Analysis of wave and wind energy in the Cádiz Gulf coast

J. Ramos, J. J. Gomiz-Pascual, M. Bruno

Abstract— **A qualitative and quantitative analysis is presented of two renewable marine energy sources: wave energy and offshore wind energy in the Gulf of Cádiz (south of Spain) putting special focus in their joint exploitation. From numerical model simulations of time series of wave and wind data, spanning the years from 2006 to 2020, provided by Puertos del Estado, we carried out a characterization of both resources for the studied region. The model was validated with time series from two oceanographic buoys. The temporal and spatial variability of both resources was also studied through the construction of wind and wave roses, and several maps, where the seasonal mean values of wave and wind power were evaluated. Two high-energy episodes that took place during the study period were selected: the storms Emma and Elsa, and their power peaks were analyzed. The main conclusion of this work indicates that there is an area of the Gulf, on the eastern side of the region, and above the 300-meter isobath, where both resources show significant power values, and it would be the ideal place for the joint exploitation of the two resources.**

Keywords—**Gulf of Cádiz, hydrodynamic model, atmospheric model, marine renewable energy, Wave power, Wind power.**

I. Introduction

THE development of marine renewable energy industry is considered to be 10-15 years behind wind energy industry. However, having started its development later could be somewhat beneficial, as this industry can make use of more advanced engineering and science, so it is expected to progress rapidly [1]. Some authors estimate that the usable offshore wind power on a global scale is 329,600 TWh/year [2], whereas the global potential associated with waves is estimated at 29,500 TWh/year [3]. Despite the fact that the national objectives of the European countries included reaching 43 GW of installed marine power by 2020, these objectives have not been achieved. In the specific case of Spain, the installed power of marine origin is especially low, with 5 MW from offshore wind and 4.8 MW from other marine sources, according to the International Renewable Energy Agency.

The Atlantic coastlines of Western Europe are favorable places for taking advantage of the wave energy resource for two reasons: their location at the eastern boundary of the Atlantic Ocean and the prevalence of western winds in mid-latitudes [4]. To be able to take advantage of this available resource adequately, it is not only required a technological development that allows to transform in an efficient and economically profitable way the wave energy into electricity; in addition, it is necessary to carry out resource assessments in a local and comprehensive way.

Hybrid marine energy technologies are currently being developed, which combine various forms of energy use with the aim of achieving greater production of electrical energy for longer periods of time. For example, combinations of floating wind technology and wave energy converters could produce energy even at times when the wind is calm. This fact is possible since it has been proven that in many deep-water areas around the world, wind and wave resources are decoupled [5]. However, the combined use of these devices increases the complexity of the infrastructures and their control: the incorporation of wave converters in offshore wind plants raises specific problems derived from the interaction between them, the wind turbines and the platform itself. An example of this type of combined systems would be the W2Power concept developed by the company EnerOcean. It consists of two wind turbines mounted on a semi-submersible platform, with integrated wave converters [6].

The Gulf of Cádiz encompasses the coastal region to the southwest of the Iberian Peninsula, bathed by the waters of the Atlantic Ocean, including the coasts of the provinces of Huelva and Cádiz. Regarding the hydrodynamic regime, it is considered that the Gulf of Cádiz presents a mesotidal regime, being the main

J. Ramos was studying the Master's Degree in Oceanography at the Andalusian Center for Marine Studies, University of Cádiz, Avenida República Árabe Saharaui, S/N, 11510 Puerto Real, Cádiz, Spain. Now he is at the Mediterranean Institute for Advanced Studies, University of the Balearic Islands, Carrer de Miquel Marquès, 21, 07190 Esporles, Illes Balears, Spain (email: jorge.ramos@uib.es).

J.J. Gomiz-Pascual is with Department of Applied Physics, Andalusian Center for Marine Studies, Avenida República Saharaui S/N, 11510 Puerto Real, Cádiz, Spain (e-mail: juanjesus.gomiz@gm.uca.es).

M. Bruno is with Department of Applied Physics, Andalusian Center for Marine Studies, Avenida República Saharaui S/N, 11510 Puerto Real, Cádiz, Spain (e-mail: miguel.bruno@gm.uca.es).

constituents of the semi-diurnal character, and with an average range of tides in spring of 3.06 m in Huelva, 2.96 m in Cádiz, 2.30 m in Barbate and 1.22 m in Tarifa [7]. The main winds in the region are the winds from the west (Poniente) and from the east (Levante). The waves in the Gulf of Cadiz are about 0.5–3.5 m high under wind sea conditions (with Poniente as the dominant wind), and 1.5-4.4 m under swell conditions (when either Levante or Poniente can dominate) [8]. The continental shelf in the Gulf of Cádiz is delimited by the 100 m deep isobath. In front of Cape Santa María, located in the municipality of Faro (Portugal), the continental shelf is very narrow (less than 5 km wide) and ends in a continental slope that descends abruptly to more than 600 m deep in less than 4 km. To the east of this cape, the continental shelf widens rapidly to more than 40 km in front of the Guadalquivir river [9].

The Strait of Gibraltar is considered to be one of the most energetic ocean locations in the world, the tidal current potential in the Strait would have a theoretical power capacity of 7 GW. The potential of wave energy in the region has also been studied, with predictions of up to 2 GW, and with especially interesting perspectives if this resource is exploited in combination with offshore wind energy in the Gulf of Cádiz, as revealed the study commissioned by the Andalusian Energy Agency [10]. In this study, the annual mean wave flow fields were calculated through hydrodynamic wave modeling. The results showed average wave flows of up to 10 kW/m, values that are not too high, and for this reason it was concluded that a combination of wave and wind energies would be necessary to justify their commercial exploitation [10].

Different types of wave energy converters have been also analysed [10], opting for "floating superposition" devices, combined with wind turbines for the Gulf of Cádiz. Comparison of simultaneous wind and wave data showed that both power sources have a low correlation, so even in low wind conditions, combined devices could still produce power through the waves. It was concluded that the low frequency of storm events in the area make the Gulf of Cádiz a privileged region for testing and developing technologies that will be used mainly in areas with higher energy, such as northern Spain, northern Europe and overseas.

II. MATERIAL AND METHODS

A. *Simulation models in the studies of coastal processes and SIMAR dataset*

Numerical models are used in oceanography to describe the temporal evolution of the oceans, through the simulation of various natural processes. Among those models that reproduce physical processes are wave models, which study their generation and propagation.

We carried out this study with data provided by Puertos del Estado, which are based on the waves model WAM [11] and Wavewatch III® wave model [12]. They are made available within the SIMAR data set. The SIMAR series collects data from 1958 to the present, and has been developed by merging two subsets of data: SIMAR-44 (1958-2005) and WANA (2006-present). The data used in the present study belong to the second subset, which comes from the sea state prediction system that Puertos del Estado has developed in collaboration with the Spanish State Meteorological Agency (AEMET). It has been generated by forcing with the outputs of the atmospheric models HIRLAM [13] and HARMONIE-AROME [14] since 2018. They are diagnostic or analysis data [15].

