Article:

# Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014–2016)

Ibarra-Berastegi, Gabriel; Sáenz, Jon; Ulazia, Alain; Serras, Paula; Esnaola, Ganix; Garcia-Soto, Carlos

Ocean Engineering 147 : 20-29 (2018)

# Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014-2016)

Gabriel Ibarra-Berastegi[1,2] , Jon Sáenz[1,3], Alain Ulazia[4], Paula Serras[2],Ganix Esnaola[1,5], Carlos Garcia-Soto[1,6]

(1) Joint Research Unit. Spanish Institute of Oceanography -University of the Basque Country. Plentzia Itsas Estazioa. University of the Basque Country (UPV/EHU).
(2) NE & Fluid Mechanics Dept., University of the Basque Country (UPV/EHU). Bilbao.
(3) Applied Physics II Dept., University of the Basque Country (UPV/EHU). Leioa.
(4) NE & Fluid Mechanics Dept., University of the Basque Country (UPV/EHU). Eibar.
(5) NE & Fluid Mechanics Dept., University of the Basque Country (UPV/EHU). Donostia-San Sebastian.
(6) Spanish Institute of Oceanography (IEO). Promontorio de San Martin s/n; 39004 Santander (Spain)

## ABSTRACT

Mutriku has recently become the first commercial wave farm to release its operating data. The plant has 14 OWC operating turbines, and this study has conducted an analysis of hourly data corresponding to the 2014-2016 period. The plant's capacity factor has been calculated for this period, and its seasonal evolution characterized. Additionally, a plant efficiency index has been defined as the ratio between the wave energy flux at a reference buoy and the average power generation across the active turbines. The Mutriku wave farm's annual output in the period analysed has been 246,468.7 kW-h, with an average of around ten working turbines. The results indicate that Mutriku's average capacity factor is around 0.11, with higher values in winter than in summer. These values are below the capacity factors reported for other renewable energy sources. The plant efficiency index is 0.26, and further advances in regulation and control may also raise this parameter's values, as may lower rated power alternators. This will also help to improve the Mutriku wave plant's capacity factor, and OWC technology in general.

**Keywords:** *Mutriku wave farm, OWC, fluid mechanics, applied physics*

## 1. INTRODUCTION

Following the latest IPCC AR5 report, under the 450 Scenario, nearly 60% of the power generated in 2040 is projected to come from renewables [1][2].

The theoretical global potential of wave power has been calculated as 29,500 TWh/year, and by 2050 it is estimated that 337 GW could be obtained from wave and tidal energy [3]. In the EU, the aim is to reach 100 GW of combined wave and tidal installed capacity by 2050 [4][5]. In the particular case of Spain, the Spanish Renewable Energy Plan 2011-2020 was approved in 2011, and included a target for ocean energy of 100 MW of installed power by 2020 [2].

The Mutriku wave farm was commissioned in July 2011 [6], and uses Oscillating Water Column (OWC) technology. Incoming waves pressurise the air in 16 chambers inside the breakwater, which is then directed up into the Wells fixed-pitch turbines above. For turbine regulation purposes, there are 16 butterfly valves with an adjustable degree of opening, thus controlling the air flow connecting the air chamber below with each turbine. This is used in combination with a rotation speed adjustment system [7]. Each Wells turbine is 2.83 m high, weighs around 1200 kg, and includes two five-blade rotors with a diameter of 1.25 m. A major difference with the Islay LIMPET layout is that the turbines in Mutriku are positioned vertically, instead of horizontally. The top opening is connected to a turbo-generator with a rated power of 18.5 kW [6]. Electricity is generated in AC and then rectified to DC, and finally converted to 50 Hz AC. After covering the Mutriku wave farm's own electricity needs, the electricity is sold to the grid. More specific details on the general layout can be found in the literature [6][7][8].

A recent review of the state-of-the-art indicates that although OWC is one of the most popular and promising technologies [8], there is pressing need for a major improvement in the devices, adjusting and fine-tuning their design. Accordingly, the combined use of CFD simulations and small-scale lab tests is required [9][10][11][12][13][14][15][16], although some aspects, such as the effects of air compressibility and the subsequent loss of efficiency when transferring results to full-scale devices, have not been properly addressed. Additionally, phase control is an area in which efficiency improvements can be expected [8][9].

Regarding OWC performance, as reported in the aforementioned literature, it is important to note that the main focus of interest has, so far, been on the device itself. However, looking ahead to the future development of wave farms as a reliable source of energy, it will also be necessary to characterize the overall performance of multiple OWC devices working in a fully operational commercial wave farm equipped with this technology, and regularly supplying electricity to the grid. Apart from an analysis of the device itself, an overall indicator of this nature should incorporate the entire chain of factors affecting performance, from the incoming waves to the electricity finally generated.

A useful indicator for characterising the average load of any power plant, including Mutriku, is the capacity factor (CF) [17]. It allows comparing different facilities or even technologies. Given a time reference (usually the number of hours in a period) the CF is the length of time a plant operates at rated power ($P_r$, stated in kW), as given by Eq.1.

$$CF = (\text{kW-h generated in a period})/(\text{number of hours in that period x } P_r) \qquad (1)$$

In the case of more mature renewable energy sources, such as solar or wind power, there are numerous facilities operating worldwide, and reliable figures for CF can be found in the specialised literature [18][19][20][21]. In the case of Spain, the CF for solar energy ranges between 0.2 and 0.45 depending on the technology used and the number of devices installed [17]. For wind farms, an assessment of CFs across Europe indicates that their average is no higher than 0.21 [21]. However, it should be noted that the annual CF of offshore wind farms can be as high as 0.49 in optimal locations, such as Danish waters [22].

Regarding wave energy, a recent study [23] provides estimations of the CF for different types of devices and 20 locations in the North Atlantic area. The CF seems to be dependent on local sea conditions, and is somewhat different when the whole year or only winter months are considered.

Another useful indicator for characterising and comparing the performance of different Wave Energy Converters (WECs) is the so-called capture width, $C_w$. If the performance curves corresponding to a given WEC are known, $C_w$ [m] is the ratio between the power output [kW] obtained at a given location and the wave energy flux [kW/m] at the same place. An extensive intercomparison of WEC devices using $C_w$ and a derived hydrodynamic efficiency indicator can be found in the literature [23][24]. Other studies have focused on analysing this parameter for WEC control purposes [25].

It is important to stress that the values of CF and $C_w$ have not been calculated on actual WECs in these works. These indicators have been obtained by combining the power matrices of the wave generators with the scatter diagrams giving the bivariate distributions of the sea states defined by wave height and period values at a specific location. It is also to be noted that wave heights and periods have been computed using reanalysis data, and not actual local measurements.

Nevertheless, although the CF estimations have been obtained on hypothetical standalone devices, and not from actual WECs working in operational wave farms, these studies are the only reference for a wave energy technology that is currently at very early stages of development.

More particularly, the results gathered in one of these studies [23] for one of the devices, which is based on OWC technology (OCEANTEC, rated power 500 kW), provides a marker for contextualising the performance indicators obtained in this study at Mutriku, also operating with OWC technology.

With more mature renewable energies, such as wind and solar power, which launched their commercial operations some time ago, power efficiency and production also tend to be analysed jointly. The focus in many cases is on the study of the factors that have an impact on the overall efficiency of the solar or wind farm as a whole [19], [20].

In the case of wave energy, the technology is at an earlier stage, with many standalone prototypes still being developed, and performance in many cases is calibrated within the framework of lab-scale tests.

However, in the coming years, as more and more commercial wave farms come into operation, it will also be necessary to characterize their overall performance, just like other more mature renewable energy sources.

The aim here is therefore to provide an evaluation of Mutriku’s CF and provide a performance indicator for it.

Additionally, besides the core activity of generating electricity from waves, new prototypes are currently being tested in this wave farm, with further developments and designs of OWC technology. The main advantage Mutriku has, as a test facility, is that being a fully operational wave farm any new prototype can be tested in real-life conditions, which among others include plant start-stop protocols depending on the sea state or power grid requirements. This allows a more complete calibration and performance evaluation of any OWC device. To the best of our knowledge, this is the only commercial breakwater OWC wave farm [8] currently operating and regularly supplying electricity to the grid. An analysis of recently released operating data covering a period of almost three years (Jan 2014-Oct 2016) can therefore provide insight into the performance of a group of Wells fixed-pitch turbines operating in real-life conditions in a wave farm.

The paper’s first objective is to provide as complete a description as possible of the operational behavior of the Mutriku wave plant over the period in question, including its CF.

