A joint evaluation of the wave and wind energy along the west Iberian nearshore

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ABSTRACT

There is a growing interest in extracting marine renewable energy and contributing in this way to the green road towards a low carbon future. From this perspective, the Iberian nearshore represents a coastal environment with very high potential. In this context, the objective of the work proposed herewith is to perform a joint evaluation of the wave and wind power along the west Iberian coastal environment. The analysis is structured in two-time intervals. The first is the 20-year period (2001-2020), for which the ERA5 wind data have been considered. The second 20-year period (2026-2045) corresponds to the near future and in this case, wind data provided by the climate model RCA4 (Rossby Centre regional atmospheric model, version 4) have been processed and analysed, corresponding to the climate scenario RCP4.5. (Representative Concentration Pathway). The same two periods have been considered for the evaluation of wave power. In this case simulations with spectral phase averaged model SWAN (Simulating WAves Nearshore) have been performed. This wave modelling system was implemented for the entire North Atlantic basin and focused on the west Iberian coastal environment. Finally, the results also indicate that there is a good synergy between wind and wave power in the west Iberian nearshore. As a conclusion, the development of joint wind–wave projects along the west Iberian coastal environment represents a viable direction for the near future. Especially, the Northwestern part of the Iberian nearshore has a very good potential both in terms of wave and wind energy.

KEYWORDS

Iberian nearshore, wave power, offshore wind, joint evaluation, hybrid farms

INTRODUCTION

In the last decades, the changes in the climate can be noticed and it becomes very obvious that this dynamic is significantly influenced by human activities [1]. For this reason, effective measures for decarbonisation are currently taken by many international and national authorities [2]. Since about 75% of the emissions are generated by the energy sector the translation to the green energy represents a very important direction for a sustainable development towards a low carbon future.

From this perspective, the European Commission published in December 2019 the 'European Green Deal' [3]. This is a programmatic document defining the most important steps for the future development of Europe promoting research and innovation efforts across by supporting

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the most impactful technologies in the European Union's transformation to a low-carbon energy system. According to this new strategy marine renewable energy (MRE) will have a significant place in the global energy portfolio. Thus, the EU targets for 2050 are a 300 GW for offshore wind capacity and 40 GW for other ocean energy sources. If we account that in 2021 the offshore wind capacity was 12 GW while for the other sources 13MW, this implies 25 times increase for the offshore wind and more than 3000 times for ocean energy. These very ambitious targets imply on one hand large geographical extensions for harvesting marine renewable energy and on the other hand significant technological advances.

The west Iberian nearshore represents a very attractive coastal environment from the point of view of extracting marine renewable energy. Its coastal areas have considerable wave energy resources [4-6] and in the last decade, various technologies for wave energy extraction have been experimented there [7-9]. Furthermore, different projections made using advanced wave modelling systems [10] indicate that in the next twenty years the wave energy will continue to be significant in this coastal environment. Many technologies for wave energy extraction are still under development and considering the very ambitious targets established for ocean energy in the framework of the European Green Deal, it is expected a significant advance in the very near future. At this point it has to be highlighted that the marine energy farms, and especially the wave farms, can play an important role also for coastal protection [11-14].

As regards offshore wind, this is based on proven technology and has a more than 30 years history of success [15]. This is illustrated by the very high development of offshore wind energy extraction noticed in the last decades. Although this spectacular advance from the last decades is related to the fixed offshore wind turbines (WT) that can operate up to about 60 meters of water depth, in the last years relevant developments concerning floating wind technologies can be also noticed. Such floating wind turbines can operate until 200 meters water depth (or more) and they can be used also for solar panels.

In Europe, the pioneer in terms of extracting offshore wind energy is the Baltic Sea, where the first offshore wind farm (Vindeby), which is still operational, was installed in 1991 by Denmark [15] and where more than 20 wind projects are currently operational. On the other hand, the most resourceful environment from the point of view of offshore wind energy extraction is the North Sea which has indeed very high wind energy [16] and where about 40 wind farms are currently operating, while other outstanding projects are under development.

Although it has not so high wind energy potential as the Baltic or the North Seas, the west Iberian nearshore has wind energy resources [17-19] which on the north-western side of the peninsula can be considered significant. On the other hand, as already mentioned above, these coastal areas have very good resources in terms of wave energy, and they can be considered among the most significant coastal environments from the point of the joint wave-wind marine renewable energy potential [20]. Finally, it can be noticed also that besides wave and wind energy this coastal area is very resourceful also from the point of view of solar energy [21].

