriku exhibits its minimum electricity production under these conditions. This interpretation aligns with the corresponding ERA5 mean values, which indicate swell-wave (SW_p) periods below 6 s, well within the typical range associated with wind-sea waves.

Sea state SS04 also displays a pronounced spectral peak associated with wind sea. This configuration has been linked to the maximum electricity generation regime at the Mutriku plant (Ibarra-Berastegui et al., 2021). It corresponds to a low-occurrence sea state, mainly observed in spring, in which wind speeds WS reach high values and, in combination with the swell component(s), result in the most energetic conditions.

When all cycles are analyzed jointly, the relationship between ERA5-derived T_m values and mean cycle lengths at a daily time scale, is depicted in Fig. 11. Linear regression based on 365 daily paired observations yields a coefficient of determination of $R^2 = 0.42$, indicating a statistically significant relationship between T_m and $CycleLen$ and thereby quantitatively characterizing the linkage between these variables.

3.2.2. Significant wave height

Another relevant observation from Table 1, is that the most energetic sea states—namely, SS04, SS02, and SS06 which exhibit the

Table 4

Summary table on Zipf's compliance by the variables analyzed.

Variable	R^2	ρ slope	N# of different words
$CycleLen$	0.94	-1.32	35
ΔP	0.95	-1.21	51
$\Delta P_{1/3}$	0.98	-1.26	47
H_s	–	No slope	4
T_m	–	No slope	4
WEF	–	No slope	4
WS	0.93	-0.81	116
WW_p	0.95	-0.97	98
SW_p	0.95	-1.20	53

highest ERA5 wave energy flux (WEF) values, also correspond to the largest significant wave heights. This relationship is likewise evident within the air chamber, where these sea states yield the highest mean ΔP and, more importantly, $\Delta P_{1/3}$ values, thereby establishing a clear linkage between ERA5 H_s and $\Delta P_{1/3}$ in Mutriku's air chamber. As a confirmation, in Table 1 it can be seen that the relative variations in $\Delta P_{1/3}$ among the different SS, closely mirror the ratios observed for H_s .

In deep-water conditions, the distribution of individual wave heights within a given sea state is conventionally modeled using a Rayleigh distribution, and the significant wave height is defined as the mean value of the highest one-third of all wave-height realizations (Holthuijsen, 2010). As illustrated in Fig. 12, the histograms of ΔP computed from the 3.2 million individual cycles, stratified by SS, display the characteristic form of a Rayleigh distribution. This correspondence indicates that the pressure fluctuations within the air chamber exhibit a statistical structure analogous to that of wave heights, suggesting an underlying physical linkage between the two.

Fig. 13 illustrates the relationship between the daily mean of the upper tercile of pressure fluctuations, $\Delta P_{1/3}$ (Pa), and the significant wave height (m). Despite the difficulties regarding ERA5 data discussed below, the fitted regression exhibits a strong association between the two variables, yielding a coefficient of determination of $R^2 = 0.81$.

3.3. Zipf's law

As mentioned above, and following Primo et al. (2007), the linear regression in Eq. (4) was applied to evaluate the degree of compliance with Zipf's law of both, the Mutriku variables on the one hand, and ERA5 variables on the other. In a logarithm scale, for each variable, r represents the rank in occurrence order of the four-letters words and $f(r)$ the frequency (%) of occurrence. A perfect agreement with Zipf's law would yield a value of $R^2 = 1$. The results of the regression according to Eq. (4) can be seen in Table 4

It can be seen that the Mutriku's air chamber variables behave similarly with a number of different words between 35 and 51, R^2 above 0.94 and slope values of ρ around $-1.2 \sim -1.3$. This indicates a clear compliance with Zipf's law and with a close similarity for the three variables considered in the air chamber.

Coming to the ERA5 variables, it can be seen that three variables (T_m , H_s , and WEF) clearly depart from Zipf's law, with only four different words generated and a slope ρ which is not present (e.g. is not different from 0 at a 95% confidence level). However, WS , WW_p and SW_p , exhibit strong conformity with Zipf's law, as evidenced by high R^2 values and statistically significant slopes. In contrast to the air chamber variables, these relationships are characterized by markedly different ρ values and by variations in the number of intervening words. In the **Supplementary Material section.10.3** a more visual representation of these results can be seen in Figures S1, S2, S3, S4, S5, S6, S7, S8, S9.

