

Article

Hybrid Wind–Solar Generation and Analysis for Iberian Peninsula: A Case Study

Jesús Polo 

Photovoltaic Solar Energy Unit (Energy Department, CIEMAT), Avda. Complutense 40, 28040 Madrid, Spain; jesus.polo@ciemat.es

Abstract

Hybridization of solar and wind energy sources is a promising solution to enhance the dispatch capability of renewables. The complementarity of wind and solar radiation, as well as the sharing of transmission lines and other infrastructures, can notably benefit the deployment of renewable power. Mapping of hybrid solar–wind potential can help identify new emplacements or existing power facilities where an extension with a hybrid system might work. This paper presents an analysis of a hybrid solar–wind potential by considering a reference power plant of 40 MW in the Iberian Peninsula and comparing the hybrid and non-hybrid energy generated. The generation of energy is estimated using SAM for a typical meteorological year, using PVGIS and ERA5 meteorological information as input. Modeling the hybrid plant in relation to individual PV and wind power plants minimizes the dependence on technical and economic input data, allowing for the expression of potential hybridization analysis in relative numbers through maps. Correlation coefficient and capacity factor maps are presented here at different time scales, showing the complementarity in most of the spatial domain. In addition, economic analysis in comparison with non-hybrid power plants shows a reduction of around 25–30% in the LCOE in many areas of interest. Finally, a sizing sensitivity analysis is also performed to select the most beneficial sharing between PV and wind.

Keywords: wind and PV power modeling; hybrid energy systems; SAM modeling; capacity factor



Academic Editors: Frede Blaabjerg and Tapas Mallick

Received: 18 June 2025

Revised: 21 July 2025

Accepted: 23 July 2025

Published: 24 July 2025

Citation: Polo, J. Hybrid Wind–Solar Generation and Analysis for Iberian Peninsula: A Case Study. *Energies* **2025**, *18*, 3966. <https://doi.org/10.3390/en18153966>

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Renewable energy systems play an important role in reducing fossil fuel usage in the energy mix worldwide. The increase in renewable energy share is expected to reach over 40% by 2030, according to the International Energy Agency (IEA), where wind and solar power dominate the contributions [1]. In Spain, for instance, renewable energies produced over 50% of the Spanish electricity mix in 2024, and at the beginning of 2025, the total PV and wind capacity installed was around 32 GW each (<https://www.ree.es/en>, accessed on 20 July 2025). However, the intermittent nature of renewable resources is a challenge for the dispatch of energy to the power network. Hybrid wind–solar power systems may benefit from the resource complementarity and shared power equipment and interconnections. The resource complementarity refers to the compensation of the energy generation taking place when two or more energy sources are combined. On the other hand, recent studies have proven the financial advantages of co-locating a PV system alongside an existing wind power facility [2], or vice versa, due to shared substation and grid connections, both with and without battery energy storage systems (BESS). Thus, the

interest in studying hybrid renewable systems has increased notably during the last few years, and many works, including modeling, site-specific analysis and optimization, can be found in the recent literature [3–10]. In addition, complementarity analysis of wind and solar PV has been studied in different regions and spatial scales using reanalysis wind speed data and satellite-derived solar radiation data [11–13].

The analysis of the potential assessment of hybrid solar–wind power for grid-connected and standalone systems requires different types and levels of complexity in input data. A review of the data required, including long-term production, geo-spatial planning and generation cost models, was recently conducted with particular focus on the Spanish situation [14]. The level of detail needed in the available data for mapping hybrid potential or analyzing the optimal locations for hybrid systems varies across different studies. Thus, the use of a digital elevation model, along with average values of wind velocity and solar irradiation, can be used to combine the energy resource with topography and environmental constraints [15–17]. Correlation analysis can also be used in regional analysis of hybrid potential to explore the areas with higher complementarity of wind and solar resources [18,19]. For instance, a negative solar–wind correlation coefficient was estimated for Italy at the hourly, daily and monthly basis [20]. Similar results were found in a recent study for specific sites in Portugal [21]. Analysis of coupled wind–solar with daily data in southern Spain showed several seasonal patterns [22]. In addition, recent studies of the Iberian electricity market with day-ahead forecasting have revealed an increase of 4% average yearly net revenue from hybrid PV–wind–storage systems [23,24]. Moreover, a simplified analysis using monthly data and different GIS layers show a suitability index for hybrid solar–wind plants in Spain [25].

In this paper, an extensive model of a hybrid solar–wind power plant of 40 MW has been developed using the SAM (System Advisor Model) hybrid model for the Iberian Peninsula. Additional modeling of individual PV and wind power plants of 40 MW is included for the comparison between hybrid and non-hybrid systems. SAM (version 2023/12/17) is a widely used software tool for modeling different renewable energy systems [26]. Among all the systems, SAM allows for modeling more than one type of power technology in a single grid-connected plant; in other words, a hybrid power plant. On the other hand, several studies have used HOMER PRO to optimize the combination of different renewable energy sources [3,7,27]. However, SAM offers much more versatility in terms of output variables associated with plant performance and power output; in addition, it allows for massive computing and dynamic control of input variables and configuration through PySAM (<https://github.com/NREL/pysam>, accessed on 20 March 2025). In this work, hybrid PV–wind power plants and individual PV or wind power plants, each of 40 MW, are defined in the modeling. Reanalysis and satellite-derived (ERA5 and PVGIS) data are used for the wind and solar meteorological inputs required by SAM for its system models. The modeling results and comparisons with individual PV power and wind power plants of the same capacity are used to map hybrid potential and analyze the spatial distribution of solar–wind complementarity and energy generation. The results of the modeling are presented in maps of different variables of interest, including the annual energy, wind–solar correlation coefficient and combined capacity factor, which show the spatial distribution of the hybrid solar–wind potential in the Iberian Peninsula. Finally, a sensitivity analysis of the sizing of PV and wind power in the hybrid plant is studied as a function of the capacity factor. The main novelty of this work lies in the fact that it is the first map that analyzes the wind–solar hybridization potential in the Iberian Peninsula in purely energetic terms. In addition, to illustrate the economic aspects, a comparison of the levelized cost of electricity (LCOE) is presented using the default economic scheme of SAM. Using the default

economic scheme of SAM and the hybrid and no-hybrid modeling, a 25–30% reduction in LCOE is observed associated with the hybridization.

2. Materials and Methods

2.1. Meteorological Data

Solar and wind resource meteorological data on an hourly basis are needed to create weather input files for any power plant model in SAM. In this work, the required meteorological data were obtained, on an hourly basis, from satellite and reanalysis retrievals. The spatial domain selected for this work covers 35.9–44.2° N in latitude and –9.6–4.5° E in longitude, corresponding to the Iberian Peninsula (Spain and Portugal). Typical Meteorological Year (TMY) is used to represent the long-term meteorological conditions at every point in the domain.

