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Complementarity of offshore energy resources on the Spanish coasts: Wind, wave, and photovoltaic energy

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ABSTRACT

The complementarity of the solar, wind, and wave energy resource in hybrid offshore platforms has the potential to increase productivity and reduce the variability in the energy output that a single type of energy source can generate. In this study, ERA5 reanalysis is used to calculate wind, solar and wave energy resources in Spanish potential locations for offshore platforms. The results indicate that wind energy presents the largest energy resource for all Spanish offshore regions, followed by photovoltaic energy. However, taking in count the “drought periods” (periods in which no energy is obtained from any of the analysed technologies), wave energy presents an opportunity to provide a continuous flow of energy, especially in the northwestern Iberian Peninsula and the Canary Islands. The evaluation of the complementarity of the three energy sources shows that the use of hybrid platforms would not only increase energy production but also reduce variability. In terms of energy production, wind energy along with solar energy are the largest energy generators. But in terms of minimizing variability, wave energy along with solar photovoltaic energy are the most important. Thus, this study is paving the way to introduce multiple energy converters on hybrid platforms as a pathway toward more powerful and sustainable energy production.

1. Introduction

In recent decades, the increase in energy demand, the depletion of non-renewable energy sources, and the rise in concentration of greenhouse gasses in the atmosphere make it increasingly essential to advance in new renewable energy technologies or improve existing ones. Largest increase in installed capacity in recent years over the world was led by onshore wind and photovoltaic deployment [1], but offshore renewable projects are expected to grow in the next few years [2–5]. Increasing the contribution of renewable generation in the energy mix plays a fundamental role for meeting mitigation goals of the anthropogenic climate change and the EU energy security strategy, implementing different plans at the EU level (European Climate Action and European Green Deal; [6]) with the aim of making Europe the first climate-neutral continent by 2050 [7].

Case of Spain, the government is encouraging the development of new renewable energy technologies, particularly offshore resources in the context of the In the EU commitment towards a NetZero carbon energy system [8,9]. Ongoing plans include reaching a share of 74% in the national energy generation by 2030 and a 100% renewable power system by 2050 [10]. However, achieving these goals requires a thorough study of regions with the greatest potential for energy exploitation. With this aim, the government of Spain has established a legal framework to streamline the establishment of offshore wind farms through Maritime Spatial Planning. These regions, with significant potential, have been delineated for the expansion of offshore wind energy [11].

To date, most studies dedicated to the evaluation of the renewable energy resources in European countries have primarily focused on onshore solar and wind energies (e.g., Ref. [12–16]). But these studies have been increasingly widespread also to offshore regions in the last decade (e.g. Ref. [17–19]). In fact, it has been demonstrated that the offshore wind speed is 25% higher than the shore [20], although it also presents some disadvantages associated with the cost of offshore platform installation [21]. As for solar photovoltaic energy, the differences between onshore and offshore are smaller than in wind energy in terms of resource, but offshore can take advantage on the improvement on photovoltaic performance due to the cooling effect of water [22]. Although its development is in a less mature stage, some installations have already been tested in the Maltese islands and the Dutch north sea [23,24]. Natural variability of the resources makes that to meet the

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proposed objectives of renewable capacity by the mid-21st century, different approaches to address this problem needs to be performed. One of the proposals of interest for the development of the offshore renewable energy technologies would be to complement more than one type of energy in a hybrid platform. This would reduce the variability that a single energy resource could generate. Moreover, hybrid platforms may have cost reductions in equipment, energy transmission, permitting, project development costs, operating, and maintenance monitoring cost [25].

Evaluating the energy resources in offshore regions opens the opportunity to embrace a rising energy source, primarily developed in northern European countries: wave energy. In this regard, incorporating a third energy resource such as wave energy would enable improvements in both energy generation and reduction of the production variability for these installations. This kind of technology has some important advantages when compared to other renewable energies, primarily because it exhibits minimal energy losses, better predictability, and higher energy density [26–28]. However, both solar photovoltaic and wind energy still have certain advantages over wave energy as they have a higher technological maturity (decades of development) and lower costs [29,30]. Although each of the energy sources mentioned earlier (solar photovoltaic, wind, and wave) has advantages and disadvantages, there is growing interest in the combination of the three technologies both through the interconnection of installations in different areas, or in the same location. Thus, it is essential to understand, in terms of resource availability, where each of them is most effective in dealing with seasonal and interannual variability. Furthermore, not just individually, but also where the complementarity of these technologies can increase production and play a crucial role in maintaining a constant energy flow [31,32]. Regarding complementarity and synergy assessment between renewables in general, there are several studies in the relevant literature, examining both wind and solar (e.g., Ref.[30,33,34]), wind and wave (e.g., [35,36]) power onshore or offshore, or all of them but individually (e.g. Ref. [37–43]).

Nomenclature	
CF_t	Total capacity factor
CF_{solar}	Solar photovoltaic capacity factor
CF_{wave}	Wave capacity factor
CF_{wind}	Wind capacity factor
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth generation ECMWF reanalysis
EU	European Union
H_s	Significant wave height
MSP	Maritime spatial planning
P_e	Electric power expected
RP	Rated power
RSDS	Surface-downwelling shortwave radiation
TAS	Surface air temperature
T_e	Energy period
T_p	Peak period
V	Wind speed at 100m height
V_I	Cut-in wind velocity
V_R	Rated wind velocity
V_0	Cut-out wind velocity
VWS	Surface wind velocity
WEC	Wave energy converter

Recent work has been carried out in Spanish regions to assess those resources in offshore regions. These studies focus on specific areas of the Spanish coast, such as the northern Iberian Atlantic coasts [35,44–46], the Spanish archipelagos ([30,47,48]; Balearic Islands and Canary Islands), or the coasts of the Iberian Peninsula in general, excluding Canary islands and only using a type of energy [43,49,50]. In this regard, a specific insight has been gained for each of these regions, emphasizing the advantages of the offshore platforms. However, a comprehensive study evaluating all these areas together to identify where the greatest resources are located, whether there is a variation in resources depending on the technology, and whether these technologies are complementary within the same offshore platform has not yet been conducted. In pursuit of this goal, Esteban et al. [51] evaluated solar, wind and wave resources in Spanish regions, but no analysis was performed regarding the complementarity of them within the same region. Furthermore, despite having a specific view of different regions, these studies are solely focused on one or two technologies and do not consider all three energy sources together.

