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Offshore wind energy in the Iberian Peninsula: A comparative analysis of availability, persistence, and complementarity with onshore wind and solar photovoltaic generation

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ABSTRACT

Incorporating renewable energy sources is crucial to achieve European climate neutrality by 2050. The Iberian Peninsula (IP) is a benchmark in this regard, with significant potential in offshore wind energy. This study analyzes availability, persistence, complementarity, and synergy with existing solar and onshore wind sources, using the COSMO-REA6 reanalysis and real generation data from iberian electricity grids. Offshore wind energy exhibits higher availability and lower seasonal variability compared to solar and onshore wind, particularly at medium-high capacity factor thresholds. Offshore wind energy shows significant potential to complement solar and onshore wind energy, especially in summer, when peak electricity demand occurs. The great geographical diversity of offshore wind resources determines substantial differences in the complementarity characteristics of the representative offshore wind areas in A Coruña, Girona, Malaga and Lisboa. Thus, the incorporation of offshore wind energy into the Iberian renewable energy mix can reduce dependence on a single energy source, increase energy security and mitigate the risk of energy shortages, especially during peak demand periods. This integration is aligned with the objectives of the European Green Deal and supports the transition to a more sustainable and secure energy system in the IP.

1. Introduction

The integration of renewable energy sources into European electricity systems responds to one of the main objectives of the European Green Deal: to achieve zero net greenhouse gas emissions by 2050. This is in line with the Global Energy Trilemma, which stresses the need for secure, equitable, and environmentally sustainable energy [1]. The Iberian Peninsula (IP) has abundant renewable resources that will play a key role in the sustainability of the future electricity market. According to Eurostat's renewable energy statistics (https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20250221-3), its share of energy from renewable sources in electricity surpasses the European average reaching approximately 57% in Spain and 63% in Portugal in 2023. Although solar and onshore wind are the most utilized renewable energy sources in these countries, their generation cycles alone do not adjust with peak electricity demand in winter and summer. For instance, [2] demonstrate that the North Atlantic Oscillation (NAO) significantly modulates the interannual variability of wind, hydro, and solar resources in Iberia, further complicating the reliability of these sources during seasonal demand extremes. Meanwhile, [3] show that in Spain, climate change is expected to shift peak electricity demand from winter to summer, driven by increased cooling needs, which challenges the current seasonal alignment of renewable supply and demand. Therefore, incorporating less exploited renewable resources like geothermal energy, wave energy, and/or offshore wind energy can enhance system flexibility and resilience in the Iberian context [4]. Geothermal energy can offer reliable baseload power with socio-economic benefits [5], wave energy provides high energy density and predictability [6], and offshore wind energy delivers higher and more consistent wind speeds than onshore alternatives [7]. Among them, offshore wind is considered one of the most competitive and

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rapidly developing technologies and it is set to play an important role in future energy systems [8] as it is at the core of the European Green Deal. In the IP, this resource presents a great potential for exploitation, specially at the northwestern coast, near the Gulf of Lion or around Strait of Gibraltar. Offshore wind resources along the Iberian coast are significantly influenced by regional-scale circulation features, such as coastal low-level jets, which enhance wind power density and are well represented in high-resolution reanalyses like ERA5 [9]. In particular, long-term analyses show that the northwestern Atlantic coast and the Gulf of Lyon exhibit high wind power density and capacity factor values, with a positive trend throughout the 20th century [10]. According to [11], both the northwestern coast and the Strait of Gibraltar are promising areas for floating offshore wind development due to favorable wind conditions and suitable bathymetric profiles. Furthermore, [12] highlighted the frequent occurrence of strong regional winds, such as the Levante and Poniente, in the Strait of Gibraltar, reinforcing its viability for offshore wind exploitation. The spatial complementarity among these regions helps mitigate temporal variability in wind energy production and aligns well with seasonal electricity demand patterns [13]. In this context, the Spanish and Portuguese governments have provided a legislative framework delimiting suitable areas to encourage the development of offshore wind farms in the coming years (Royal Decree 363/2017 and Decree-Law No. 38/2015, respectively).

The temporal variability of solar and wind resources significantly influences the stability of energy production. Solar power generation, related with the solar irradiance, has highly predictable but intermittent production patterns because it has a marked daily and annual cycle, and also depends on the motion of clouds and weather systems [14]. In contrast, wind power can be more erratic, with variability spanning a broader range of timescales—from minutes to seasons making its behavior less predictable [15]. This variability is influenced by synoptic circulations and localized factors such as topography features and thermal contrasts, particularly near water bodies and mountainous regions [16]. To mitigate these fluctuations and enhance system reliability, integrating wind energy requires careful consideration of its temporal and spatial complementarity with other renewable sources [17]. Thus, when solar and wind energy sources are combined, their differing variability can complement each other, making the energy supply more resilient to fluctuations in individual resource availability. In tropical and subtropical regions, [18] demonstrate that solar-wind hybrid systems, benefit from this complementarity by minimizing daily energy fluctuations and reducing storage requirements. Similarly, in Latin America [19] highlight that the seasonal negative correlation between solar and wind availability enhances energy security and helps mitigate operational challenges associated with the variability of individual sources. In the IP the available studies agree that the combination of solar and onshore wind energy improves the stability of the electricity system. [20] demonstrated that spatially optimized deployment of wind and solar plants across southern IP can substantially reduce the variability of total energy input, especially during autumn when balancing patterns are strongest. [2] reveal that wind and solar potentials often respond oppositely to NAO phases, suggesting a natural complementarity. [21] extended this analysis by showing that the temporal variability of combined wind and solar production remains largely stable under future climate scenarios. Subsequently, [22] showed that optimized spatial distribution and technology shares can reduce monthly production variability by up to 60% in specific regions, offering actionable strategies for planning resilient hybrid systems. Additionally, offshore hybrid farms integrating solar, wind [23], and wave energy [24], exhibit greater stability throughout the year compared to systems relying on a single energy source approach.

There is no established standard metric for assessing the temporal complementarity between solar and wind resources, understood as the capability of one resource to compensate for the absence of the other. As [25] points out, the absence of a standardized methodology makes comparisons between studies difficult and underscores the need for unified analytical frameworks. [26] reinforces this concern, emphasizing that correlation based techniques, mainly Pearson's coefficient, are frequently employed in complementarity assessments despite their limitations. These methods require a linear relationship, normal distribution and homoscedasticity, assumptions that are difficult to meet for wind and solar time series [17]. In this sense, [27] propose a methodology based on the percentage of hours in which the availability of resources is opposed, with one resource being available and the other unavailable. This could be applied to investigate the complementarity of solar and wind sources in any region of the world [25]. To determine the availability of a resource, a minimum production threshold must be set. This requirement often leads to disagreements between studies. Different minimum generation thresholds have been applied for solar and wind power, each based on specific empirical measurements. For instance, [27] established a wind resource threshold of 240 W/m^2, based on the upper limit of the poor wind power class at 80 m, while setting the solar minimum resource at 170 W/m^2. [28] adopted a wind power density threshold of 100 W/m^2 and evaluated solar complementarity using multiple thresholds (25–100 W/m^2), illustrating the variability in methodological choices. Similarly, [29] considered 210 W/m^2 for wind resources and 113 W/m^2 for solar energy. However, this approach has the disadvantage of noncomparable generation thresholds for solar and wind resources, making it also challenging to compare results across different studies. Nevertheless, capacity factor (CF) thresholds are an alternative metric commonly used in the energy sector that allow for more straightforward comparisons between different resources. This metric represents the efficiency and utilization of an energy-generating system, defined as the ratio between the actual energy output over a given period and the maximum possible energy output over that period. Different CF thresholds, up to 0.2, are used to identify low or non-generation events depending on the region and the objective of the study. For example, [30] reveals that CFs decline during high-demand winter periods but can recover under specific meteorological conditions in Great Britain. In contrast [31] apply a CF threshold of 0.20 to delineate technically viable areas for wind turbine deployment in Germany. [32] define energy production droughts as periods when CFs fall below 0.2 or 0.5 of the mean, thereby quantifying the frequency and duration of low-generation events across Europe. Similarly, [33] assess the risk of low renewable output in Germany and Europe using CFs derived from satellite and reanalysis data, demonstrating that spatial diversification and resource complementarity can mitigate the occurrence of low CF periods. [34] focus on multi-day events of low wind and solar output in Germany using a CF threshold of 0.06 to identify critical supply shortages, particularly when coinciding with increased electricity demand due to cold weather. Meanwhile, [35]use CFs ranging from 0.22 to 0.47 to evaluate offshore wind technical potential in the United States, showing how regional siting constraints and turbine technology influence energy yield.

