Trends in Renewable Energies Offshore – Guedes Soares (Ed)

Monthly distribution of wind and wave energy resources in Canary Islands

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ABSTRACT: The diversification of clean energy resources is often considered a useful procedure for the efficient planning of strategies. In particular, offshore wind and wave energy exhibit marked spatial-temporal variability. However, given the intrinsic variability and the uncertainty, it is essential to examine the individual and joint occurrences of the energy potential to optimize supply throughout the year. This technological strategy should make it possible to overcome, or alleviate as far as possible, the effects of the alternating nature of energy resources. In this vein, this paper examines temporal variability of wind and wave power over the year on a monthly basis for a given set of offshore reanalysis grid points off the Fuerteventura and Lanzarote islands west coast. Specifically, the energy distribution associated to each process is assessed and subsequently compared to explore the degree of alternation or simultaneity of both resources. It is observed that the combined use of these resources could mean a significant improvement towards energy sustainability of the islands.

1 INTRODUCTION

The rising demand for energy requires the implementation of hybrid energy sources. Recent policies seek research that makes this need practicable. In this sense, studies on the spatial and temporal distributions of marine energy resources improves projects of government and industry regarding reducing resource dependence. In recent years, marine wind and wave energy has advanced due to the concerns about global changing, exhausting fossil fuels, as well as the reduction targets on industrial waste gas emissions (Guedes Soares et al. 2014). Normally, the first step for implementation of these types of technologies are to accurately identify the distribution of the resource as well as its variation over the year. Among the accessible renewable energy resources, marine wind and wave energy represents the core source of energy for new electricity generation and a key player in the world energy market. However, different types of common challenges are encountered, such as: spatial-temporal variability in the distribution of energy, layout of installations, operation and maintenance logistics, structural damage prevention, as well as cost and investment strategies are commonly faced in the implementation of marine wind and wave farms. Investigations that address crucial challenges for wind energy such as, logistics of installing offshore turbines, wind farm maintenance, mechanic-structural fatigue and economic feasibility factors can be read in Agarwal & Manuel (2009), Bagbanci et al. (2012), Santos et al. (2015, 2018), Uzunoglu et al. (2016), Yeter et al. (2016), Kang et al. (2019) and Castro-Santos et al. (2020). Therefore, it is relevant to discuss aspects concerning the situation of local resource. Defining the distribution in terms of months and dominant direction of the observations are essential for correct estimation of the potential energy. Pioneer simulations for assessing the offshore wind resources along the Portuguese coast are performed in Salvação et al. (2013, 2014). Succeeding, Salvação et al. (2015, 2016) extended the work assessing the offshore wind energy resources for the Iberian coasts.

On the other hand, the energy derived from ocean waves is different from wind energy. Mainly, the generation mechanism as well as structural requirements are varied. It depends on the level of interaction between the marine environment and the structure that converts the energy. Consequently, this interaction varies significantly during the months. Taking into account the intensity and degree of monthly occurrence, it is possible to assess the load that the environment applies on a given Wave Energy Converter (WEC) device. Studies using numerical methods to assess wave energy resources along various coastal areas such as: Mainland Portugal (Rusu & Guedes Soares 1999), the Spanish coast (Iglesias & Carballo 2009, 2010), coastal waters of