In this general context, the main objective of the present work is to perform a joint analysis of the wave and wind power along the west Iberian coast. The proposed analysis is structured in two different time intervals. The first is the 20-year period (2001-2020), for which the ERA5 wind data have been considered. The second 20-year period (2026-2045) corresponds to the near future and in this case, wind data provided by the regional climate model RCA4 (Rossby Centre regional atmospheric model, version 4) have been processed and analysed, corresponding to the climate scenario RCP4.5. (Representative Concentration Pathway). The same two periods have been considered for the evaluation of wave power. In this case simulations with spectral phase averaged model SWAN (Simulating WAves Nearshore) have been performed downscaling towards the west Iberian nearshore a wave modelling system implemented for the entire North Atlantic [10].

METHODS AND MATERIALS

The target area

The west Iberian nearshore is a region characterized by high marine renewable resources and represents the target area of the present study. Figure 1 presents the geographical domain where ten reference points were chosen to evaluate the wave and wind power. Information about the geographical coordinates of these reference points and the corresponding water depths are provided in Table 1. These positions are characterized by water depths that allow the location of both wave and wind farms, so the simultaneous exploitation of both renewable energy resources is possible.

The objective of this study is to evaluate both resources for their common exploitation, something that would be beneficial both from an economic point of view, because common infrastructures could be used when independent farms are developed, but also from a practical perspective by stabilizing the flow of energy to the electrical grid. The synergies between wave energy and offshore wind can lead to reduced resource variability which would solve the electricity grid's need to receive a stable energy source.

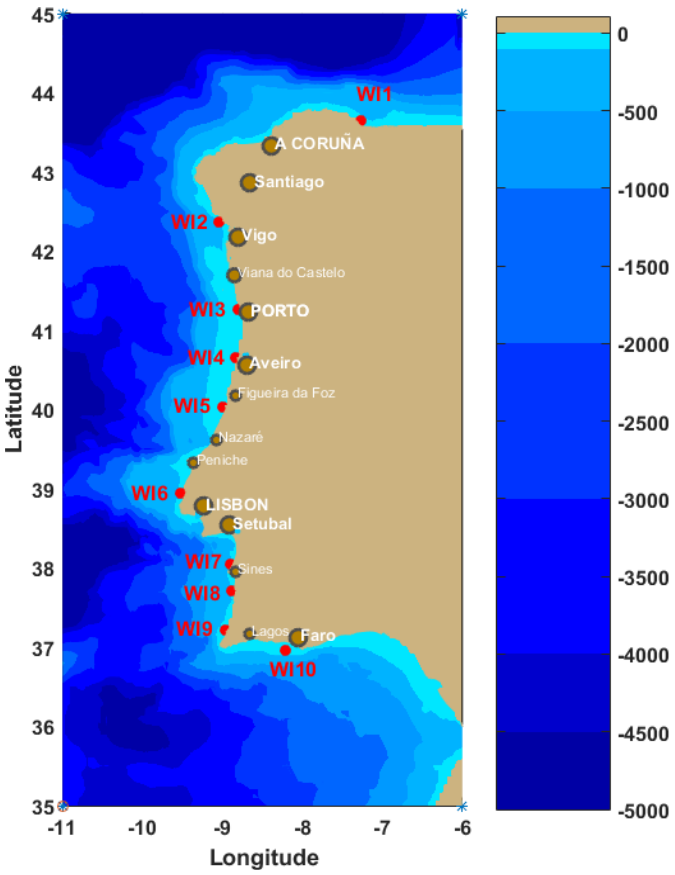

Figure 1. The geographical domains of the SWAN simulations and the geographical locations of the ten reference points considered for analysis (from WI1 to WI10).

Table 1. Positions of the reference points considered in the West Iberian nearshore.