The main aim of this study is to assess the potential temporal complementarity of offshore wind energy with solar photovoltaic and onshore wind energy in the Iberian Peninsula, in order to determine if the future deployment of offshore wind energy can offer an added value for the Iberian power system. A particular focus is put on winter and summer, the periods of highest energy demand. Moreover, different thresholds of generation capacity factor are considered. This analysis uses real generation data from the Spanish and Portuguese electricity grids for solar photovoltaic and onshore wind energy, along with data from the COSMO-REA6 high-resolution reanalysis for offshore wind energy. The study examines the availability and persistence of these resources, as well as their complementarity and synergy.

2. Data and methods

2.1. Offshore wind resource

The hourly wind components at 150 m datasets from COSMO-REA6 reanalysis [36] were used to estimate the offshore wind capacity factor. This reanalysis has a spatial resolution of 0.055°, and it is based on the COSMO numerical weather prediction model covering the CORDEX EUR-11 area from 1995 to August 2019. In a comparative evaluation of reanalysis datasets for offshore wind applications, COSMO-REA6 demonstrated a near-zero mean bias in surface wind speed estimates when validated against satellite-derived products, confirming its suitability for wind resource assessments [37].

The normalized wind power capacity factor (CF) was computed using the piecewise polynomial representation of turbine power curves proposed by [38]. Specifically, we adopted the parameterization provided for the Haliade-X 13 MW turbine, as detailed in their Appendix C (figure a), which serves as a representative model for turbines with a hub height of 150 m.

The CF is expressed as a function of the hub-height wind speed w_h, capturing the turbine's operational behavior across distinct wind speed regimes:

- Below the cut-in speed ($w_i = 3\,\mathrm{m/s}$), the turbine does not generate power.
- Between the cut-in and rated speed ($w_r = 14\,\mathrm{m/s}$), the output increases following two cubic polynomials, separated by a turning point at $w_{\mathrm{split}} = 9\,\mathrm{m/s}$.
- From the rated speed up to the cut-out speed ($w_o = 25\,\mathrm{m/s}$), the turbine operates at full capacity.
- Above the cut-out speed, it shuts down for safety reasons.

The coefficients of the polynomials were derived from the turbine's power curve and normalized by the rated power $p_r = 13\,\mathrm{MW}$ as follows:

$$CF(w_h) = \begin{cases} 0, & \text{if } w_h < w_i \\ \frac{0.006w_h^3+0.048w_h^2-0.246w_h+0.155}{13}, & \text{if } w_i \le w_h < w_{\mathrm{split}} \\ \frac{-0.0448w_h^3+1.323w_h^2-11.007w_h+30.622}{13}, & \text{if } w_{\mathrm{split}} \le w_h < w_r \\ 1, & \text{if } w_r \le w_h < w_o \\ 0, & \text{if } w_h \ge w_o \end{cases} \quad (1)$$

The wind power CF was calculated at four main representative offshore wind areas on the coast of the Iberian Peninsula located at different coastal orientations: A Coruña, Girona, Málaga and Lisboa (Fig. 1). They represent the optimal combination of four representative offshore wind areas that reduce the hourly variability of the aggregate wind capacity factor in the IP, according to [13]. These areas belong to potential areas for the development of offshore wind energy included in the Spanish and Portuguese governments' Maritime Spatial Plans. The offshore wind CF was also calculated at the peninsular level for each time step as the average of these four main representative offshore wind areas.

Fig. 1. Location of the optimal combination of four Iberian representative areas of offshore wind potential based on [13].

2.2. Solar and onshore wind resources

Spanish and Portuguese power systems datasets were used to estimate the Iberian observed capacity factor (OCF) of both solar photovoltaic and onshore wind from aggregated real-time generation (RTG) and installed capacity generation (ICG) data. This metric allows the comparison with the previously estimated offshore wind CF. Thus, aggregated peninsular Spanish data was extracted from the operator information system known as *e · sios* (https://www.esios.ree.es/es, last access: July 2023) developed by Red Eléctrica de España. As the Balearic Islands electricity system has been interconnected underwater with the mainland since 2012, allowing its integration into the Iberian electricity market [39], it has been also considered. *e · sios* system provides hourly RTG and monthly ICG since 2015 at peninsular level and since 2019 in the Balearic Islands. Aggregated peninsular Portuguese data was solicited to the Portuguese Energy Networks (https://datahub.ren.pt/, last access: July 2023), where it was available since 2010, in the case of RTG at 15-minute and for ICG at monthly temporal resolution. The data from both countries was processed and homogenized, calculating the Portuguese RTG time average, converting the local times to UTC, and interpolating the monthly ICG data to match the UTC time intervals. In this way, the Iberian OCF at hourly temporal resolution was estimated for each resource (solar and onshore wind) for the common period with the offshore wind CF from September 2015 to August 2019 as follows:

$$OCF = \frac{(RTG_{peninsular\ Spain} + RTG_{Balearic\ islands} + RTG_{Portugal})}{(ICG_{peninsular\ Spain} + ICG_{Balearic\ island} + ICG_{Portugal})} \quad (2)$$

where, *OCF* is the Observed Capacity Factor, *RTG* is the Real-Time Generation and *ICG* is the Installed Capacity Generation.

It is important to note that during this period, the installation of new solar and wind power systems was minimal, and there were few instances of curtailment (reductions in scheduled energy delivery when generation exceeds demand or system conditions impose operational constraints [40]). This was mainly due to the still low installed capacity of solar power. Consequently, these observed CF data are a good representation of the solar and onshore wind energy resources.