In the case of solar resource, TMY on an hourly basis from PVGIS SARA3 collection, covering the period 2005–2023, was used. PVGIS TMY hourly data is generated by combining satellite-derived solar irradiance data and ERA5 reanalysis for the other meteorological variables [28]. PVGIS SARA3 solar irradiance data accuracy and reliability have been validated extensively elsewhere [29–33]. PVGIS data can be seamlessly accessed in the proper format by using the pvlib iotools library [34]. In the case of wind, ERA5 hourly wind velocity at 10 m and 100 m height, as well as pressure and temperature, were used for 2005–2023 [35]. Wind velocity at those two heights was derived from the *u* and *v* components of the wind velocity, which are the output variables of ERA5 regarding wind velocity. The month candidates to TMY were obtained from the PVGIS data; therefore, for each site, the single month and year identified in PVGIS as TMY are considered the month candidates to form a TMY. Thus, the TMY file for wind resources is created by concatenating the selected months from the ERA5 2005–2023 hourly data. It is recognized that ERA5 reanalysis data are sufficiently reliable to assess wind resource [36,37]. Moreover, the consideration of ERA5 as the most reliable reanalysis has encouraged its use in this hybrid wind–solar energy potential modeling [38]. The spatial resolution is limited by the coarser resolution of PVGIS and ERA5; thus, the spatial resolution used for the meteorological input was $0.25^\circ \times 0.25^\circ$, which is the grid resolution of ERA5. In addition, within the gridded points selected in the domain, only those above sea level are suitable to retrieve data from PVGIS. Finally, around 1200 files, in the proper format for modeling power plants with SAM for solar and wind resources, were used from the PVGIS and ERA5 databases.

2.2. Methodology

The approach used in this work for determining hybrid potential consists of defining a model of a hybrid wind–solar plant of reference and the individual equivalent PV and wind power plants of the same capacity as the hybrid one. Figure 1 shows the capacity ranges of most wind and PV power plants in the Iberian Peninsula according to public and available information [39]. There is a significant number of plants in the range of 40 MW of capacity. Thus, it is reasonable to select 40 MW as the power capacity for the reference plant to simulate in this work.

Three reference plants were considered in this analysis: a hybrid 40 MW power plant (consisting of 20 MW wind Power, 20 MW nameplate capacity PV Power), a pure PV power plant of 40 MW nameplate capacity, and a pure wind power plant of 40 MW. The pure PV and wind power plants share the same technical characteristics of the corresponding hybrid system, except for the system capacity. The PV subsystem selected is a bifacial system with a single-axis tracking and surface azimuth of 180° (south-oriented), since this is the current trend in Spanish PV plants. Simple assumptions are taken for the boundary

conditions of the reference plant. Thus, there is no interconnection limit imposed to avoid grid curtailment.

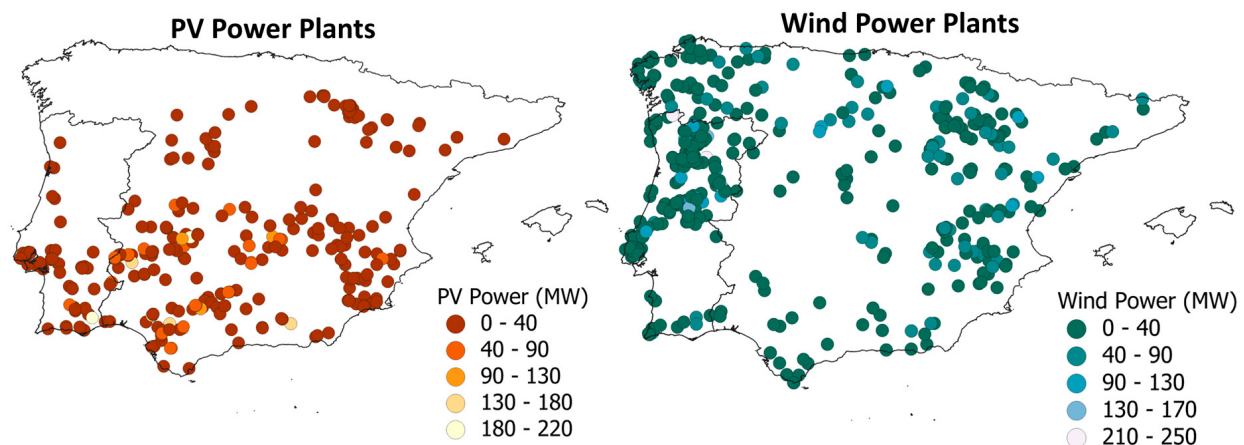


Figure 1. PV (left) and wind (right) power facilities in Iberian Peninsula.

Wind power is estimated in SAM by the empirical power curve in the SAM turbine database, which determines the turbine power as a function of the wind speed [40]. PV power is calculated by the PVWatts model [41], which uses the following simplified equation to estimate the DC power (P_{DC}) as a function of the irradiance and module temperature (T_m):

$$P_{DC} = \frac{I}{1000} P_0 (1 + \gamma (T_m - 25)) \quad (1)$$

where I is the incoming solar irradiance to the module (also known as plane of array irradiance) and γ is the temperature coefficient of power. DC to AC conversion of the estimate by the technical coefficients of the specific inverter model in the SAM database.

Table 1 summarizes the main technical characteristics of the hybrid plant. SAM user interface automatically includes many input variables with the default values for the type of plant selected. All these values were reviewed, and changes to the parameters were introduced according to the technical characteristics of the selected plants. Individual wind and PV power plants share all technical parameters, except for nominal power, with the hybrid reference plant to allow for proper comparison. Then, all the parameters were stored as a JSON-formatted file for each power plant considered in this work, and a proper script using PySAM was prepared to load all the parameters and run the plant model.

Table 1. Technical characteristics of the hybrid reference plant.

Parameter	Value
PV nameplate capacity	20 MW
PV DC to AC ratio	1.3
PV Rated Inverter size	15.38 MW
PV orientation and tracking	1-axis tracking south-oriented
Total PV losses (soiling, shading, wiring, ...)	14%
PV Bifaciality	0.7
Wind Power	20 MW
Number of turbines	10
Turbine model	Gamesa G114 2.0 MW

The approach is then to model, using PySAM, the hybrid, individual PV and wind plants for each point in the domain under study to compare the hybrid generation with the generation of a non-hybrid plant [42]. The procedure of modeling three plants allows for presenting most of the results in a relative way (i.e., hybrid power plant performance

is determined by comparison with the individual standalone PV or wind performance). Therefore, the results are dependent on the technological parameters and the economic scheme used in the input is minimal.