Therefore, our main goal is to assess the resources of wind, solar photovoltaic, and wave energy within the areas designated for offshore energy development in Spanish. To do this, we consider both the Iberian Peninsula and the Balearic and Canary Islands. Along with the resource assessment, we evaluate the complementarity of these three energy technologies with the aim of implementing hybrid platforms that generate higher energy production with a continuous flow, reducing variability.

This paper is structured as follows: Section 2 deals with the description of the used data and methodologies, Section 3 shows the obtained results and a further discussion about them, finally Section 4 summarizes the conclusions of the work.

2. Data and methods

2.1. Data

In order to reach our objectives, we use data from ERA5 [52], which is the fifth-generation reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF), which combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems. The analysis is produced at an 1 h time step using a sophisticated state-of-the-art 4D-var assimilation scheme. Its horizontal resolution is approximately 30 km, and it computes atmospheric variables at 139 pressure levels. One of the main advantages of ERA5 compared to other atmospheric reanalyses is its coupled wave model. This feature allows for studies like the one proposed in this work, where both energies generated from atmospheric variables (solar photovoltaic and wind) and oceanic variables (wave energy) can be evaluated using the same dataset.

In this work, 33 years (1 January 1980–31 December 2012) of available wind and wave data were utilized for the Atlantic Ocean and Mediterranean Sea (defined in Fig. 1). For the significant wave height and the wave energy period the data were extracted on a $0.50^\circ \times 0.50^\circ$ spatial grid, while for the atmospheric resolution, ERA5 data were extracted on a $0.25^\circ \times 0.25^\circ$ spatial grid and we use wind speed at 100 m height (i.e., at a typical wind turbine hub height), surface-downwelling shortwave radiation, surface air temperature and surface wind velocity (10 m). ERA5 has been utilized in numerous studies to assess solar energy [53–55], wind energy [40,56,57], and wave energy [27,58]. These studies highlight ERA5's ability to adequately represent the main variables associated with the three energy sources. However, to evaluate these capabilities, we compared both wind speed and significant wave height (Table S1) at four points located in the study regions with the SIMAR dataset [59] from the year 2000–2003. SIMAR is an ensemble of modelling metocean data created upon a high-resolution (around 12.5 km) numerical model by the Spanish Oceanographic Agency Puertos del Estado, which covers the coast along the Iberian Peninsula, Balearic and Canary islands between 1958 and 2020 with a temporal resolution of 1h. SIMAR is the combination of WaveWatch III simulations with ERA-Interim, complemented by the Spanish sea state prediction system.

In this comparison, ERA5 is observed to present very similar data to the dataset, with high correlations (above 0.8 in the case of H_s) and very similar mean values. It is noteworthy that ERA5 presents higher mean wind speed values than SIMAR in the Atlantic regions, while in the Mediterranean regions, they are lower. Additionally, it shows lower Hs values in all four zones. However, in terms of both resolution and wave coupling, ERA5 remains one of the most comprehensive tools for conducting this type of complementarity study.

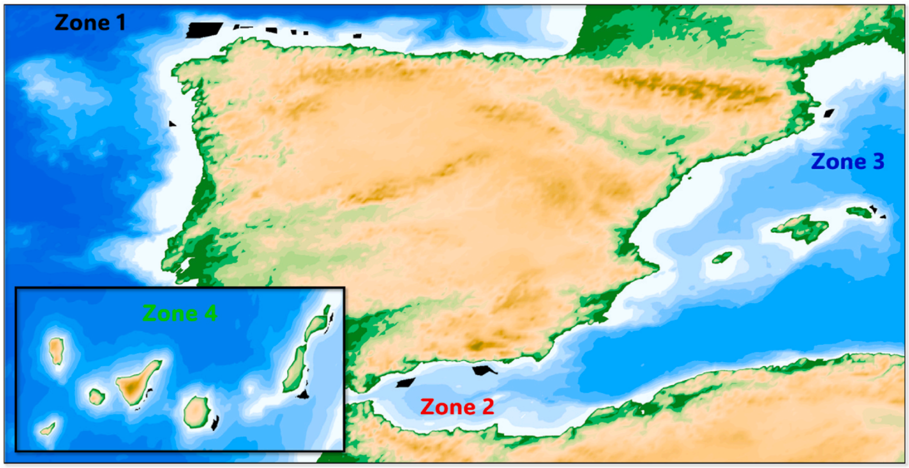

Fig. 1. Location of the Spanish offshore wind potential areas based on the public information available in the Spanish government Maritime Spatial Plans.

2.2. Specific offshore areas

The future deployment of offshore power plants around Spain (Iberian Peninsula, Balearic and Canary Islands) is regulated by the Royal Decree 363/2017, through Maritime Spatial Planning (MSP). In the framework of this MSP, information about offshore areas with high potential for power installations is publicly available in the INFORMAR geoportal [11]. These referenced areas will be used in our analysis and are represented in Fig. 1. Among the High Potential Areas for the Development of Offshore Wind Energy, 4 regions stand out, defined as:

- Zone 1: Northwestern Atlantic region, where the regions extend from the Asturian coast to Galicia, even including a small region near the Portuguese coast
- Zone 2: Southern Mediterranean region, with two regions near the coasts of Malaga and Granada
- Zone 3: Northern Mediterranean region, with two small areas east of Menorca and another on the Catalan coast.
- Zone 4: Canary Islands region, where the areas are distributed to the south of the islands of Tenerife, Las Palmas de Gran Canaria, Fuerteventura, and Lanzarote

It is worth noting that in our analysis, we use the average values over these regions, understanding that the proximity between points in the same zone results in very similar climate conditions.