2.3. Analysis approach

The temporal complementarity characteristics between solar, onshore and offshore wind resources were assessed over a common period of 4 full years, from September 2015 to August 2019. This study utilizes several metrics proposed by [27] that address the availability and intermittency of generation, as well as, the temporal complementarity and synergy between pairs of resources. In addition, a new metric is introduced to estimate the synergy among the three resources. These metrics require the establishment of generation thresholds, so the calculation of normalized CF values for each resource allows a common threshold to be applied for a better comparison between resource generation. Since there are no standard CF thresholds for this type of analysis, this work set the metrics under different CF generation threshold ($CF_{gen\_threshold}$) ranging between 0.1 and 0.9. Additionally, the analysis is performed by the entire study period as well as the winter (December–January–February, DJF), and summer (June–July–August, JJA) periods. Thus, each of the following metrics was calculated for each period and $CF_{gen\_threshold}$.

2.3.1. Availability and persistence

Generation availability (A), expressed as a percentage of hours where the CF exceeds $CF_{gen\_threshold}$, was calculated for each resource as shown below:

$$A = \frac{h}{N} \cdot 100\ with\ \{h \in hours \mid CF_{resource} \geq CF_{gen\_threshold}\} \tag{3}$$

where h is the number of hours and N is the total number of hours of each period considered.

The persistence was also analyzed for each resource by counting consecutive hours above threshold generation (ATG, $CF_{resource} \geq CF_{gen\_threshold}$) and below the threshold generation (BTG, $CF_{resource} < CF_{gen\_threshold}$). In the case of solar resource, values of $CF = 0$ were filtered to avoid night hours. Here, the mean and the characterization of the frequency distribution through boxplots was computed. Moreover, the numbers of events for selected durations (3, 7 and 15 days) was also estimated.

2.3.2. Temporal complementarity and synergy

The temporal complementarity (C) between resources is computed based on the different scenarios proposed by [27]. Each scenario represents the capacity of a first resource (R1) to complement a second one (R2) at the same timestep. This occurs when the CF of R1 exceeds the threshold generation and the CF of R2 falls below it, as described by the following equation:

$$C(R1, R2) = \frac{h}{N} \cdot 100\ with\ \{h \in hours \mid CF(R1) \geq CF_{gen\_threshold}\ \wedge\ CF(R2) \leq CF_{gen\_threshold}\} \tag{4}$$

In this case, h is the number of hours within a given period during which the capacity factor (CF) of a resource exceeds the specified generation threshold and N is the total number of hours of each period considered.

Synergy is analyzed taking into account two and all three resources (Eqs. (5) and (6), respectively) expressed as percentage. In the case of two resources, exclusive-OR operator (⊕) is used to represent a scenario when in the same timestep only one of the two resources exceeds a certain $CF_{gen\_threshold}$ as follows:

$$S(R1, R2) = \frac{h}{N} \cdot 100\ with\ \{h \in hours \mid CF(R1) \geq CF_{gen\_threshold}\ \oplus\ CF(R2) \geq CF_{gen\_threshold}\} \tag{5}$$

where h is the number of hours and N is the total number of hours of each period considered.

The three-resources synergy is here proposed as an extension of the aforementioned two-resources synergy approach (Eq. (5)). This scenario represents when, at the same timestep, the synergy between a first (R1) and a second resource (R2) are given or when the synergy between the second one (R2) and a third resource (R3) occurs, as described by the following equation:

$$S(R1, R2, R3) = \frac{h}{N} \cdot 100 \quad \text{with} \quad \{h \in hours \mid CF(R1) \geq CF_{gen\_threshold} \oplus CF(R2) \geq CF_{gen\_threshold} \vee CF(R2) \geq CF_{gen\_threshold} \oplus CF(R3) \geq CF_{gen\_threshold}\} \tag{6}$$

3. Results and discussion

3.1. Availability

The percentage generation availability for each resource, period and CF threshold is shown in Fig. 2. Availability decreases as the CF threshold increases, but differently depending on the resource and the period. At peninsular level, offshore wind presents the highest availability at any period and CF thresholds, reaching the unavailability only in summer at CF = 0.9. On the contrary, the onshore wind power shows the fastest decrease, reaching full unavailability at CF = 0.7 at the entire period and winter, and at CF = 0.5 in summer. Solar energy maintains its unavailability threshold at CF = 0.7 at any period. Moreover, it is noticeable that in the entire period and summer, the onshore wind has the lowest availability of the three resources, from $CF \geq 0.3$. The strong availability advantage of offshore wind energy becomes clear for a low-medium generation CF threshold of 0.3. For the whole period, offshore wind has 70% availability above that threshold, while onshore wind and solar have a 30% availability. In winter, the availability values are respectively 72% (offshore wind), 45% (onshore wind) and 20% (solar), while in summer the advantage of offshore wind with respect to onshore wind availability is striking: 66% vs. 11%. Summer solar availability above that threshold is 40%, also below offshore wind.

In the case of representative offshore wind areas, in general terms, they have lower values than peninsular offshore wind at low CF thresholds, but this is reversed at $CF > 0.6$. A Coruña and Girona exhibit the highest availability (ranging from 30% to 90%) at any CF threshold, except during summer. In this season, Lisboa shows the greatest availability at low CF values (0.1 to 0.3), while Girona stands out at higher CF thresholds (from 0.5).

3.2. Persistence

The analysis of persistence in generation episodes for each resource is performed through their mean values (Fig. 3) and frequency distribution (not shown) as well as the number of events over 3, 7 and 15 days (Fig. 5). Here, both consecutive hours above and below-thresholds generation are compared, focusing on low CF values (0.1 to 0.3) as values below higher thresholds could no longer be interpreted as non-generation or low generation. The purpose is to compare medium-high generation with low generation.

The mean duration of consecutive hours above/below-threshold generation (Fig. 3) becomes shorter/longer as the CF value increases. Furthermore, the frequency distribution analysis reveals that longer mean episodes also present a greater variability (not shown). At the peninsular level, wind resources have higher mean durations above-threshold generation (>20 h) than solar resources, which barely exceed 10 h. In summer, for wind resources the mean number of consecutive hours above the generation threshold decreases compared to winter, while in the case of solar energy, it increases slightly. Offshore wind is the only resource where the average duration of above-threshold generation episodes consistently exceeds below-threshold generation episodes, irrespective of the CF threshold value and time periods. At the lowest CF threshold (0.1), its best pair of consecutive hours of above/below-threshold generation is given for winter (120 h/5 h), while onshore wind has 110 h/12 h. In summer, this decreases to 70 h/5 h for offshore wind and 35 h/8 h for onshore wind. At a medium CF threshold (0.3), offshore keeps a similar pair of consecutive hours of above/below-threshold generation in both winter and summer (20–25 h/10 h). In contrast, onshore wind present a great increase of hours of below-threshold generation in summer (10 h/88 h) compared to winter (37 h/49 h). This pair of consecutive hours of above/below-threshold generation in summer is the worst result of the analysis. In general, representative offshore wind areas show worse pairs of consecutive hours of generation above/below the threshold than at the peninsular level. Among the areas, A Coruña has the best pair results, except in summer when Lisboa has the best pairs.

Fig. 4 shows the frequency of events with 3, 7 and 15 consecutive days of above/below-threshold generation for onshore and offshore wind energies. Solar energy is excluded from this analysis due to its daily cycle, with CF values close to 0 in the sunrise and sunset hours and, therefore, it barely achieves 3 consecutive days of above-threshold generation (not shown). Consistent with previous results, the frequency of events of above-threshold generation decreases with the value of CF, while that of events below increases.