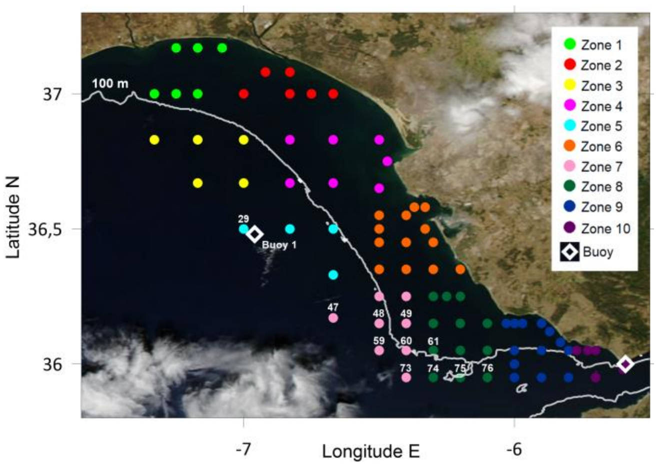

Fig. 1. Points for which data were available. SIMAR points are represented by circles, while the buoy is represented by a rhombus. The different colours of the SIMAR points represent classification into the zones that was made to aid the characterization of the wind and waves variability.

The data series corresponds to 80 points located in the area of the Gulf of Cádiz (Fig. 1), and covers 15 years of duration, from 2006 to 2020, with a temporal resolution of 1 hour. We also requested historical wave data corresponding to two buoys for validation purposes.

B. *Wave resource power*

To analyze the waves data it is necessary to consider it behaves as a stochastic process, in which the statistics associated remain unchanged during a given period of time. In order to assume this approach, it is necessary to work with instants of time in which the process can be considered as weakly stationary. These moments are called sea states. The statistical and spectral characterization of the waves in the sea states is known as short-term analysis. The parameters used to characterize these states are variable over time, and the statistical characterization of the time series of these parameters serves to describe the long-term maritime climate in a given area [16].

One of the wave parameters needed to estimate the wave power is the wave height, which can be expressed in terms of the spectral moment of order zero m_0, related to the representative wave height of the sea state, H_{m0}, or wave height of the zero order moment, by the following relationship:

$$H_{m0} = 4.004\sqrt{m_0} \quad (1)$$

If the process is narrow-banded and the wave height distribution is a Rayleigh one, this value coincides with the significant wave height, Hs, which is the mean height of the N/3 largest waves in a free surface record of N waves [16]. The average flow of energy, which is called wave power, represents the power available in a sea state, and is given by (2).

$$J = \rho_w\, g \int_0^{2\pi}\int_0^{\infty} c_g(\omega, h)\, S(\omega)\, d\omega\, d\theta \quad (2)$$

where ρ_w is the water density, g is the standard gravity, $S(\omega)$ is the spectral density function that represents the sea state, c_g is the group velocity, which is a function of the angular frequency ω and the depth h, and ϑ is the direction of wave propagation. If each sinusoidal component is considered to be a wave train, whose period is T, it will travel at a phase velocity given by the following expression:

$$U = gT/2\pi \quad (3)$$

The energy of the wave train, per horizontal area unit, will be expressed as a function of the root mean square wave height:

$$E = \rho_w\, g\, {H_{m0}}^2/16 \quad (4)$$

The wave oscillations transport this energy in the direction of propagation, therefore the temporary average energy flow will be given by the product between the average energy and the group velocity, which in deep waters can be considered as $c_g = U/2$ [17]. This approach to the calculation of the energy flow can be used to estimate the power of the waves as follows:

$$J = E\, c_g = E\, U/2 = \rho_w\, g^2 T_e {H_s}^2/(64\pi) \quad (5)$$

C. *Wind resource power*

The available power of the wind is related to its speed through the following expression:

$$P = (1/2)\, A\, \rho_a\, v^3 \quad (6)$$

where ρ_a is the air density, A is the area of the air stream considered and v the wind speed. However, it is not actually possible to extract all the available energy from the wind flow that is passing through the rotor of a wind turbine. Belz's Law establishes the maximum usable limit, by which only the fraction of 16/27 of the total available wind power can be converted into mechanical power [18]. The power that can actually be achieved depends on other factors, such as wind speed, which tends to present great variability on different temporal scales, from sub-hourly to multi-decadal scales [19], or the type of technology installed. Offshore wind plants add structural difficulties to these limitations, since the hydrodynamic factors are added to the aerodynamic problem. The transport of the energy to land must also be considered, which sometimes requires cabling that covers long distances. All this factors finally mean higher costs as compared to onshore installations.

III. RESULTS AND DISCUSSION

D. *Model validation*

In addition to the SIMAR points, time series of two buoys were available, and we used them for the model validation. We searched the closest points to both buoys: point 29, in open waters of the gulf, separated just over 4 km from buoy 1, and point 71, which is located less than 1 km from buoy 2, close to Tarifa. Fig. 2 shows, for the month of December 2019, the series of mean significant wave height and wind speed for point SIMAR 29 and for buoy 1.

There is a quite satisfactory agreement between the results of the numerical models and the experimental values measured through the buoy. We chose the period of December 2019 because during this time, one of the most energetic episodes took place on the coast of Cádiz, the storm Elsa, named on December 16, and whose effects could be felt in Spain from the 18 to the 20 of December, although the storm associated with zonal circulation continued throughout the week. During this storm, the buoy registered wave heights of over 5 m, and wind speeds up to 15 m/s.

In order to validate the results of the model, we calculated the Pearson correlation coefficient associated

TABLE I
CORRELATION COEFFICIENTS BETWEEN THE TIME SERIES OF THE BUOYS AND THE CLOSEST SIMAR POINTS

	Buoy 1 - point 29	Buoy 2 - point 71
Hs	0.91	0.84
Wave power	0.89	0.83
v	0.84	-
Wind power	0.84	-

TABLE II
STATISTICAL ERROR METRICS BETWEEN THE TIME SERIES OF THE BUOYS AND THE CLOSEST SIMAR POINTS

		MAE	RMSE	BIAS
Hs (m)	Buoy 1 - point 29	0.20	0.28	-0.01
	Buoy 2 - point 71	0.24	0.35	0.12
Wave direction (º)	Buoy 1 - point 29	21.34	49.80	9.75
	Buoy 2 - point 71	44.32	58.79	24.74
v (m/s)	Buoy 1 - point 29	1.41	1.82	0.75
Wind direction (º)	Buoy 1 - point 29	23.96	39.02	2.52