The second objective is to define and characterize an overall plant efficiency index for the Mutriku wave farm. This index is an adaptation of the capture width, and its calculation also needs to incorporate sea-state information from nearby buoys in order to evaluate the total conversion efficiency from waves into watts.

This paper proceeds as follows. The next section describes the data used, and provides details on the methodology applied. Section 3 analyses the results, section 4 includes a discussion of the same, and the final section provides the conclusions and future outlook.

# 2. DATA AND METHODS

## 2.1. DATA:THE MUTRIKU WAVE FARM

In 2011 the Basque Regional Government approved its own Energy Strategy for 2020, setting a target for ocean energy of 60 MW by 2020 [26][27]. It is estimated that the potential energy in the Bay of Biscay could supply between 37% and 50% of household electricity consumption in the Basque Country, which would avoid the emission of 0.96 to 1.54 million tonnes of $CO_2$ per year.

The Mutriku wave farm plays a key role in meeting these objectives. The plant is run by the Basque Energy Agency (EVE), a public sector company belonging to the Basque Regional Government in Spain. It is located in northern Spain [2.38ºW, 43.31ºN], on the Bay of Biscay (Fig. 1), and was designed as a supplementary use for the breakwater that protects the local harbour by taking advantage of the construction work to introduce some form of wave-based power generation. Its design and implementation were largely inspired by the Islay LIMPET (UK) wave power device and the European OWC wave power plant on the Island of Pico/Azores [28][6].

This study has combined data from four different sources.

1. The Mutriku wave farm has a SCADA system that also keeps a log of hourly records of the most important variables regarding plant control and operation. SCADA operates with two redundant systems, so when one of them does not work properly, data from the other are available. SCADA has been systematically recording since late 2013. For this reason, the period in question here runs from 1 January 2014 to 7 October 2016. For several reasons, many data were missing, and the percentage of reliable data was below 20%, which meant a total of 3262 hourly cases. The hourly records at a given time t correspond to the following variables:

    a. Average power generated by each turbine over the past five minutes
    b. Number of working turbines over the past five minutes
    c. Inlet valve position
    d. Total pressure at the inlet chamber for each turbine

2. After a small fraction of the electricity generated by the turbines has been diverted for local uses in the plant, it is sold to the grid. This study has used the hourly records from the plant's electricity meter corresponding to the same period. They represent an independent source of data belonging to the electric company, providing accurate information on the total energy supplied to the grid.

3. The second objective of characterizing a plant efficiency index involved the use of sea-state information. The idea was to choose a buoy in which the wave energy flux (WEF, kW/m) recorded could be related to the waves generating electricity at Mutriku. The flux may be interpreted as the hydraulic power held

by waves per meter of crest length. Several buoys located at a range of 100 km were initially considered. Finally, the Bilbao-Bizkaia buoy [3.05°W, 43.64° N, depth=600 m], at a distance of 65.6 km from Mutriku, was selected (Fig. 2). At this buoy, the predominant incoming direction of WEF is NW (Fig. 3), which is roughly the geographical direction connecting this buoy and the Mutriku wave farm. Out of all the candidate locations, this buoy was selected because its geographical alignment made it reasonable to expect -albeit with a certain delay- a relationship between flux observations here and power generation at Mutriku. This buoy is run by the Spanish Port Authority (Puertos del Estado), and among other parameters it takes hourly records of significant wave height, mean wave period, and incoming wave direction, which allow calculating the flux. The flux is never measured directly, and is a function of significant wave height (Hws) and the mean wave period ($T_z$) [29]. WEF is affected by the bathymetry of the area, and if the depth is more than half the wave length, it is considered that the deep-water hypothesis has been met, and bed shoaling, partial reflection and diffraction effects can be ignored [29]. For a value of $g = 9.81$ m/s$^2$, assuming a seawater density of $\rho \sim 1025$ kg/m$^3$, and according to the deep-water hypothesis, $H_{ws}$ and $T_z$ combine according to Eq. 2 to yield the magnitude of WEF [29].

$$\mathrm{WEF[kW/m]} = \rho g^2 (64\Pi)^{-1} Hws^2 T_z \sim 0.491 Hws^2 T_z \qquad (2)$$

4. Finally, due to the impact bathymetry is reported to have on the Islay LIMPET experimental plant [8], it was decided that bathymetry should also be incorporated into the analysis of Mutriku's performance. To that end, 1 m resolution bathymetric data corresponding to the area in front of the Mutriku breakwater, along with a recent orthophotograph, were downloaded from the Basque Government's geoinformation repository [30]:

## 2.2. METHODS

In a first step, hourly data from the SCADA system and the plant's electricity meter were retrieved, and an initial stage of data cleaning and pre-processing was needed to arrange all the hourly data in the same timeline.

All the Wells fixed-pitch turbines at the Mutriku wave plant have exactly the same design. However, turbines #1 and #16 do not accumulate enough pressure at the inlet because chambers #1 and #16 need a structural redesign, so these two turbines did not generate any electricity during the period analysed. The breakwater that houses the Wells turbines is designed to maximize the protection of Mutriku harbour, which means it has a boomerang-type shape (Fig. 4), so its walls face incidental sea waves at a varying angle. The air chambers and turbines inside the breakwater are also arranged following this design, so they receive different waves due to changes in sea depth before each chamber and a non-constant incidental angle. For this reason, the incoming air flow reaching each one of the 14 turbines differs, and the total pressure at the inlet is moderately different (Fig. 5). As a result, despite sharing the same design, they do not generate the same power (Fig. 6).

Besides, owing to maintenance and repair activities, the number of active turbines is not always the same. The approach here has therefore been to calibrate an average power for all the working turbines, regardless of how many are generating electricity at a particular time. The combination of these sets of data has been used to meet our first objective, and provide as thorough a description as possible of the Mutriku plant's most relevant operational aspects. This included determining the CF at Mutriku and its monthly/seasonal values for a close comparison with those from the literature [23].

Our second objective was to define an indicator of the plant's overall performance, and characterize its evolution. Certain recent studies have focused on the simulation of several WECs, given a wave climate at a certain location.

Mutriku is the only commercial breakwater OWC wave farm regularly supplying electricity to the grid. The recent release of the operating data has prompted the need to define an indicator to calibrate its overall performance.

This indicator will be referred to here as the Plant Efficiency Index (PEI), and is a further development of the aforementioned capture width, $C_w$ [24]. The PEI [m] is defined as the ratio between the average power generated over five minutes [kW] by the active turbines and the wave energy flux [kW/m] at a specific sea location. The PEI is different to the $C_w$ in two aspects:

1. It is applied to a wave farm, and not to a standalone device. In the case of Mutriku, as there is not a constant number of regularly active devices and, as mentioned above, they do not yield the same power, the calculation of PEI implies an average value of the power generated by the active turbines at a given time t.
2. The reference location is not the same place where the device is installed (impossible because there is a breakwater), but instead at the nearest location where actual measurements –and not reanalysis data- are available. In this case, a buoy located 65.6 km away from the Mutriku wave plant.

Accordingly, data from the Bilbao-Bizkaia buoy were incorporated into the study. At the initial stages of this work, and after considering other buoys in the area, there was clearly a significant correlation between the flux [kW/m] at this buoy and the average power [kW] generated by all the turbines at Mutriku. The correlation coefficient between hourly observations of these two variables peaks at 0.572, with a delay of four hours (Fig. 7). This means that the sea states at the Bilbao-Bizkaia buoy are statistically related to the waves that generate electricity four hours later and 65.6 km away in Mutriku, and in the same direction as the predominant flux (Fig.2-3).

The Bilbao-Bizkaia buoy is located in open sea. Being a breakwater located on the coast, the waves near Mutriku have smaller values of WEF. However, the way in which the waves transform from the Bilbao-Bizkaia Buoy into the waves observed in Mutriku due to diffraction, reflection and shoaling is systematic. In other words, in Mutriku (near the coast, shallow waters) waves have lower WEF values than at Bilbao-Bizkaia, but the waves' WEF decreases on their way to Mutriku always following the same path and according to the same decreasing pattern. In the absence of sea-state hourly measurements at a closer location, data from this buoy were used to characterize the Mutriku plant's PEI.

The four-hour delay detected was incorporated into the analysis by combining hourly data from SCADA and the electricity meter at a given time t, along with data from the buoy at t-4 hours.

Finally, bathymetric data were overlaid onto a georeferenced orthophoto of the area to represent the local bathymetry leading up to the Mutriku breakwater (Fig. 4).