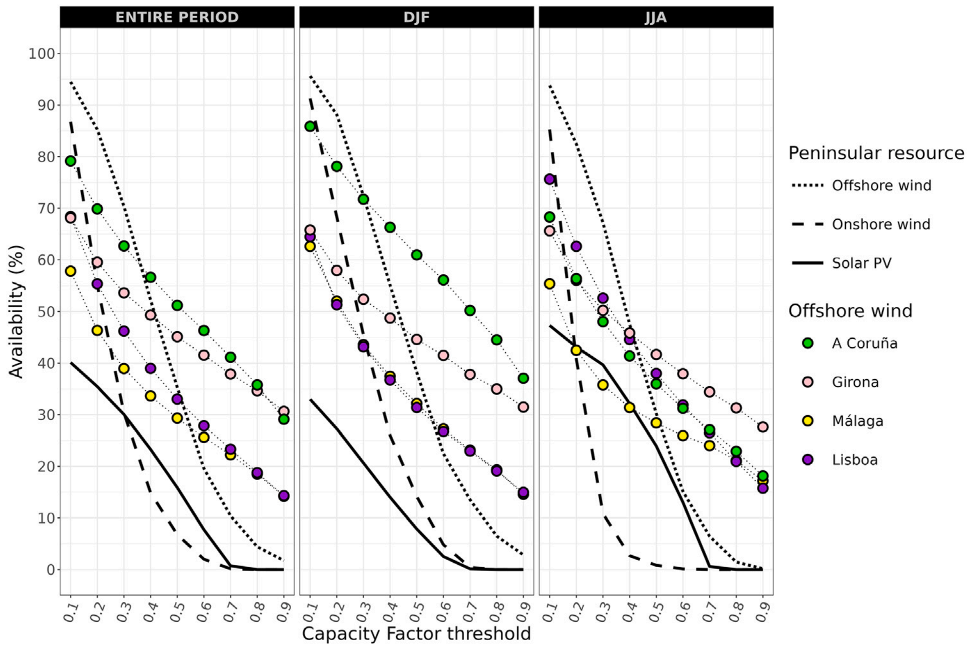

Fig. 2. Generation availability (%) for each resource at peninsular level (lines) and for representative offshore wind areas (colored points) for different capacity factor thresholds (x-axis) over the entire period (Sep2015–Aug2019), winter (DJF) and summer (JJA) seasons. Peninsular level: Solar (solid), Onshore wind (dashed) and Offshore wind (dotted). Representative offshore wind areas: A Coruña (green), Girona (pink), Málaga (yellow) and Lisboa (purple).

Offshore wind at peninsular level presents better pairs of frequency of events above/below-threshold generation than onshore regardless duration, period and CF values. For example, for the entire 4-year period, offshore wind events of 7 days above-threshold generation decrease from 68 instances to 10 instances at CF = 0.3. There are very few below-threshold events at any CF threshold. Conversely, onshore events of above-threshold generation decrease from 40 at CF = 0.1 to 4 at CF = 0.3, while below-threshold events reach a maximum of 35 at CF = 0.3. For longer events (lasting 15 consecutive days), both offshore and onshore wind energies reach a maximum of approximately 10 instances of above-threshold generation at CF = 0.1. At higher CF thresholds, there are scarcely any events. Remarkably, over the span of four summers, offshore wind exhibits frequencies similar to those in winter for 3, 5, and 7 consecutive days above-threshold generation, while frequencies below-thresholds remain close to zero. In contrast, for onshore wind, from CF = 0.2, the frequencies of above-threshold generation significantly decrease in summer compared to winter, with the number of events below-threshold even surpassing those above. Representative offshore wind areas show lower frequencies of events above-threshold generation and higher frequencies of below-threshold generation it compared to the peninsular level. Among these areas, A Coruña stands out with the highest frequencies of events above-threshold generation, particularly during winter.

3.3. Temporal complementarity

Fig. 5 depicts the temporal complementarity of offshore wind, solar and onshore wind resources under different $CF_{gen_t hreshold}$ through six different scenarios representing when the generation of one resource complements the absence or low generation of another. Thus, a resource that complements another means that, at the same time step, the first exceeds $CF_{gen\_threshold}$ while the second is below that threshold. Only the CF thresholds between 0.1 and 0.7 are displayed, as higher thresholds do not present any complementarity. Clearly, the figure reveals that wind complements solar to a greater extent than solar complements wind resources, but the percentage values change under different CF values and periods.

Fig. 5a–b illustrate how offshore wind complements solar and onshore wind, respectively. At the peninsular level under low CF generation thresholds (0.1 to 0.3), offshore wind energy complements solar energy more significantly than onshore wind energy. However, from $CF \geq 0.4$ the complementarity to both resources is similar. The maximum difference is observed at CF between 0.1 and 0.2 in winter, where the offshore wind complements the solar by 65% and the onshore wind by 5%. In summer, the maximum complementarity to onshore wind is reached at CF = 0.3 ($\sim 60\%$), while the complementarity with solar energy is remarkably high ($\sim 40\%$) taking into account the large summer availability of solar energy. Representative offshore wind areas also show a higher complementarity with solar energy than onshore wind at low CF thresholds, but these values are lower than those at the peninsular level. However, at high CF thresholds, all of them exceed it. Compared with them, A Coruña always presents the highest complementarity values throughout the period and in winter, while in summer they are Girona and Lisboa.

Fig. 5c–d depict the contrasting scenarios where the solar and onshore wind complement the offshore wind, respectively. Solar energy complements offshore wind less effectively than onshore wind, particularly in summer, reaching a maximum of 15% for offshore wind at a CF threshold of 0.3, compared to 35% for onshore wind. The complementarity of onshore wind (Fig. 5d) to offshore wind peaks at 5% in winter. For solar energy, complementarity ranges from 45% in summer to 60% in winter at low CF generation thresholds, decreasing as CF thresholds increase. Representative offshore wind areas receive more complementarity than at the peninsular level. In summer, Málaga benefits the most from solar energy (up to 25%), while Lisbon benefits the least (up to 15%).

3.4. Temporal synergy

Temporal synergy is analyzed with different values of $CF_{gen_t hreshold}$ (Fig. 5), in four scenarios. Three of these scenarios represent the synergy combinations of two resources (Fig. 6a-b), that is, when in the same timestep only one resource exceeds $CF_{gen\_threshold}$. The fourth scenario depicts the synergy of the three resources (Fig. 6c), where up to two resources exceed the $CF_{gen\_threshold}$.