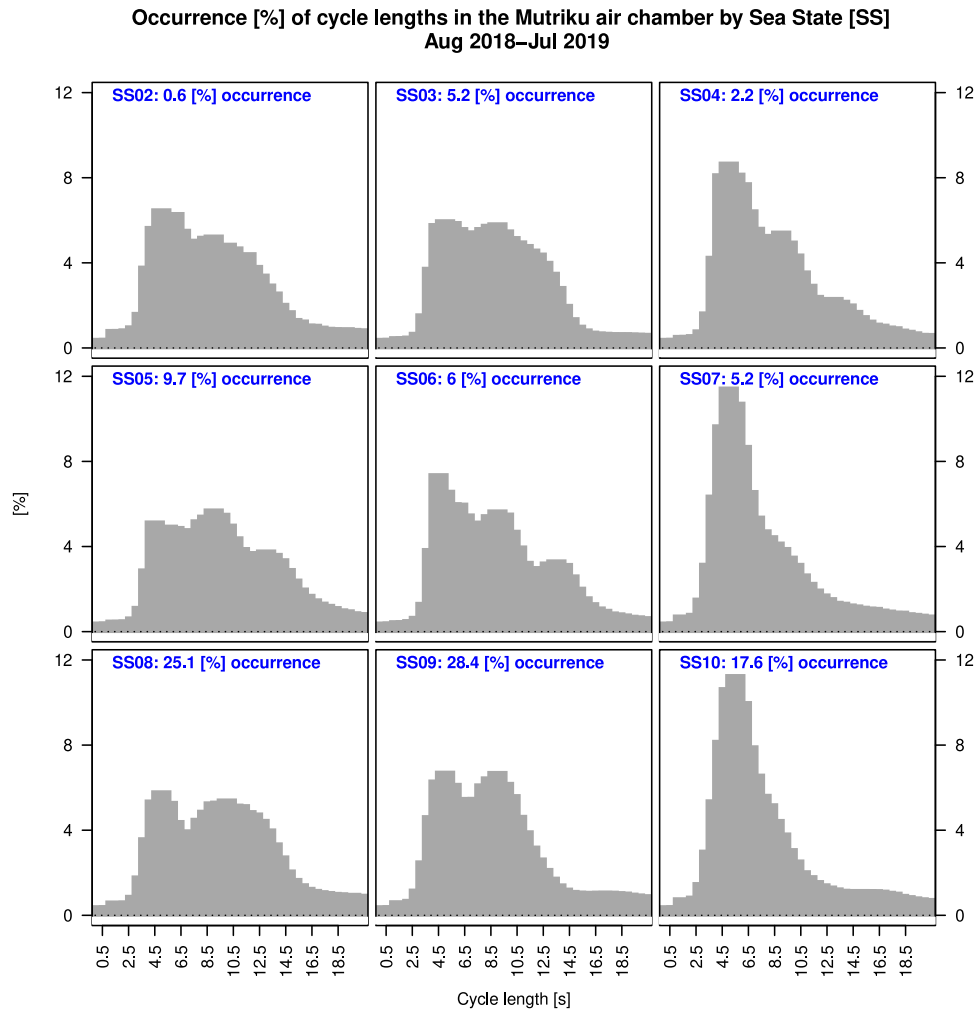


Fig. 10. Histograms of cycle lengths by SS. 3.2M cycles. August 2018–July 2019.

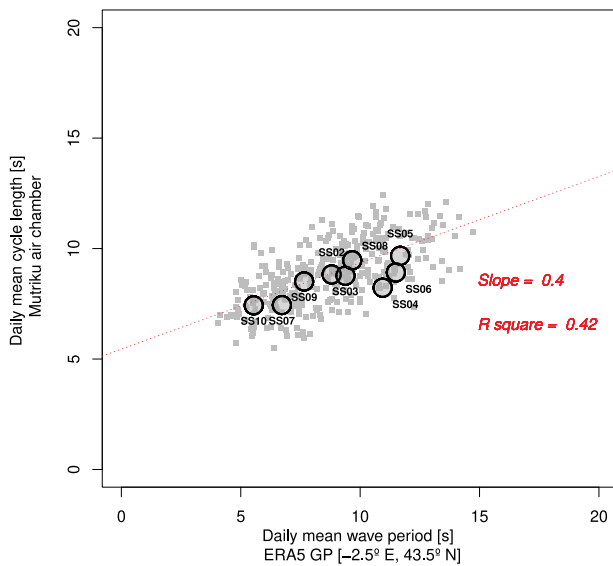


Fig. 11. Mean wave period in $[-2.5^\circ \text{ E}, 43.5^\circ \text{ N}]$ and mean cycle length in Mutriku. The centers of gravity of the SS are also depicted. August 2018–July 2019.