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the United States (Ahn et al. 2020) as well as Atlantic coast of the US southeastern (Defne et al. 2009), Canada (Dunnett & Wallace 2009), Sweden (Waters et al. 2009), French coast (Gonçalves et al. 2014), among others. These studies typically use numerical methods to study the corresponding swell propagation as well as waves induced by local winds. Several studies address aspects of estimating wave resources around islands, which are especially interesting cite applications in insular territories as: Hawaii (Stopa et al. 2011), Taiwan (Chiu et al. 2013), Madeira and Azores (Rusu & Guedes Soares 2012a, b), Sardinia (Vicinanza et al. 2013), Canary Island (Gonçalves et al. 2014) as well as Cape Verde (Bernardino et al. 2017). Taking into account the location of the current work, it's important to mention that some studies have explored the wave energy resource in the context of the whole archipelago of Canary Islands such as Rodriguez et al. (2002, 2015) and Chiri et al. (2013). Nevertheless, some individual islands are detailed by Iglesias & Carballo (2010, 2011) for La Palma and El Hierro respectively. Sierra et al. (2013) for Lanzarote, Veigas & Iglesias (2013) around Tenerife, and Rodriguez et al. (2016) for the west coast of Fuerteventura. Results provided by the cited studies have evidenced relatively high wave energy potential existing for insular areas.

The current situation of wave energy compared to wind energy indicates that although the energy density is much higher in waves than in wind, the exploitation of wave energy has lagged behind that of wind (Falcão 2010). The main reason for this global scenario is probably due to the solid progression of wind energy exploitation from land to nearshore locations and more to offshore sea zones in recent decades. The major benefit of wind turbine technology is that it can offer cost-effective solutions that in the long-term can compete with energy from conventional sources. However, recently many wave energy devices have been developed to solve some of the earlier mentioned challenges associated with converting wave energy, which are similar to those associated with wind energy converters. Individually, the marine energy resources are alternating and variable on the spatial and temporal scales. Both the energy potential of waves and winds show marked spatial-temporal variation, and such resource variability is worrisome when considering the supply of energy to the electrical grid. However, whether designed to operate by wind, waves, or even in combination, the fundamental operation ability of these energy converters technologies can be limited by the inherent variability in each individual distribution.

With the increasing use of renewable energies in the electricity sector, overcoming alternation between the resources is strategic to establishment of marine resources as reliable energy supply. Therefore, as technologies for marine renewable energies are required, the accurate evaluation of such alternation of both resources, as well as the individual variability pay a significant impact on the guarantee of energy supply for the future. In this sense, the diversification of marine resources is beneficial to supply energy. It has the advantage of presenting a greater accessibility of resources during the year when combined. The main idea is to reduce dependence on a single resource in local energy production.

The benefits of a more diverse marine renewable energy technologies allow to highlight long-term economic and environmental implications. However, to materialize these benefits, it is necessary to understand the energy demand, as well as the resources existing in a certain area. The article investigates this variability in terms of monthly spatial and directional distribution of energy power potential, both for winds and waves. The main objective is to quantify the spatial and the temporal distribution jointly, focusing in the alternating of occurrence for both resources. The description of such alternation in the occurrence is based on the monthly distributions of its dominant direction along the vital points for future supply. Information of the distributional variability is essential for reliable planning for the supply of a single energy resource. However, nowadays all planning must consider mixing existing energy sources. In which the variability in the individual distribution between months is high and can be reduced when another resource with a different distributional behavior is included. Considering such monthly alternation in the distribution of occurrence between two different marine energy resources represents a robust way to plan energy supply in the long term.

This study is organized as follows: the next sub introductory section describes the alternation of marine wind and wave energy distribution as well its effects in the electricity supply. Section 2 explains the methodology for ocean wind and wave power density estimations. The section 3 illustrates the location considered in the study as well as the datasets applied for estimations. The section 4 reports the results of spatial and directional variability of the monthly distribution for wind and wave energy resources, as well as the discussions. The final section 5 is dedicated to defining the relevant and remarkable conclusions.

1.1 *Alternation in the occurrence of wind and wave energy*

The contributions of marine renewable energy to the electrical system are limited by different factors. An important factor addressed in the current work is the spatial-temporal variability regarding its directional occurrence. Naturally, the occurrence of energy resources derived from winds and waves presents a marked variability. When the recognition of this variability is based on two different energy resources evaluated, leads us to the concept of combined alternation. The ability in supplying energy is induced by the natural randomness of the marine environment and directly affects the capacity of the resource.