## 3. RESULTS

An analysis of the hourly readings from the electricity meter indicates that Mutriku is supplying energy to the grid 74.4% of the time. The rest of the time, mainly due to low energy waves, the plant stops. A few cases have also been detected in which the plant also stops due to maintenance operations or extreme waves, and then obviously no energy is generated. The highest hourly production recorded by the electricity meter has been 158 kW-h. The minimum value has been 1 kW-h, with the average being 37.4 kW-h.

The hourly power flow in Mutriku wave plant as recorded by the electricity meter, exhibits a high autocorrelation (Fig. 8a), although at time scales in the order of seconds, intermittency can be expected to be much higher.

The electricity production follows the same seasonal pattern (Fig. 8b) as can be seen in the flux, with minimum values in summer and maximum ones in winter (Fig. 9).

The total amount of kW-h sold in the Jan 2014-Oct 2016 period was 691867 kW-h, which makes a yearly average output of 246,468.7 kW-h. If compared with the hypothetical production of 14 turbines, each with a rated power of 18.5 kW over a standard year of 8,760 hours, the farm's CF can therefore be calculated as

$$CF = 246468.7 /(18.5x14x8760) \sim 0.11 \qquad (3)$$

However, CF also records a strong seasonal behavior, and when calculated on a monthly basis, the CF in December and January records values of 0.22, while in July-August it drops to 0.03.

The number of active turbines in the period studied ranges from 1 to 14, with an average of 9.94. Furthermore, as mentioned above, the active turbines do not all generate the same power. To take this into account, the average values of the power generated over the past five minutes by all the active turbines at a given time t have been used.

The average five-minute yield $\overline{P_{5min}}$ is 3.6 kW, although again, a strong seasonal behavior similar to WEF and the electricity generated (high in winter, low in summer) can be observed (Fig. 6).

Using this variable in combination with the WEF at the selected buoy, the PEI has been calculated according to Eq. 4.

$$PEI\ [m] = \overline{P_{5min}}\ [kW]/WEF\ [kW/m] \qquad (4)$$

The average value of PEI for the period analysed is 0.26 and, in contrast to the CF, it does not have a clear seasonal behavior (Fig. 10). The highest PEI medians have been recorded in April (0.31) and October (0.30), and are associated with moderate values of the wave energy flux.

The values of PEI at time t in Mutriku depend mainly on the sea conditions (Fig. 11). Based on the observations at the Bilbao-Bizkaia buoy at t-4 hours, the maximum value for this period was 1.91, recorded on 1/9/2015 at 19 h, with a significant wave height of 1.3 m, a period of 4.9 s, and waves from the N-NW. In this case, the WEF at the Bilbao-Bizkaia buoy was 4.05 kW/m, while the average total pressure at the inlet chambers was 5,486.5 Pa. The control valves were open to 68.36º degrees [90º completely open, 0º closed]. There were 11 turbines working at that moment, with a five-minute average power yield of 7.73 kW. Fig. 11 shows that the highest values of PEI are obtained around this combination of $H_{ws}$ and $T_z$. Lower values of PEI are recorded when moving away from this point to other sea states.

It is important to note that the combination of $H_{ws}$ and $T_z$ leading to the maximum PEI is far from the sea states leading to the maximum power generated (Fig. 12). The maximum average power recorded in this study was of 12.72 kW. This observation was recorded on 17/02/2015 at 12 h, with $H_{ws}$ = 4 m, $T_z$ = 6.6 s and WEF = 51.744 kW/m. At that moment, eight turbines were operational, and the PEI was 0.24, slightly below the mean value of 0.26. The butterfly valves were open to 33.125º, and the average total pressure across the eight active chambers was 11592.1 Pa, which suggests that non-negligible compressibility effects may have been involved.

# 4. DISCUSSION

When it came online, the Mutriku wave farm was expected to operate with 16 turbines and produce 600,000 kW-h per year [6]. However, as shown above, the average yearly output for the period analysed is only 41% of initial expectations, which is roughly the same as reported at Islay LIMPET [28], although a mimetic attribution to the same causes at both farms would be highly misleading. At Islay, the experimental facility that inspired the Mutriku wave farm, the discrepancies between the lab-scale model and the final prototype were largely attributed to a poor representation of the actual offshore bathymetry before the facility and to the fact that the flare of the gully was not properly designed [28].

In the case of Mutriku, the reasons are different. Firstly, owing to design problems in the air chambers only a maximum of 14 out of 16 turbines can actually operate. Additionally, due to sundry reasons related to maintenance, the average number of turbines working simultaneously over the period analysed was 9.94. This means that, on average, only 62% of the turbines initially considered are routinely operating. This definitively accounts for an important part of the shortfall between initial expectations and recorded output, although other aspects may also be involved. In Mutriku, the total pressure generated in the air chambers by the incoming waves creates the static pressure drop between each turbine’s inlet and outlet, and also provides the kinetic energy necessary to move the air flow through the Wells turbines. In the absence of specific measurements, it is impossible to know which fraction moves the air flow, but the high values of the total pressure observed in some cases suggest that on these occasions the air crossing the turbines may be flowing at Mach numbers beyond 0.3. As a result, compressibility effects should not be ignored [31], as aerodynamic efficiency in the turbines would deteriorate, and this may subsequently have an impact on total power output. The rest may be explained by other aspects, such as the fact that not all the turbines generate exactly the same amount of electricity or certain features of the regulation mechanisms that are very difficult to simulate with the lab-scale model.

The above factors leave little room for any other major causes of discrepancies – such as bathymetry- between expectations and the actual working regime. This is confirmed by comparing the bathymetric representation used at the modelling stage and the actual bathymetry with a resolution of 1 m. The analysis of a S-N bathymetric transect (Fig. 4, dotted line) indicates that in the first few hundred meters before the wave farm, the seafloor changes smoothly, with a gentle slope of ~0.01, moving from a depth of 5-7 m at the foot of the breakwater to around 25-30 m at a distance of 1.8 km, in good agreement with the model-scale representation [6].

On the other hand, when compared with Islay LIMPET, it is also important to stress that Mutriku is a significant step forward, because the former only sells electricity to the grid for 50% of the time [28]. In Mutriku, by contrast, this value is roughly 50% higher (74.4%). This reflects a significant improvement not only in the design and implementation of OWC technology, but also in the regulation and maintenance protocols.

Mutriku's average CF is 0.11, and its PEI is 0.26. In the absence of similar wave farms for comparing the actual figures, the simulated CF values of standalone OWC devices, as gathered in the literature, can be used as an initial reference [23][24]. For example, the OCEANTEC OWC device with a rated power of 500 kW based on OWC technology is reported to have a (hypothetical) CF between 0.0726 and 0.157, peaking at 0.33 for a particular location (Iceland) in winter [23]. The CF reported seems to be rather dependent on local conditions, and according to the authors the results for CF have a seasonal behavior. The values of CF obtained at Mutriku with a winter maximum of 0.26 and a minimum of 0.03 seem to move roughly between similar boundaries. In the absence of further studies, this convergence with prior studies points to this range of CF values for OWC technology. However, these figures are below the CF reported for other renewable energy sources.

The plants overall performance as described by the PEI is 0.26, although the PEI peaks at 1.91 and, as mentioned above, this point is associated with rather small values of Hws, $T_z$ and WEF. As the sea conditions diverge from this point, the PEI falls sharply in Mutriku. It is especially interesting that the point of highest PEI (WEF = 4.05kW/m) and the peak of power generation (WEF=51.744 kW/m) are very distant from each other in terms of sea conditions. Nevertheless, the difference in the average $\overline{P_{5min}}$ yield in both cases is much smaller (Max. PEI = 7.73 kW, Fig. 11 vs. Max. $\overline{P_{5min}}$ = 12.72 kW, Fig. 12). The distance between these two reference points is only slightly higher than in other renewable technologies, such as hydropower, which generally speaking also operates with turbines.

Considering the operating turbines do not all generate exactly the same power, this indicates an adjustment and control system in Mutriku that is working reasonably well, although improvements in this area are clearly needed. A recent study has pointed out that due to the large power variations on the second scale, short-term energy storage may also be needed for smoothing the output power, and improving both power quality and the dynamic response [32].

In Mutriku, 18.5 kW alternators are needed to deal with occasional highly energetic waves, but most of the time they are working at powers well below their rated one. On average, the alternators produce 3.6 kW, which means they work at roughly 20% of their rated power, a similar figure to the one reported at Islay LIMPET [28]. Alternators working so far below their rated power typically perform less efficiently. For this reason, technological advances towards more efficient regulation and control methods, mainly in the case of highly energetic waves, would permit the use of alternators with a rated power below 18.5 kW. This will also mean that the true and rated powers may be closer, and the alternators' efficiency can be expected to increase significantly. Any improvement in these fields (short-term storage, regulation and control, lower rated powers) will also lead to an automatic increase in CF values for the Mutriku wave farm in particular, and for OWC technology in general. Similarly, it will also increase the PEI values for more sea states than the optimum one, thus contributing to an increase in the overall production of kW-h per farm.