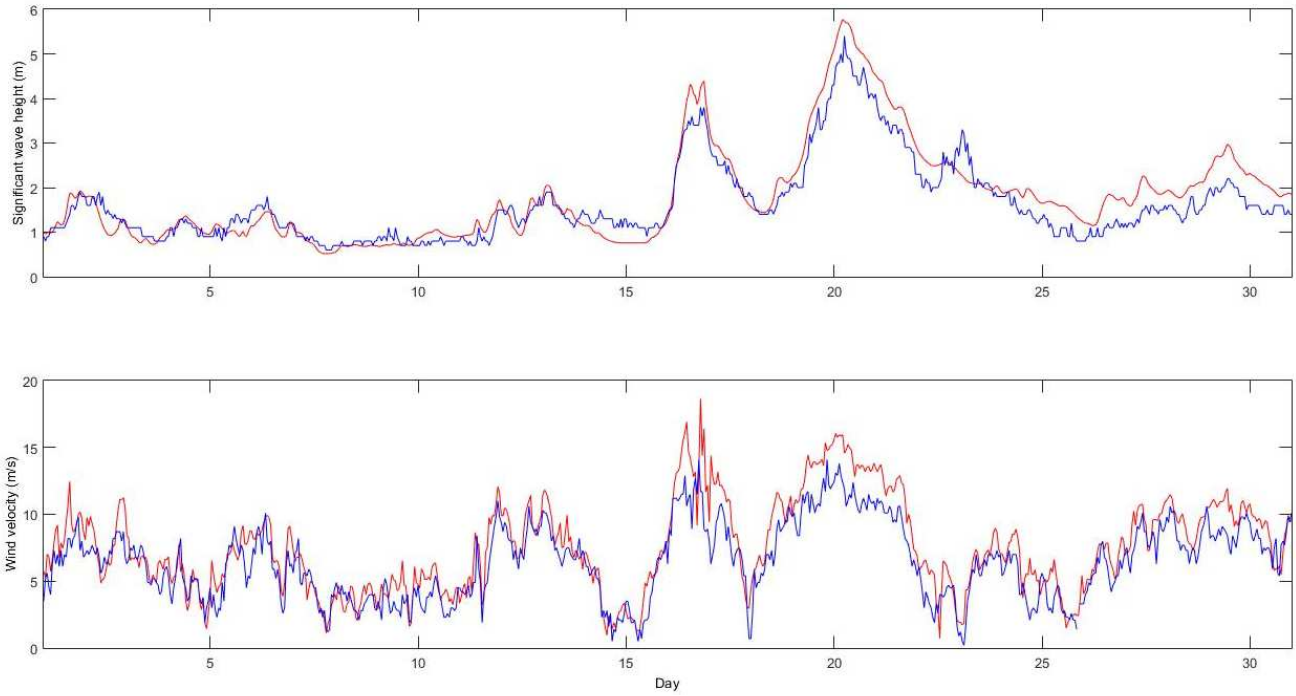

Fig. 2. Above, hourly averages significant wave height for point SIMAR 29 (in red) and for buoy 1 (in blue), below, hourly average wind speed for point SIMAR 29 (in red) and for buoy 1 (in blue), for the month of December 2019.

with the SIMAR-buoy data in each case during the 15-year period for which data were available. In addition, we calculated some statistical error metrics for the same period: mean absolute error (MAE), root mean square error (RMSE) and the bias. Table 1 shows the correlation coefficients for the series of significant wave height and wind speed, as well as their associated powers. Table 2 shows the statistical error metrics for significant wave height and wind speed between both data sets. It should be noted that for buoy 2 only wave data was available. Although the correlation is higher in general for the waves, these correlation coefficient values close to 1 indicate a good correlation between the data sets. Also, the statistical error metrics show small discrepancies between the two data sets. These results allow us to validate the results obtained by the models used for the SIMAR points.

E. Characterization of the energy resources of waves and wind in the Gulf of Cádiz

We evaluated and characterized wave and wind energy resources in the 80 available SIMAR points. In table 3 some points have been selected, for which both wave power and wind power results showed the highest values within our study area. These points are those that are depicted in Fig. 1. For the waves, the mean spectral significant height is specified at each point, with its standard deviation, the maximum spectral significant height in the period studied, the mean wave power and the maximum power. For the wind, at each point the time averaged wind speed is specified, with its standard deviation, the maximum speed over the 15 years, the time averaged wind power and the maximum power.

In general we can observe that the wave height values

TABLE III
SUMMARY OF STUDY POINTS, LOCATION AND DEPTH, MOST IMPORTANT PARAMETERS OF WIND AND WAVE RESOURCES

Site no.	Location	Depth (m)	Zone	$(H_s)_{mean}$ ± std. dev.(m)	$(H_s)_{max}$ (m)	J_{mean} (kW/m)	J_{max} (kW/m)	v_{mean} ± std. dev.(m/s)	v_{max} (m/s)	P_{mean} (kW/m²)	P_{max} (kW/m²)
47	36.17º N, -6.67º W	496	7	1.38 ± 0.79	7.59	11.40	376.46	6.69 ± 3.54	24.44	0.36	8.94
48	36.15º N, -6.50º W	113	7	1.35 ± 0.78	8.11	9.76	350.75	6.72 ± 3.62	25.06	0.37	9.64
49	36.15º N, -6.40º W	80	7	1.33 ± 0.74	7.89	8.92	324.33	6.67 ± 3.61	24.65	0.36	9.17
59	36.05º N, -6.50º W	230	7	1.43 ± 0.82	8.25	11.01	364.30	7.01 ± 3.84	25.72	0.43	10.42
60	36.05º N, -6.40º W	117	7	1.43 ± 0.79	8.24	10.56	359.11	7.03 ± 3.89	25.69	0.44	10.38
61	36.05º N, -6.30º W	73	7	1.37 ± 0.76	7.76	9.38	315.82	7.05 ± 3.94	25.55	0.45	10.22
73	35.95º N, -6.40º W	327	7	1.48 ± 0.80	8.34	11.53	366.19	7.16 ± 3.93	24.71	0.46	9.24
74	35.95º N, -6.30º W	127	7	1.45 ± 0.78	8.2	10.86	358.25	7.22 ± 3.99	25.12	0.47	9.71
75	35.95º N, -6.20º W	108	8	1.41 ± 0.76	8.07	10.10	351.14	7.27 ± 4.04	25.1	0.48	9.69
76	35.95º N, -6.10º W	237	8	1.36 ± 0.74	7.95	9.22	343.56	7.27 ± 4.05	24.91	0.49	9.47

and the associated powers are limited, especially if we compare them with other coastal regions, such as the Galician coast, where evaluations of SIMAR points offer values of mean significant wave height of more than 2.5 m in some cases, and associated mean powers of more than 50 kW/m [4]. However, in some areas values of more than 10 kW/m of average power are reached, generally corresponding to the points farthest from land, and therefore at greater depths. Also, in these areas we can find the maximum wave heights and power peaks for the period under study, with heights of more than 8 m, and powers above 350 kW/m.

Average wind speeds are between 5 and 8 m/s along the Gulf of Cádiz, indicating that it is a significant resource. The highest speed values occur in the area closest to the Strait of Gibraltar. The maximum wind speeds at some points show extremely strong wind values (> 25 m/s), of force 10 on the Beaufort scale, which correspond to episodes of storm.

The high standard deviation values obtained for wave heights and wind speed indicate large dispersions of the values with respect to the mean. However, it should not be forgotten that we are working with fifteen years long series at intervals of one hour, therefore this variability was expected.

F. *Wave and wind roses*

In order to study the distribution of the directions of origin of waves and wind, the 80 points were divided into 10 zones (Fig. 1). For each zone we constructed wind and wave roses for the studied period. The quadrants are defined clockwise, the first quadrant is the one between the north and east directions.

In the case of waves (Fig. 3), the directions and the wave height are clearly different in the areas located closer to the coast of Huelva, from than in those located on the coast of Cádiz and in the Strait. On the coast of Huelva (zones 1 and 2), the predominant wave directions are SW, almost perpendicular to the coastline, and also less frequently SE directions, which wave height rarely exceeds one meter. In the area of the Guadalquivir Estuary and the coast of Cádiz (zones 4 and 6), the predominant direction of the waves is W, and in this case the frequency of heights between 1 and 2 m is higher, and to a lesser extent exceed 2 m. In these areas, directions located in the second quadrant are also seen, with frequencies lower than 10%. As we move away from the coast, at depths between 200 and 500 m, but still far from the Strait (zones 3 and 5), the predominant direction is again the W, with waves of greater heights than in the shallower zones. In this case, the directions in the third quadrant (SE) are a bit more frequent, and are associated with higher wave heights. In the innermost region of the Strait of Gibraltar (zones 7, 8, 9 and 10), the most frequent swell comes from the W and NW. In this case we can find directions in the 4 quadrants, which is probably due to the topography of this area. As we move towards open waters of the Atlantic, the NW direction is gaining importance, and in general the waves are higher than in the innermost part of the Strait, being this region (zone 7) the one that registers the highest heights (average and maximum) of all the points studied in the Gulf of Cádiz. Likewise, SE directions can be observed, with frequencies around 15%, whose wave heights are above 2 m in most cases.