Thus, a reliable renewable energy generation system must consider the alternation of the resource, hence increasing the supply pf energy available capacity.

This capacity conventionally measures the percentage of maximum potential output that can statistically be contributed to the energy supply. However, the capacity of supply for any given marine energy farm is not constant. It depends of some aspects including: (i) the geographical and spatial distribution of prevailing resources, (ii) total amount of devices in operation, and the final (iii) aspect encompass the relationship between (i) and (ii) in which the levels of theoretical energy potential at different locations and the proportion of each individual technology considered in the mixed marine energy farm are included.

The average capacity of a particular renewable technology such as wind declines as the amount of installed capacity of that technology increases, since there is an increasing risk that periods of low output from renewables plants could coincide with periods of high demand. If wind is the only source of energy generation, then significant back-up capacity will be required to cover the reducing contribution to security of supply. The amount of conventional capacity required to back-up each additional MWh of output increases as more renewable plants are constructed. However, it is not unreasonable to expect that adding wave and tidal capacity would lead to increase the total capacity of the entire renewables mix and hence lead to a reduction in the amount of back-up capacity required. The accuracy in predicting and identifying changes in wind and wave power output is a growing area of research, and presents a significant impact on the total of reserve capacity that must be provided. The reserve capacity is required to fill sudden and unforeseen deficits in supply or increases in demand. Improving the ability of the system operator to predict such changes will reduce the amount of the reserve that is needed.

Although it is possible to predict the energy production of a wave power plant as well as a marine wind power plant, regardless of the production source, there is a degree of variability. Given the random nature of the phenomenon that induces energy production, a wave power plant is considered to be less variable than a wind power plant and can be predicted more accurately. Nevertheless, both sources of energy production can be satisfactorily predicted to plan a reasonable and rational harvest of the resource. Even more, if the information from the resources is used combined, revealing remarkable monthly and directional alternation.

The uncorrelated energy output of wave and wind generation is proper for effective harvest of marine energy resources. The alternation in the temporal and directional sense of the marine energy production can supply energy for the demand in the whole year. Moreover, increasing diversification in alternating renewable supply benefits to progressively reducing the dependency of fossil fuel high-carbon generation. Thus, the spatial and temporal alternation of marine resources occurrences for a given location is indispensable for the diversification of wind and wave power plants. It will therefore convey a positive economic benefit to alternate plants in their energy supplies, as it reduces the negative correlation between production and captured price. Moreover, questions of future scenarios suggest that marine technologies can complement each other, increasing the cost-effectiveness of renewable energy and, ultimately, expanding the potential share of renewable energy in the overall generation mix.

2 METHODOLOGY

The energy potential of the waves as well the wind normally is associated by a degree of spatial and temporal variability in which define the recurrent alternation of both resources. This information describes the variability of the distribution for each resource over the year, in which it is possible to compare the months with relatively high and low energy potential, revealing possible cyclical seasonal patterns.

2.1 *Wind power density estimation*

The power density of the wind velocity is the most significant characteristic for the wind energy potential. It represents the quantity of energy produced by the wind. Assuming that A is the cross-sectional area through which the wind spins out perpendicularly. The average wind energy available for a given wind rotor blade with sweep area A (m^2) at any given site with an average wind speed U_{10} (m/s) can be expressed as:

$$P_{wind} = \frac{1}{2}\,\rho_a\,U_{10}{}^3 \tag{1}$$

where a standard sea level air density is taken (ρ_a =1.225 kg/m^3).