## 5. CONCLUSIONS AND OUTLOOK

The release of operating data from a commercial OWC wave farm for the first time has informed this study. Certain parameters of great interest for OWC devices today, such as air flow speed in the turbines, are not currently being gathered by Mutriku's SCADA, although this would allow addressing challenges such as compressibility effects on turbine performance.

Regarding electricity production, the initial expectations have not been met because of the poor design of two air chambers and regular maintenance activities, which mean that on average only 10 turbines out of the initial 16 are actually working. Other aspects, such as compressibility effects in certain extreme cases and the alternators' average performance of around only 20% of their rated power, are likely to have an impact on efficiency, and explain why the total yearly output is 246,468.7 kW-h instead of the 600,000 kW-h initially expected.

The need to define an indicator of overall performance for a fully operational wave farm, and not only standalone devices, has led to the proposal of a Plant Efficiency Index (PEI). This indicator has been defined as the ratio between the average five-minute power generated and the wave energy flux measured at sea.

This PEI provides a realistic indication of the overall performance of a wave farm under operating conditions. The PEI obtained (0.26) can be used in the future as a reference when new tests using other OWC designs are carried out in the same facilities. It can also be used as a reference in future benchmark exercises when more and more commercial wave farms with technologies other than OWC come into operation worldwide. Using operating records from a commercial wave farm has allowed moving from standalone devices calibrated in simulated experiments to actual performance in a fully operational wave farm with many devices. This realistic characterization involves taking into account practical aspects, such as not all the devices perform equally or the impact that maintenance protocols have.

The CF of this plant is 0.11, with higher values in winter than in summer. These values obtained at the Mutriku commercial wave farm with several turbines are broadly similar to those estimated for standalone hypothetical OWC devices. If confirmed in future studies, this will indicate a smaller CF than in other renewable energies, such as hydro, wind and solar power. If OWC technology is to become commercially viable and a competitive source of energy, higher CF factors are needed. The challenge in this field is to narrow the gap between alternators' average yield and their rated power, thus increasing alternator efficiency, CF, and PEI. Significant improvements in regulation and control are therefore needed, mainly regarding highly energetic waves. This is one of the major challenges that OWC technology is facing over the coming years.

Following a thorough description and characterization of a fully operational wave farm such as Mutriku, the next step is to address the problem of the intermittency of the electricity generated and sold to the grid. This is currently a major challenge for most renewable energy sources [33][34]. Addressing this issue involves, among other things, developing efficient methods for the short-term prediction of the electricity generated [33][34][35][36][37].

For this reason, now that the Mutriku wave farm has been characterized in this work, the next challenge is to move on to the forecasting of this wave farm's power output. Studies have so far focused on forecasting simulations based on several hypothetical WECs under different sea conditions, as power series from actual wave farms have yet to be made public [33]. A more accurate prediction of short-term electricity production may contribute to a better integration of wave energy in the general power system [34].

In this case, now that data from Mutriku have been released and used in this study to characterize its general performance, the authors are currently conducting further research to move from forecasting wave energy in the Bay of Biscay [35][36][37] to predicting power output at the Mutriku wave farm. In this sense, the high autocorrelation of the electric power flow, with values above 0.8 up to 10 hours ahead

(Fig. 8a), poses a major challenge to any forecasting effort aiming at outperforming persistence.

## Acknowledgements

The authors want to express their gratitude to the Basque Energy Agency (EVE) for releasing their operating data from the Mutriku wave farm and to Puertos del Estado for providing the buoy data for this study. Special thanks to Olatz Ajuria and Imanol Igeregi from the EVE for kindly answering all our questions. This work has been funded by the Spanish Government, MINECO project CGL2016-76561-R (MINECO/EU ERDF), and the University of the Basque Country (projects GIU14/03 and PES17/23). Most of the calculations and plots have been carried out within the framework of R [38].

## References

[1] Ocean Energy Systems https://www.ocean-energy-systems.org/ocean-energy-in-the-world/spain/ (Retrieved on 2017/05/15).

[2] International Energy Agency World Energy Outlook 2016. International Energy Agency. Executive Summary. 2016 https://www.iea.org/topics/renewables/subtopics/ocean/ (Retrieved on 2017/05/15).

[3] The Future of the Ocean Economy: Exploring the prospects for emerging ocean industries to 2030. Ocean Energy Discussion Paper. Prepared by Eoin Sweeney, ITO Consult Ltd Funded by the Technology Collaboration Programme on Ocean Energy Systems (OES) JUNE 2015

[4] Magagna, D., Uihlein, A., 2015. Ocean energy development in Europe: Current status and future perspectives. International Journal of Marine Energy, 11, 84-104.

[5] Blue Energy- Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond, and accompanying EU Commission Staff Working Document, Impact Assessment. EU Commission, Brussels, 20.1.2014

[6] Torre-Enciso, Y., Ortubia, I., López de Aguileta, L. I. and Marqués, J., 2009. Mutriku Wave Power Plant: from the thinking out to the reality. Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden 319-329.

[7] Amundarain, M., Alberdi, M., Garrido, A. J., Garrido, I., Maseda, J., 2010. Wave energy plants: Control strategies for avoiding the stalling behaviour in the Wells turbine. Renew. Energy 35, 12, 2639-2648.

[8] Falcao, A. F. O.; Henriques, J. C. C., 2016. Oscillating-water-column wave energy converters and air turbines: A review. Renew. Energy 85, 1391-1424.

[9] Shehata, A. S., Xiao, Q., Saqr, K. M., Alexander, D., 2017. Wells turbine for wave energy conversion: a review. Int J Energy Res 1, 6-38.

[10] Viviano, A., Naty, S., Foti, E., Bruce, T., Allsop, W., Vicinanza, D., 2016. Large-scale experiments on the behaviour of a generalised Oscillating Water Column under random waves. Renew. Energy 99, 875-887.

[11] Farrokh Mahnamfar & Abdüsselam Altunkaynak, 2017. Comparison of numerical and experimental analyses for optimizing the geometry of OWC systems. Ocean Eng. 130, 10–24.

[12] Mora, A., Bautista, E., Méndez, F., 2017. Influence of a tapered and slender wave collector on the increment of the efficiency of an oscillating water column wave-energy converter. Ocean Eng. 129, 20–36.

[13] Lopez, I., Pereiras, B., Castro, F., Iglesias G., 2014. Optimisation of turbine-induced damping for an OWC wave energy converter using a RANS-VOF numerical

