

# Exploring the offshore wind and wave generation complementarity in Portugal for a sustainable and resilient power system

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**Abstract.** Exploring variable energy sources generation complementarity can, among several benefits, help in the reduction of the negative impacts of variability from individual sources, and lower the system's flexibility requirements. This study focuses on the complementarity between offshore wind and wave energy aiming to identify its overall value to the power system. Using Portugal as a case study, this work examines two offshore regions of the Plan for the Allocation of Offshore Renewable Energy in Portugal using standard approaches to assess the level of complementarity. The findings show a clear seasonal mismatch in the summer between wind and wave energy, which supports their complementary nature and helps smooth out seasonal fluctuations in offshore renewable generation. The results indicate that wave energy brings value to diversifying the offshore energy mix. When compared with onshore renewable generation, the combined use of offshore wind and wave power significantly enhances the stability of energy supply, reduces extreme events, which can contribute to decrease the need for additional system flexibility in future nearly 100% renewable-based power systems.

## 1. Introduction

Several European countries, including Portugal, are committed to fully decarbonizing their power systems, with onshore wind and solar photovoltaic (PV) playing a central role (1). However, a nearly 100% renewable power system, with a high reliance on weather-dependent technologies increases the power system vulnerability and the overall system costs (2). Supported by their high theoretical potential, the development of emerging offshore renewable technologies, such as floating wind, wave, and tidal energy, can offers a promising path to increase the share of renewables and diversify the energy mix, helping to address the challenges associated with the energy transition (3).

The potential of offshore renewable energy has already been explored, mainly through fixed offshore wind parks across the world. Portugal recently made progress in this area by installing the first floating offshore wind park with a capacity of 25 MW - Wind Float Atlantic Park (4). To support further expansion in the offshore regions, many countries have established Maritime Spatial Planning (MSP) frameworks. In Portugal, a comprehensive approach, which included a public consultation, led to the creation of the Plan for the Allocation of Offshore Renewable Energy (PAER) (5), which identifies four main areas suitable for commercial-scale projects with the potential to install up to 9.4 GW of offshore capacity. This ambitious target is supported by a high



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offshore wind resource potential, as identified in the OffshorePlan project (6). Nevertheless, Portugal also has significant potential for wave energy, although current technologies are still in early stages of development (7,8).

Beyond increasing renewable energy capacity, offshore development also offers a valuable opportunity to explore the complementarity between different variable renewable energy (vRES) technologies (9,10). In this context, the concept of complementarity refers to the idea that different renewable energy resources can be planned and operated synergistically to help overcome the inherent variability of each individual resource (11). Complementarity can be assessed in different dimensions: temporal (variation over time), spatial (variation across locations), and spatiotemporal (a combined analysis of both time and space). Several studies have shown that combining wind, solar, and wave energy generation can help smooth resource variability, and enhance overall grid reliability (11,12). When these technologies are co-located and share a single point of common coupling (Pcc) (11), additional advantages can be achieved, such as higher load factors for electrical infrastructure. This can help reduce grid connection costs as well as the technical and environmental challenges associated with grid expansion.

A comprehensive review of benefits and works addressing generation complementarity is available in (12). In (13) the authors investigate the temporal dynamics and complementarity of solar, wind, and wave energy resources in the Polish Exclusive Economic Zone of the Baltic Sea, showing how this synergy can enhance system resilience, particularly during extreme weather events. In (14) an analysis of the spatial and temporal complementarity between solar, wind, and wave energy resources along nearshore coast in Portugal based on the ERA5 reanalysis data revealed that the energy contribution of the selected wave energy conversion system was relatively low. This suggests that, for the targeted coastal regions, alternative types of wave energy converters may currently be more suitable. In (15), the authors highlight the advantages of co-locating a wave energy converter device with an offshore wind park, emphasizing potential synergies in energy production and infrastructure use. In (16), the authors found that wind-solar and wave-solar resources at the WindFloat Atlantic Park location exhibit negative correlations, which is beneficial for energy complementarity. However, they also noted a positive correlation between wind and wave resources, which may limit their combined effectiveness in balancing variability. Indeed, several authors have noted that the level of complementarity between wind and wave energy can vary significantly by region, largely due to their shared origin (17). Since waves are primarily generated by wind, their behaviour is often closely linear correlated, particularly in more confined or semi-enclosed areas. As a result, in such regions, the temporal patterns of wind and wave energy tend to align, which can limit the degree of complementarity between the two resources. Despite this, in (10) the authors identified the western offshore areas of Europe and the Portuguese west coast, characterized by open sea conditions as having the lowest positive correlation between wind and wave variability. This makes these regions particularly promising for combined exploitation, as their energy outputs are more likely to complement each other.