Points	Longitude (°)	Latitude (°)	Depth (m)
WI1	-7.27	43.65	38
WI2	-9.02	42.36	47
WI3	-8.78	41.26	31
WI4	-8.79	40.66	14
WI5	-8.94	40.03	13
WI6	-9.46	38.94	26
WI7	-8.87	38.05	48
WI8	-8.85	37.71	54
WI9	-8.91	37.22	14
WI10	-8.21	36.96	50

Datasets

The wave and wind data that are used in this analysis cover two time periods, each of 20 years. The first 20-year period is 2001-2020, also called the recent past (RP), and the second period 2026-2045 refers to the near future (NF). For the RP period, the wind fields from ERA5 are used, both to force the SWAN model and to evaluate the wind energy. Similarly, for the NF period, the RC4 wind fields simulated under RCP4.5 scenario are considered. To evaluate the wave power in the reference points, the results obtained from the simulations with the SWAN model in the target area are used [10], while the wind power at 100 m above sea level is computed based on the wind speed recalculated at that height [22].

The wave transport components (i.e. energy flux per unit of the wave crest length in kW/m), denoted also as wave power, are computed by SWAN based on the next relationships:

$$Etr_x = \rho g \iint c_x E(\sigma,\theta) d\sigma d\theta$$
$$Etr_y = \rho g \iint c_y E(\sigma,\theta) d\sigma d\theta \qquad (1)$$

where $E(\sigma,\theta)$ is the directional wave energy density spectrum, x and y are the grid coordinate system, and c_x, c_y are the propagation velocities of the wave energy in the geographical space (absolute group velocity components). Then, using the following relationship, the wave power in each reference point is computed.

$$Etr = \sqrt{Etr_x^2 + Etr_y^2}. \qquad (2)$$

The atmospheric models typically provide wind speed values at 10 meters above sea level, but if there is interest in assessing the wind energy potential at a hub height of 100 m, where most of the future wind turbines are estimated that would operate, the logarithmic law is applied for such transformation of the wind speed [23]. Thus, the wind speed U_z at a height z above sea level is computed as following:

$$U_z = U_{zref} \frac{ln(z/z_0)}{ln(z_{ref}/z_0)} \qquad (3)$$

where U_{ref} is the known wind speed at the reference height z_{ref} (10m), while the value of the sea surface roughness length z_0 is taken 0.0002 m, as indicated for the marine environment in [23].

In the next step, the wind speeds at 10 m height as provided by each database (for the periods RP and NF, respectively) were interpolated to the positions of the ten reference points using a triangle-based linear interpolation method, and then the values of U_{100} were calculated using Eq (3). Then, in each reference point, the wind power density P_w (W/m^2) per unit of swept area is computed as:

$$P_w = \frac{1}{2}\rho_{air}U_z^3 \tag{4}$$

with ρ_{air} the air density having the value 1.225 kg/m^3.

RESULTS AND DISCUSSIONS

In the development of the wave energy farms, in addition to the wave energy potential at the respective locations, it is important to know the wave climate, and especially the extreme conditions that influence the operating periods of the devices as well as their maintenance. Therefore, the values of the significant wave height (Hs) and of the wave power were analysed using some statistical parameters in order to obtain an overview of the wave climate and wave power potential in the western part of the Iberian nearshore by means of the results in the reference points considered.

Thus, Figure 1 presents the maximum and mean Hs values in the reference points, near future against recent past data. From this figure, it can be noticed that in seven reference points the maximum values of Hs are expected to increase (except for points WI5, WI6 and WI9), and the highest enhancement seems to occur in the reference point WI2 (about 13%), located on the Galician coast. On the other hand, small decreases in all Hs mean values (from 2.8% to 6.6%) are expected in the future in all reference points.