model. Appl. Energy 127, 105-114.
[14] Lopez, I., Pereiras, B., Castro, F., Iglesias G., 2015. Performance of OWC wave energy converters: influence of turbine damping and tidal variability. Int. J. Energy Res. 39, 4, 472-483.
[15] Vyzikas, T., Deshoulières, S., Barton, M., Giroux, O., Greaves, D., Simmonds, D., 2017. Experimental investigation of different geometries of fixed oscillating water column devices. Renew. Energy 104, 248-258.
[16] Mustapa, M. A., Yaakob, O. B., Yasser M. Ahmed, Chang-Kyu Rheem, Koh, K. K., Faizul Amri Adnan, 2017. Wave energy device and breakwater integration: A review. Renew. Sust. Energ. Rev. 77, 43-58.
[17] Izquierdo, S., Montañés, M., Dopazo, C., Fueyo, N., 2010. Analysis of CSP plants for the definition of energy policies: The influence on electricity cost of solar multiples, capacity factors and energy storage. Energ. Policy 38, 10, 6215-6221.
[18] Barthelmie, R. J., Jensen, L. E., 2010. Evaluation of wind farm efficiency and wind turbine wakes at the Nysted offshore wind farm. Wind Energ. 13, 6, 573–586.
[19] Hong-Ping Cheng, Ming-Ta Yu, 2013. Effect of the transmission configuration of wind farms on their capacity factors. Energ. Convers. Manage. 66, 326-335.
[20] Zhaohua Wang, Yi Li, Ke Wang, & Zhimin Huang, 2017. Environment-adjusted operational performance evaluation of solar photovoltaic power plants: A three stage efficiency analysis. Renew. Sust. Energ. Rev. 76, 1153-1162.
[21] Boccard, N., 2009. Capacity factor of wind power realized values vs. estimates, Energ. Policy 37, 7, 2679-2688.
[22] ENS Register of Danish Wind turbines. Posted in Energy Numbers 2017/4/28. url: http://energynumbers.info/capacity-factors-at-danish-offshore-wind-farms
[23] Rusu, E., Onea, F., 2016. Estimation of the wave energy conversion efficiency in the Atlantic Ocean close to the European islands. Renew. Energy 85, 687-703.
[24] Babarit, A., 2015. A database of capture width ratio of wave energy converters. Renew. Energy 80, 610-628.
[25] Hardy, P., Cazzolato, B.S., Ding, B., Prime, Z., 2016. A maximum capture width tracking controller for ocean wave energy converters in irregular waves. Ocean Eng., 121, 516-529.
[26] Energy Strategy of Euskadi-The Basque Country 2030. Department of Economic Development and Infrastructures. Basque Government.
http://www.euskadi.eus/plan_programa_proyecto/estrategia-energetica-de-euskadi-2030/web01-s2ekono/es/ (Retrieved on 2017/05/15).
[27] Galparsoro, I., Liria, P., Legorburu, I., Bald, J., Chust, G., Ruiz-Minguela, P., Pérez, G., Marqués, J., Torre-Enciso, Y., González, M., Borja, A., 2012. A marine spatial planning approach to select suitable areas for installing Wave Energy Converters (WECs), on the Basque Continental Shelf (Bay of Biscay). Coast. Manage., 40,1–19, 2012.
[28] Hamish Ellen, Cuan Boake, Whittaker, T. J. T., 2003. Operational experience with the LIMPET full-scale, grid connected, shoreline OWC device. Fifth European Wave Energy Conference. Proceedings of an International Conference, Cork, Ireland. 357-362.
[29] Multon, B. Marine Renewable Energy Handbook. Wiley. 2012.
[30] Basque Government GEOEUSKADI website
http://www.geo.euskadi.eus/geograficos/batimetrias-marinas-pais-vasco-ano-2009/s69-geodir/es/

[31] Anderson, J.D. Fundamentals of Aerodynamics. McGraw-Hill Science. ISBN-10: 0072373350.

[32] Yue Hong, Waters, R., Boström, C., Eriksson, M. Engström, J., Leijon, Matts, 2014. Review on electrical control strategies for wave energy converting systems, Renew. Sust. Energ. Rev. 31, 329-342.
[33] Reikard, G., 2013. Integrating wave energy into the power grid: Simulation and forecasting. Ocean Eng. 73, 168-178.
[34] Esteban, M., Leary, D., 2012. Current developments and future prospects of offshore wind and ocean energy. Appl. Energy 90, 128–136.
[35] Reikard, G., Robertson, B., Bidlot, J.R., 2017. Wave energy worldwide: Simulating wave farms, forecasting, and calculating reserves. Int J Marine Energy. 17, 156-185. http://dx.doi.org/10.1016/j.ijome.2017.01.004
[36] Ibarra-Berastegi, G., Saenz, J., Esnaola, G., Ezcurra, A, Ulazia, A., 2015. Short-term forecasting of the wave energy flux: analogues, random forests, and physics-based models. Ocean Eng. 104, 530-539.
[37] Ibarra-Berastegi, G., Saenz, J., Esnaola, G., Ezcurra, A, Ulazia, A., Rojo, N., Gallastegui, G., 2016. Wave Energy Forecasting at Three Coastal Buoys in the Bay of Biscay. IEEE J. Oceanic Eng. 41, 923-929.
[38] R Core Team, 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. url: https://www.R-project.org/

Figure 1. Location of the Mutriku wave farm.

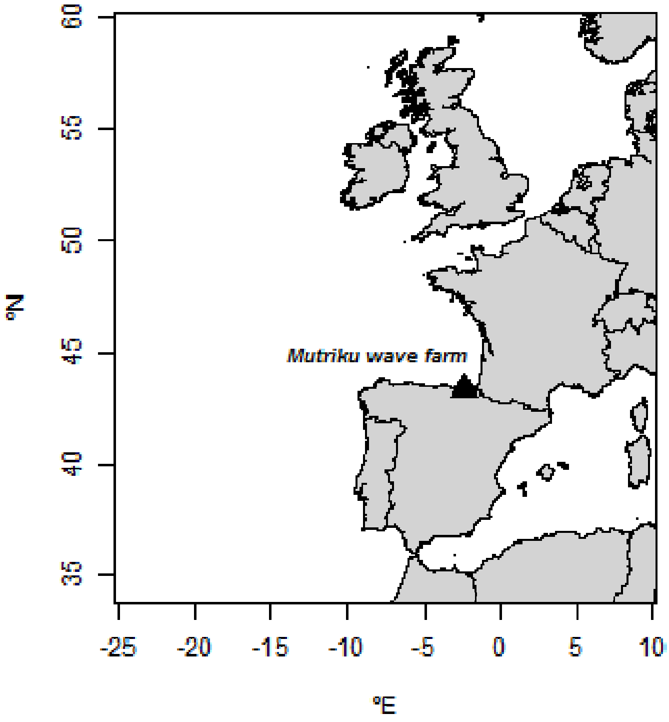

Figure 2. Location of the Bilbao-Bizkaia buoy.

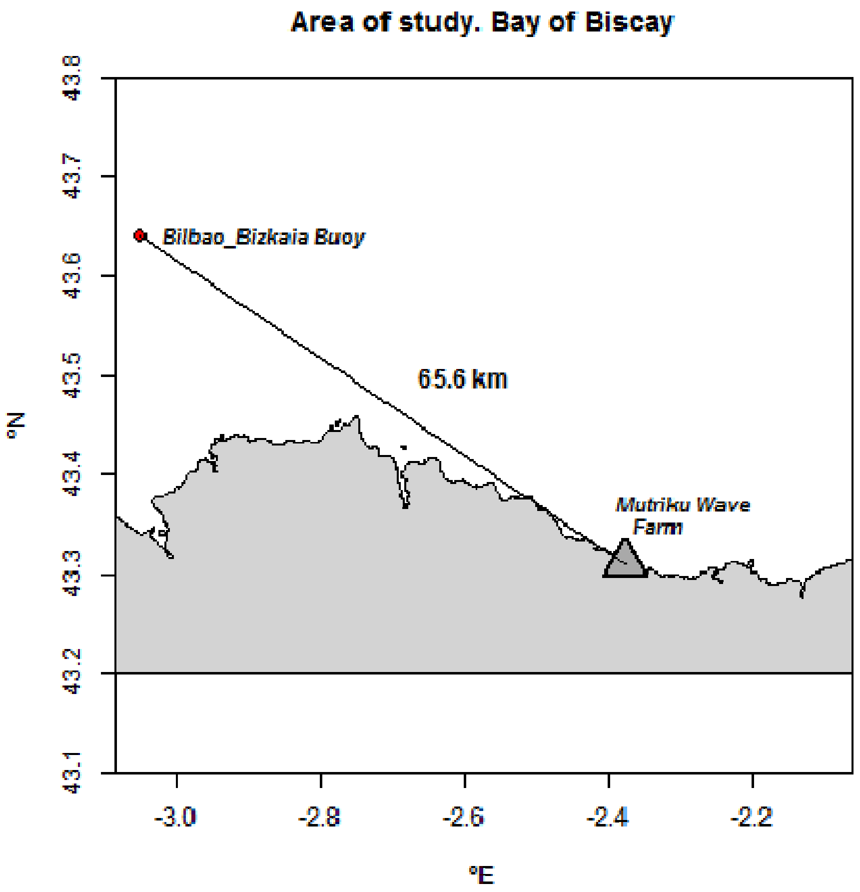

Figure 3. WEF rose at the Bilbao-Bizkaia buoy.