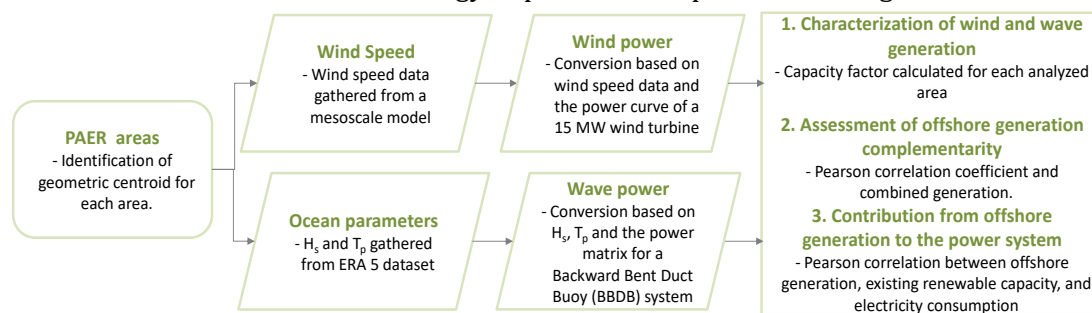
Most of the previous studies for Portugal have focused on specific locations or were limited by constraints in methodology and data, such as using only reanalysis datasets or assessing wind potential at low altitudes, which may not adequately capture the atmospheric vertical stratification over the offshore regions. Now that Portugal has officially designated offshore areas for renewable energy development through the PAER, there is a critical need to assess and quantify the potential complementarity between different vRES. This study investigates the relationship between wind and wave energy generation, aiming to understand *i) How does the*

*complementarity between wind and wave energy resources vary across different offshore locations?*, and ii) *What are the temporal patterns of complementarity between offshore and onshore vRES generation in Portugal?* Answering these questions enables to understand the complementarity dynamics between offshore renewable energy technologies in the designated PAER zones, while can support more effective planning and implementation of renewable energy projects in these regions. Moreover, evaluating how offshore technologies can complement onshore vRES generation will help meet electricity demand more reliably. This integrated approach can be easily implemented in other regions and in the context of energy islands.

Section 2 describes the methodology used in this study, while Section 3 presents the primary data sources. Section 4 details the case study and discusses the key results. Finally, Section 5 presents some final remarks and future work.

## 2. Methodology

A schematic flowchart of the methodology implemented is presented in Figure 1.



**Figure 1.** Schematic flowchart of the main steps implemented in this work.

To support the characterization of vRES generation and evaluate their complementarity, the capacity factor (CF) was calculated for each technology and the different locations. The CF is defined as follows:

$$CF = \frac{\text{Power generation (kWh)}}{\text{Installed capacity (kW)} \times \text{Numbers of hours (h)}} \quad (1)$$

### 2.1 Measuring complementarity

The complementarity between vRES can be identified through spatial and temporal dimensions. In the spatial complementarity the absence of resource availability for a specific technology in one region (e.g., wind in Region A) is compensated by its availability in another region (e.g., wind in Region B). The second focuses on temporal complementarity, where a lack of one resource (e.g., wind) at a given location is compensated by the availability of another resource (e.g., wave) at the same site (18,19). By analysing different offshore technologies (floating wind and wave) and onshore (existing wind and solar PV) this study covers the two approaches.

To provide a comprehensive analysis of vRES complementarity, this work study applies both correlation-based (e.g., Pearson's and Spearman's coefficients) and energy-based (combined capacity factor) metrics. While correlation helps evaluate how resource patterns relate at different temporal scales, energy-based indicators offer insights into the actual joint energy output. Correlation metrics, particularly Pearson correlation, are widely used in the literature to measure the linear relationships between time series. These coefficients range from  $-1$ , indicating

perfect negative correlation (strong complementarity), to +1, indicating perfect positive correlation (strong similarity) (19).

### 3. Data

For this study, one-hour resolution data for the year 2019 were used. As supported by (20,21), this temporal resolution allows for a sufficiently detailed representation of energy system flexibility requirements. The analysis incorporates various datasets, including historical aggregated onshore wind and solar photovoltaic generation and demand data provided by the transmission system operator (TSO) (22), as well as offshore renewable resource data, specifically wind offshore and wave energy. In the case of offshore renewable energy, losses due to wake effects, as well as internal and external grid losses, are not considered.