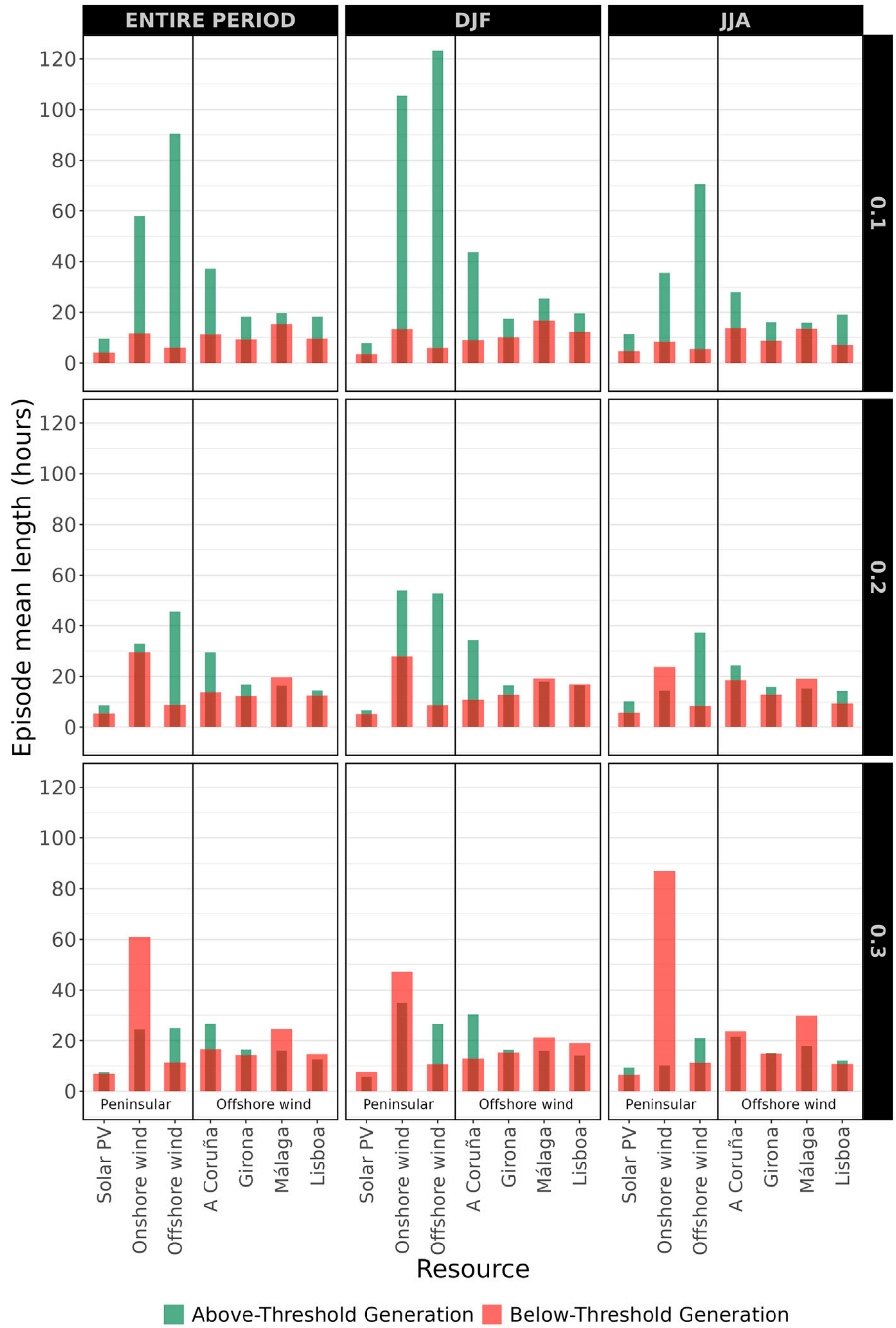

Fig. 3. Histogram of the consecutive hours mean of above-threshold generation (green) and below-threshold generation (red) for each resource (x-axis) at the peninsular level (solar PV*, onshore wind and offshore wind) and for representative offshore wind areas (A Coruña, Girona, Málaga and Lisboa) for different capacity factor generation thresholds (y-axis right) during the entire period (Sep2015–Aug2019), winter (DJF) and summer (JJA) seasons. $^{*}CF_{solar\ PV} = 0$ were discarded.

The synergies between solar-offshore wind and solar-onshore wind (Fig. 6a) are similar at low CF generation threshold (0.1) for the entire period (approximately 60%) and winter (approximately 65%). However, in summer, solar-onshore synergy is slightly greater (approximately 60% vs. 55%). In both cases, synergy decreases as the CF threshold increases. For higher CF thresholds, the solar-offshore wind synergy surpasses the solar-onshore wind synergy. The synergy advantage of offshore wind with respect to onshore wind is very clear for CF thresholds of 0.4 and above. At the individual offshore wind site level, under low generation thresholds (0.1–0.3), the synergy is similar to the peninsular level, while at high CF thresholds, it is greater. A Coruña exhibits the highest synergy compared to other areas for the entire period and winter. In summer, the synergy values are similar among the representative offshore wind areas, although Girona shows slightly higher values than the rest.

The synergy between the wind energies (Fig. 6b) is lower than the synergy between solar energy and each wind energy source, respectively. This is particularly evident at low CF generation thresholds. For instance, at CF = 0.1, the wind synergy is at least 40% lower. The maximum synergy is reached at CF = 0.3 in summer (approximately 60%). Representative offshore wind areas exhibit greater synergy compared to peninsular levels at the lowest and highest CF thresholds. At low thresholds, the wind synergy between different areas is relatively consistent, ranging from 25% to 45%. A Coruña shows the lowest