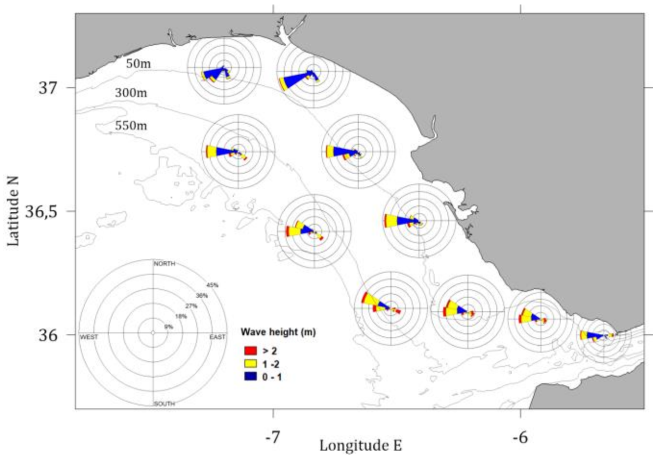

Fig. 3. Gulf of Cádiz wave roses for the period under study. The bars point at the direction of waves origin.

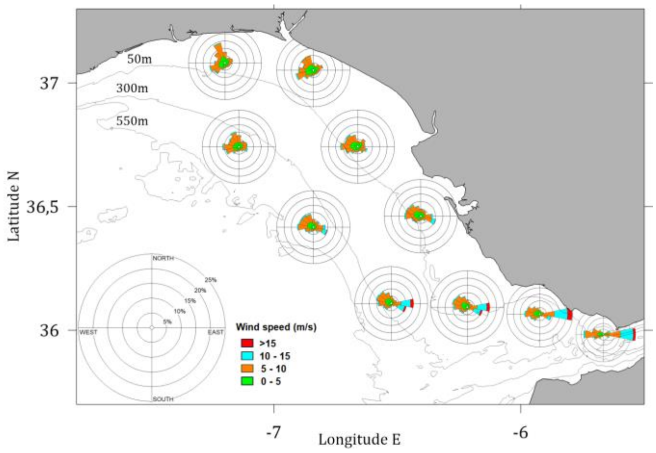

Fig. 4. Gulf of Cádiz wind roses for the period under study. The bars point at the direction of wind origin.

In regard to wind (Fig. 4), we can see that wind and wave directions do not seem to be related to each other. In addition, the directions of origin of the wind are very different along the areas of the Gulf of Cádiz. On the coast of Huelva (zones 1 and 2), there are directions distributed between quadrants I, III and IV, the NW and SW directions are especially frequent, and the wind speeds are mostly between 5 and 10 m/s. When descending to the south, through the area of the Guadalquivir Estuary, and the coast of Cádiz, both in the shallower regions and open waters (zones 3, 4, 5 and 6), most of the winds are grouped in the fourth quadrant, although there are winds from all directions of origin. As we descend in latitude (zones 7, 8, 9 and 10), it can be seen that the winds coming from the E (Levante) and the SE are gaining importance, become more frequent and have associated higher speeds (usually above 10 m/s). The importance of the east wind is evident in the innermost area of the Strait (zones 9 and 10), where the east wind is not only the most frequent, taking place more than 25% of the time, it also has high speeds, mostly between 10 and 15 m/s, and in many cases above 15 m/s.

G. Characterization of the sea states

Usually, sea states are characterized according to their significant wave height (H_s) and their energy period (T_e). This type of spectral characterization is useful when choosing the type of devices to use for energy conversion.

In Fig. 5 we represented a dispersion of the sea states against significant height and wave period, also indicating the occurrence of the sea states, in hours per year, and including a representation by colours of the annual energy per meter of wave front, in MWh/m, calculated over the 15-year period under study. To calculate the annual energy, the diagram was divided into squares of 0.3 m (ΔH_s) and 0.5 s (ΔT_e), and for each of them we counted the number of hours per year in which the parameters waves are within the limits of the grid. Finally the hours counted were multiplied by the energy flow, calculated through (5), using the mean values of H_s and T_e corresponding to each grid.

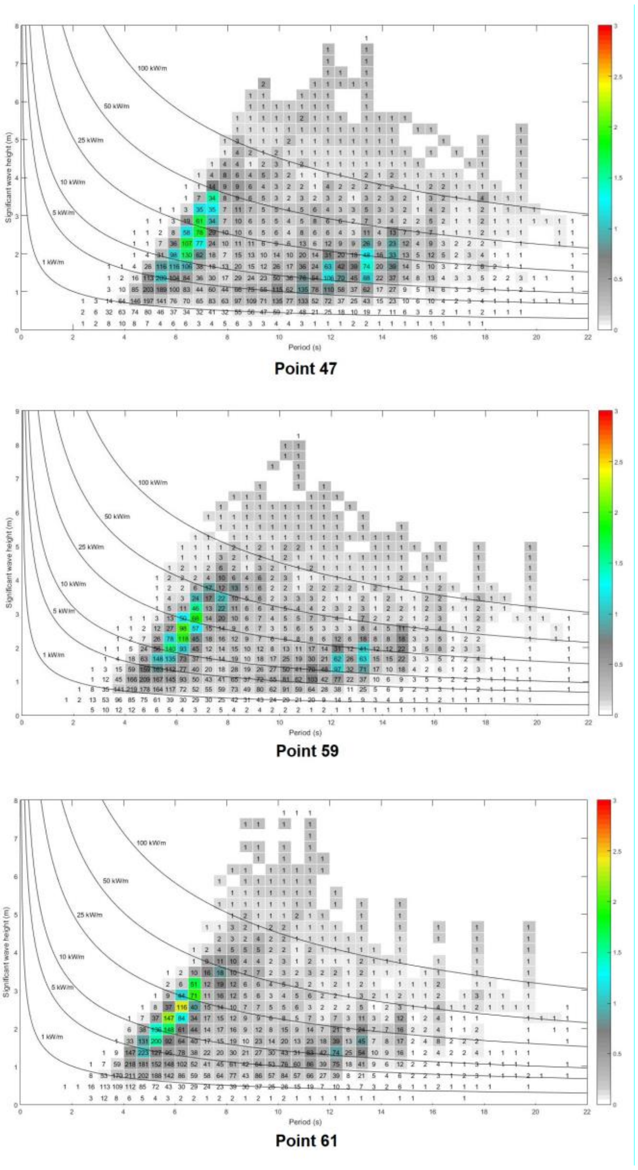

Fig. 5. Characterization of the wave energy resource for the period under study (2005 - 2020), in zones 1 to 3, in terms of the significant wave height (Hs) and the energy period (Te). The numbers represent the occurrence in hours per year for each sea state. The different colours indicate the annual energy in MWh/m.