#### 3.1 Offshore wind power

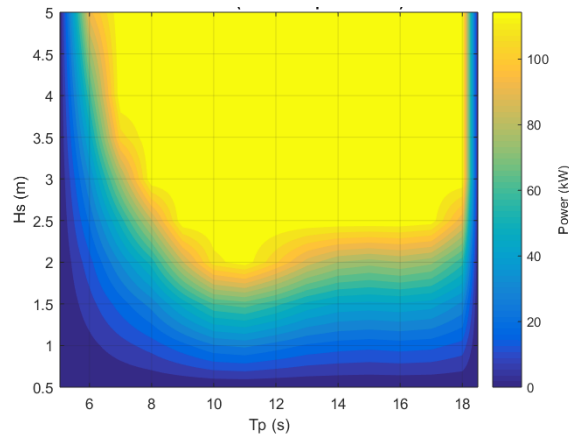
Numerical Weather Prediction (NWP) models enable the characterization of wind speeds across various spatial and temporal scales without the need for an extensive and costly network of meteorological or anemometric stations. These models can accurately simulate the evolution of air masses and explicitly account for phenomena such as turbulence and atmospheric stratification, both of which are crucial for assessing wind speed and, by extension, wind power potential (23). In this study, wind speed data from (24) obtained using a numerical mesoscale were used. The model outputs provide hourly wind data with a spatial resolution of 1 km. Wind speeds at 160 meters above ground level were extracted for the central points of the regions defined within the PAER considered in this work. The dataset spans a three-year period from 2015 to 2018. To extend it through 2019, a measured-correlated approach was applied, as described in (25). Wind energy production was estimated by applying the power curve of the Vestas V236-15 MW offshore wind turbine to the modelled wind speeds. This turbine was chosen as a representative example of current large-scale offshore wind technology. For confidentiality reasons, the specific power curve cannot be presented in this work.

#### 3.2 Wave power

Portugal's extensive coastline and its position facing the energetic Atlantic Ocean make it a global hotspot for wave energy exploitation. With an average wave energy density of 25–30 kW/m and a theoretical annual potential of 390 TWh-eight times the nation's current electricity consumption-wave energy stands as a cornerstone of Portugal's renewable energy strategy. Among several technologies, the Backward Bent Duct Buoy (BBDB), an Oscillating Water Column (OWC) device, was selected for this study since it is considered a compelling solution tailored to Portugal's maritime conditions (7).

Developed by Yoshio Masuda, the BBDB features an *L*-shaped duct that bends backward or forward beneath a floating structure, enabling energy capture through both heave (vertical) and pitch (rotational) motions. This dual-mode operation enhances efficiency across a broader range of wave frequencies compared to single-mode devices. Experimental studies demonstrate that the BBDB achieves peak capture width ratios larger than 0.5 for optimized configurations and maintains robust performance under irregular waves (26). The specific BBDB considered in this study is detailed in (27), from which pneumatic power outputs for various sea states were derived. Energy losses in the turbo-generator system are estimated at ~50% (28). The peak capacity factor of 0.3 was assumed based on data from (29). While there is no standardized method for defining the nominal power of wave energy converters, for example in (28), the nominal power of the device is assumed to be 400 kW. The power matrix (electrical power) of the

device used in this study is shown in Figure 2, showing a performance as a function of as a function of significant wave height ( $H_s$ ) and peak wave period ( $T_p$ )

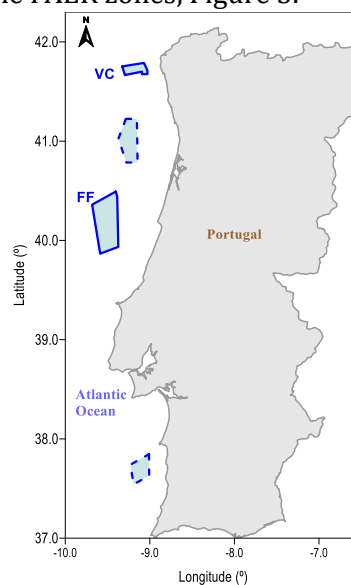


**Figure 2.** Power matrix (electrical power) of the BBDB device used in this study as a function of as a function of significant wave height ( $H_s$ ) and peak wave period ( $T_p$ ).