3. Results

3.1. Energy Generation

Modeling the energy generation of each plant (individual PV, individual wind and hybrid plant) with PySAM for each gridded point in the domain was performed using TMY files generated from PVGIS and ERA5 retrievals. For mapping purposes, a 2-D linear interpolation was performed at a spatial resolution of $0.05^\circ \times 0.05^\circ$, which corresponds to around 5 km of spatial resolution. Figure 2 shows the annual generation maps, which represent the long-term performance of each reference plant. PV generation is considerably higher than wind energy, except in some specific regions, which is also remarked in the hybrid annual energy map. In addition, PV annual generation is much more homogeneous along the domain than wind annual energy. On the other hand, the wind annual energy map has a wider range of variability, but most of the territory has an annual wind energy in the range of 40–70 GWh. The highest wind generation is placed on the west and northwest, close to the shore. The hybrid annual generation pattern shows higher similarity with the individual wind power generation, since wind power exhibits much higher variability than PV power. Nevertheless, hybrid annual energy is higher than individual wind power generation, except in a few local regions where the wind resource is very high. Finally, there are some regions where the annual energy generated by the hybrid 40 MW plant outperforms the energy of a pure 40 MW PV plant.

3.2. Analysis of Hybrid Potential

The Iberian Peninsula has very good resources for renewable energy systems, including both solar and wind. The integration of both resources can be analyzed by the correlation in the hourly generation of wind and PV power. The correlation coefficient of wind and PV power can be calculated from the hourly values of the simulation results of the individual wind and PV reference plants. The mathematical expression for estimating the correlation coefficient is

$$r = \frac{\sum_h (P_{PV} - \overline{P_{PV}})(P_{Wind} - \overline{P_{Wind}})}{\sqrt{\sum_h (P_{PV} - \overline{P_{PV}})^2 (P_{Wind} - \overline{P_{Wind}})^2}} \quad (2)$$

where P_{PV} refers to hourly values of PV power, P_{Wind} is the hourly time series of wind power, and h is the hourly timestamps in the period of analysis (8760 values for a complete year). In order to study the complementarity of wind and PV power, the correlation coefficient is estimated for hourly values exclusively during the daytime. Negative values indicate that an increase in wind power corresponds to a decrease in PV power and vice versa; on the other hand, positive values are associated with a simultaneous increase or decrease in both variables. In fact, the correlation can be computed for aggregation at different time scales. Figure 3 shows the map of the correlation coefficient on an hourly basis for daytime, daily and monthly time scales.

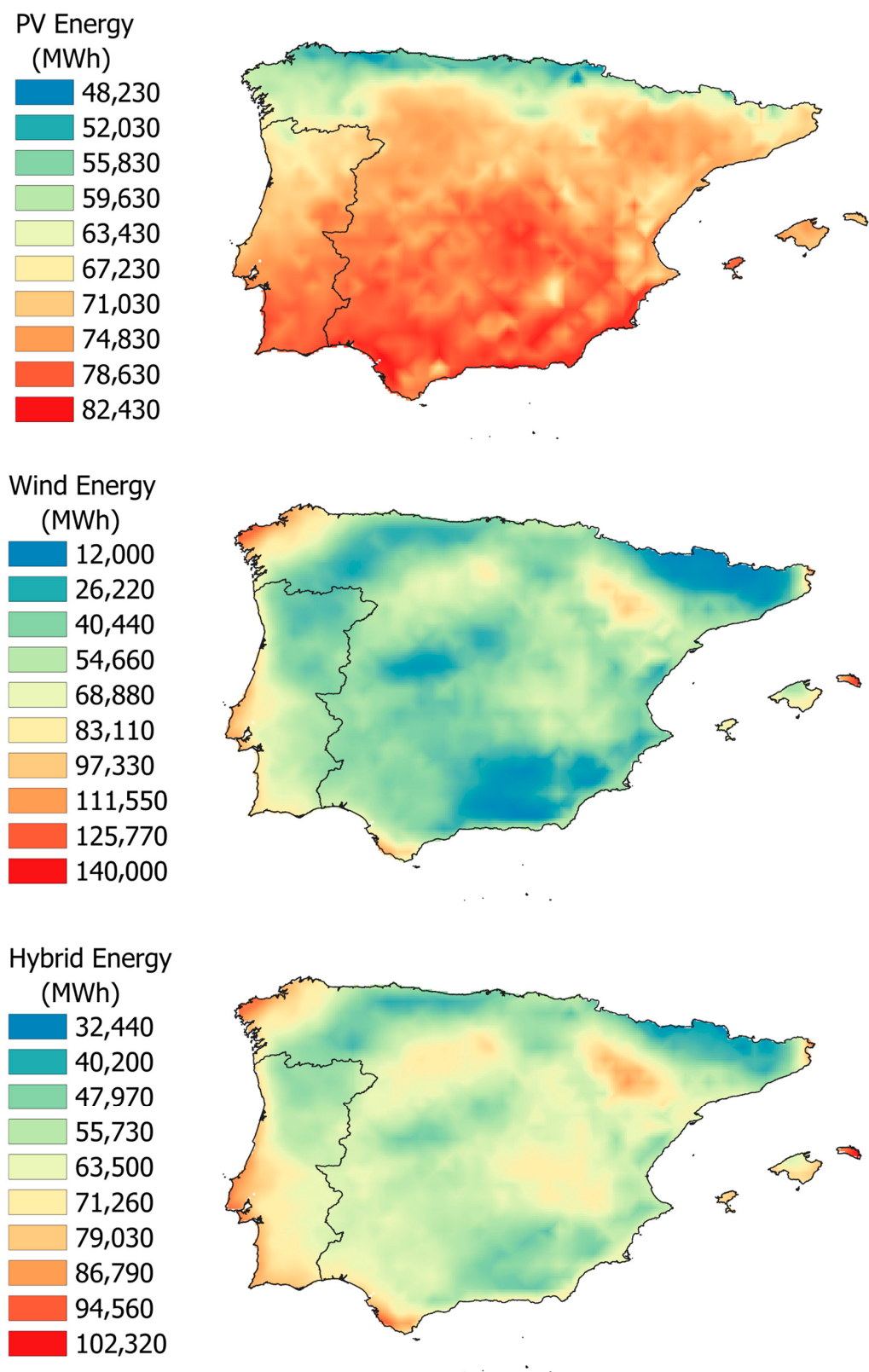


Figure 2. Annual generation maps: PV (**upper**), wind (**middle**), hybrid plant (**bottom**).