4. Discussion

The methodological framework adopted in this study, which consists in partitioning SCADA measurements acquired at 0.5 s intervals into individual cycles, has enabled the characterization of the mean intra-cycle evolution of instantaneous pressure, rotational speed, and power for cycles of variable duration. This analysis builds fundamentally on previous work by the authors in which, from an energy-production perspective, a set of sea state types was identified at a daily time scale.

It must be stated that the SCADA records reflect the response of the Wells turbine under the operational instantaneous control and regulation algorithms that govern the generation of electric power. An additional regulation mechanism exists: the butterfly valve whose position is one of the control variables of the Mutriku OWC plant. The valve begins to operate (Lopez-Mendia et al., 2025) when the root mean square pressure reaches 5250 Pa (below this threshold the valve remains fully open at 90°) and production is stopped when the pressure reaches 15,250 Pa, corresponding to a fully closed position (0°). In contrast to rotational speed control, the butterfly valve position does not adjust instantaneously. Instead, its setting is determined from the root mean square value of the inlet pressure, which is acquired by the SCADA system at 0.5 s intervals and evaluated over a time window spanning the preceding several minutes. As a result, the valve remains at a constant position for time scales on the order of minutes, even in the presence of substantial pressure fluctuations induced by individual

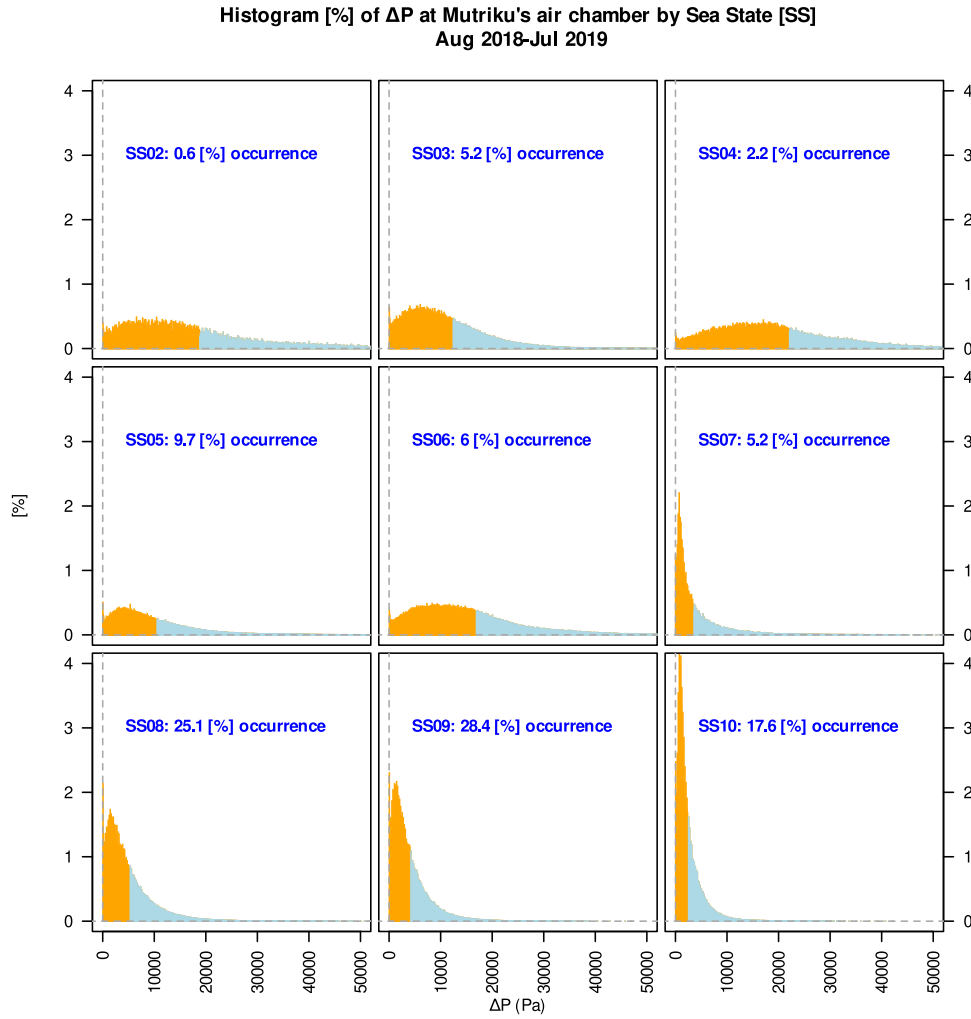


Fig. 12. Histogram of individual values of ΔP for the 3.2M cycles by sea state. The blue tail indicates the area corresponding to the highest third ($\Delta P_{1/3}$) August 2018–July 2019.