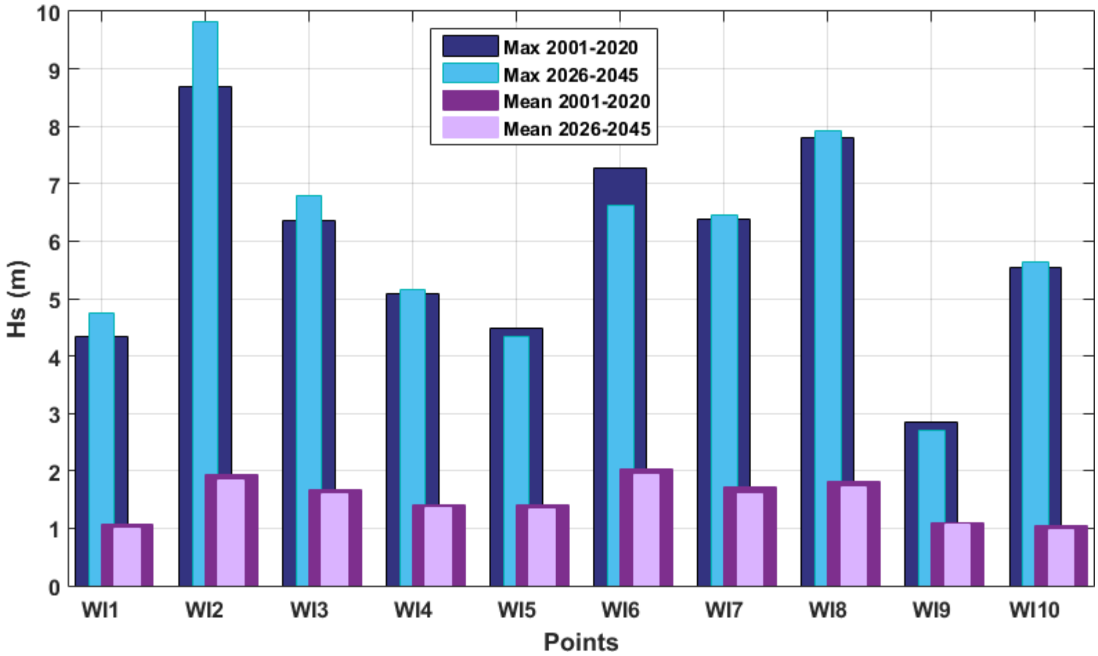

Figure 2. Extreme versus average Hs values in the reference points, near future projections (2026-2045) against hindcast data for the recent past (2001-2020).

Figure 3 illustrates the values of the 50th and 95th percentiles for Hs in the reference points, near future against recent past data. In this case, all the values of percentiles for the near future are lower compared to those computed for the recent past (for the 50th percentiles from 2.9% in WI9, to 8.6% in WI10, and for the 95th percentiles from 1.7% in WI4, to 7% in WI7).

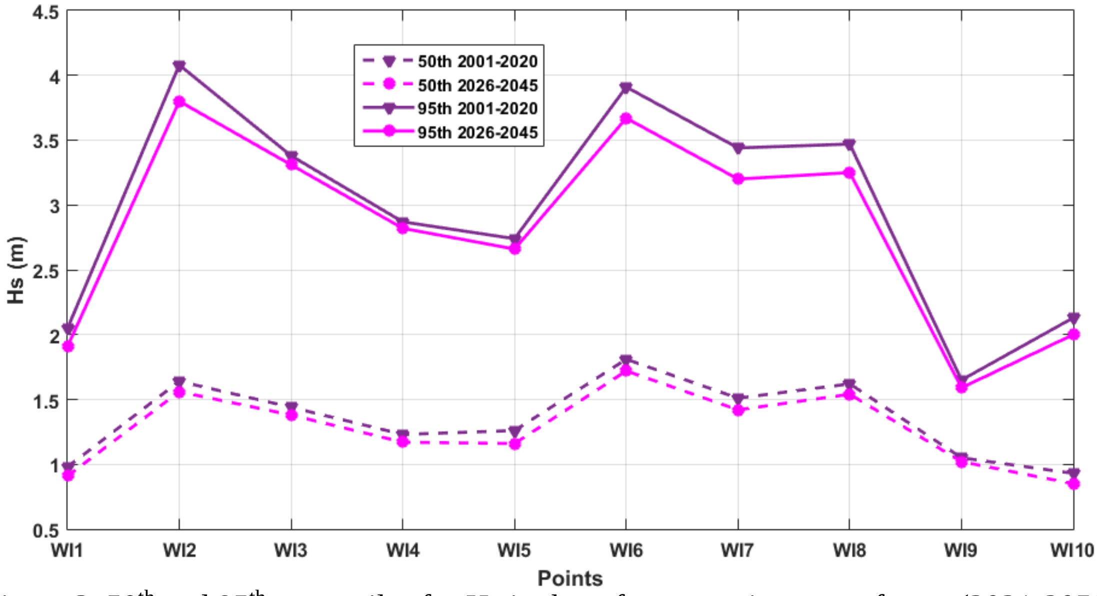

Figure 3. 50th and 95th percentiles for Hs in the reference points, near future (2021-2050) against historical data (1990-2019).