Nevertheless, the precise evaluation of the marine wind potential for a given site requires the information of the wind speed at various hub heights. The standard height of measurement is generally 10 meters, but during a prospect of a site, in order to draw up a wind project, it is preferable to take measures at altitudes representing an energy interest. A typical offshore wind turbine hub height of 80 meters is selected for the purpose of analysis, then, the vertical wind profile up to a height of 80 meters is extrapolated using the expression:

$$\frac{U_{80}}{U_{10}} = \left(\frac{80}{10}\right)^{\alpha} \tag{2}$$

The exponent α depends on such factors as surface roughness and atmospheric stability. The exponent (α) is the friction coefficient or Hellman exponent, a function of the topography at a specific site and usually assumed as a value of 1/7 for open land. There is a variety of wind shear coefficients for different types of topography and geography. A value of 0.10 is more appropriate for lakes and oceans (see Hsu et al. 1994 for detailed discussion) and is therefore used in the present work.

$$U_{80} = U_{10}\left(\frac{80}{10}\right)^{\frac{1}{10}} = 1.23\ U_{10} \tag{3}$$

The equation (1) to compute the wind power density per unit area, A=1 (m^2) is then re-writhen and expressed by:

$$P_{wind} = \frac{1}{2}(1.225)U_{80}^3 = 0.6125\ U_{80}^3 \tag{4}$$

where P_{wind} is the wind power per unit of area (kW/m^2) and U_{80} the wind speed at 80 meters. For more detail in the estimating of offshore wind energy, see Salvação et al. (2015, 2016 and 2018) as well Onea et al. (2016).

2.2 *Wave power density estimation*

The estimation of the wave energy resource as well as its monthly distribution are performed for all points. To compute the theoretical wave power, the energy period is required. Then evaluate the following expression for each sea state assuming the sea water density and gravitational acceleration as ρ_w=1025 kg/m^3 and g= 9.81 m/s^2.

$$P_{wave} = \frac{\rho_w g^2}{64\pi} H_s^2 Te = 490.6\ H_s^2 Te \tag{5}$$

where P_{wave} is the wave power per unit of crest length (kW/m), Hs is the significant wave height, Te is the energy period. According to Cahill & Lewis (2014) this can be done according to a ratio between Te and T_{02} (also known as Tz). A detailed description of the estimation of ocean wave energy flow is given by Rodriguez et al. (2016).

3 STUDY AREA AND DATA

3.1 *Location*

The Canary archipelago forms part of a Spanish territory being an autonomous community. Nowadays includes eight major volcanic islands and several islets in the Atlantic Ocean, located about 100 Km off the African coast and 2000 Km from the mainland. The complex geometry of the island's coasts as well the proximity of the African continent is shown in Figure 1. Fuerteventura and Lanzarote are located in the oriental sector of the archipelago and this group of islands share some important common features for marine energy planning. It is observed that these islands have a high ratio of land surface portion versus coastline length. This makes it easier to find an optimal location for the installation of energy converters and, at the same time, increases the probability of occurrence of the resource. It is also seen that population settlements as well as the most important economic activities are concentrated in low-lying east coast lines, where it is the coast that is most protected from the extreme energetic events. Another interesting aspect is the topography and relief of the islands, featuring U-shaped valleys and low-lying mountains. Fuerteventura presents a maximum altitude close to 800 m as well as Lanzarote with 670 m.

Concerning its climate, Canary Islands are located in the southern edge of Azores, under the direct influence of the trade winds. Furthermore, the cold Canaries current advects abundant fresh and wet air to the northern slope of the higher islands. Low-lying islands with elevations under 750 m receive no rain from the passing trade winds so that habitats and climate here are drier. Occasionally, the Archipelago experiences eastern dry winds from the nearby Saharan desert, raising the air temperature and transporting desert dust suspended in the air, which reduces the visibility and the relative humidity. In terms of population, Gran Canaria and Tenerife represent the two most populated islands. The rest of the residents are mainly concentrated in Fuerteventura, Lanzarote, while the minor islands as El Hierro, La Gomera, La Palma and La Graciosa are scarcely populated. However, the number of tourists visiting the islands during the year is extremely high.