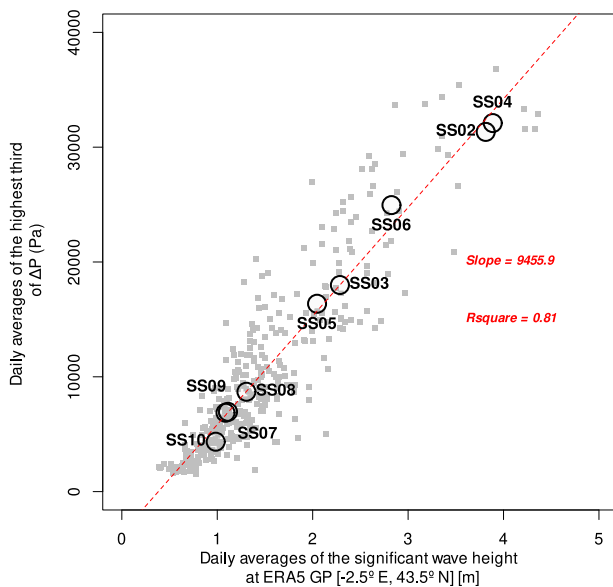


Fig. 13. Daily $\Delta P_{1/3}$ at Mutriku breakwater vs the H_s at ERA5 grid point $[-2.5^\circ \text{ E}, 43.5^\circ \text{ N}]$. The centers of gravity of the SS are also depicted. August 2018–July 2019.

waves. The complete suite of control and regulation mechanisms implemented at the Mutriku facility has been thoroughly analyzed and is documented in the scientific literature (M'zoughi et al., 2024; Lekube et al., 2018; Lopez-Mendia et al., 2025), as well as in the references cited therein.

An additional source of variability is the deposition of saline aerosol on the turbine blades between freshwater cleaning operations (typically performed every 90 min), which can also modify the aerodynamic performance of the rotor.

The data segmentation by sea state and cycle length was followed by data averaging, thus enabling the identification of 7353 operating points of the air-chamber–Wells turbine system, and characterizing the operational behavior of the Mutriku plant. Averaging was applied to address the minor uncertainties identified above and capture in 7353 centroids the underlying mechanisms relating pressure, rotational speed and power generation. The interpolated surface obtained in the subsequent stage was represented by a fourth-order polynomial. This surface obtained herein exhibits a characteristic geometry governed by the real-time control algorithms implemented at turbine T02. As previously indicated, this surface constitutes the end product of a data reduction procedure in which 3.2 million cycles are compressed into a tractable fitted surface that preserves the principal features of the turbine response, while achieving a substantial decrease in data complexity at the expense of a relatively modest increase (overestimation) in the associated error. As a result, it captures the dynamic interaction between the control strategy, the air-chamber pressure and

the bidirectional airflow that governs both electrical power production and the turbine-generator rotational speed.

Most power curves provided by developers of different wave energy converters deployed in the open sea, use as inputs the local values of significant wave height, (H_s), mean wave period (T_m) or even peak period (Ibarra-Berastegui et al., 2023; Ulazia et al., 2023). Frequently, these performance curves are expressed in dimensionless form to facilitate device size scaling. In the case of a breakwater wave farm like Mutriku, this is not possible because the electric power is driven by wave-induced air flows, rather than directly by the incident waves.

The control and regulation mechanisms governing the Wells turbine inherently confine its operation to the domain depicted in Fig. 6, thereby preventing operation outside the region encompassed by the available experimental data. As the surface has been obtained from 7353 data points within this domain, the validity of the resulting fitted equation is strictly limited to these bounds and should not be extrapolated beyond them.