2.3. Capacity factors

The capacity factor is a metric defined as the ratio between the total energy output of a power plant and the theoretical maximum electricity generation of the plant operating at full capacity. We have calculated the capacity factor of the different technologies as explained below.

2.3.1. Wind power capacity factor

We calculate wind capacity factor (CF_{wind}) as in previous studies [12, 47,60] considering a normalised standard power curve for the wind turbine as can be seen in Eq. (1). The parametric values considered are the cut-in wind velocity, $V_I = 3$ m/s; the rated velocity, $V_R = 12$ m/s; and the cut-out velocity, $V_0 = 25$ m/s. We use the wind speed at 100 m height (V) provided by ERA5.

$$CF_{wind} = \begin{cases} 0 \text{ if } V < V_I \\ \dfrac{V^3 - V_I^3}{V_R^3 - V_I^3} \text{ if } V_I \le V < V_R \\ 1 \text{ if } V_R \le V < V_0 \\ 0 \text{ if } V \ge V_0 \end{cases} \quad \text{Eq. 1}$$

2.3.2. Solar photovoltaic power capacity factor

The solar photovoltaic capacity factor (CF_{solar}) is calculated as in Jerez et al. [61]:

$$CF_{solar} = P_R \frac{RSDS}{RSDS_{STC}} \quad \text{Eq. 2}$$

where *RSDS* is the surface-downwelling shortwave radiation and *STC* refers to standard test conditions ($RSDS_{STC} = 1000$ W m^{-2}). P_R is the performance ratio formulated as follows:

$$P_R = 1 + \gamma(T_{cell} - T_{STC}) \quad \text{Eq. 3}$$

where $T_{STC} = 25$ °C and γ is taken here as -0.005x°C^{-1}, considering the typical response of monocrystalline silicon solar panels [62]. Finally, T_{cell} is modelled as follows:

$$T_{cell} = a + bTAS + cRSDS + dVWS \quad \text{Eq. 4}$$

where *TAS* and *VWS* are surface air temperature and surface wind velocity respectively, with $a = 4.3$ °C, $b = 0.943$, $c = 0.028$ °C m^2 W^{-1} and $d = -1.528$ °C s m^{-1} according to Chenni et al. [63]. It must be considered that for this approximation, the inclination of the solar panels is not considered.

2.3.3. Wave power capacity factor

Similarly to wind power, in which the performance of wind turbine is obtained by combining the specific power curve with the wind measurements, in the case of a wave energy, a power matrix (defined by the manufacturer; Fig. 2) is used. In this work, we use the Wave Dragon [64, 65] wave energy converter (WEC), which presents the larger capacity factor among the other WECs [66–69]. As a first step, the electric power expected to be generated by the Wave Dragon is calculate as follows [68, 70]:

$$P_e = \sum_{i=1}^{nT} \sum_{j=1}^{nH} PW_{ij} \cdot PM_{ij} \quad \text{Eq. 5}$$

where PW_{ij} includes the bin defined by column j and line i, whereas PM_{ij} is the expected power output defined in the power matrix for the same

Fig. 2. Power matrix of Wave Dragon.

bin, where P_e depends on both the significant wave height (H_s) and the wave energy period (T_e) used by WECs developers. The H_s values were obtained from ERA5 outputs, but as numerical simulations did not output the T_e, we estimated it from the peak period (T_p), as $T_e = AT_p$ where A depends on the wave spectrum shape [69]. This value was taken equal to $A = 0.9$ [71–73].

Once P_e is obtained, the wave capacity factor (CF_{wave}) is calculated as follows:

$$CF_{wave} = \frac{P_e}{RP} \qquad \text{Eq. 6}$$

where RP represents the rated power of the Wave Dragon, which values is 5900 kW [64,68].

2.4. Complementary analysis

To evaluate the benefits of the combination of the three sources of renewable energy generation in a hybrid project, following [74], we use the total capacity factor (CF_t) defined as:

$$CF_t = \alpha CF_{wind} + (1-\alpha)[\beta CF_{wave} + (1-\beta) CF_{solar}] \qquad \text{Eq. 7}$$

where CF_{wind}, CF_{wave}, and CF_{solar} are the wind, wave and solar photovoltaic capacities factor, respectively, and α and β, are weights—α is the wind contribution to total CF, (1- α) β is the wave energy participation, and (1- α) (1- β) is the solar percentage. Thus, when $\alpha = 1$, only wind is being used; when $\alpha = 0$ and $\beta = 1$, all power comes from wave; when $\alpha = 0$ and $\beta = 0$, there is just solar photovoltaic generation. It was assumed