The mean values of the wave power (Etr) in each reference point are illustrated in Figure 4 for both periods (RP and NF, respectively). As expected, in all points the future mean values are lower than those computed for the recent past. The most important decrease (about 16%) is registered at the southernmost point (WI10), and the smallest decrease (about 1.6%) is expected at the northernmost point (WI1). In general, it can be observed that the decrease in terms of wave energy is accentuated from north to south.

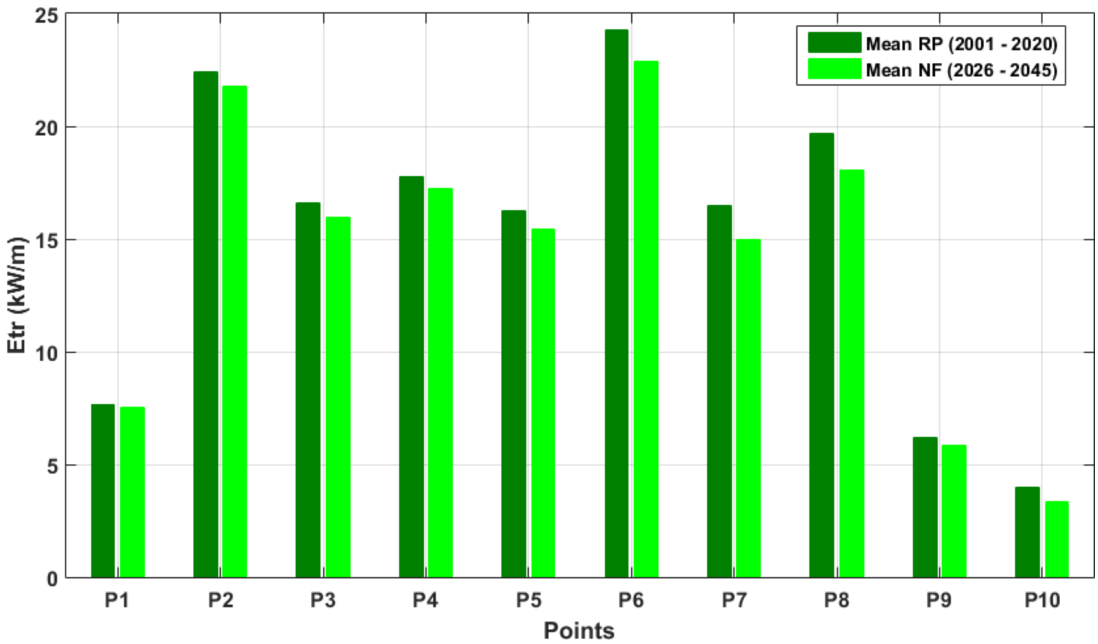

Figure 4. Average wave power values in the reference points for the near future (NF) against recent past data (RP).

In Figure 5 the skewness (Skew) and standard deviation (Std) values computed for the wave power (RP and NF, respectively) are represented. It can be noticed from the figure that no important differences between the standard deviations computed in each reference point are encountered. In the same Figure 5 the skewness values for wave power are also illustrated for each point. In general, the skewness values indicate the degree of asymmetry of the wave power time series distribution around its mean. Thus, the high value of Skew is characteristic of the non-symmetric time series, that usually characterize an unstable behaviour influenced by extremes, as described in [24]. Skew values computed for near future show higher values in all the reference points, with the highest difference in WI2 (4.3 for NF compared with 3.6 for RP).