We chose these points because they are the ones that obtain the highest average wave power values, their locations and depths can be found in table 3. The sea states with wave heights above 2 m and periods of between 4 and 8 s stand out, accumulating energy values of almost 3 MWh/m throughout the year. These most energetic sea states are located approximately between the 5 kW/m and 25 kW/m isolines, of power per meter of wave front. In general, in all areas, most of the sea states throughout a year present wave heights below 2 m, although in the areas further from the coast we can find sea states with waves of greater height than in the areas closer to the coast.

H. Temporal and spatial variability

We constructed seasonal maps of the powers associated with both resources in the Gulf of Cádiz. Since the points for which data were available were spatially presented in an irregular manner, in order to be able to construct rectangular meshes, we carried out Kriging interpolations. This method allows obtaining exact interpolations, sometimes offering better predictions than regression analyzes, using space-filling designs to give more weight to neighboring observations [20].

In Fig. 6 we can see the maps for the wave resource, and in Fig. 7 for the wind resource. It is striking that the maximum power values of each resource do not coincide in time, whereas for the waves winter is the most energetic season, in the case of wind it is spring. This could be beneficial for the jointly use of both energy resources, being able to compensate each other. It also shows that both resources are decoupled over time. On the other hand, summer registers the minimum power values for both the waves and the wind.

The wave resource shows in summer very small power values, spring and autumn represent transition seasons, in which wave power becomes more significant in the southern part of the Gulf, especially at greater depths. Winter is clearly the most energetic season. The wave resource is generally limited, however it reaches higher values in the southern part of the Gulf, where there are greater depths. The fact that the continental shelf is extensive in this area may be favorable for the possibility of taking advantage of this resource. In certain places, specifically near the coasts of Conil and El Palmar de Vejer, where depths are around 50 m, average values of up to 15 kW/m are reached in winter, and 10 kW/m in spring and autumn, something that usually occurs at greater depths, on coasts with more energetic waves.

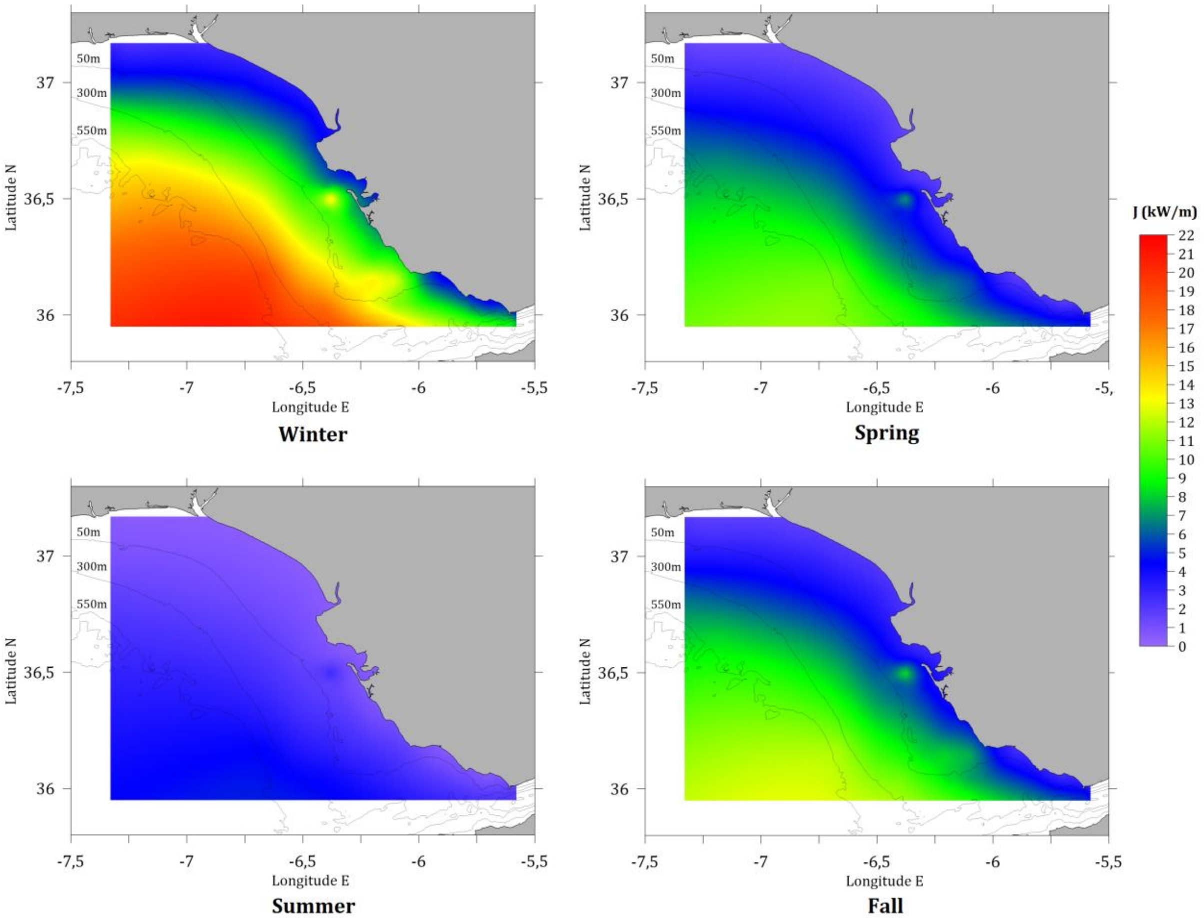

Fig. 6. Seasonal mean values of wave power in the Gulf of Cádiz for the study period.