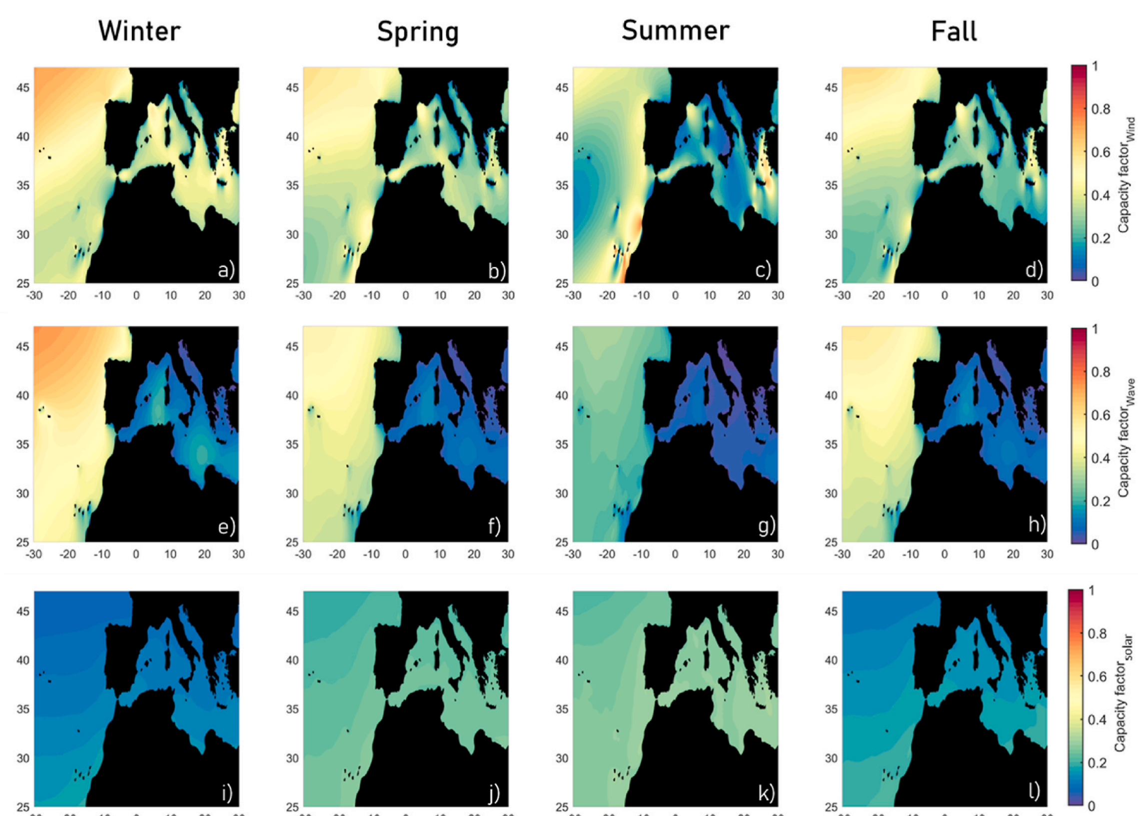

Fig. 3. Capacity factors for wind (top), wave (middle) and solar photovoltaic (bottom) calculated in the four seasons, averaged 33 years hourly series.

that each station would contribute equally to its source final CF.

Compared to other methods applied in similar studies, the used methodology allow us to see different combinations of technologies and the complementarity grade in each case. The 'event-based' complementarity approach used in other references (e.g. Ref. [27,58]) for instance, show areas with higher complementarity between resources, but there is no optimization results in terms of combination of technology. In this sense, this analysis try to be a more applied study, proposing different scenarios of complementarity.

3. Results and discussion

In order to make a first assessment of the renewable resources in our study area, we calculated the seasonal *CFs* for each of the technologies (Fig. 3). Regarding wind energy, we found values above 0.4 in both the Atlantic and Mediterranean regions, with the lowest values in the Canary Islands and the eastern Spanish coasts, and the highest values in the northwestern region (around 0.7) during the winter months, similar to the findings of Thomas et al. [75]. These peaks, decrease seasonally in spring and summer, increasing again in autumn both in the Atlantic and Mediterranean regions. However, it is precisely in summer when we find the highest wind energy values, located in the Canary Islands.

Similar results were found by Onea et al. [49] when assessing the wind potential along the Spanish coast. They found a well-defined seasonal cycle with maximum values in winter and the lowest in summer, identifying the Spanish northwestern coasts to be more productive than the mediterranean coasts. Additionally, Carreno-Madinabeitia et al. [50] categorized the regions of the Spanish coast according to their wind potential, identifying also the northwestern Spanish region as having the greatest wind resource. However, these studies do not provide a comparison with the Canary Islands region, which has been shown to have the highest *CFs* during summer. In this regard, the intensity of the trade winds varies in relation to the displacement of the Azores high throughout the year. When the distance between the Azores high and the Canary Islands shortens, the pressure gradient tends to increase, leading to a significant increase in the intensity of the trade winds (summer). In winter, the situation is more variable than in summer. The Azores high typically moves northward and away from the Canary Islands, resulting in high-pressure systems over the southern islands. In this case, an east to southeast wind regime appears, weakening the influence of the trade winds.

Wave energy shows a seasonal and spatial pattern like wind energy, with peak values during the winter months in the northern region of Spain. However, smaller values can be found throughout the Mediterranean region (below 0.2) that persist throughout the year. It is worth noting that in the entire Atlantic region, the seasonal minimums are found during the summer months, contrary to the maximums found in the Canary Islands as in the wind power. Once the summer minimums are reached in the Atlantic region, the *CF* increases again in autumn. In this regard, Esteban et al. [51] found the highest wave potentials in the northeastern region of Spain (Galicia and Cantabria) and a high wave potential in the Canary Islands. This is easily explained by the fact that the north of the Canary Islands, as well as the Atlantic region in the north of the Iberian Peninsula, are regions dominated all year by the presence of swell, which corresponds to very regular and stable sea state conditions. The high wave potential is mainly found in the north faces of the Canary Islands, which have a higher *CF* than the south faces (see Fig. 3). Regarding the regions with the worst wave potential, they refer to those located both to the north and south of the Spanish mediterranean coasts, which aligns with the findings of this study.