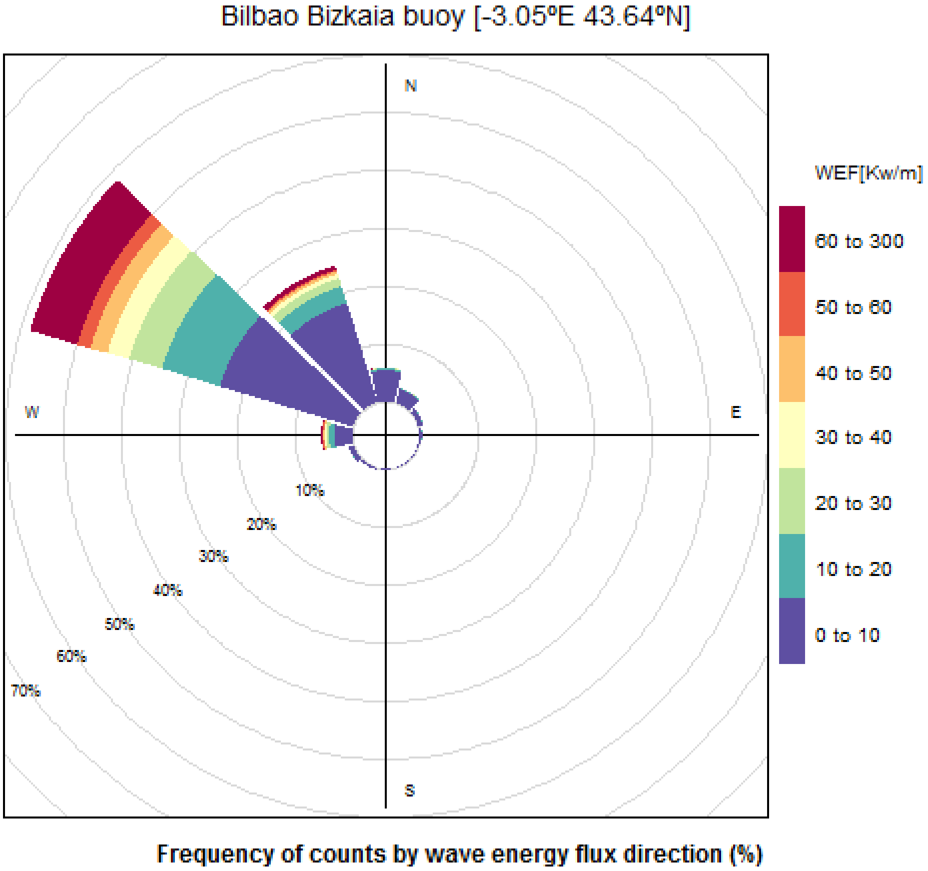

Figure 4. Mutriku wave farm and nearby bathymetry

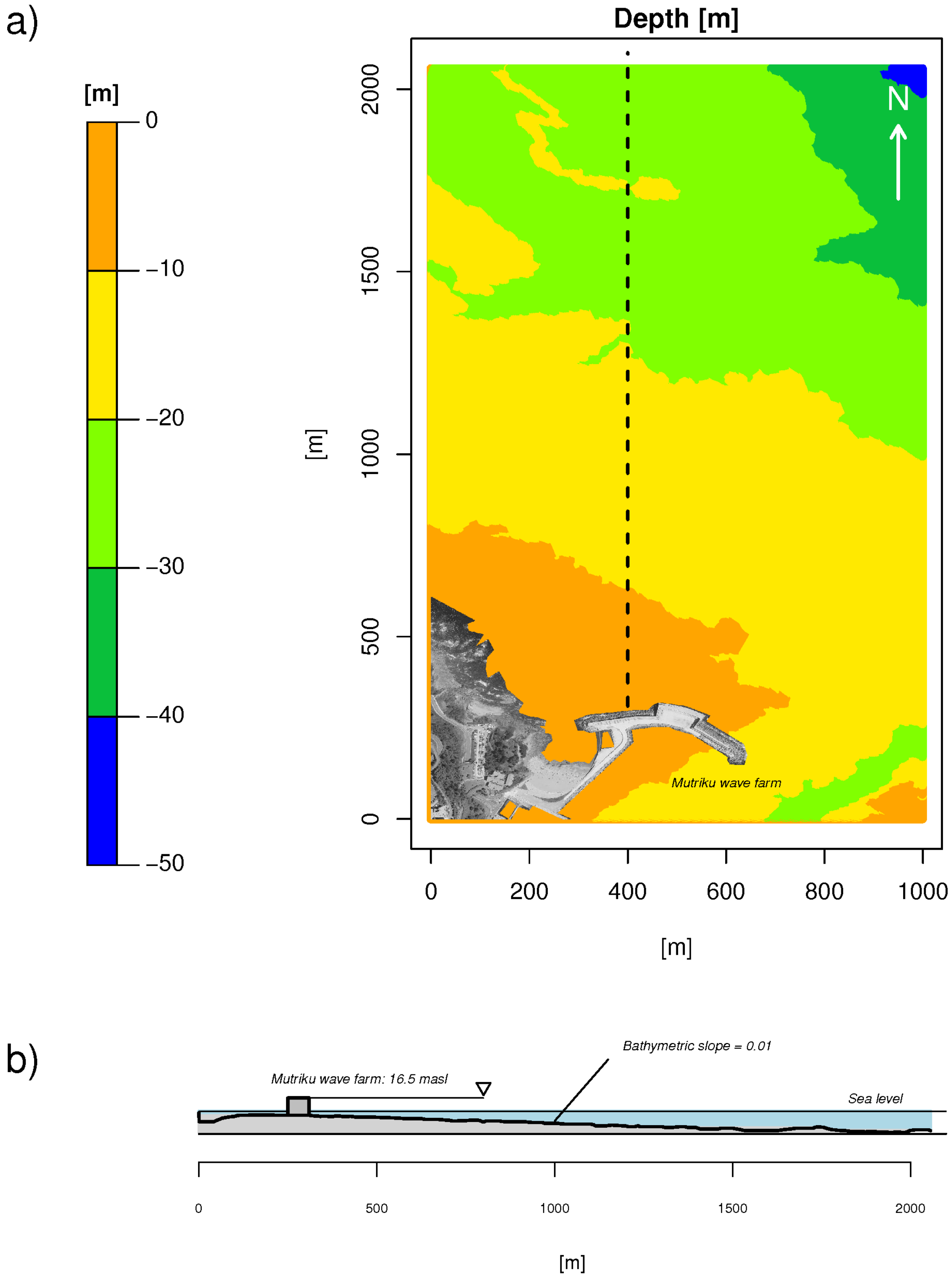

Figure 5. Pressure in the chambers below the turbines. Mutriku. 2014-2016.

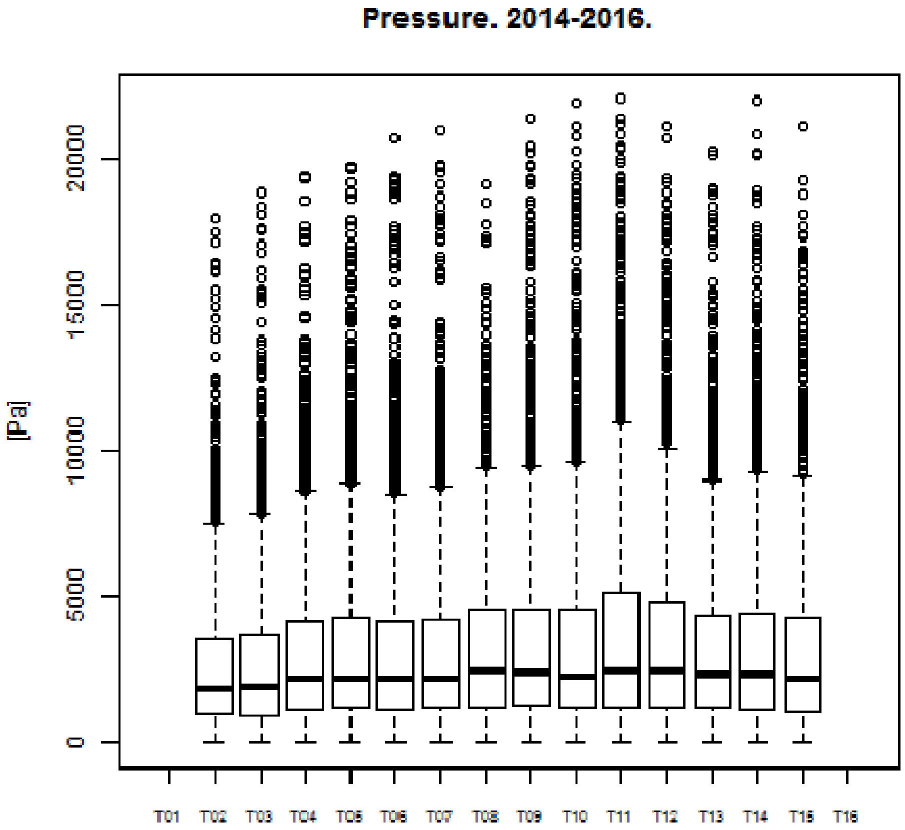

Figure 6. Electric power (kW) generated by Mutriku OWC turbines. 2014-2016.