Hourly wave parameters (significant wave height and peak wave period) were extracted from the ERA5 dataset (30) for the four grid points closest to the central locations of the regions under analysis in this work. The values at the central points were then estimated using inverse distance weighting interpolation. According to (31), ERA5 data shows reasonable agreement with observed measurements. Its accuracy improves with increasing distance from the shore but does not significantly vary with changes in water depth.

#### 4. Case study and results

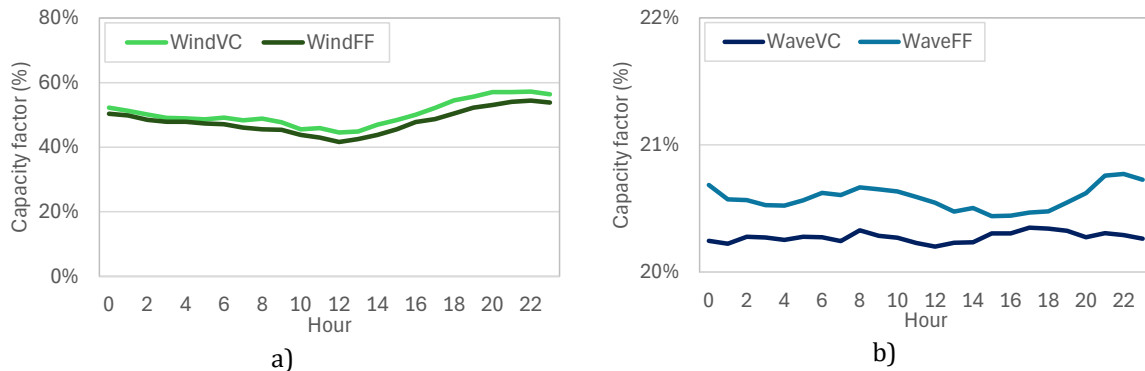
For brevity, this case study focuses on two of the four regions designated in the PAER for offshore renewable energy projects: Viana do Castelo (VC), selected for its high wind power potential, and Figueira da Foz (FF), the largest of the PAER zones, Figure 3.



**Figure 3.** Identification of the (commercial) PAER areas. The areas analysed in this work (VC and FF) are outlined with solid lines.

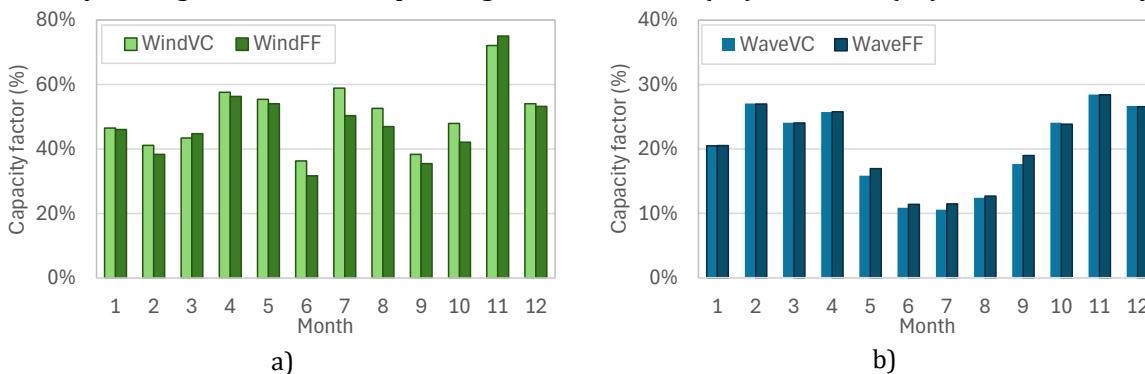
4.1 Daily and monthly average profiles

The analysis of the complementary nature between wind offshore and wave energy starts with a general overview of their potential in considered two locations. The average hourly and monthly capacity factors for each source are presented in Figure 4 and Figure 5, respectively.



**Figure 4.** Daily average profiles of: a) offshore wind and b) wave power in Viana do Castelo (VC) and Figueira da Foz (FF).