For solar photovoltaic energy, we find values that remain zonally constant and increase as latitude decreases during the winter and autumn months. These values are lower than those represented for the other two energies (between 0 and 0.2), associated with a higher number of hours without production. This latitudinal pattern was also evidenced in different studies (e.g., [45,46,76]), with the highest values found at southern regions. In spring and summer, the *CF* value increases to reach 0.4. Unlike the autumn and winter months, we find that there is not such a clear latitudinal pattern during these seasons, with almost the same values on both Spanish mediterranean coasts and the Canary Islands. In agreement with our results, Esteban et al. [51] identified the southern-southeastern regions of Spain and the Canary Islands (more specifically, the southern side of the islands), as the most promising from a solar production perspective.

Given that the main results found in the *CFs* for each of the energy sources show both spatial and seasonal variability, we divided the study into four regions based on the offshore wind platform areas designated by the Spanish government (Fig. 1).

In Zone 1, we find that during the winter months, both CF_{wind} and CF_{wave} have median values close to 0.5, with a greater dispersion of their values in wind energy (ranging from 0 to 1). On the contrary, solar photovoltaic energy has the lowest values during these months, where values above 0.5 are considered anomalies. While CF_{wave} values are the highest in winters, wave energy exhibits significant seasonal variability compared with the other technologies, reaching its minimum in summer (median around 0.2). Although wind energy also hits its minimum in summer, its values do not oscillate as much, maintaining a seasonal minimum (median) above 0.35. These results are similar to López-Franca et al. [43]. It is worth noting that CF_{wind} consistently has minimum and maximum whiskers at 0 and 1, respectively. Regarding the seasonality of CF_{solar}, it peaks in summer, suggesting that it could complement other energy sources well. However, we find that the median of solar photovoltaic energy does not exceed 0.2 at its seasonal maximum value (summer).

In the regions located in the Mediterranean Sea (Zone 2 and 3), we find a seasonal pattern in CF_{wind} like that of northern Spain, with peaks in the winter months (more pronounced in Zone 3) and lows in the summer [58]. However, these values are lower than those found in Zone 1, and an amplified seasonality in the case of Zone 3. While there are differences in CF_{wind}, the most significant disparities are found in CF_{wave}, where the median values are below 0.2 throughout the year, and most values above this threshold are considered anomalies. In general, these outliers appear above the 75th percentile in wave energy (specially in Mediterranean regions), which could be associated with an increase in resources due to the storms [77], along with the increase of the action of the local winds in western mediterranean [49]. Once again, CF_{solar} reaches its peak in the summer months [58]and exhibits very similar *CFs* across zones 2 and 3. Finally, a different pattern is found in Zone 4, the Canary Island, as the climatic conditions for this region are completely different with respect to the others. We find the peak CF_{wind} values in summer, which coincide with the CF_{solar} peak. However, like Zones 2 and 3, we find CF_{wave} values around 0.25, with peaks in the winter months.

Although performing spatial averages in each of the areas results in a loss of specific information from each model cell, carrying out this procedure allows us to simplify the study by zones, generating valuable information about the complementarity and resource of each of the technologies. Nevertheless, the seasonal cycles previously observed do not significantly differ from the results obtained from the grouping by zones. In this regard, we find that the region with the greatest potential in terms of resources is Zone 1 [78,79], where the median values of wind energy remain relatively stable throughout the year (reducing seasonal variability). Wind energy is complemented by wave energy, especially during the winter months, and solar photovoltaic energy during the summer months (e.g., [35,50]). Mediterranean regions exhibit a higher solar potential compared to wind and wave energy, as shown in Esteban et al. [51]. This is primarily due to the low wave conditions in Mediterranean regions, associated with the low effects of the swell and the fact that the peak winds, for example, on the coasts of the Balearic Islands and the Franco-Spanish border, are generated by regional winds (Tramontane; [49,80]) that often exceed the maximum wind limits supported by wind turbines.

Finally, it is worth noting that the maximum wind energy in Zone 4 is generated in the summer months (due to the position and intensity of the Azores high), with higher seasonal variability than Zone 1, which coincides with the solar photovoltaic energy peak. As for wave energy, one might expect higher values than those represented in Fig. 4. However, the regions authorized for offshore energy implementation are located south of the islands, precisely in areas with lower wave potential, as noted by Esteban et al. [51]. Therefore, wave energy exhibits significantly lower values compared to those found in Zone 1. It should be noted that although wave technology presents lower values in terms of resource, its energy generation capacity is greater than for wind and solar photovoltaic energies [81–83], so even with a lower resource, it could have a higher energy generation potential, making it a more significant energy source than the others [49].

In order to evaluate the seasonal relationships among CFs, we calculated for each zone the monthly correlation using 33 years of hourly data, with the aim of assessing the complementarity between energies in the same area. Therefore, Fig. 5 depicts the seasonal hourly correlation cycle between energies. In this regard, a value of 1 indicates low complementarity, while −1 indicates high complementarity.

When we correlate CF_{wind} with CF_{wave}, we find that Zone 1 and Zone 2 exhibit a seasonal pattern, with correlations above 0.5 in the months of January through April and from October to December. This pattern is much clear for Zone 1, as during the summer, the correlations practically reach values of 0. This decrease in summer is primarily associated with the reduction of storms in the northern part of Spain during this season, resulting in the waves being mainly driven by the swell and a less coupling between the two resources.

Zone 3 shows the highest values (above 0.5) that extend throughout the year. Lastly, Zone 4, unlike Zone 1, shows its peak correlation in July and its minimum in September. By adding CF_{solar}, either alongside CF_{wind} or CF_{wave}, the correlations remain close to 0 throughout the year for all zones. This demonstrates the connection between wave generation from wind and how solar photovoltaic energy could play an important role in complementing energies generated from wind or waves. The correlation between wind energy and wave energy is much more noticeable in Mediterranean regions, where the morphology of the basin itself prevents wave propagation, so it is mainly generated by the effect of the wind. In the case of Zone 1 and Zone 4, there is a combination in wave generation between the wind effect and the swell. However, it is evident in Zone 4 that as the wind intensifies in the summer months, there is a higher correlation between CF_{wind} and CF_{wave}.