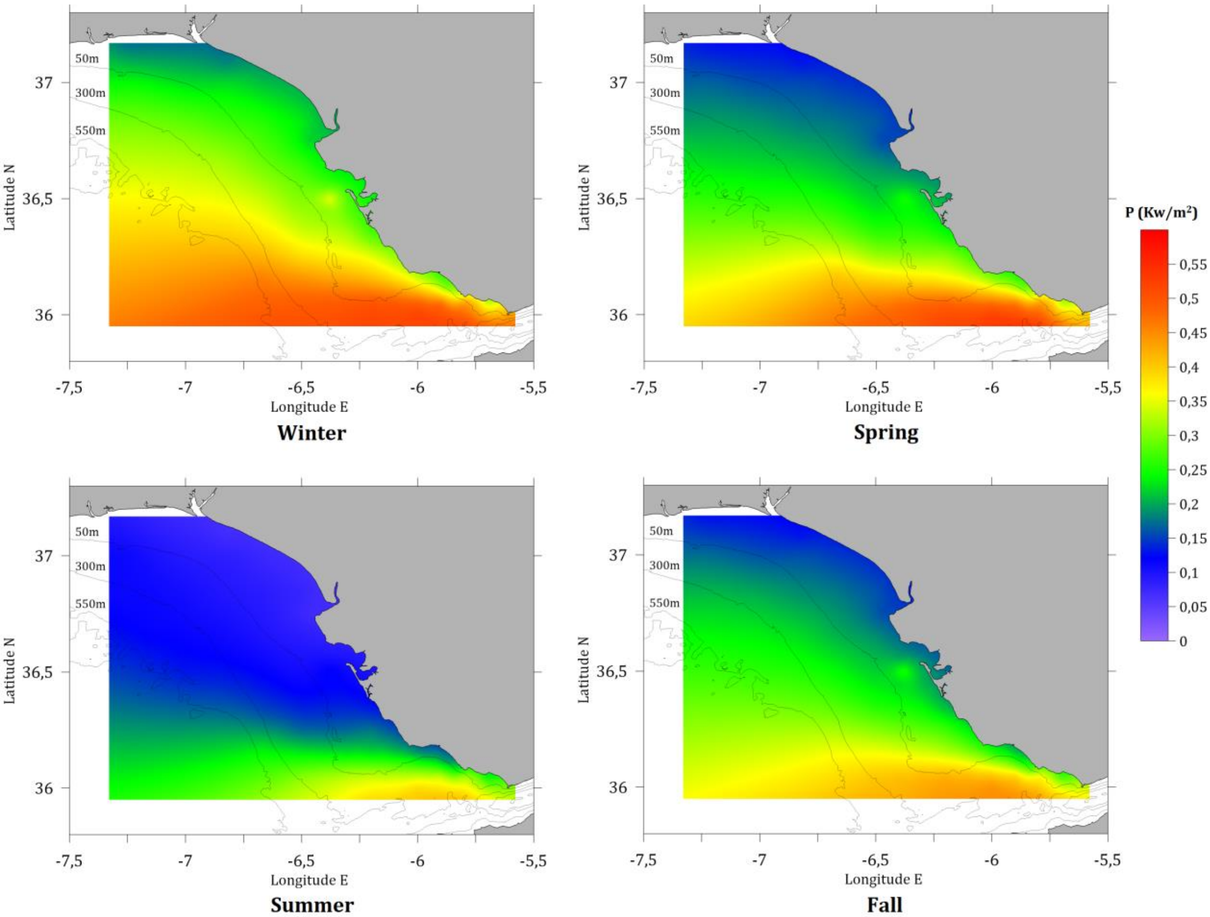

Fig. 7. Seasonal mean values of wind power in the Gulf of Cádiz for the study period.

This fact may be due to a unique bathymetry, it has been shown that in coastal areas with sudden changes in depth, concentrations of wave energy can occur, as a result of the interaction of the waves with the currents near the coast [21].

The wind resource is clearly marked by the influence of the Strait of Gibraltar. It is known that the Strait area is frequently subjected to strong winds (10-20 m/s), with the eastern winds being the dominant ones. This resource shows maximum powers in spring, however, these high values are localized in the Strait area, which is consistent with the fact that the east winds have their highest intensities in spring. In winter, significant wind power values are reached throughout the Gulf, probably as a consequence of the greater frequency and intensity of the west winds in this season, which come from the Atlantic and cover the entire region of the Gulf of Cádiz, finding no obstacle. The powers registered in autumn and summer are more limited for this resource, and significant values are only seen in the Strait area. The region located in front of El Palmar de Vejer, with depths of less than 50 meters, registers average powers from 0.25 kW/m² in summer to 0.5 kW/m² in spring.

I. High energy events

The study of high-energy marine events is important to determine their impact and estimate their recurrence

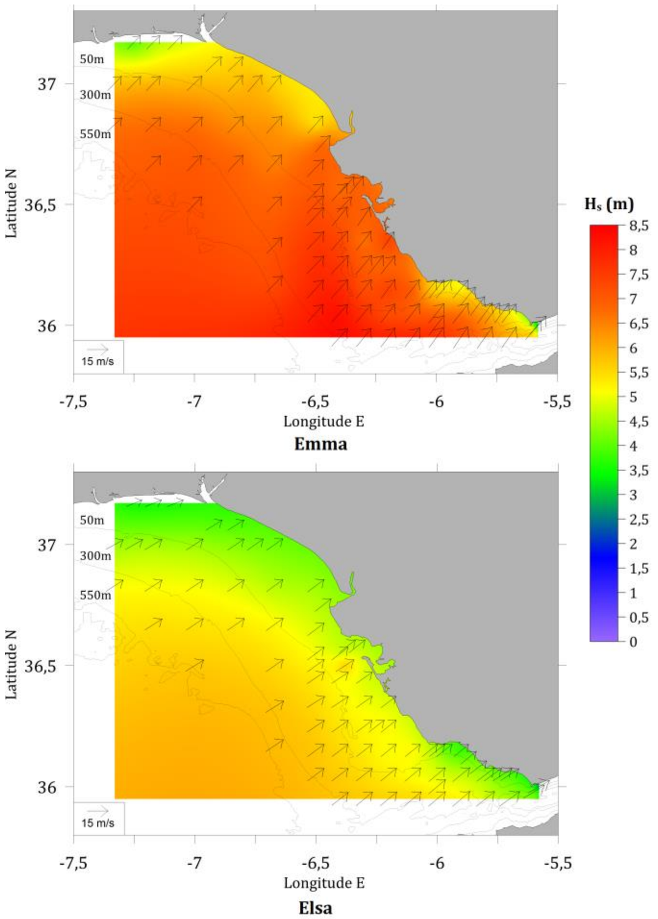

Fig. 8. Storms Emma (above) and Elsa (below), at the moments when the maximum wave heights were detected in each case. The wave height has been represented by colours, and the intensity and direction of the wind by vectors.

periods. It is necessary to be able to predict these types of events to try to minimize the damage that they can cause in various areas, also in structures and devices for energy use in the sea. With this objective in mind, we attempted to analyze and characterize some of the higher energy events that took place in the Gulf of Cádiz during the period under study, specifically two storms: the storm Emma, which affected the Iberian Peninsula in the first days of March 2018, and the storm Elsa, whose effects could be seen from the 18 to the 20 of December. For both storms, we built maps where the wave height is represented through colours, and by means of vectors, the intensity and direction of the wind, for the moment in which the maximum wave height was detected at some point in the Gulf in each storm (Fig. 8).

We can see in both cases that the direction of origin of the wind is similar, from the SW. This seems to indicate that this types of events are associated with winds from the west, since it is difficult for the east winds to generate episodes of such energy in the Gulf, because despite their intensity, the east winds encounter too many obstacles to affect the entire Gulf of Cádiz. Regarding the intensity of the wind, we find values between 10 and 20 m/s at all points, and we can see no decrease in magnitude as the wind enters the gulf. This could be due to the fact that the wind coming from this direction has more space and time to move without encountering obstacles in its path that could reduce its magnitude, as occurs at the points closest to the coast, where the wind vectors reduce their size. It is observed that for the Elsa storm, the waves reached 6 meters at some points, while for Emma storm, the waves reached more than 8 meters, which represents waves of grade 7 on the Douglas scale. Although this type of phenomenon is not common on the coasts of the Gulf of Cádiz, it is necessary to take them into account, as their effects can cause great damage. The storm Emma registered the largest waves of the entire period under study, and caused numerous personal and material damages in the provinces of Huelva, Sevilla and Cádiz.

J. Best areas for combined energy use

We were looking for an area where a hybrid-type installation, which took advantage of the resources of the waves and the wind at the same time, could be suitable. Based on this, point 60 was chosen to perform a wave and wind analysis through the construction of roses. It is located 117 m deep, and far enough from the Strait to not be affected by heavy maritime traffic from the Strait of Gibraltar. Likewise, for this point we obtained one of the highest values of average wave power and also of average wind power. In Fig. 9 it is represented the seasonal wave roses and in Fig. 10 the seasonal wind roses for this point.