It must be also stated that the analysis of the SCADA records identified short and intermittent periods during which the Wells generator, under the action of the control and regulation system, operates in motor mode at low rotational speeds. This operating strategy is implemented to prevent rotor stalling and to maintain the boundary-layer conditions required for effective torque production. Such operating conditions were excluded from the present analysis, which focuses exclusively on the behavior of the Wells turbine under power-generation mode. Restricting the analysis to generation mode explains why the rotational speed observed in Figs. 6a and 6b is above 500 rpm.

Because all 14 air chambers and Wells groups in Mutriku are identical, this description does not apply solely to one turbine; rather, it can be understood as a representation of how Mutriku wave farm as a whole, converts waves into electric power, independent of how many turbines are operating at any given time.

In the Mutriku wave farm, the air chamber constitutes a critical link in the energy conversion chain, transmitting energy from the incident waves to the electrical grid. Consequently, it is essential to characterize the behavior of this component, which hydraulically and pneumatically couples the sea and the Wells turbines, when even within a given sea state, a wide range of individual waves is observed. Since for several reasons, air flow rates are not directly measured at Mutriku, the system's response to variations in the incident wave field can only be inferred from the resulting pressure oscillations within the air chamber. A major challenge in undertaking such an analysis is the absence of direct wave measurements in the immediate vicinity of the plant, which precludes a precise characterization of each individual wave as it propagates into the air chamber below sea level.

As ocean waves propagate from deep to shallow waters, their main characteristics evolve due to their interaction with the seabed. Wave transformation in coastal areas is an intrinsic process primarily controlled by depth variations, which influence wave amplitude, breaking, celerity, and refraction processes (Li and Chabchoub, 2023). In particular, the significant wave height and wave period exhibit different behaviors as waves approach the coast.

Other physical processes such as refraction, diffraction, and reflection contribute to the transformation of waves in coastal areas. These processes control the transformation of the wave field as waves propagate over variable bathymetry (Eldrup and Andersen, 2020; Andriolo, 2019). In particular, refraction is associated with the bending of wave crests during propagation toward the coast (Magdalena and Pudjaprasetya, 2014).

In coastal environments characterized by mild bottom slopes, such as the Mutriku site, these transformations occur over relatively long cross-shore distances. This behavior is consistent with nearshore wave studies showing that wave conditions in shallow water are strongly influenced by bed slope through partial reflection processes (Contardo et al., 2023).

Finally, the wave conditions at Mutriku are further influenced by the presence of the breakwater-integrated OWC plant. The interaction between incoming waves and the structure induces reflection and diffraction processes, modifying the local wave field, with partial reflections playing a dominant role under shallow water conditions. Contardo et al. (2023) showed that these processes can significantly affect nearshore wave amplitude (Contardo et al., 2023). Consequently, the wave conditions reaching the Mutriku plant differ significantly from offshore wave characteristics, which must be considered when analyzing the operational response of the OWC system.

In the absence of in situ measurements, ERA5 data have been used. Those data are the outputs of the WAM oceanic model after assimilating observational data (ECMWF, 2026). The resolution of ERA5 for oceanic variables is $0.5^\circ \times 0.5^\circ$ and therefore the values recorded at the nearest grid point [-2.5° E, 43.5° N] from Mutriku (22 km of distance) can be considered to be representative of a $0.5^\circ \times 0.5^\circ$ pixel as shown in Fig. 14(a). For this reason, the plain understanding of the ERA5 observed variables as associated to those specific coordinates in strict geographical terms, may be misleading. The area covered by that pixel includes deep waters, shallow waters and land areas (Fig. 14(a)) so as highlighted in previous works on the area by authors, coastal effects may not be captured accurately (Ibarra-Berastegui et al., 2016). For this reason, ERA5 cannot be considered to be a perfect representation of the actual waves entering Mutriku's air chamber, nor of the oceanic conditions in [-2.5° E, 43.5° N]. Fig. 14(b) presents a full-scale representation of the bathymetry seaward of the Mutriku breakwater. The water depth is relatively shallow, and the seabed exhibits a gentle slope in the direction of wave propagation toward Mutriku. Such conditions can introduce energy dissipation due to bottom friction and, consequently, can lead to a reduction in the wave period as waves travel from the open ocean toward the coast.