So far, we have identified the zones with the highest CFs and the correlations between these energy sources. However, it is of utmost importance to determine whether these energies exhibit a high or low CF associated with low resource availability or a high number of hours of drought (e.g., Ref. [13,30,47]). In this regard, we have calculated the percentage of hours for each of the zones in which production is 0 (Fig. 6). This analysis allows us to identify whether we will have continuous energy production from the energy converters on an individual basis or, conversely, if there is a high number of hours without production.

For wind, we find that the percentage of drought hours for Zone 1, 3, and 4 is below 20%, with values slightly exceeding this percentage in the summer for Zone 3, and, conversely, being practically 0 in the Canary region (Zone 4). However, we find that Zone 2 has values above 20%, reaching up to 30% during the summer months. It is noteworthy that Zone 2 had CF_{wind} values lower than the other regions (Fig. 4), which could be highly related to the higher number of hours with CF = 0 (Fig. 6a). However, during the winter months, the CF_{wind} of Zone 2 and Zone 4 were quite similar, with Zone 2 having higher production than Zone 4 if we do not consider wind drought hours.

The CF_{wave} shows very low percentages droughts, almost close to 0 in all four zones, and these values remain consistent seasonally. These percentages slightly increase in the summer months in Zone 3, nearly reaching 15%. Therefore, it is noteworthy that the CF_{wave} values found in Fig. 6 are partially associated with the amount of resource that generates energy rather than a high number of hours in drought.

Unlike the other energy sources, CF_{solar} exhibits a high percentage of drought hours, close to 60% during the autumn-winter months, which decreases to around 40% in the summer months. These percentages are very similar across zones, highlighting the similarity found earlier in the average CFs values. These high percentages are primarily due to the absence of solar energy production during nighttime hours. Therefore, during the day, solar energy production surpasses wind and wave energy by a significant margin.

In order to calculate the percentage of total droughts in each of the zones, we assessed the coincidence of all three energy sources being 0 at the same time. However, due to the wave energy having a very low drought percentage, the percentage for this calculation was always 0 (not shown). Since the previous results suggest that solar photovoltaic and wind energy appear to be the primary energy sources in terms of

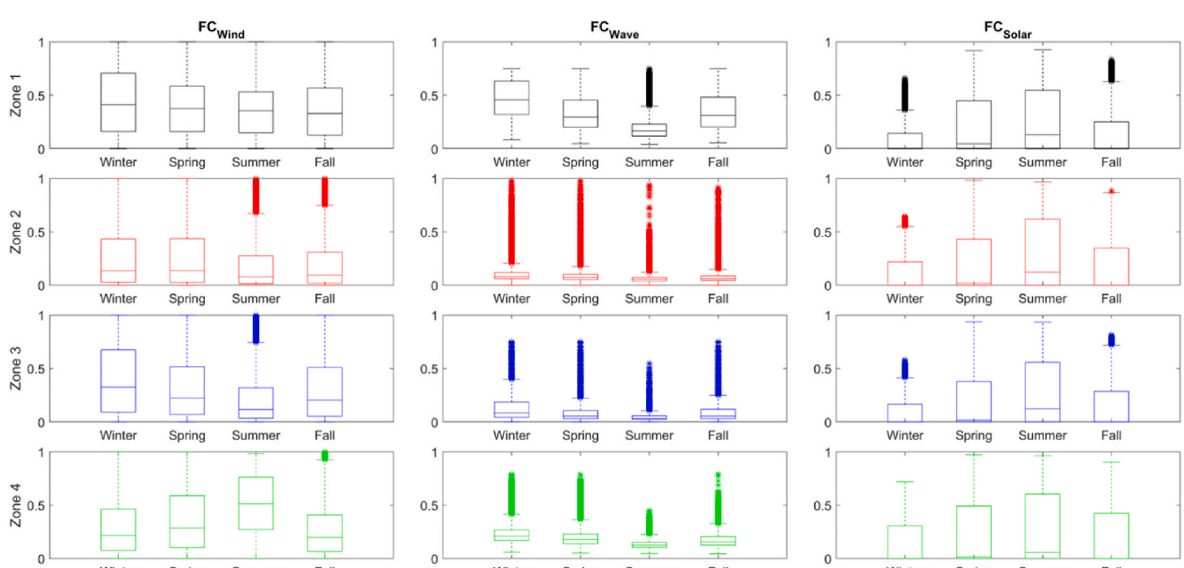

Fig. 4. Box plots calculated seasonally for the CF_{wind} (left), CF_{wave} (middle) and CF_{solar} (right) in the 4 zones for the 33 years hourly series. The box limits correspond to the 25th and 75th percentile.