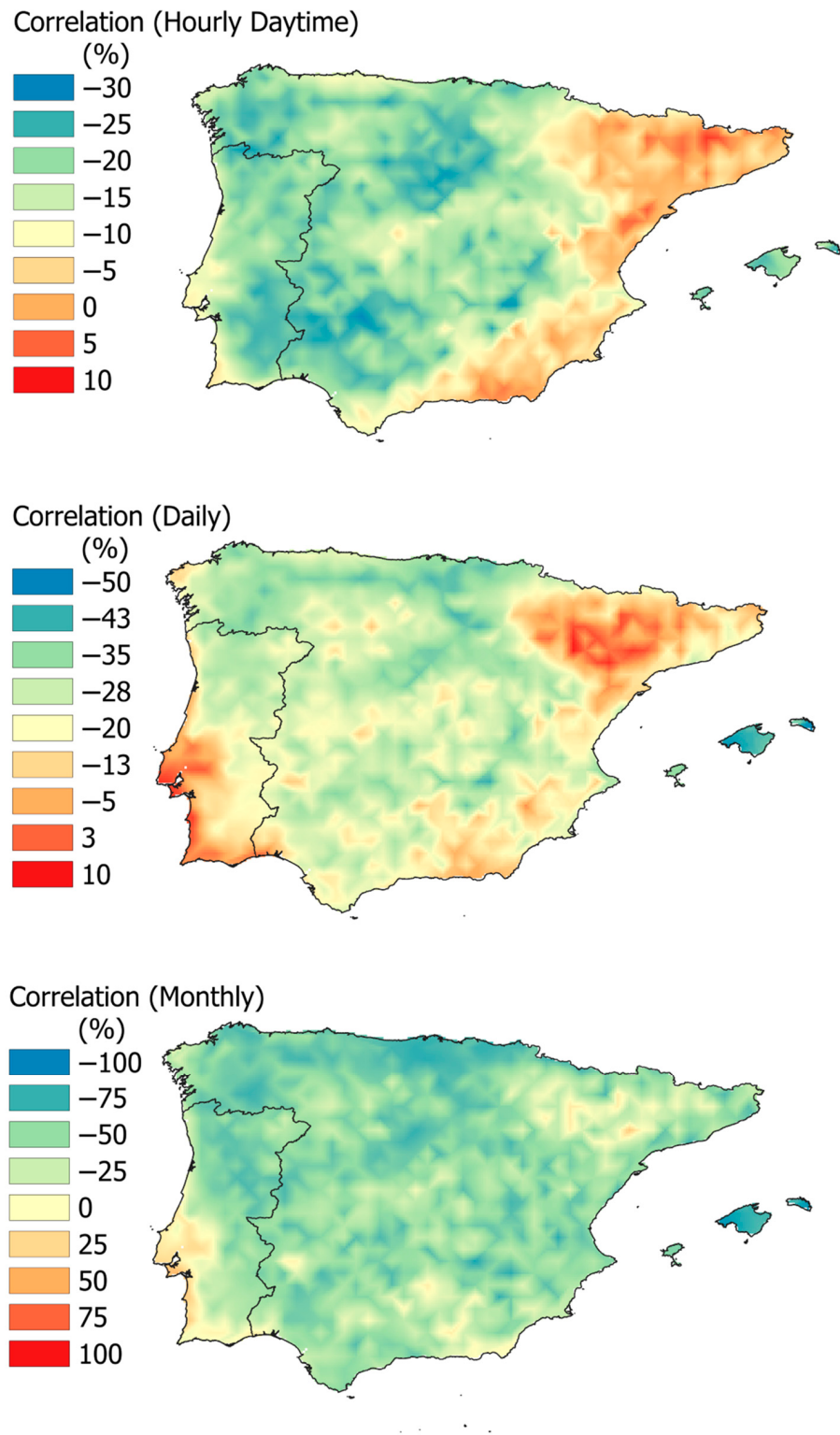


Figure 3. Map of correlation between wind and PV power at three scales: hourly during daytime, daily and monthly.

The maps are mostly dominated by a negative correlation. In the case of hourly correlation, the west and center areas indicate some degree of complementarity between wind and PV power, reaching up to -30% , indicating a good potential for hybridization of solar and wind. The eastern part of the map shows lower correlation, and only a few local areas show positive correlation. The results shown in Figure 3 are in general good agreement with a previous study performed for Portugal by Couto and Estanqueiro [21]. Analysis of

224 existing wind parks in Portugal using high spatial resolution data on an hourly basis for 2015–2016 resulted in clustering the locations in eight groups. The complementarity of wind and solar PV, estimated on an hourly basis, resulted in a correlation of -20% for the central and northern regions of Portugal, which is comparable to the range found in this work (-15 to -20%). In addition, the results for Lisbon and southeast areas (around -10% and -5% , respectively) also showed general agreement with the aforementioned previous study [21]. A similar agreement with the Couto and Estanqueiro analysis is also found at daily scales, where a high negative correlation (-35%) is found in north Portugal, a lower negative correlation is estimated for the Lisbon area, and even a slightly positive correlation is found in the southwest. Finally, the monthly correlation shows a smoother distribution than daily.

In the analysis of hybrid potential, geographical and physical constraints should be taken into account in addition to the energy generation features. Thus, digital elevation model and land cover information can be used to elaborate realistic limitations to the available geographic areas for installing power plants. The elevation model used was the SRTM30. The slope of the terrain was calculated using the digital elevation model, and a binary mask was applied to eliminate areas with a slope greater than 10% , which are considered unfeasible areas for PV deployment [43,44]. In addition, the Global Land Cover 2000 was used to exclude the regions that fall into the following categories: artificial surfaces, water bodies, snow and ice, and irrigated agriculture. Taking into account the available geography limited by the elevation and land use conditions, the ratio of annual hybrid energy to annual non-hybrid energy can be calculated for PV and wind. Figure 4 shows this ratio along with the location of PV and wind power plants. The maps for the index hybrid to PV and the index hybrid-to-wind power would show those areas where hybrid generation outperforms the pure PV generation or pure wind generation for the same nameplate capacity, respectively. The location of actual power plants helps identify the best areas for hybrid power plants since some electric power infrastructure is already present on site. The hybrid to PV ratio index shows very large geographic regions in the range of 0.8 – 1.2 ; the top northeast has an index around 1.6 – 1.7 because PV and wind generation are very unbalanced (very high wind power with the highest values in the domain and very low PV generation in the lowest range). Similar behavior can be observed in the hybrid-to-wind ratio regarding the wind–PV unbalance; in the areas close to mountain ranges, the wind generation is significantly much lower than in the rest of the spatial domain under study, and the results can be unrealistic since, in practical terms, PV deployment is not feasible for technical and economic reasons. Since the PV annual energy range is much narrower than that of wind energy, there are small regions in the domain where the hybrid-to-wind ratio increases abruptly. Nonetheless, the comparison of both maps indicates a higher ratio of hybrid-to-wind than hybrid-to-PV. In fact, PV generation in the Iberian Peninsula is rather high in most of the territory. Thus, the gain of incorporating PV power plants on existing wind power seems to be higher than the opposite.