Both regions exhibit similar daily patterns across the two technologies as depicted in Figure 4. As expected, wind energy shows significantly higher potential, particularly in the Viana do Castelo (VC) area. Wave power shows a remarkably stable generation profile in both regions, with capacity factors consistently around 20 % with a variation below 0.5 % throughout the day. This type of stable generation profile highlights the reduced variability expected from this technology, especially when compared with other sources such as wind. Indeed, offshore wind in both regions shows pronounced diurnal variation. Capacity factors drop to their lowest values in late morning, reaching a minimum of 45% (VC) and 42 % (FF) around hour 12. After, wind generation increases gradually through the afternoon, peaking at around 57 % (VC) and 54 % (FF) at end of the day.



**Figure 5.** Monthly average profile of: a) offshore wind and b) wave power in Viana do Castelo (VC) and Figueira da Foz (FF).

From Figure 5 is possible to observe that both regions show very similar trends for offshore renewable generation throughout the year, and the trend identified is consistent with similar works addressing the wind and wave generation profiles (7). As expected, the monthly data shows that wave energy is more pronounced during November to March, when capacity factors are highest (around 20%). During the summer months, especially in June, July, and August, wave energy drops to its lowest levels, below 7%. Offshore wind shows a different pattern. It performs best in late autumn and winter, with November showing the highest capacity factors. A significant offshore wind generation is also expected during the summer months, particularly in July. This is

an important finding, suggesting that this increase observed in these months in offshore wind production could be associated with local thermal effects, such as sea and land breezes. However, since these breezes do not generate large waves, wave production remains low during this season. This seasonal relationship between the two energy sources highlights the potential benefits of combining both technologies to help balance seasonal variations and reduce overall variability in renewable energy supply that might contribute to reduce the need for long-term energy storage.

4.2 Assessing the offshore renewable generation complementarity

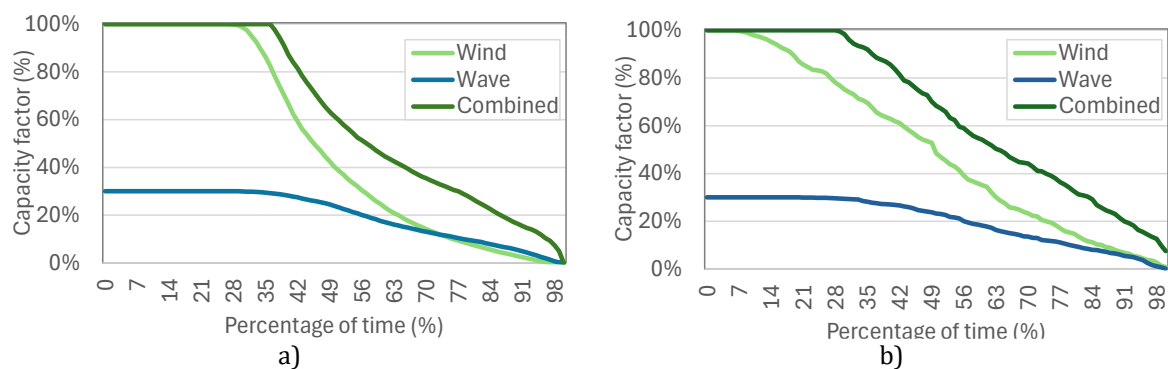
Table 1 presents the Pearson correlation coefficients between the offshore wind and wave generation across different temporal resolutions (hourly, daily and monthly) for the two regions under analysis.

**Table 1.** Pearson correlation coefficient for different temporal scales.

Region	Hourly	Daily	Monthly
Viana do Castelo	0.221	0.256	0.264
Figueira da Foz	0.297	0.355	0.417

In both regions, the correlation coefficients are positive across all temporal scales, indicating that the two energy sources exhibit a similar temporal production pattern. This means that when both technologies are deployed in the same location, they tend to generate power in synchrony to some extent. The strength of this correlation increases with the temporal scale, with the highest values observed at monthly resolution suggesting that longer-term trends in energy production are more aligned than short-term variability. Figueira da Foz consistently shows the highest correlation values. One possible explanation for this difference is that Figueira da Foz may experience less influence from large-scale phenomena, such as storms, which can introduce variability and reduce linear correlation between the generation from these two energy sources.

Figure 6 presents the capacity factor (CF) duration curves based on hourly and daily time series for the Viana do Castelo region. A duration curve provides a graphical representation of how often a particular value of a variable is met or exceeded over a specified period. In this context, it illustrates the proportion of time that different CF values are equalled or surpassed. For the purpose of comparison, it is assumed that both energy sources operate with identical installed capacities. Although not shown, the results for Figueira da Foz are similar.