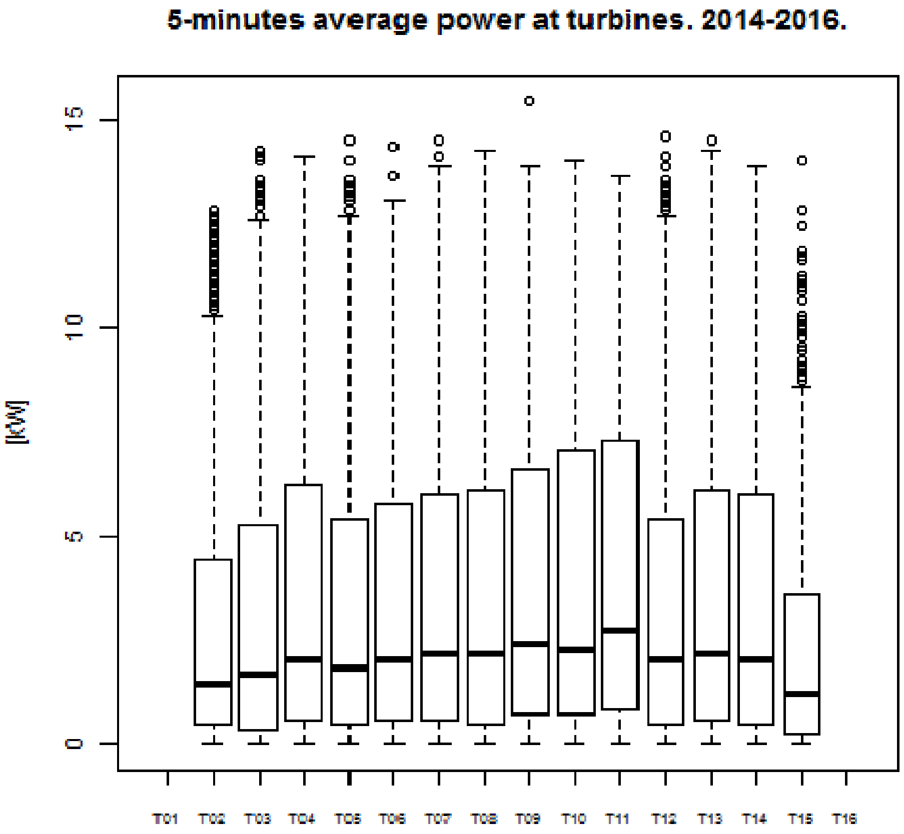

Figure 7. Wave energy flux observed at t-4 h and average electricity production at t.

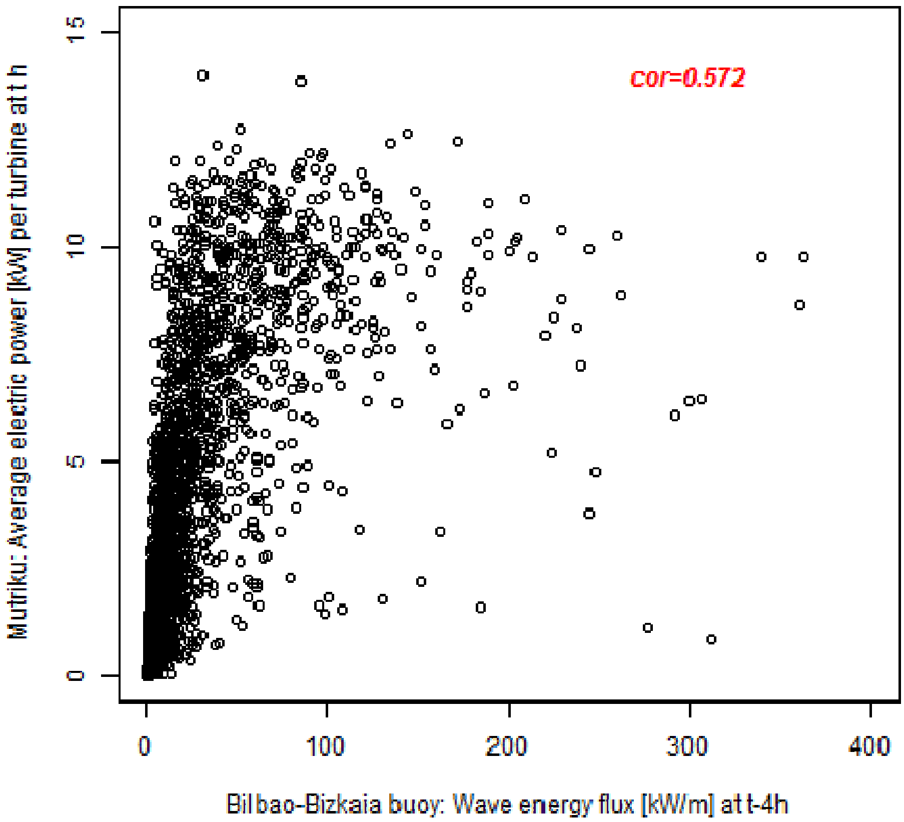

Figure 8. Electricity production at Mutriku. Hourly autocorrelation a) and average monthly evolution b). 2014-2016.

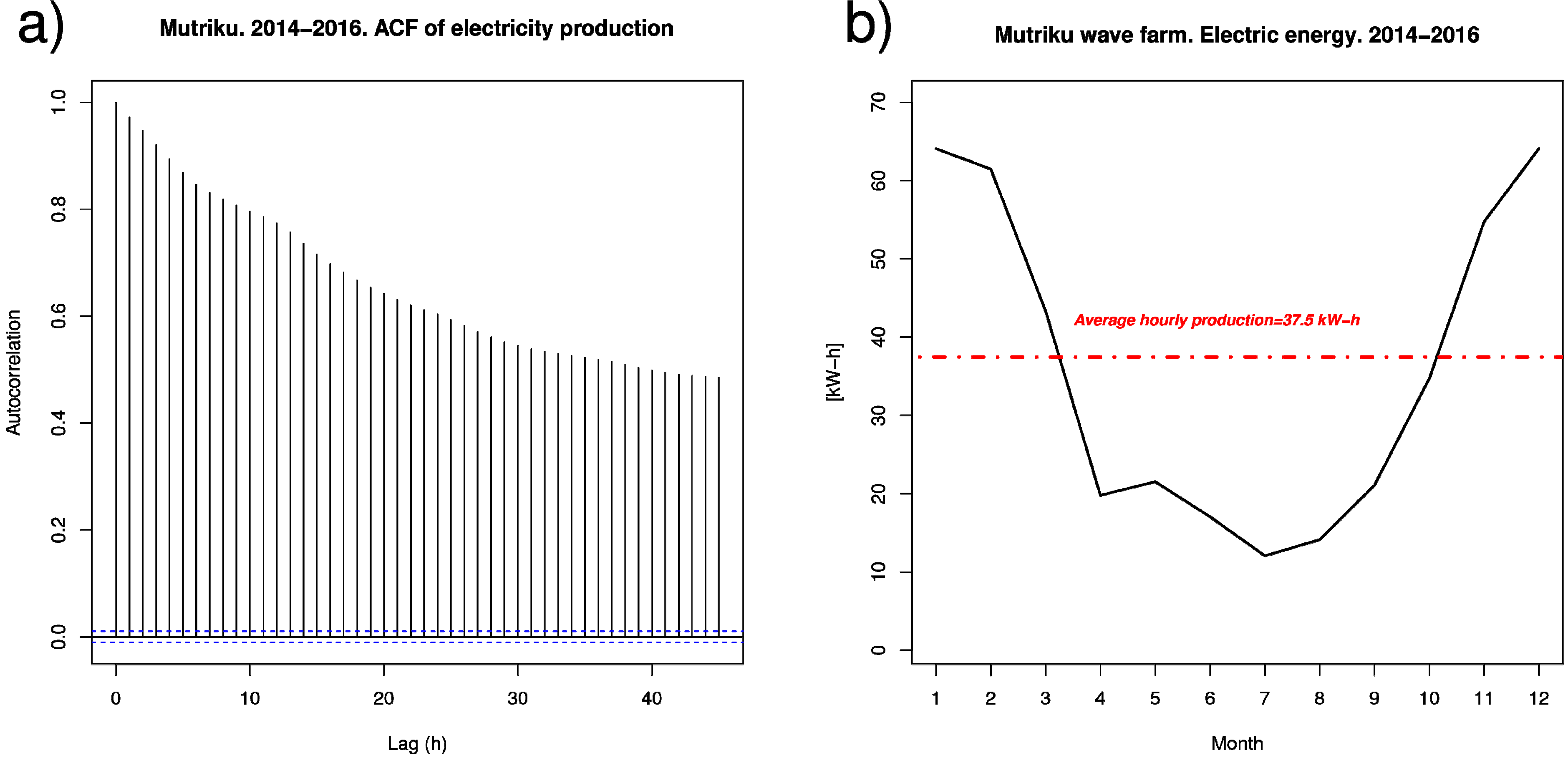

Figure 9. Monthly values of WEF [kW/m] at the Bilbao-Bizkaia buoy. 2014-2016.