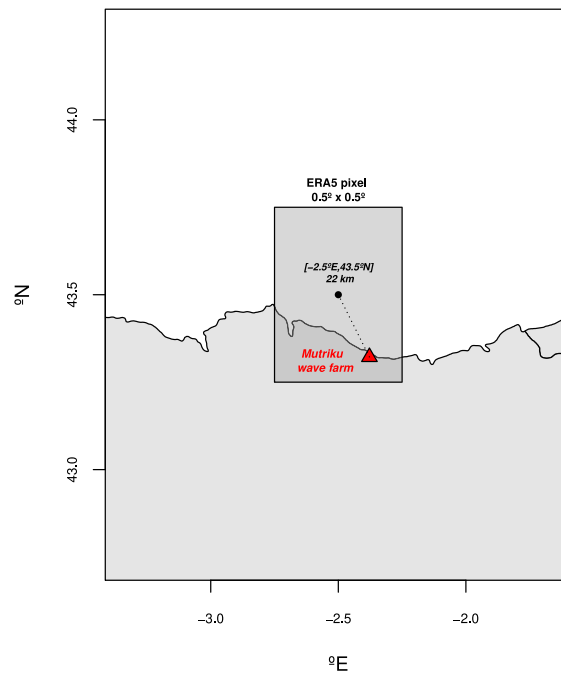
Although subject to the previously discussed limitations associated with the use of ERA5 data, the observed cycle length histograms (Fig. 10) clearly reproduce the distributions associated with the characteristic wave periods of wind sea (around 5 s) and swell(s) (greater than 9 s) in this region. More precisely, the link between wave period and cycle length (Fig. 11) produces an R^2 (coefficient of determination) of 0.42, offering a statistically sound description of this link.

For H_s , the comparison with $\Delta P_{1/3}$ may at first appear less direct, since the two variables are reported in different physical units (m and Pa, respectively). Even so, the outcomes shown in Fig. 13 support the adoption of $\Delta P_{1/3}$ as a surrogate for H_s . In particular, wave amplitudes are directly tied to the pressure produced inside the chamber, and both measures display comparable statistical properties, with probability density functions in each case very close to Rayleigh distributions. Furthermore, the agreement between $\Delta P_{1/3}$ and H_s —both calculated from the upper one-third of their respective datasets—is strong, with a coefficient of determination of $R^2 = 0.81$.

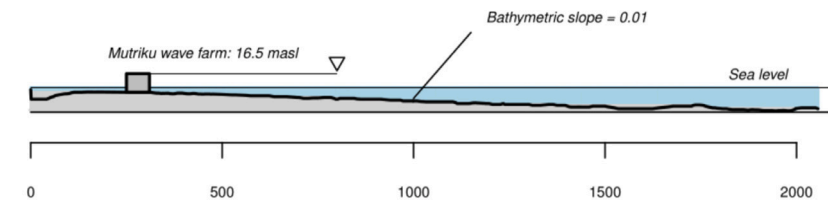
In this study, harmonic analysis demonstrates that the contribution of tidal variability to this relationship is negligible; otherwise, substantially lower R^2 would be expected. Therefore, in this paper it has been established that there is a statistically solid relationship between $CycleLen$ at Mutriku's air chamber and ERA5 T_m , as well as between $\Delta P_{1/3}$ and the H_s . Given their statistical significance, all these relationships represent a non-negligible phenomenon, which is referred to as oceanic resonance throughout this study. This suggests that the Mutriku air chamber behaves as a resonant cavity that, on time scales of the order of seconds, responds to and samples the oceanic conditions incident on Mutriku's breakwater.

Zipf's law is an observed relationship in scientific data and some recent explanations have been put forward for its universality using information theory (Corominas-Murtra and Solé, 2010) or concepts like entropy (Visser, 2013) beyond the earlier, problem-specific mechanisms that had been proposed.

Despite its observation across a broad spectrum of systems and the substantial body of empirical and theoretical work devoted to it, a



(a) Location of ERA5 referential grid point and representative area



(b) Full-scale representation of the northward sea bathymetry transect prior to the Mutriku wave farm

Fig. 14. ERA5 grid point location, pixel and bathymetry before Mutriku wave farm.

comprehensive understanding and a unified analytical framework for Zipf's law remain elusive, both at a general level (De Marzo et al., 2021; Miller, 2015) and, more specifically, in relation to its implications for oceanic applications.

In this context, it is important to stress that, to the best of authors' knowledge, the present contribution constitutes the first systematic examination of the applicability of Zipf's law to wave farm records and, more generally, to open-ocean variables. As a consequence, situating these findings within a broader theoretical and empirical framework is challenging, particularly in light of the relatively limited sample sizes available. To some extent, this has involved some constraints and limitations in the methodological adaptation shown here and used to perform the current analysis.