In order to analyze the dispatch capacity of the hybrid power plant, it could be interesting to compute the ratio of wind energy generated during nighttime in the hybrid power plant to the total hybrid generation. Figure 5 shows the distribution of the contribution of wind power during the night to the total energy dispatched. The nighttime wind power contribution can reach 35% of the energy generated only in the northwest corner of the peninsula. Nevertheless, there are several regions where the contribution of nighttime wind power is around 25 – 30% of the total energy. This information is an indicator of the dispatch capacity of the hybrid power plant. In addition, the regions with high contribution of nighttime wind power to the total energy (higher than 20%) have quite similar characteristics to the regions with higher energy generation, as shown in the hybrid generation map of

Figure 2. In the figure, the location of actual PV power plants is also displayed to illustrate the potential for hybridization by adding a wind power plant to an existing PV plant.

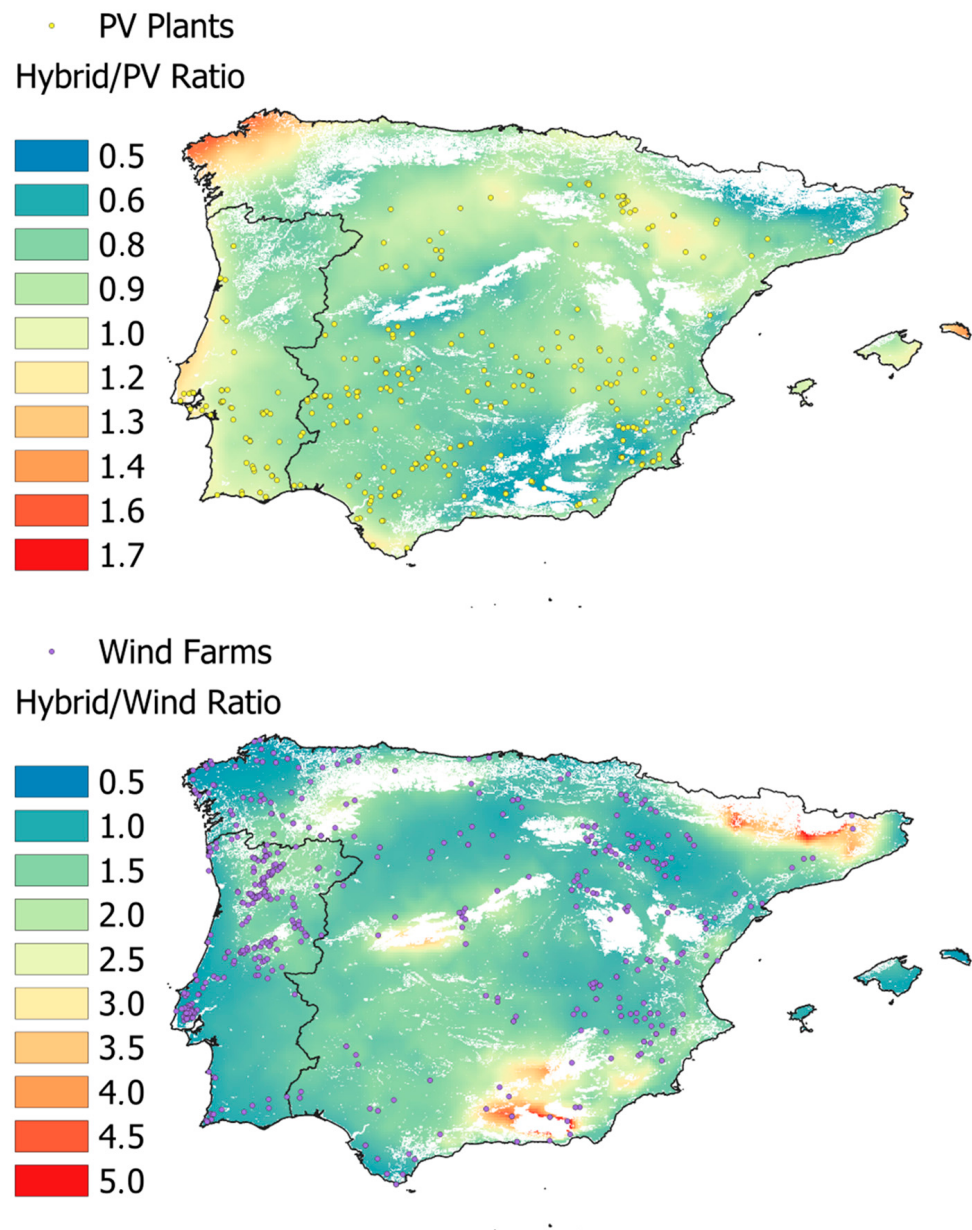


Figure 4. Hybrid-to-pure PV and -pure wind annual energy ratio. PV (**upper**), wind (**lower**).

The detailed analysis of the modeling results in some specific locations on the map can be illustrative of the contributions to the hybrid potential. To illustrate this statement, four points have been selected in the regions of most interest in the hybrid generation map, taking into account the areas with higher energy generation, relatively flat areas and good wind potential. The coordinates of the selected points are the southwest corner (37.5° N, -8° E), northwest continental (42° N, -5° E), northeast (41.5° N, -0.5° E) and central east (39° N, -1.5° E). On these points, a detailed analysis of the modeling results on a daily basis is performed by computing box and whisker plots for the monthly distribution of the wind and PV daily energy in the hybrid power plant of 40 MW. Figure 6 shows the resulting box plots. PV generation is quite similar in all the points compared to wind. The variability (represented here by the vertical size of the box) of PV is significantly smaller than the wind contribution. The hybrid capability is represented by the higher contribution

of wind power in the winter months, which complements the PV reduction. On the other hand, from April to September, the generation is dominated by PV power.