From the energetic point of view, the occidental island, as the rest of the archipelago, relies almost exclusively on fossil fuels to meet their energetic needs. Thus, the electrical power installed arises mainly from thermal power stations using oil as fuel. The remaining part is produced from renewable resources evenly divided between solar and wind energy. Additionally, the low ratio of precipitation makes this island's system dependent on desalination for freshwater supply. Consequently, the number of plants for seawater desalination increased on all the islands. The energy consumption associated with this activity represents a high energy consumption of the total productions for each island. Naturally, this fact has an immense impact on the final price of water that could be reduced by using wind and wave marine energy to desalinate seawater.

3.2 *Data*

The wind and wave energy potential around the west coast of Fuerteventura and Lanzarote has been estimated by using a time series of characteristic met-ocean parameters obtained by a hindcast approach in the context of HIPOCAS European project (Guedes Soares 2008). The implementation of the hindcast procedure was based on the use of the WAM model, a 3rd generation spectral wave model that solves the spectral wave action balance equation (Komen et al. 1994), to provide the 44-year hindcast wave climate database (1958–2001). The model was forced by the output of a high-resolution atmospheric model named REMO (regional atmospheric model). The data are provided on a 50 x 50 km grid and temporal resolution of 3 hours that's produce high-resolution information (see Guedes Soares et al. 2002). In this way, with each point of the grid for the available hindcast data, it is possible to derive characteristic met-ocean parameters to evaluate the wind and wave power resources. For detail on the methodology used in the models to obtain the final wind and wave parameters at any hindcast point in the grid are given in (Pilar et al. 2008). A comparison between the HIPOCAS and other data sets can be found in Campos & Guedes Soares (2016), showing the good consistency especially for the wave heights.

In total, twelve points on the Western grid located along the Fuerteventura and Lanzarote islands system are chosen to explore the spatial and temporal characteristics of wind and wave power conditions. Polar plots of the marine energy resources for each point are used to describe the monthly distribution. In this way it is possible to robustly define the remarkable the cyclical patterns, as well as the respective directionality. Therefore, when comparing the wind and wave resources, it is easier to appreciate the alternation in the occurrences between them.

Selection of these points is based on results of previous studies, which report large wave power variability to the North strip of all islands (Chiri et al. 2013 and Rodriguez et al. 2016). The Canary Islands archipelago, as well as the twelve studied grid points for the West coast of Fuerteventura and Lanzarote are shown in Figure 1. The average power potential generated by waves and wind is estimated for each point, as well as its monthly and directional distribution. However, only few points are shown in the article to demonstrate the monthly alternation in the occurrence of wind and wave marine energy resources for the interested area. Thus, two points are selected for this purpose as representative of the conditions of the west coast, which is the zone of energy interest. In order to explore the maximum and minimum power potential, the points selected are 1 (positioned in the South sector) and 10 (located in the North sector) respectively as emphasized in Figure 2. In this way, it is possible to obtain representative points along the island system covering the most important sectors from the west coast. Note that the numeration increases from south (Fuerteventura) to north (Lanzarote).

4 RESULTS AND DISCUSSIONS

4.1 *Wind and wave power space-time distribution*

Modeling and prediction of wind and wave resources are essential requirements in the sitting and sizing of marine wind and wave power installations. Moreover, it's evident that the variability in spatial and temporal sense takes a vital role for future decisions in terms of costs. This information reduces the variability leading us to the concept of hybrid application of marine resources. The distribution of offshore marine wind and wave resources estimated for each point including the sea and wind states are listed in Table 1. The results of directional as well as monthly variability are described in polar diagrams, permitting a better comparison between alternation of resources. First, the average distributions of each resource considering all dataset (wind and wave) along the west coast of the Fuerteventura and Lanzarote islands system are illustrated. Figure 2 shows the total average spatial distribution of wind and wave resources respectively to identify the most suitable zones, regarding the energy potential. The twelve selected points were interpolated based on an advanced geo-statistical procedure that generates an estimated surface from a dispersed set of points with z values called kriging. Figure 3 firstly presents the monthly variability for wind and wave resources only for the point number 10. For clear description, the figure illustrated the average monthly occurrence in a bar graph. In this way, the variability and dependence on only one source of energy conversion are reduced. In the comparative assessment of the monthly distribution of wind and wave energy, it is also possible to appreciate a noticeable alternation in the occurrences.