Nevertheless, the general methodology originally developed in Primo et al. (2007) and adapted here has enabled a quantitative evaluation of the degree of conformity with Zipf's law. Among the variables analyzed, three (T_m , H_s , and WEF) exhibit clear deviations from Zipfian behavior, whereas the remaining variables show a high degree of agreement with the law.

Despite the limitations discussed above, the procedure used in this study nonetheless allows for an unambiguous categorization of the variables into those that comply with Zipf's law and those that do not, with no intermediate or borderline cases detected.

Accordingly, the results presented in this work should be regarded as a preliminary step toward a systematic investigation of Zipf's law compliance in oceanic variables in a broad sense. Future research

employing the same methodological framework, while extending both the temporal coverage and the spatial domains considered, is expected to provide a more robust and comprehensive assessment of the extent to which oceanic variables adhere to Zipf's law. Future results in this field might also provide additional information of the specific underlying mechanisms that could shed light on the results obtained here, with some variables departing from Zipf's law while others exhibiting a close conformity.

Finally, it is worth noting that, in general terms, Zipf's law appears to be fundamentally related, at a very basic level, to other empirical regularities such as Benford's law (Pietronero et al., 2001). Accordingly, in the preliminary phase of this study, the same set of variables was analyzed for adherence to Benford's law; however, this initial examination produced only inconclusive evidence in all cases.

5. Conclusions and future outlook

In this study, SCADA measurements from a fully operational wave farm, spanning an entire year at a temporal resolution of 0.5 s, have been analyzed. The adopted methodology focuses on observations within the air chamber at the scale of individual waves, enabling the identification of more than 3.2 million pressure cycles associated with wave-induced motion.

This cycle-based framework has been integrated with a previously developed classification of sea state types based on energy generation by the authors. By computing averages as a function of sea state

and cycle length, it was possible to condense and extract the operational patterns corresponding to the 3.2 million recorded cycles. Consequently, 7353 operating points, relating instantaneous pressure, rotational speed, and generated power, were identified and used to fit the operational surface of one of the Mutriku turbines. This surface additionally incorporates the turbine control and optimization algorithms, which have already been refined and are presently deployed in routine operational use for the Wells group by the team responsible for the management of this facility. Since all turbines share the same design and operate in parallel to deliver electricity to the grid, this operational surface can also be interpreted as a characterization of the wave-to-electricity conversion process for the entire wave farm.

Additionally, this methodological approach has demonstrated that, beyond its role in power generation, the Mutriku air chamber can be characterized as a resonant cavity forced by the surrounding oceanic conditions. A clear relationship has been established between the mean wave period and the characteristic duration of the pressure cycles, on the one hand, and between the significant wave height and the resulting pressure response, on the other. Nevertheless, although a robust statistical relationship has been identified, the coarse spatial and temporal resolution of ERA5 imposes certain limitations. To address these constraints, higher-resolution outputs from spectral wave models such as SWAN are required.

Current research efforts are directed toward a more rigorous characterization of how the air chamber of the Mutriku plant is correlated with wave height and mean wave period, derived from high-resolution model outputs at the nearest offshore location. This can account for key physical processes, including the bathymetric transition from the open sea to the breakwater, as well as the hydrodynamic and structural effects induced by the breakwater itself.

Finally, for the first time, the applicability of Zipf's law has been examined in the context of wave farms and oceanographic variables. Preliminary results indicate that certain variables exhibit behavior fully consistent with Zipf's law, whereas others display marked departures from the expected scaling. In the absence of a comprehensive theoretical framework capable of explaining compliance with Zipf's law — both for geophysical data in general and for oceanic variables in particular — there is a clear need for additional case studies supported by more extensive datasets and longer observation periods. Authors are currently working along these lines.

CRediT authorship contribution statement

Gabriel Ibarra-Berastegui: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Eider Mendiburu-Valor:** Writing – review & editing, Visualization, Investigation. **Alain Ulazia:** Writing – original draft, Validation, Software. **Jon Saénz:** Validation, Software, Data curation. **Hodei Ezpeleta:** Software, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Copilot/ChatGPT5 to enhance the clarity of the English language and to refine the LaTeX layout (including tables and figures). The authors have conducted a thorough review of the manuscript and assume full responsibility for the version submitted.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.oceaneng.2026.128496>.

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