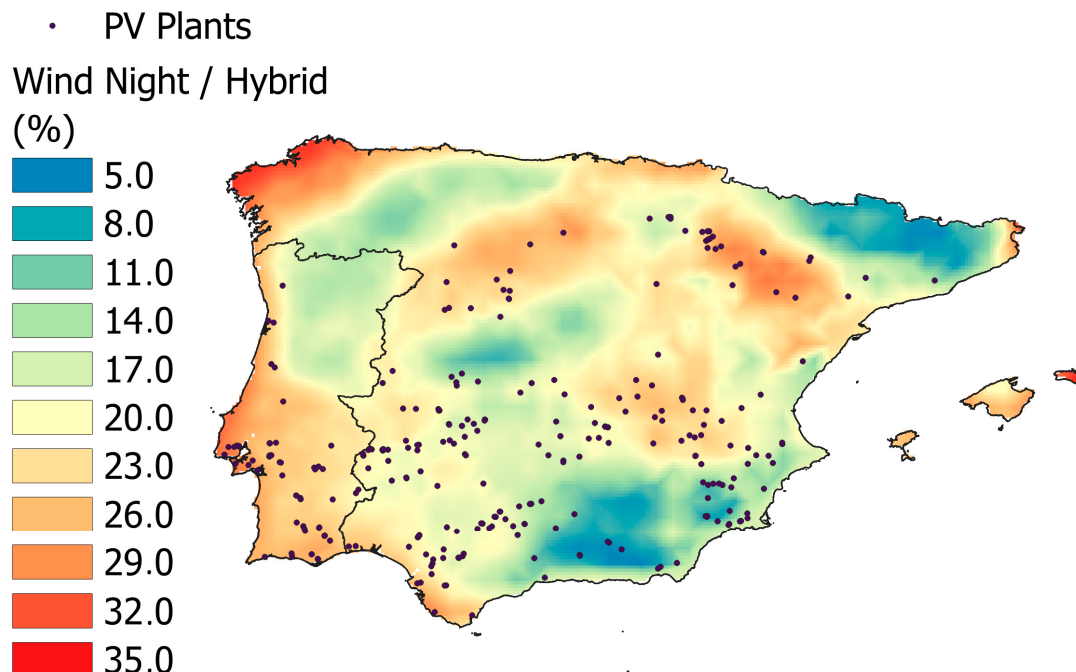


Figure 5. Contribution of nighttime wind power to the hybrid plant's total energy. Dots represent the locations of PV power plants.

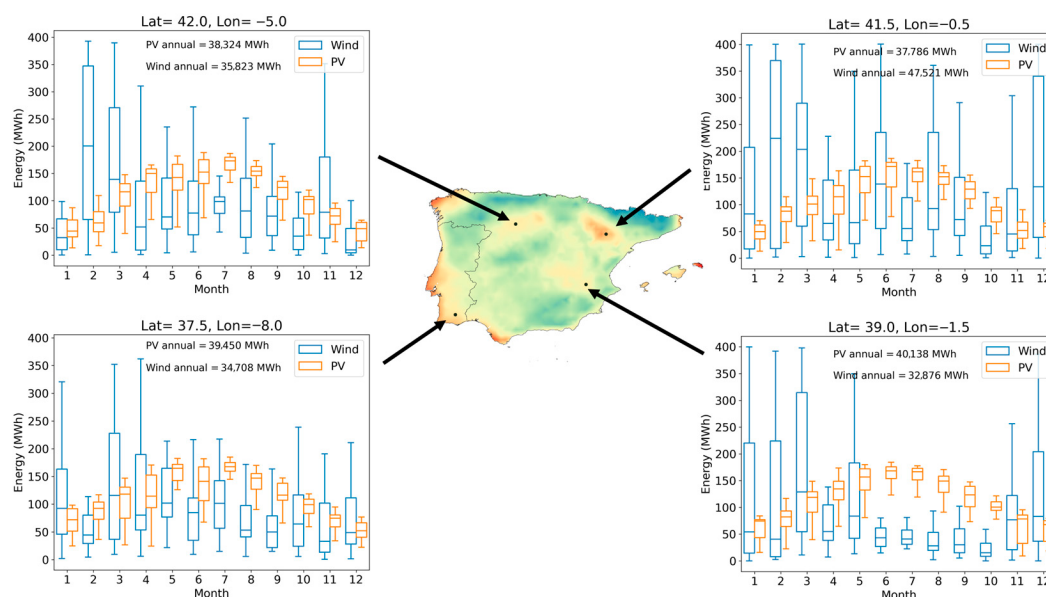


Figure 6. Boxplot of the monthly distribution of wind and PV generation of the hybrid plant for several points.

4. Discussion

The stability and complementarity of wind and solar energy are fundamental features to accomplish proper hybrid power generation. The complementarity of wind and solar power, in terms of correlation coefficient on an hourly basis, was described in the previous section. A large part of the domain exhibits a negative correlation that indicates complementarity (wind power increases when solar decreases and vice versa). It is expected that the correlation increases for longer time scales [20,45]. On the other hand, PV power

generation is more stable than wind power. The interquartile distance of the monthly wind power generation (represented by the size of the boxes in the Boxplot graphs of Figure 6) is much higher during winter than that for PV generation; this dispersion of monthly wind power, especially in winter months, somehow limits the wind–solar complementarity.

The capacity factor (CF) of the hybrid power plant can be defined as the sum of the capacity factor of each subsystem, weighted by the corresponding ratio of the nameplate capacity:

$$CF_{Hybrid} = \frac{N_{PV}}{N_{TOTAL}} CF_{PV} + \frac{N_{Wind}}{N_{TOTAL}} CF_{Wind} \quad (3)$$

where N_i refers to the system's nominal power for the PV and wind subsystems and the total hybrid power plant. Similar combinations of the individual capacity factors have been used in previous works on the optimization of solar–wind hybrid systems [8,46]. The base case in this work consists of 20 MW of PV and 20 MW of wind power; in this case, the hybrid capacity factor is just the average of the PV and wind individual CFs. Figure 7 shows the map of the capacity factor for the hybrid 20/20 MW plant. This map is very similar to the map of annual energy of the hybrid plant shown in Figure 2.