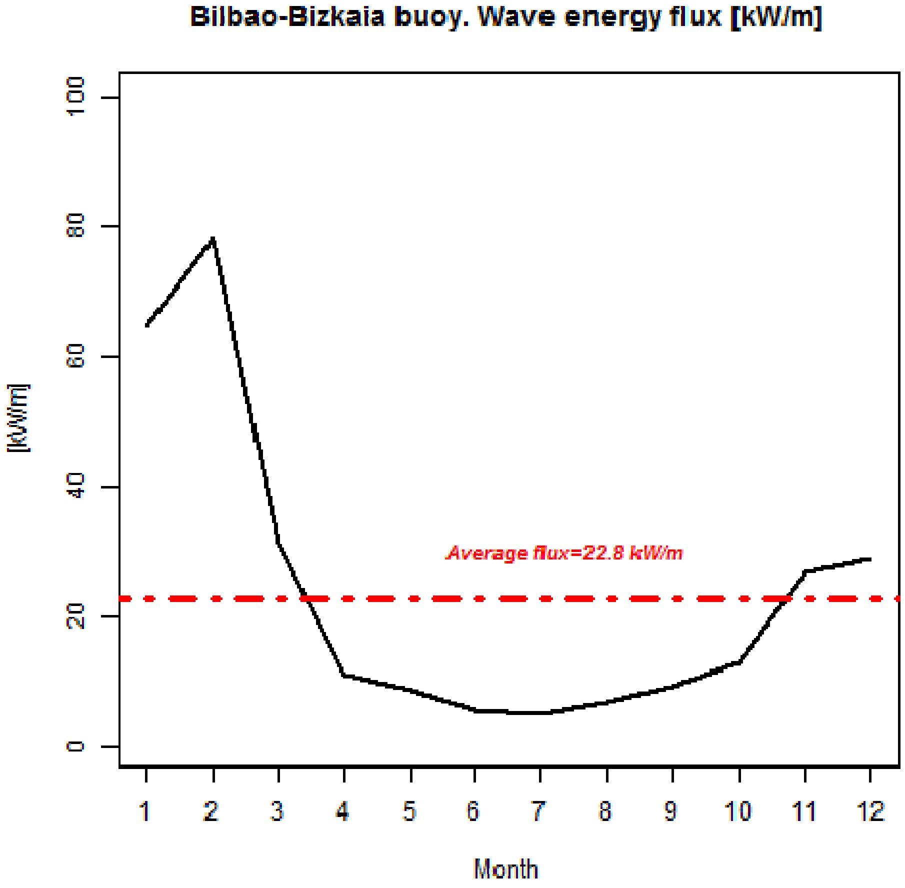

Figure 10. Monthly values of  the Plant Efficiency Index (PEI) at Mutriku. 2014-2016.

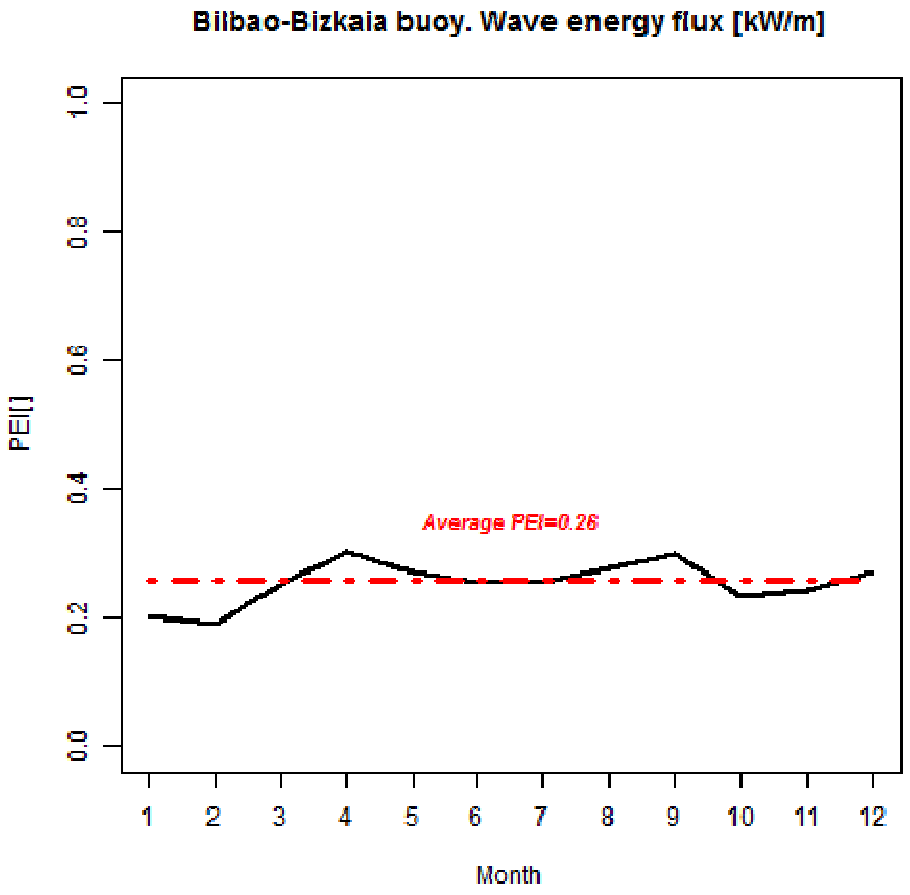

Figure 11. Plant Efficiency Index at Mutriku at time t and sea state at the Bilbao-Bizkaia buoy at time t-4.

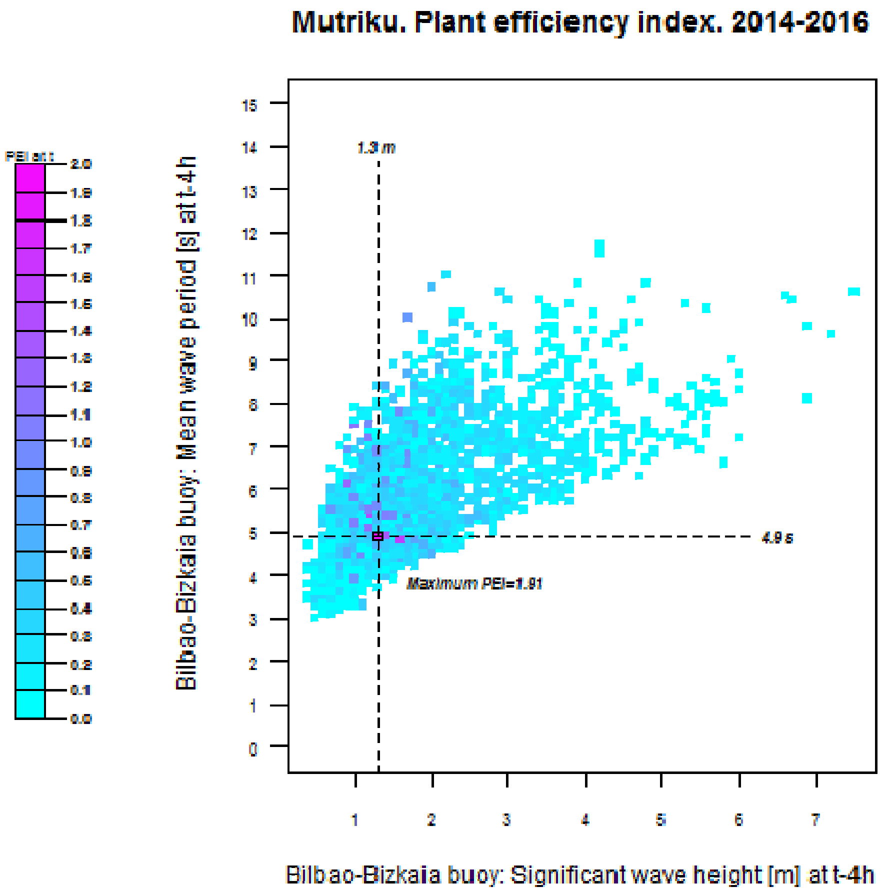

Figure 12. Average five-minute power at time t and sea state at the Bilbao-Bizkaia buoy at time t-4.