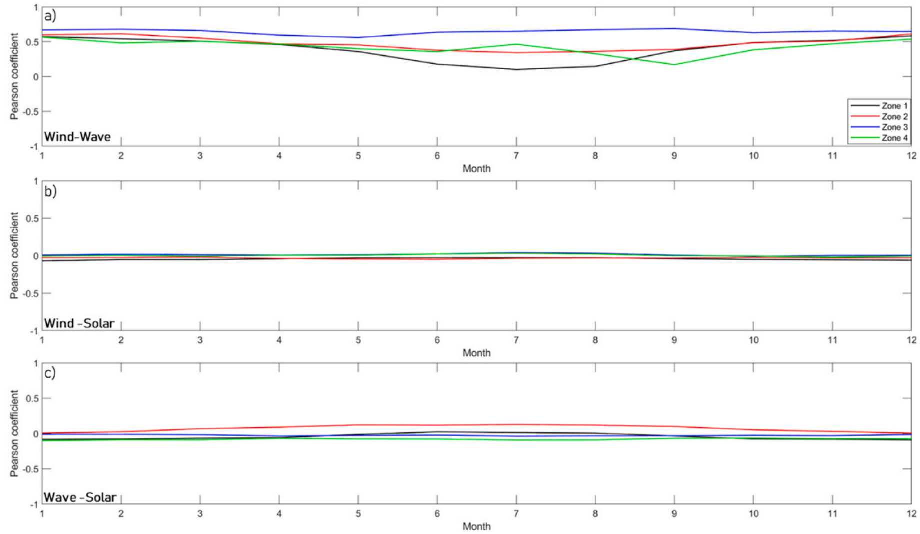

Fig. 5. Seasonal Pearson coefficient calculated between CF_{wind} and CF_{wave} (a), CF_{wind} and CF_{solar} (b) and CF_{wave} and CF_{solar} (c) for the 33 years hourly series in the 4 zones.

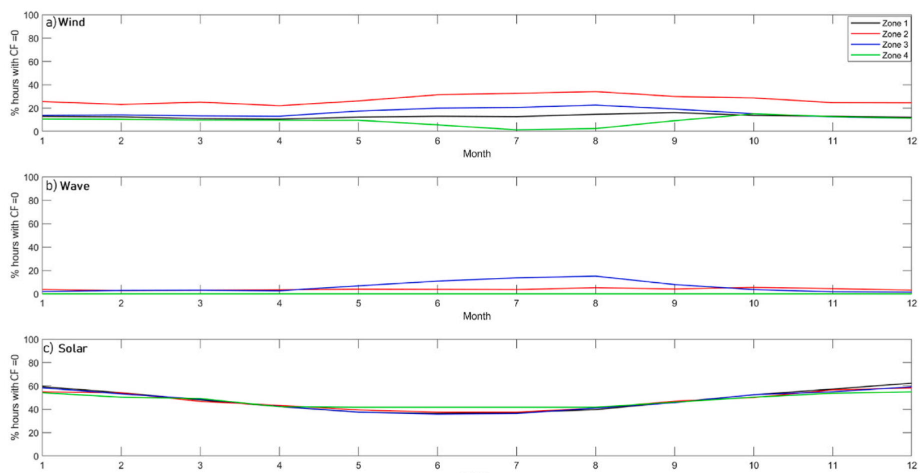

Fig. 6. Percentage of hours for each of the zones in which CF is 0 for the hourly time series (33 years), calculated seasonally for CF_{wind} (a), CF_{wave} (b) and CF_{solar} (c).

production, we decided to calculate the percentage of coincidence for both solar and wind energy with a CF = 0, thus excluding wave energy from this calculation (Fig. S1). In this regard, we find that Zone 3 has approximately a 15% overlap where the CF of both coincide at 0, resulting in no production whatsoever (only wave production would be available). The remaining zones have percentages below 10%, with Zone 4 standing out, where during the summer months, there are practically no hours in which solar and wind energy coincide with zero production.

To assess the combination of the three energy sources, we calculate the total capacity factor (CF_t; Eq (7)), which allows us to obtain useful information about the complementary seasonal behaviour of the three energy sources in the same region. Moreover, to get information about the zones with lower variability, we calculate the standard deviation for the CF_t in the 33 years. This analysis allows us to investigate the better combination of technologies for a higher energy output for each zone and the better combination of technologies for a more stable energy output for each zone (Fig. 7).

Starting with Zone 1, we find the annual highest values when α is 1 and β is 0. This means that the CF_t is maximum when only the wind energy is used. While the only use of wind energy shows the highest CF_t values' ideal conditions for continuous production do not always exist. In this case, both wave and solar energy would complement wind energy seasonally. Thus, we calculate the standard deviation of the CF_t to assess the variability of the three energy sources and analyze what percentage of each energy would be ideal to generate a more stable energy resource. We found that we precisely reach this minimum (~0.13) when we use 20% of wind energy, nearly 50% of wave energy, and slightly over 30% of solar energy (Table 1). This demonstrates that even though we may have a greater resource in terms of the average of wind energy, using both wave and solar energy could provide a more stable energy output. The Zone 2 exhibits the lowest CF_t values compared to the other zones, with these values also being associated with a higher contribution of wind energy, accompanied in this case by solar energy. It is worth noting that in this region, we also find the minimum standard deviation (around 0.07), associated with a predominant contribution of wave energy (almost 90%). Zone 3 exhibits higher CF_t values, although it shows a similar pattern to the previous regions, where the presence of wind energy generates greater complementarity. However, in this zone, the significant wind variability results in a 0% contribution, making energy generation much more stable. Once again, wave energy contributes 87%, while solar energy contributes 13%. Finally, Zone 4 exhibits CF_t values higher than Zones 2 and 3 and very similar to Zone 1, where once again, wind is the major contributor to CF_t. However, this