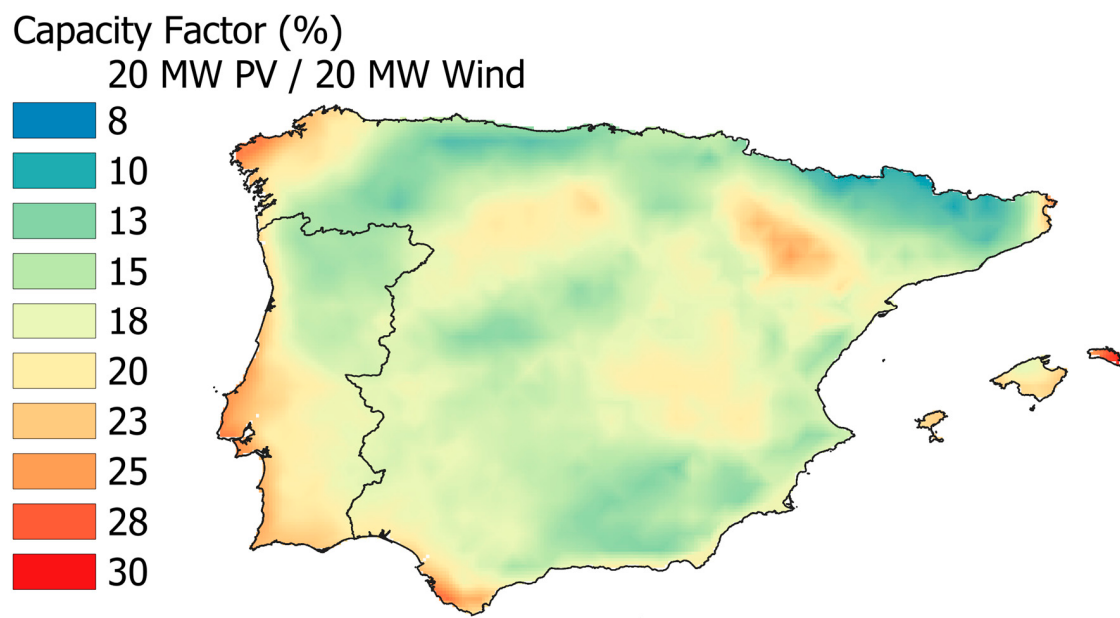


Figure 7. Map of CF for the hybrid power plant 20/20 MW.

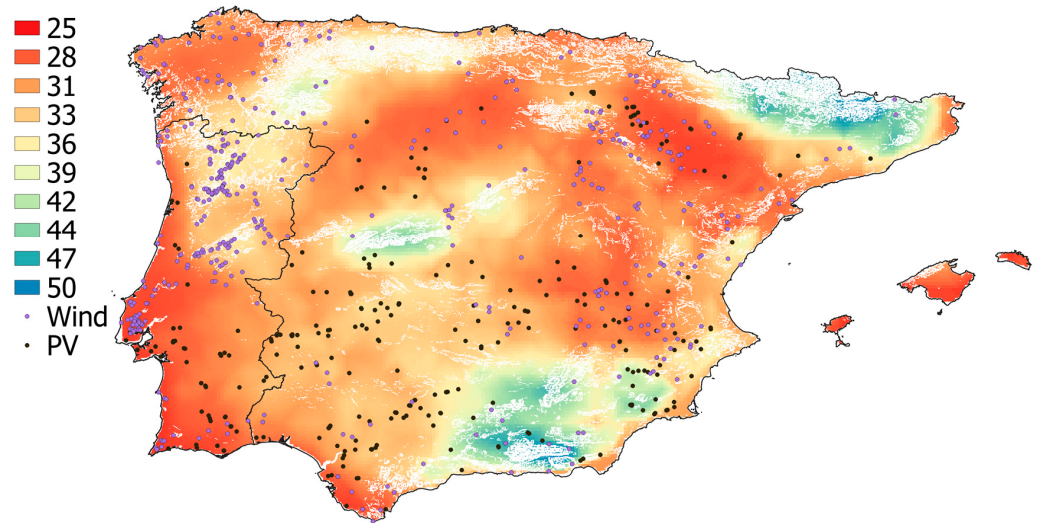
The economic analysis of the hybrid power plant performance would require additional details about the market and the operational strategy of the power plant (battery dispatch, curtailment, energy pool, and so on), and many of them have local characteristics that would require local information on the grid, which is not widely available. However, using the economic scheme implemented in SAM, a simple economic comparison can be performed to illustrate the comparison of hybrid versus individual power plants in economic terms for a few selected sites. As an example, an analysis is performed for several selected points, according to the hybrid potential shown in the different maps, to illustrate the economic differences. Table 2 presents the results of energy and LCOE for the individual plants (i.e., the sum of PV and wind non-hybrid cost of energy) compared to the hybrid plant assuming a power plant of 40 MW of capacity.

Table 2. LCOE comparison of PV, wind and hybrid plant for 40 MW of capacity for the northeast site.

Coordinates	LCOE Hybrid (cent/kWh)	LCOE Individual (cent/kWh)
37.5° N, −8.0° E	7.30	10.43
39.0° N, −1.5° E	7.43	10.76
41.5° N, −0.5° E	6.28	8.57
42.0° N, −5.0° E	7.30	10.34
43.5° N, −5.5° E	11.80	18.38

The results expressed in Table 2 show the economic benefits of hybrid power plants compared to individual power plants without hybridization for the same nameplate capacity. Even in less efficient emplacements (i.e., the north Cantabrian coast with coordinates 43.5° N, −5.5° E), the solar–wind hybridization outperforms the individual single wind and PV configuration for the case of a 40 MW power plant. Using the default economic scheme of SAM for the solar–wind hybrid case of 40 MW and comparing it with the results of the economic analysis of standalone PV and wind plants, the LCOE is expressed in relative terms independently of the economic model used. Thus, Figure 8 shows the percentage reduction in LCOE resulting from hybridization across the whole domain under study. Pixels with a slope in terrain exceeding 10% have been removed under the hypothesis that it is considered unrealistic for PV deployment. The map shows LCOE reduction of 25–35% in regions with wind power plants and terrain conditions that allow the deployment of a PV power plant. It should be remarked again that areas close to high mountain ranges show unrealistic results since PV deployment is not feasible.

LCOE Reduction (%)

**Figure 8.** Reduction in LCOE in percentage associated with the use of a hybrid solar–wind.

A sensitivity analysis on the sharing of nominal power can be conducted to explore the optimal sizing of a 40 MW hybrid power plant. Seven different shares of the PV/wind power have been used here to explore the optimal sizing: 4/36 MW, 10/30 MW, 16/24 MW, 20/20 MW, 24/16 MW, 30/10 MW and 36/4 MW. The criterion for selecting the optimal share was to maximize the CF_{Hybrid} using Equation (2). The combination of nominal power that results in maximum capacity factor for a 40 MW hybrid solar–wind power plant is shown in Figure 9. The resulting capacity factors and the spatial distribution of the sizing cases show the dominant impact of PV in most of the territory. Few regions, mainly on the east near the shore, showed the benefit of oversizing wind power. These results suggest the potential of installing PV on existing wind farm locations.