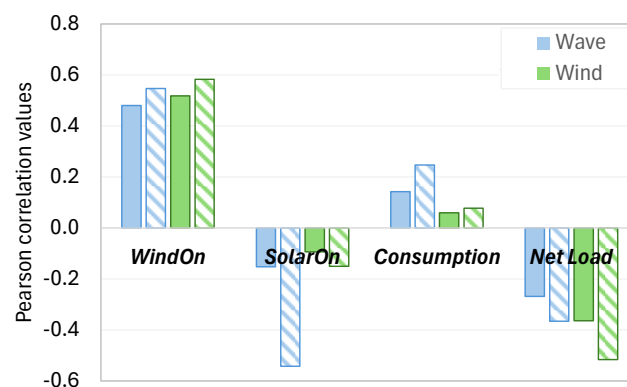


**Figure 6.** Generation duration curves at: a) hourly and b) monthly scales for both individual technologies and their combination in the Viana do Castelo region.

As expected, the duration curves reveal more stable and uniform values for wave energy generation, while wind power exhibits greater variability. The curves also demonstrate that combining the two technologies increases the number of hours with a CF close to 100% and helps reduce periods of low offshore generation availability. For example, at the hourly scale, wind power alone achieves a CF above 20% for 64% of the time, while in wave power the time is reduced 55% of the time. When both sources are combined, for the same CF value, the time rises significantly to 86%, highlighting the benefit of hybrid generation. A similar pattern is observed in the analysis at the daily time scale. Therefore, the figure highlights that the combined use of wind and wave energy can mitigate part of the fluctuations observed, leading to reduced variability and less extreme values, which is an important from the power system operation perspective. In addition, as discussed in (15), this results emphasizing the potential synergies in energy production and infrastructure use.

#### 4.3 Assessing the contribution from offshore generation to the Portuguese power system

This section provides a simple analysis of the linear relationship between offshore renewable generation and both wind and solar onshore national aggregated generation, consumption and net load (consumption minus the onshore wind and solar production). Pearson correlation coefficients are used (Figure 7) to help understand how these energy sources interact and affect the overall energy balance.



**Figure 7.** Correlation values at hourly (solid bars) and daily (hatched bars) resolutions between offshore wind and wave generation in Viana do Castelo and national onshore aggregated vRES production, electricity consumption, and net load.

At both hourly and daily scales, wave and offshore wind generation show moderate to strong positive correlations with onshore wind, especially at the daily level. This means they are often influenced by the same large-scale weather systems. Both wave and offshore wind also show negative correlations with solar PV generation, as expected according with discussion in (16). In particular, wave energy has a strong negative correlation with solar at the daily scale (near -0.5), suggesting good complementarity, i.e., wave power tends to produce more on cloudy, stormy days, while solar has the highest level of production on sunny days. Offshore wind shows a weak negative correlation with solar, suggesting that the generation can be expected under a wider range of weather conditions, both from large-scale weather phenomena and locally-induced winds. Although not shown in Figure 7, onshore wind complements solar better than offshore wind. In terms of electricity consumption, both resources show low positive correlations, slightly stronger for wave energy (up to 0.24 daily). Notably, both wave and offshore wind contribute to reducing net load, with offshore wind showing the strongest negative correlation. These results

show the potential of offshore renewable energy sources to meet demand and reduce the need for conventional power sources.

## 5. Final remarks and future work

This study investigates the relationship between wind and wave energy generation, aiming to understand the complementarity between wind and wave energy resources across different offshore locations and the temporal patterns of complementarity between offshore and onshore vRES generation in two regions of the Portuguese Plan for the Allocation of Offshore Renewable Energy.

At a shorter time scale, the combined use of wave and offshore wind energy reduces the frequency of low generation periods and helps smooth overall variability. Pearson correlation coefficients are positive across all time scales analysed (hourly, daily, and monthly), indicating that wind and wave energy tend to generate in a similar way. When compared with existing technologies in the Portuguese power mix, offshore renewable resources exhibit a negative correlation with solar photovoltaic. By reducing net load and supporting supply during periods with low solar generation, offshore wind and wave energy could, in the future, significantly increase the renewable energy penetration while contributing to the decarbonization and resilience of the power system.

To fully assess the role of offshore renewables in the Portuguese power system, further studies are needed. These should include power system dispatch modelling and the evaluation of different wave energy converter technologies. Additionally, improvements in ocean resource data, including a more extensive period and higher spatial resolution model and/or observed data will be essential to support informed planning and investment decisions.

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