Observing the wave roses, we can see that in all cases the most frequent direction is NW–W, especially in summer, when this direction takes place over 50% of the time, with waves of small height. Also the SE-E direction

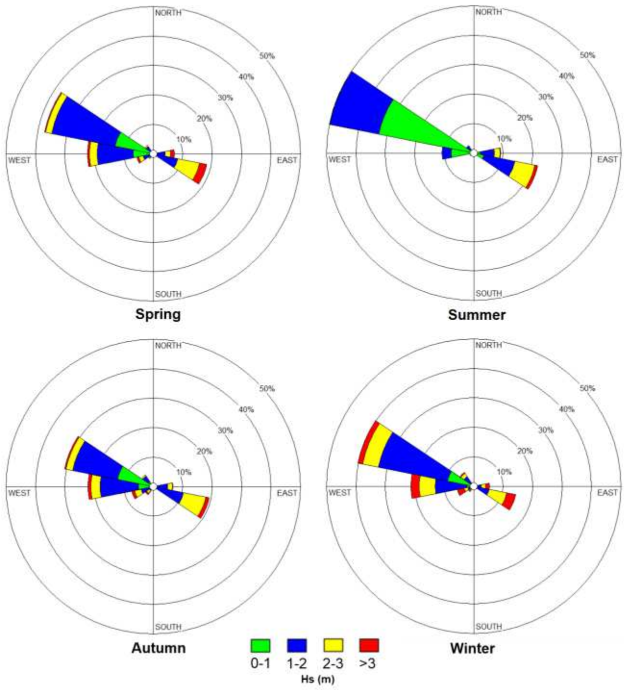

Fig. 9. Seasonal wave roses for the point 60.

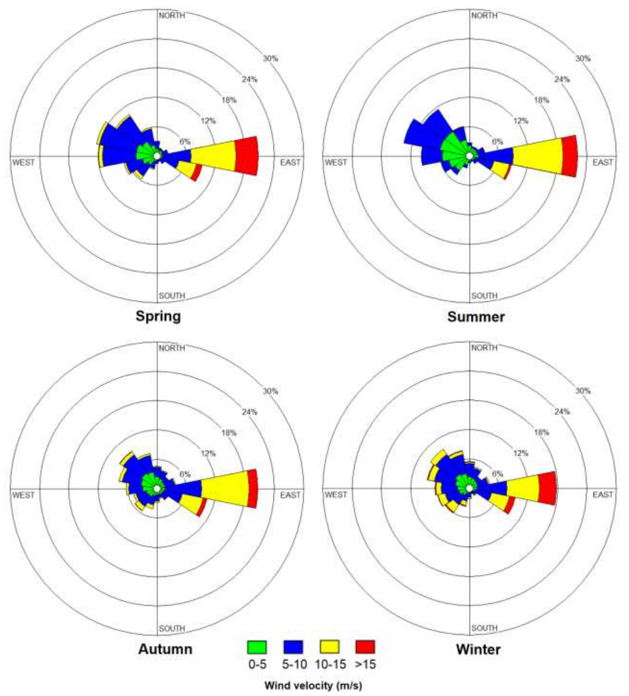

Fig. 10. Seasonal wind roses for the point 60.

appears in all cases, which is associated with higher wave heights, even in summer. These two directions take place almost the entire period studied at this point. It is in winter when, in general, the highest wave heights appear at this point, with episodes of more than 3 meters taking place with relative frequency.

Fig. 10 shows a great predominance of the Levante wind, which also has high speeds, between 10 and 15 m/s most of the time, and sometimes above 15 m/s. This east wind reaches its maximum frequency in spring, taking place approximately 25% of the time. It is also in spring when it seems to show the highest speeds, since around a third of the times that there is an east wind in spring, it exceeds 15 m/s. The NW-W direction is also important,

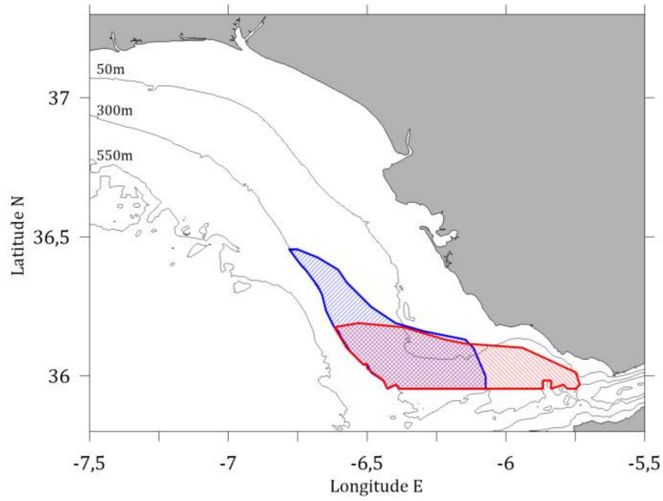

Fig. 11. Map of the best areas of the Gulf of Cádiz for energy use of wave (in blue) and wind (in red) resources.

taking place 10% of the time, with minimum speeds in summer and maximum speeds in winter; however, winds coming from this direction rarely exceed 15 m/s.

The main objetive of this work was to determine the most favorable area of the Gulf of Cádiz for the installation of hybrid devices, capable of harnessing the energy of the waves and the wind. For this, we considered the areas where both resources are significant, and depths above 300 meters.

In Fig. 11 the most favorable sectors for the use of both resources have been represented. We marked through blue lines inclined to the right the best area for harnessing wave energy, and with red lines inclined to the left, the most favorable sector for harnessing wind energy. Both areas partially overlap, delimiting the optimal area for the jointly use of both resources, located near the coasts of El Palmar, Conil and Cape Trafalgar. Particularly interesting is the fact that part of this area is located above the 50 meter isobath. This limit could serve to divide the area into two sub-regions: above 50 meters of depth it could be the ideal place for the installation of fixed structures, whereas for greater depths floating structures should probably be chosen.

IV. CONCLUSIONS

The main conclusions to highlight would be the following:

- The validation of the model data corresponding to point 29 with the data of the buoy 1, and to the point 71 with the data of the buoy 2 offered good correlations, demonstrating the accuracy of the model results.
- The wave and wind resources in the Gulf of Cádiz are decoupled, both temporally and spatially. Whereas the maximum power of the waves occurs in winter, it is in spring when the wind reaches its highest speeds. Regarding the spatial distribution, the waves are largely conditioned by the underwater topography, which in general causes the highest

wave heights to appear in the deepest areas. In the case of wind, it is the land topography that mainly determines the scope of this resource, causing the east winds to be limited to the area of the Strait of Gibraltar, whereas those from the west affect the entire Gulf.

- As a main conclusion, an optimal zone has been determined for the jointly use of both resources. This region is located off the coast of El Palmar de Vejer, approximately between latitudes 35.95º N and 36.15º N, and between longitudes 5.75º W and 6.5º W. It is especially interesting that part of this area is located above the 50 meter isobath, which could serve as a limit to divide the area into two subregions, so that above 50 meters depth it could be the ideal place for the installation of fixed structures, while for greater depths should probably be chosen floating structures.

ACKNOWLEDGEMENT

We are grateful to Puertos del Estado for providing the data set with which we have worked in this article. We are also grateful to NASA for distributing the MODIS data used in this study, and to the AERONET project for the MODIS AQUA RGB True Color Images, especially Huelva station.