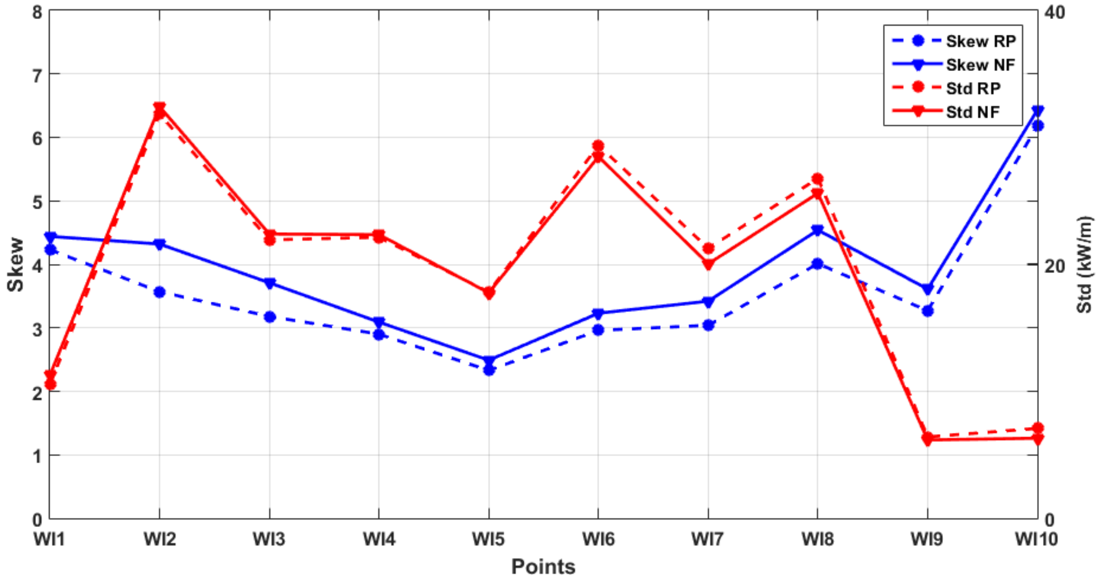

Figure 5. Skewness and standard deviation of the wave power in the reference points for the near future (NF) against recent past data (RP).

In Table 2 some other characteristics of the wave power in each reference point are presented. It is observed that in two points located at water depths of around 14 m (WI4 and WI5) the percentiles have values comparable to those located in deeper water. In addition, the Skew computed in these points has low values, which identifies them as points with good potential for the wave power exploitation.

Table 2. Wave power characteristics corresponding to the reference points computed for each 20-year time interval considered.

Points	Recent past (RP)			Near future (NF)		
	Max (kW/m)	50th (kW/m)	95th (kW/m)	Max (kW/m)	50th (kW/m)	95th (kW/m)
WI1	171.5	4.2	25.9	194.8	3.7	27.1
WI 2	449.5	10.7	83.8	638.4	10.2	77.9
WI3	272.3	8.4	60.7	309.0	7.7	57.3
WI4	222.6	9.6	62.0	219.0	8.8	59.9
WI5	173.1	9.6	53.3	161.4	8.5	51.3
WI6	346.6	13.7	83.8	322.5	12.6	77.3
WI7	241.5	8.6	60.8	281.0	7.7	53.2
WI8	416.1	10.5	68.8	431.4	9.5	60.8
WI9	94.2	4.1	18.6	86.0	3.8	16.9
WI10	153.4	1.9	14.5	149.0	1.5	12.2

The integration of renewable energy sources into the power system is difficult due to their variability. A good indication of their variability is given by the coefficient of variation (CoV) calculated as the ratio of the standard deviation to the mean value [25]. Usually, the electricity grids work with a consistent flow of power that can be adjusted to the daily changes in demand, but in the case of renewable resources itis difficult to predict many days in advance how much power will be produced. However, if combined farms are deployed, the power variability of the resources can be reduced. This happens when the variable sources balance each other's variations [26].

The complementarity of the wave and offshore wind power is very well reflected by the cross-correlation between them [27]. Thus, considering two generic signals (in this case the signals are time series of wave power and wind power) denoted by $x(k)$ and $y(k)$, the cross-correlation is computed as:

$$c(\tau)=\frac{1}{N}\sum_{k=1}^{N-\tau}\frac{[x(k)-\mu_k][y(k+\tau)-\mu_k]}{\sigma_x\sigma_y} \quad (5)$$

where μ_x and μ_y are the mean values of x and y, respectively, while σ_x and σ_y are the corresponding standard deviations; τ represents the time lag between the signals (in this work τ = 0), and the $c(\tau)$ shows their correspondence. The values of $c(\tau)$ are between -1 until 1, the unit value indicating a perfect correspondence. The wind power time series used in this study are those encountered in [22], where the geographical positions of the reference points are the same as in the present work.

Figure 6 presents the CoV indexes and the cross-correlation coefficients between wind and wave power computed for each reference point (time series for the recent past period). The lowest values of the CoV indexes for wave power are noticed in the points WI4, WI5, WI6 and WI9 (in the range 1.04-1.25), while for wind power in the points WI6 and WI9 (about 1.3). Together with the reasonable values of the cross-correlation between the wind and wave power (about 0.39), the reference point WI6 seems to be a good option for the combined wave-wind exploitation.