For point 10 regarding the monthly cycle of the winds, the intensity predominant is for the month of July (0.35 kW/m^2) followed by the maximum in August and July, which presents values of wind energy potential close to $0.3 kW/m^2$ and $0.28 kW/m^2$. On the other hand, observing the distribution of the waves in the point 10, an appreciable dominance in the month's contrary of the winds is detected. That is, the highest intensities are in the winter months.

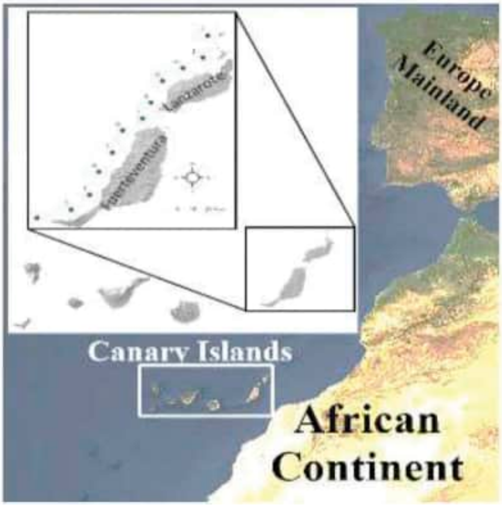

Figure 1. Canary archipelago and the points of wind and wave data used to estimate the power potential on the west coast of Fuerteventura and Lanzarote Island (highlighted box).

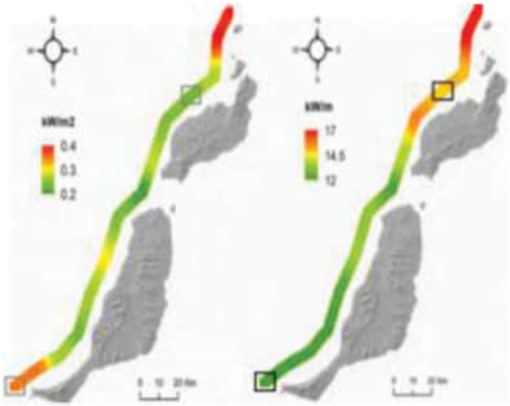

Figure 2. The global average of spatial distribution of wind (left) and wave (right) power potential along the west coast.

Table 1. Average offshore wind and wave power potential as well as the parameters used for estimations.

Points	H_{mo} (m)	T_e (s)	U_{80} (m/s)	P_{wave} (kW/m)	P_{wind} (kW/m^2)
P01	1,61	7,23	6,07	11,96	0,35
P02	1,55	7,67	5,40	12,09	0,26
P03	1,53	7,78	5,09	12,01	0,23
P04	1,54	7,79	5,43	12,27	0,26
P05	1,67	7,53	5,70	13,48	0,30
P06	1,64	7,68	5,19	13,29	0,24
P07	1,52	7,87	4,87	12,07	0,20
P08	1,66	7,28	5,44	13,72	0,28
P09	1,79	7,55	5,12	15,55	0,24
P10	1,74	7,67	5,07	14,71	0,23
P11	1,76	7,61	5,38	14,87	0,27
P12	1,94	7,16	6,17	16,78	0,39

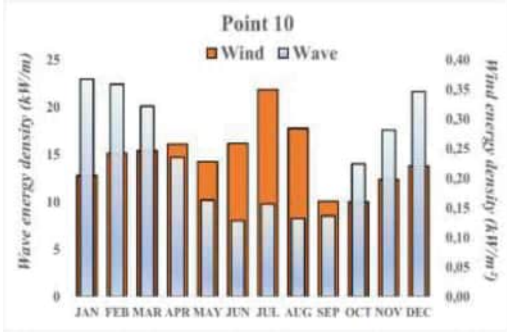

Figure 3. Monthly distribution of wind (left panel) and wave (right panel) as well the power potential over the year for the representative point 10.