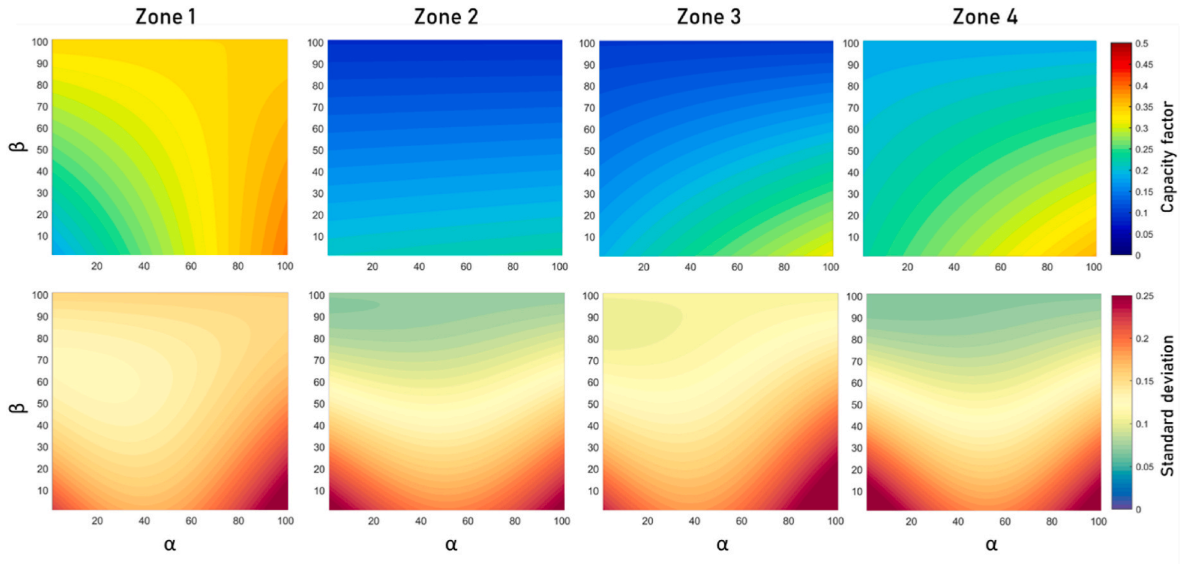

Fig. 7. Total capacity factor (top) calculated for the 4 zones and Standard deviation of total capacity factor (bottom) series according to weights α and β, calculated for the 4 zones.

Table 1
Percentage of each of the energies where α and β show the minimum standard deviation for each of the zones.

	CF_{wind}	CF_{wave}	CF_{solar}
Zone 1	20.00 %	49.60%	30.40 %
Zone 2	6 %	89.30 %	4.70 %
Zone 3	0 %	87.00 %	13.00 %
Zone 4	2 %	94 %	4 %

region has standard deviations very similar to Zones 2 and 3 and therefore lower than Zone 1, making it the zone with the best balance between CF_t and stable interannual resources. Based on a detailed analysis in the Mediterranean regions of the complementarity of solar and wind energy, Soukissian et al. [58] found that in Spain, the main energy generator is wind, and solar energy would complement it. Our study aligns with this work in terms of production, but if we take variability into account, adding wave energy would help achieve a more stable energy flow.

4. Conclusions

This work assesses the complementarity of wind, solar photovoltaic and wave energy in offshore hybrid platforms in the Spanish coasts. The complementarity of these resources is studied in the areas selected by the Spanish government, evaluating their capacity to provide increased production when used together and to generate a continuous flow of energy, reducing variability and avoiding production drought hours. The application of the methodology to the specific selected areas, considering restrictions from the government, provides higher target-oriented results, in comparison to previous research, where the resource analysis is made for wider offshore regions.

The results show the expected outcome in terms of energy potential and variability for a single resource, as seen in previous studies [43,49,50]. Wind energy exhibits the highest resource compared to the other two energy sources, especially in the northern region of Spain and the Canary Islands. Solar energy shows consistent values across different areas, while wave energy resources are more significant in the northern parts of Spain as opposed to the Mediterranean regions and the Canary Islands. In terms of energy production drought (or variability), we found that wave energy maintains a continuous production flow with very few hours of droughts. On the other hand, solar energy exhibits the highest number of drought-hours (associated with nighttime). However, this research presents interesting novel results about complementarity of different technologies in a hybrid platform. The optimization process gives different results depending on the objective function. On one hand, the interest of maximize the energy production make the combination of wind and photovoltaic technologies more attractive. However, on the other hand, if the target is to reduce variability, the inclusion of wave energy allows for a more continuous energy flow. In the first case, the same combination is obtained regardless of the studied region, but differences are found in the complementarity for reducing variability. In this sense, the Atlantic region (zone 1) is very different compared to the others and gives a combination of the three technologies (20 % of wind power, 30 % of photovoltaic energy, and 50% of wave energy) as the optimum choice. On the other hand, the Mediterranean and Canary regions, reduce variability with a combination of solely wave and photovoltaic.

Nevertheless, ERA5 presents some limitations regarding spatial resolution in this study. A dataset with higher spatial resolution would allow us to present results at finer scales within the main regions defined by the government, although that reanalysis product is not available nowadays for the variables needed.

This result needs to go further with a more realistic approach in terms of modelling of these hybrid platforms. Other factors associated to installation, construction, installation and operation costs could be included to indicate the better combination for either greater profit, adding restrictions to the objective function. However, these results as an initial analysis based on resources show the differences to be considered in the areas.

Also, in terms of integration into the system, further research should be conducted identifying the optimal combinations/scenarios for hybrid systems. The study of the energy output from the platforms can itself complement onshore technologies, reducing variability of the whole system what should be also studied in future works to obtain the real benefit of including those emerging technologies with their additional costs.

Finally, this work aims to provide a first approach for evaluating hybrid platforms energy output, identifying areas where different combination of the offshore technologies can achieve higher productivity in the pursuit of cleaner energy production. It also opens the possibility of conducting further studies on energy complementarity in other regions around the world.

Data availability

The ERA5 reanalysis dataset has been obtained from https://cds.climate.copernicus.eu (accessed on 30 November 2022). The provided results have been generated using Copernicus Climate Change Service information (2021).

CRediT authorship contribution statement

Rubén Vázquez: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **William Cabos:** Investigation, Funding acquisition, Formal analysis. **José Carlos Nieto-Borge:** Methodology, Investigation, Formal analysis. **Claudia Gutiérrez:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.120213.

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