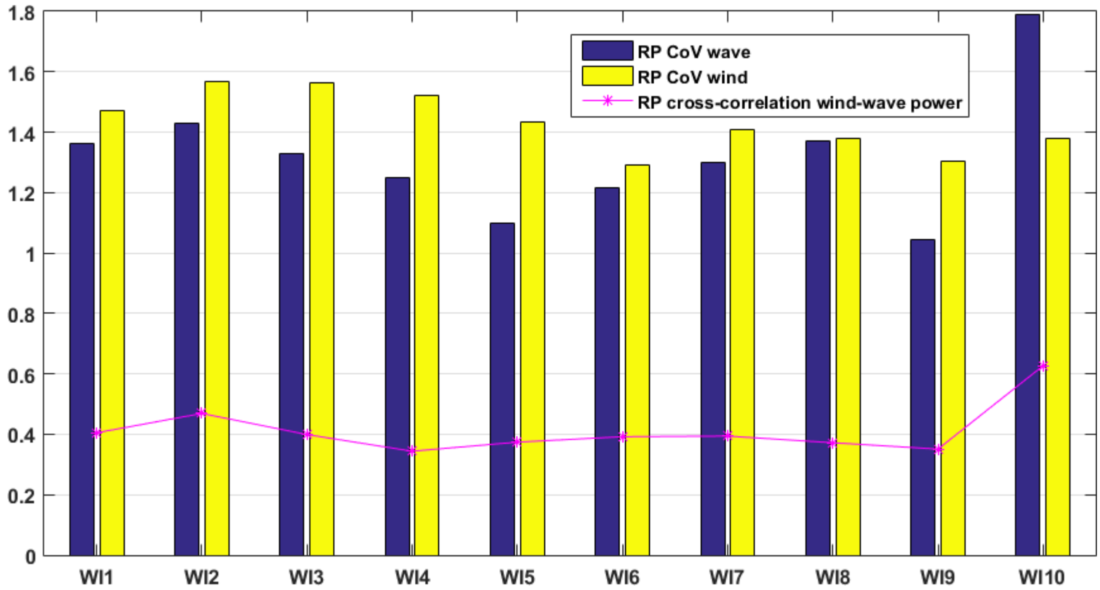

Figure 6. The coefficient of variation of the wave and wind power computed in each reference point RP, together with the cross-correlation between wind and wave power at azero-time lag.

CONCLUSIONS

In the present study, a comparative analysis of the recent past against the projections of the wave power in the west Iberian nearshore has been carried out. For the wave power estimations simulation results from SWAN model for two periods were used. The first is the 20-year period (2001-2020), for which the ERA5 wind data have been considered to drive the wave model and also to analyse the wind power. The second 20-year period (2026-2045) corresponds to the near future and in this case, wind data provided by a regional climate model (RCA4) was analysed to assess the wind power and also was used to force de SWAN model for the wave power assessment.

The results show a slight decrease of the wave power in the near future, but even so, the exploitation potential of these resources remains high on the west coast of the Iberian Peninsula. Moreover, in this region, offshore wind power presents also high values and the low values of the cross-correlation between wind and wave power indicate that they can compensate to reduce their variability.

From this perspective, it can be concluded that the development of joint wind–wave projects along the west Iberian coastal environment represents a viable direction for the near future. It can be highlighted at this point that, especially the North-western part of the Iberian nearshore has a very good potential both in terms of wave and wind energy.

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NOMENCLATURE

CoV	coefficient of variation
Etr	wave power (W/m)
ECMWF	European Centre for Medium-Range Weather Forecast
ERA5	the newest ECMWF Re-Analysis
Hs	significant wave height (m)
NF	near future
P_w	wind power (W/m^2)
RCP	Representative Concentration Pathway
RCA4	Rossby Centre regional atmospheric model, version 4
RP	recent past
Skew	skewness of the parameters
Std	standard deviation of the parameters
SWAN	Simulating WAves Nearshore
*U*100	wind speed at a height of 100 m above the ground (m/s)
ρ_{air}	the air density with a standard value of 1.225 (kg/m^3)
50th	50 percentile of the parameters
95th	95 percentile of the parameters

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