REFERENCES

[1] M. Mueller, and R. Wallace, "Enabling science and technology for marine renewable energy". *Energy Policy*, vol. 36, issue 12, pp. 4376-4382, 2008. DOI: 10.1016/j.enpol.2008.09.035, [Online].

[2] J. Bosch, I. Staffell, A. D. Hawkes, "Temporally explicit and spatially resolved global offshore wind energy potentials," Energy, vol. 163, pp. 766-781, 2018. DOI: https://doi.org/10.1016/j.energy.2018.08.153 [Online].

[3] G. Ibarra-Berastegi, J. Sáenz, A. Ulazia, P. Serras, G. Esnaola, and C. Garcia-Soto, "Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014–2016)," *Ocean Engineering*, vol. 147, pp. 20-29, 2018. DOI: 10.1016/j.oceaneng.2017.10.018 [Online].

[4] G. Iglesias, and R. Carballo, "Wave energy potential along the Death Coast (Spain)," *Energy*, vol. 34, issue 11, pp. 1963-1975, 2009. DOI: 10.1016/j.energy.2009.08.004 [Online].

[5] J. E. Hanssen, L. Margheritini, K. O'Sullivan, P. Mayorga, I. Martinez, A. Arriaga, I. Agos, J. Steynor, D. Ingram, R. Hezari, and J. H. Todalshaug, "Design and performance validation of a hybrid offshore renewable energy platform," in *2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2015, pp. 1-8. DOI: 10.1109/EVER.2015.7113017 [Online].

[6] W2Power, "Mobilising the total offshore renewable energy resource," 2010. [Online] Available: http://www.pelagicpower.no/index.html

[7] L. del Río, T. A. Plomaritis, J. Benavente, M. Valladares, and P. Ribera, "Establishing storm thresholds for the Spanish Gulf of Cádiz coast," *Geomorphology*, vol. 143-134, pp. 13-23, 2012. DOI: 10.1016/j.geomorph.2011.04.048 [Online].

[8] F. J. Lobo, F. J. Hernández-Molina, L. Somoza, J. Rodero, A. Maldonado, and A. Barnolas, "Patterns of bottom current flow deduced from dune asymmetries over the Gulf of Cadiz shelf (southwest Spain)," *Marine Geology*, vol. 164, issues 3-4, pp. 91-117, 2000. DOI: 10.1016/S0025-3227(99)00132-2 [Online].

[9] J. García-Lafuente, J. Delgado, F. Criado-Aldeanueva, M. Bruno, J. del Río, and J. M. Vargas, " Water mass circulation on the continental shelf of the Gulf of Cádiz," *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. 53, issues 11-13, pp. 1182-1197, 2006. DOI: 10.1016/j.dsr2.2006.04.011 [Online].

[10] S. Robles, M. Sanchez, M. Bruno, P. Mayorga, and J. Hanssen, "The potential for Ocean Energy in the Region of Andalucia (South of Spain)," in *2011 International Conference on Ocean Energy*, Torremolinos (Málaga), Spain, 2011. DOI: 10.1109/PowerEng.2011.6036417 [Online].

[11] The Wamdi Group, S. Hasselman, K. Hasselman, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionelo, A. Guillaume, V.C. Cardone, J.A. Greenwood, M. Reistad, L. Zambresky, and J.A. Ewing, "The WAM model: a third-generation ocean wave prediction model," *Journal of Physical Oceanography*, vol. 18, issue 12, pp. 1775–1810, 1988. DOI: 10.1175/1520-0485(1988)018<1775:TWMTGO>2.0.CO;2 [Online].

[12] H. L. Tolman, "A third-generation model for wind waves on slowly varying, unsteady, and inhomogeneous depths and currents," *Journal of Physical Oceanography*, vol. 21, issue 6, pp. 782-797, 1991. DOI: 10.1175/1520-0485(1991)021<0782:ATGMFW>2.0.CO;2 [Online].

[13] P. Undén, L. Rontu, H. Jarvinen, P. Lynch, F. J. Calvo Sánchez, G. Cats, J. Cuxart, K. Eerola, C. Fortelius, J. A. García-Moya, C. Jones, G. Lenderink, A. McDonald, R. McGrath, B. Navascués, N. Woetman-Nielsen, V. Odegaard, E. Rodríguez Camino, M. Rummukainen, R. Room, K. Sattler, B. Hansen Sass, H. Savij arvi, B. Wichers Schreur, R. Sigg, T. Han, and A. Tijm, "HIRLAM-5 scientific documentation.," 2002. [Online] Available: http://hirlam.org/index.php/hirlam-documentation

[14] L. Bengtsson, U. Andrae, T. Aspelien, Y. Batrak, J. Calvo, W. de Rooy, E. Gleeson, B. Hansen-Sass, M. Homleid, M. Hortal, K. Ivarsson, G. Lenderink, S. Niemelä, K. P. Nielsen, J. Onvlee, L. Rontu, P. Samuelsson, D. S. Muñoz, A. Subias, S. Tijm, V. Toll, X. Yang, and M. Ø. Køltzow. "The HARMONIE–AROME Model Configuration in the ALADIN–HIRLAM NWP System", Monthly Weather Review, vol 145, issue 5, pp. 1919-1935, 2017. DOI: 10.1175/MWR-D-16-0417.1 [Online].

[15] M. Gómez, J. C. Carretero, "Wave forecasting at the Spanish coasts," Journal of Atmospheric and Ocean Science, vol. 10, issue 4, pp. 389–405, 2005. DOI: 10.1080/17417530601127522 [Online].

[16] I. J., Losada, C. Vidal, F. J. Méndez, R. Mínguez, S. Requejo, P. Camus, A. Tomás, M. Menéndez, C. Izaguirre, A. Espejo, B. González, N. Kakeh, F. Fernández, and F. Maza, "Evaluación del potencial de la energía de las olas. Estudio Técnico PER," 2011. [Online] Available: https://www.idae.es/uploads/documentos/documentos_11227_e13_olas_b31fcafb.pdf

[17] S. Barstow, G. Mørk, D. Mollison, and J. Cruz, "The wave energy resource," *Ocean wave energy*, pp. 93-132, 2008. DOI: 10.1007/978-3-540-74895-3_4 [Online].

[18] D. Villanueva, and F. Feijóo, "Wind power distributions: A review of their applications," *Renewable and Sustainable Energy Reviews*, vol. 14, Issue 5, pp. 1490-1495, 2010. DOI: 10.1016/j.rser.2010.01.005.

[19] C. Jung, D. Taubert, and D. Schindler, "The temporal variability of global wind energy – Long-term trends and inter-annual variability," *Energy Conversion and Management*, vol. 188, pp. 462-472, 2019. DOI: https://doi.org/10.1016/j.enconman.2019.03.072 [Online].

[20] W. C. Van Beers, and J. P. Kleijnen, "Kriging interpolation in simulation: a survey," in *Proceedings of the 2004 Winter Simulation Conference*, vol. 1, Washington, DC, USA, 2004. DOI: 10.1109/WSC.2004.1371308.

[21] R. S. Ranasinghe, Y. Fukase, S. Sato, and Y. Tajima, (2011). "Local concentration of waves due to abrupt alongshore variation of nearshore bathymetry," *Coastal Engineering Journal*, vol. 53, No 03, pp. 201-222. DOI: 10.1142/S0578563411002331 [Online].