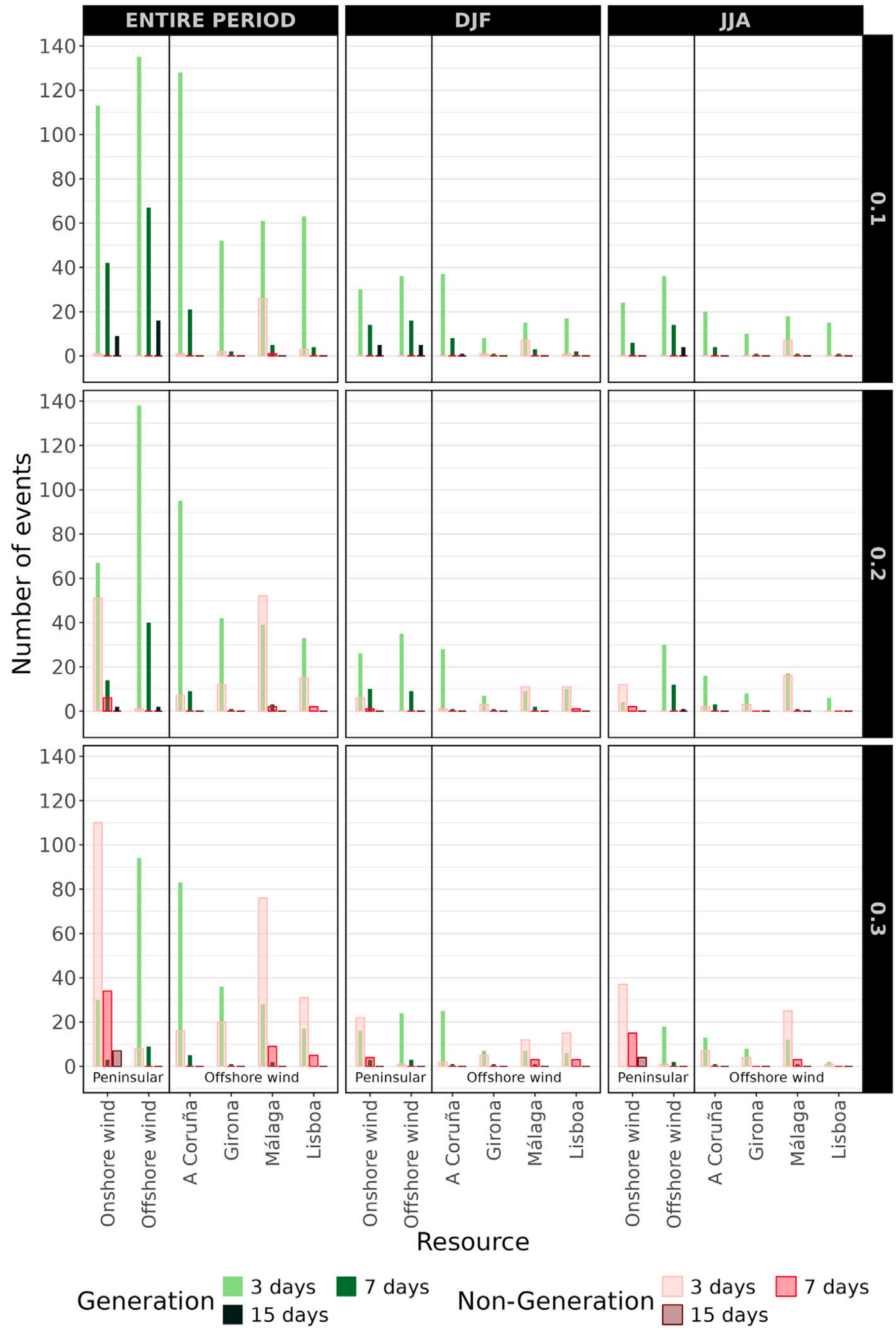

Fig. 4. Number of events of consecutive days (3, 7 and 15) of above-threshold generation (green color palette) and below-threshold generation (red color palette) of wind resources (x-axis) at different capacity factor generation threshold (y-axis right) over the entire period (Sep2015–Aug2019), winter (DJF) and summer (JJA) seasons.

synergy at CF = 0.1 for the entire period and winter. In summer, the synergy increases slightly, ranging from 30% to 50%, with Málaga displaying the highest values.

The last scenario (Fig. 6c) shows that the synergy when considering all three resources reaches the highest values compared to previous scenarios, particularly at low CF generation thresholds (0.1–0.3), ranging from 65% to 80% regardless of the period. The synergy with representative offshore wind areas exhibits a similar behavior to that at the peninsular level, surpassing it at high CF thresholds. It is remarkable that Girona is the only site showing synergy values above 30% across all periods and CF thresholds Moreover, its synergy values are also systematically high for solar.

3.5. Discussion

The analyses performed in this study highlight the advantages of integrating offshore wind energy into the Iberian electricity system. The use of real generation data and high-resolution reanalysis provides an overview not only of availability, but also of persistence and synergy compared to existing solar PV and onshore wind. Offshore wind shows higher availability and stability, especially at medium-high capacity factor thresholds ($CF \geq 0.3$). An outstanding result are the limited seasonal variations of Iberian offshore wind resources. These variations are much smaller than in other offshore areas like the North Sea. In summer, offshore wind resources do not only complement solar energy

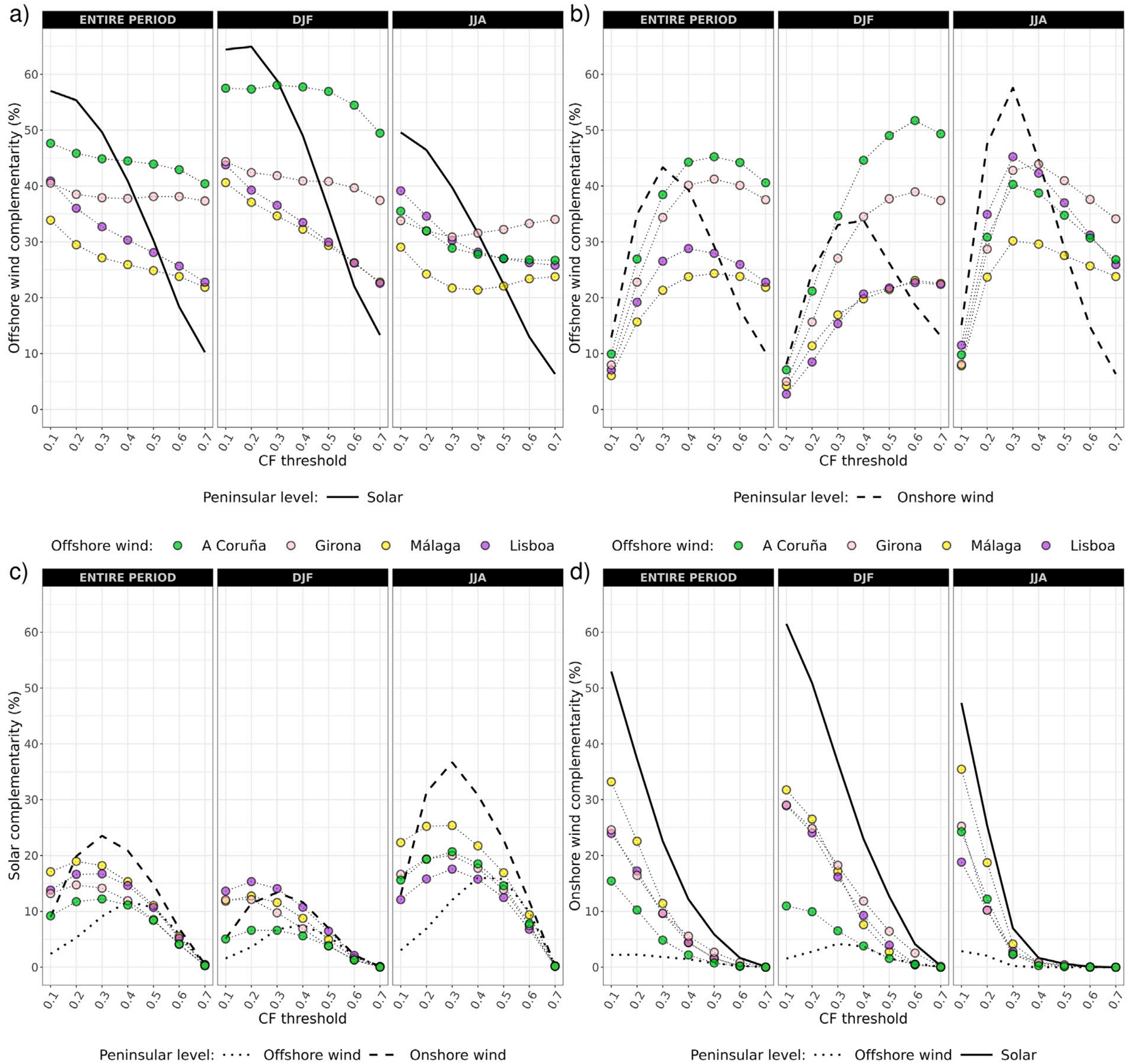

Fig. 5. Temporal complementarity scenarios among renewable resources for different capacity factor threshold (x-axis) at peninsular (lines) and individual site (colorful circles) levels: (a) offshore wind complements solar; (b) offshore wind complements onshore wind; (c) solar complements onshore wind (dashed line) and offshore wind (dotted line) and (d) onshore wind complements solar (solid line) and offshore wind (dotted line) during the entire period (Sep2015–Aug2019), winter (DJF) and summer (JJA) seasons.

but also onshore wind energy, highlighting the singularity of Iberian offshore wind characteristics.