The periods of the year with the most energetic waves appear in December, January and February, showing values of approximately 23kW/m, 22kW/m and 21kW/m, respectively. For point 10 regarding the monthly cycle of the winds, the intensity predominant is for the month of July (0.35 kW/m^2) followed by the maximum in August and July, which presents values of wind energy potential close to 0.3kW/m^2 and 0.28kW/m^2. On the other hand, observing the distribution of the waves in the point 10, an appreciable dominance in the month's contrary of the winds is detected. That is, the highest intensities are in the winter months. The periods of the year with the most energetic waves appear in December, January and February, showing values of approximately 23kW/m, 22kW/m and 21kW/m, respectively. The selected point 10 as an example to justify the alternation of marine energy resources from winds can be considered an open area and therefore receives winds and waves from different directions. Regarding the monthly alternation in the occurrence of the marine winds and waves resources, it is possible to observe a marked predominance of incidence in changing months. The most energetic winds occur in the summer months, decreasing considerably in the winter months. Meanwhile, the most energetic wave events occur in the winter months, decreasing over the summer months.

4.2 *Wind and wave power directional distribution*

According to the directionality of the previous studied points, it is possible to observe that the predominant sectors for both resources do not coincide. In general, the winds dominate a sector different from the one dominated by the waves. Figure 4 illustrates the distributions of directions of wind and wave power marine resources for points 1 and 10, considered as strategic offshore areas from the initial points. In the directionality comparison at point 1, it is appreciated that the winds vary mostly between the N-SW sectors, however some E component is observed. On the other hand, the waves scatter between the WNW-SSW sectors with the dominant component coming from the WNW. The energy potential for Point 1 in average terms for marine winds and waves are 0.35kW/m2 and 12kW/m, respectively.

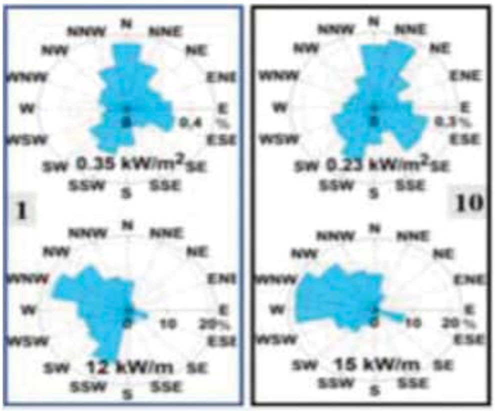

Figure 4. Spatial distribution of directionality of wind (top panel) and wave (bottom panel) as well the average power potential for points 1 and 10 (South to North).

In both resources the directionality presents larger dispersion. This marine energy hot-spot in average terms presents winds with 0.23kW/m^2 dominant from the NNE-ESE and SSW sector, while the waves present approximately 15kW/m predominantly from West quadrant sub-divide from the WNW-W and NW sectors.

5 CONCLUSIONS

The ocean, and in particular marine wind and wave energy are expected to play a key role in the transition to a more sustainable global energy system. The marine wind and wave energy resources for the grid points evaluated in the current work, present a noticeable variability as well as an alternating behavior in spatial-temporal and directional terms. This variability must be quantified whenever possible to better understand the distribution over the year. The variability drastically influences the energy potential when it is considered only one resource (winds or waves). The leverage is more efficient when considering the combined resources. Since the intrinsic variability of the phenomenon cannot be reduced, the ideal is to add another conversion mechanism to efficiently take advantage of the surplus resource.

The hybrid system makes optimal use of the power potential of both resources, whenever there is a marked and assessed natural alternation in the resources. This information is vital for the correct planning of installations of marine energy converters in the study area, which is currently facing the problem of energy demand and dependence on non-renewable conventional energy.

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