Beyond highlighting the advantages of offshore wind energy, the main contribution of this study lies in the methodological framework applied to quantify the temporal complementarity and synergy between multiple renewable resources. This approach combines established metrics with a new synergy index that simultaneously considers three resources (offshore wind, onshore wind, and solar photovoltaic) and analyzes a series of capacity factor thresholds to assess sensitivity under different operating conditions. By focusing on aggregate analysis at the system level, it provides information that is directly relevant to peninsular-level grid integration and planning. Furthermore, the methodology can be applied to any region where hourly CF time series are available, either from real generation data or from reanalysis and climate model outputs. This flexibility makes it suitable for both current system evaluations and future scenario analyses.

Another key contribution of this study is the specific analysis of offshore wind resources. The four selected representative offshore wind areas (A Coruña, Girona, Málaga and Lisbon) present different seasonal and operational profiles that enhance the overall resilience of the Iberian energy system. For example, A Coruña shows the highest availability and persistence during winter, which makes it ideal for balancing low solar production. In contrast, Girona and Lisbon perform best in summer, with Girona standing out for its consistently high synergy across all seasons and capacity factor thresholds. The south of the IP, represented by Malaga, also contributes significantly during the summer, when onshore wind energy availability is lower. This spatial diversity allows for a geographically optimized offshore wind strategy that reduces the risk of simultaneous low generation events and supports year-round energy security. This is according to [13] who identify these areas with high seasonal stability by demonstrating that aggregating offshore wind areas across different coastal orientations significantly reduces temporal variability and improves seasonal balance.

Moreover, these findings extend and align with different studies also focused on the Iberian context. [11] conducted a spatial analysis of wind conditions along the Spanish nearshore and identified Galicia as

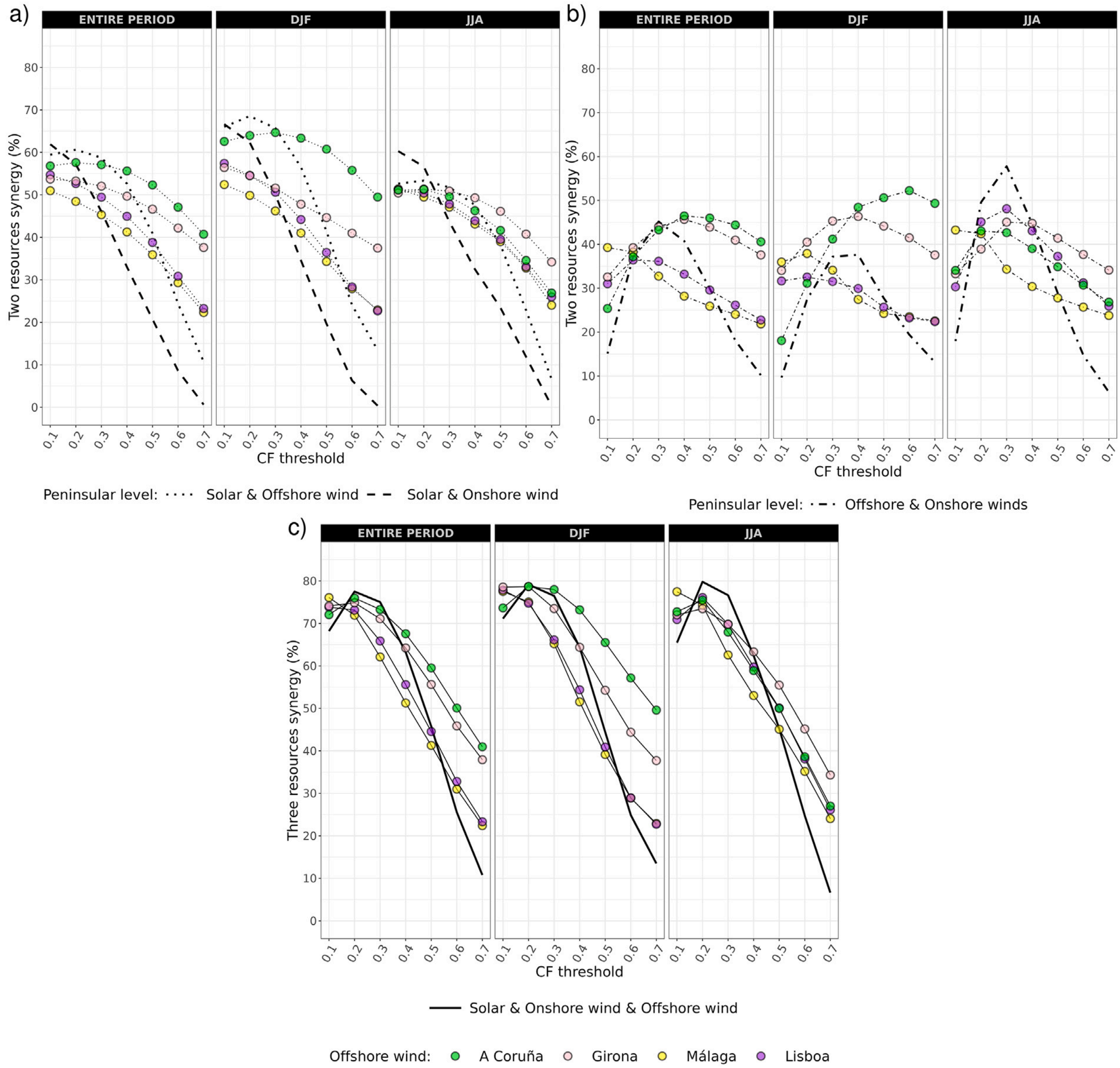

Fig. 6. Temporal synergy scenarios among renewable resources for different capacity factor threshold (x-axis): (a) solar vs. onshore wind (dashed line) and solar vs. offshore wind (dotted line); (b) onshore vs. offshore winds (dot-dashed line) and (c) the three resources synergy (solid line) during the entire period (Sep2015–Aug2019), winter (DJF) and summer (JJA) seasons.

one of the most favorable zones for offshore wind development due to its high wind speeds and CFs. Building on this, [10] provided a long-term perspective, showing that potential CFs in regions like A Coruña and Girona have increased significantly over the 20th century, suggesting growing viability over time. These historical trends reinforce the robustness of the resource and its potential resilience under future climate scenarios. [23] showed that offshore wind energy consistently exceeds the threshold of 200 W/m^2 in annual mean wind with the highest values concentrated in the northwest. In contrast, photovoltaic solar resource shows lower values in the north and peaks at around 200 W/m^2 in the southern areas. Seasonally, wind energy peaks in winter, especially in the northwest, while solar energy reaches its maximum in summer across all locations. Likewise, [24] found that wind energy exhibited the highest CFs among marine renewable resources in Spain, outperforming both wave and solar energy. Furthermore, both [23,24] emphasize the strategic value of integrating multiple renewable resources. Our study builds on this by quantifying such complementarity through capacity factor thresholds and seasonal performance metrics. The high complementarity of offshore wind with solar and onshore wind energies throughout the year reduces dependence on a single type of renewable energy, increasing energy security and reducing the risk of energy shortages. This is especially remarkable in summer, when an increase in electricity demand is expected under climate change conditions due to the intensification of extreme events such as heat waves that impact the energy system [3].

The findings on the advantages of offshore wind power compared to onshore wind power are mainly due to the fact that offshore turbines can capture wind at higher altitudes and on surfaces with less roughness, such as open water [41]. In addition, the possibility to install wind farms in deeper water provides access to stronger and more stable wind resources [42]. In their economic and political analysis of wind power deployment in Denmark, [43] noted that onshore sites are less attractive in terms of wind conditions and the capacity factor. Similarly, [44] emphasized that European governments and developers have actively supported offshore wind development, more so than in the United States, because offshore sites offer stronger and more consistent wind conditions compared to those onshore.

The low seasonality observed in several characteristics of offshore wind resources around the IP underscore the singularity of Iberian offshore wind resources compared to other areas like the North Sea. For example, [45] found that in Germany, offshore wind still exhibits notable seasonal variation, which affects its market value and requires careful integration with other renewables to maintain system stability. In contrast, our results show that offshore wind in the IP maintains high availability throughout both winter and summer, offering a more balanced seasonal profile. Similarly, [46] showed that in the North Sea, the benefits of offshore wind are maximized only when supported by a meshed offshore grid and floating wind technologies to mitigate variability.

A limitation of this study is that the period analyzed (September 2015 to August 2019) is relatively short for the analysis of certain characteristics like the interannual variability. The selection of this restricted period is due to the availability of data, as it is the only coincidence period between COSMO-REA6 reanalysis and the national electricity system data. Another limitation (due to the size of the study) is that the seasonal analysis focuses on winter and summer, omitting a detailed exploration of spring and autumn, which may also present relevant patterns of complementarity and variability.

Although the use of different data sources for offshore wind energy (reanalysis) and onshore wind/ solar photovoltaic energy (observed) ensures realistic aggregate patterns for the Iberian electricity system, it also introduces uncertainties when comparing resources and should be recognized as a limitation. Nevertheless, the accuracy of COSMO-REA6 has been evaluated in previous studies, which supports its suitability for wind resource assessment at regional scales. For example, [12] demonstrated that COSMO-REA6 reasonably reproduces the main characteristics of regional winds in the Iberian Peninsula when compared with observations. Similarly, [47] showed that COSMO-REA6 performs well for wind power applications in France, with low biases compared to other reanalyses. Furthermore, [48] confirmed that COSMO-based models accurately represent wind speed distributions and seasonal variability in offshore contexts. These validations reinforce the robustness of COSMO-REA6 for the purposes of this study. However, the accuracy of reanalysis datasets is known to vary regionally, which should be considered when assessing the uncertainty of results for individual offshore areas. Future work could include systematic validation of reanalysis-based CFs against observed CFs, particularly in studies with a high spatial detail.

Another source of uncertainty arises from the method used to calculate offshore wind CFs from reanalysis data. This approach assumes a fixed hub height (150 m) and applies a generic turbine power curve (Haliade-X 13 MW). While these assumptions are standard in large-scale assessments, they may lead to deviations from actual performance. However, given the aggregated nature of the analysis and its focus on temporal complementarity rather than absolute energy yield, these uncertainties are not expected to significantly affect the main conclusions.

4. Conclusions

This study explores the potential benefits of offshore wind energy in improving the temporal complementarity and synergy of the renewable energy system in the Iberian Peninsula, which is largely composed of solar photovoltaic and onshore wind. The focus is particularly on the winter and summer periods when electricity demand peaks. The assessment of complementarity between resources was done on the basis that one of them is above a certain generation threshold and the other is below.

Due to the lack of consensus in previous literature on establishing generation thresholds, the analyses are made under a range of capacity factors values allowing to assess the sensitivity of resource complementarity to different threshold settings. The real generation and installed capacity of solar and onshore wind at the country level of the Iberian national electricity systems are used to represent their respective capacity factors. For offshore wind potential, four areas (A Coruña, Girona, Málaga, and Lisboa) are selected to represent an optimal combination of wind power potential with data from COSMO-REA6 reanalysis This selection aims to reduce the hourly variability of the aggregated wind capacity factor in the Iberian Peninsula. These zones were previously delineated in the Spanish and Portuguese maritime spatial planning for the development of offshore wind energy. Consequently, the use of these datasets provides results that can be put into practice. Moreover, the hourly resolution of the datasets allows comparing the availability among resources and identifying periods of persistence above and below low-medium thresholds generation.

The offshore wind energy is clearly the most available and stable renewable resource in the IP compared to solar photovoltaic and onshore wind energies, especially at capacity factor thresholds generation of 0.2 or 0.3. Its temporal availability pattern remains consistent throughout both winter and summer. While solar energy shows improved availability in summer, the onshore wind experiences its poorest performance. In addition, offshore wind offers clear advantages over onshore wind: it benefits from higher and more stable wind speeds and has fewer siting conflicts, allowing the deployment of larger farms and access to vast new development areas.

The temporal complementarity and synergy results indicate that integration of offshore wind is beneficial for the overall Iberian renewable energy system. During winter, when solar energy availability is low due to shorter days and less sunlight, the offshore wind provides greater complementarity than the onshore wind. This ensures a more reliable and stable energy supply during the colder months. In summer, when solar energy production is high, offshore wind can play a crucial role as it complements solar much more than onshore wind (with complementarity values of 40%–50% for CFs of 0.1–0.3) and it also complements onshore wind (with values up to 55% at a medium CF threshold of 0.3). This fact means that the overall renewable energy output is maximized, leading to more efficient use of resources. The combined use of the three resources increases renewable generation by approximately 20% (of total hours) compared to the current interaction of solar and onshore wind. This boost remains stable throughout the year, with similar results observed in both winter and summer. The limited seasonal variations found here for several characteristics of offshore wind resources around IP corroborate the singularity of Iberian offshore wind resources compared to other areas such as the North Sea. The striking differences between Iberian offshore and onshore wind resources in summer enhance the added value of offshore wind resources for the Iberian electricity system. Despite the current higher installation costs compared to onshore wind and solar PV, the integration of offshore wind can stabilize the market value of renewables due to its comparatively constant output, thus reducing the need for onshore wind and solar PV.

The individual offshore wind locations exhibit significant availability and complementarity with solar and onshore wind at high generation thresholds ($CF > 0.4$). This is further enhanced by seasonal optimization due to geographical diversity. In winter, A Coruña offers the best resources, while in summer, Lisboa and Girona are better. Girona demonstrates good characteristics throughout the year.

This article highlights the different benefits that the integration of offshore wind energy brings to the renewable energy system in the Iberian Peninsula. The high complementarity of offshore wind with solar and onshore wind energies throughout the year reduces dependence on a single type of renewable energy, increasing energy security and reducing the risk of energy shortages. In addition, the development of individual distant offshore wind projects not only represents regional benefits by contributing to the local economy, but their geographical diversification and aggregated seasonal stability also ensure a more resilient energy supply for the overall Iberian energy system. In general, an energy system characterized by a diverse mix of renewable sources is more robust in handling the ordinary seasonal variations of these sources, enhancing the energy security.

CRediT authorship contribution statement

Noelia López-Franca: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miguel Ángel Gaertner:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Enrique Sánchez:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Claudia Gutiérrez:** Supervision, Methodology, Investigation, Conceptualization. **María Ortega:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Clemente Gallardo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Noelia Lopez-Franca reports financial support, article publishing charges, equipment, drugs, or supplies, and travel were provided by Spanish State Research Agency (AEI). If there are other authors, they 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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