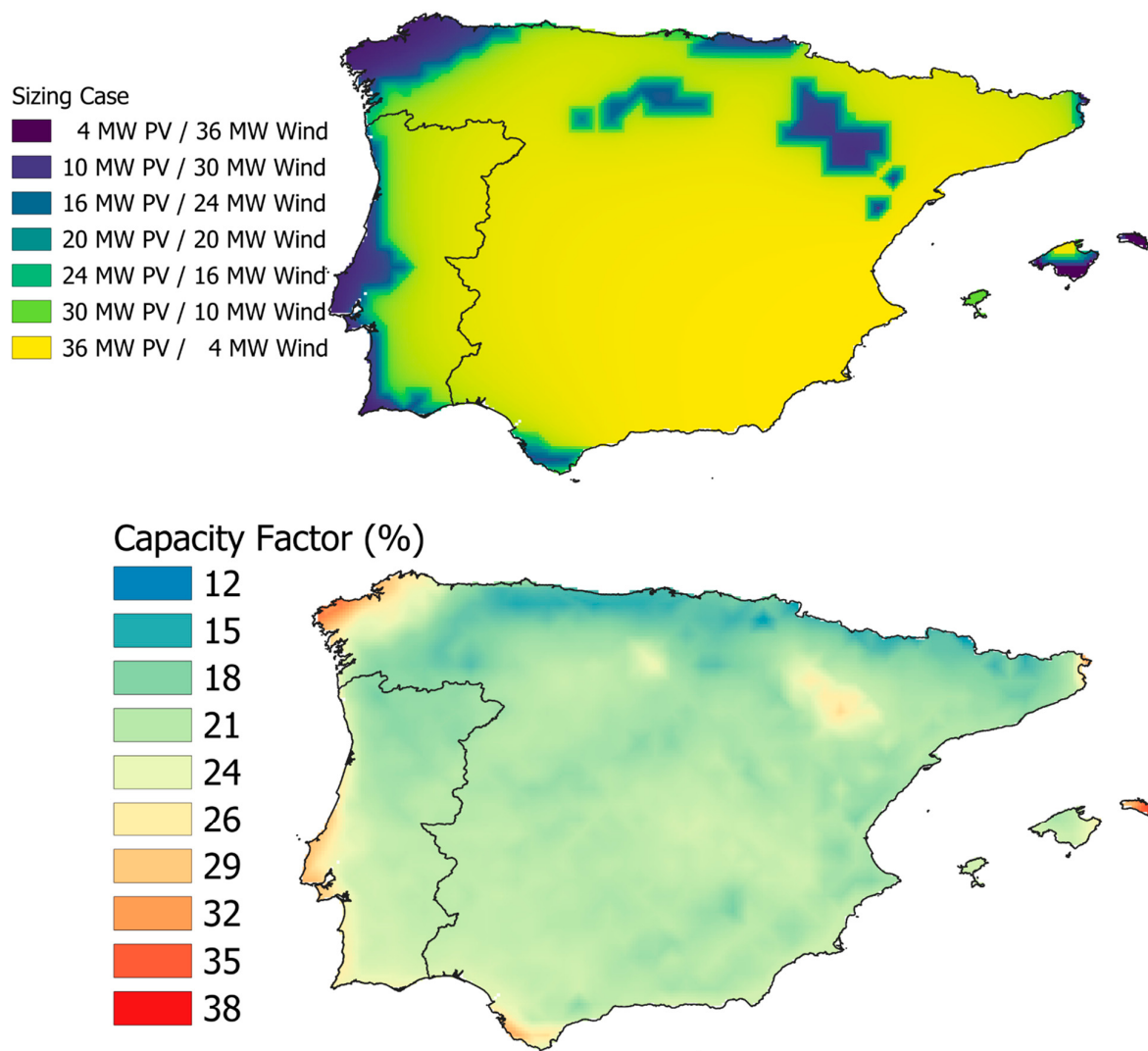


Figure 9. Capacity factor of a hybrid 40 MW solar–wind power plant with optimal combination of PV and wind subsystems.

5. Conclusions

Hybrid solar–wind power systems are being recognized as a promising solution for mitigating the effect of the intermittency of renewable resources. The complementarity of wind and solar resources may result in a higher dispatch capability of a renewable power plant. The sharing of the interconnection grid and other features is an additional advantage. Mapping of some features of solar–wind power plants through modeling of the energy generation and performance can help in better understanding the spatial distribution of the hybrid potential.

This work utilized a hybrid PV–wind power plant of 40 MW as a reference for modeling the generation of energy using SAM, employing the hybrid scheme of this tool and available TMY data from PVGIS and ERA5 for the Iberian Peninsula. Additional modeling of a standalone 40 MW PV power plant and a 40 MW wind power plant is also included to compare the hybrid capacity. The relative comparison of the hybrid plant energy to PV or wind power separately minimizes dependence on technical parameters and on the economic scheme used as input.

The correlation of wind and solar power at different time scales is negative in most parts of the domain under study, indicating a partial good complementarity of both re-

sources. The hybrid potential may be represented by the capacity factor of the plant normalized to the individual capacity factors of PV and wind. In this sense, the combined capacity factor of the PV and wind subsystems was used to analyze the sensitivity of oversizing one subsystem against the other. The results of this study show that oversizing the PV subsystem produced a higher capacity factor of the hybrid power plant in most regions of the Iberian Peninsula. In consequence, these results suggest utilizing existing wind power sites to hybridize with PV. Nevertheless, these results should be taken as a general first attempt to analyze the hybrid potential in the Iberian Peninsula, since the meteorological information used here has a coarse spatial resolution. Since wind velocity is highly variable locally, further details should be studied in those areas of high interest using the finest spatial and temporal resolution of the meteorological data. Finally, the reduction in the LCOE due to hybridization is estimated to be around 25–35% for most areas of interest. The results and methodology of this work encourage the planning of future work that involves detailed analysis and the impact of storage, grid curtailment and other parameters associated with the energy market, which will enhance the actual initial analysis of hybrid potential in the Iberian Peninsula.

Funding: We acknowledge partial funding through MEDIDA C17.I2G: CIEMAT. Nuevas tecnologías renovables híbridadas, Ministerio de Ciencia e Innovación, Componente 17 “Reforma Institucional y Fortalecimiento de las Capacidades del Sistema Nacional de Ciencia e Innovación”. Medidas del plan de inversiones y reformas para la recuperación económica funded by the European Union—NextGenerationEU.

Data Availability Statement: The data presented in this study are available on request from the author.

Acknowledgments: The author also wishes to acknowledge the effort and studies being carried out by the Renewable Energy Division of CIEMAT on the topic of hybridization of renewable energies.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery Energy Storage System
CF	Capacity Factor
GW	Gigawatt
ERA5	ECMWF Reanalysis
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
MW	Megawatt
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
SAM	System Advisor Model
TMY	Typical Meteorological Year

References

1. IEA Renewables 2024. Analysis and Forecast to 2030, Paris. 2024. Available online: <https://www.iea.org/reports/renewables-2024> (accessed on 20 February 2025).
2. Chinaris, P.P.; Psarros, G.N.; Papathanassiou, S.A. Hybridization of Wind Farms with Co-Located PV and Storage Installations. *Renew. Energy* **2024**, *240*, 122057. [CrossRef]
3. Pérez Uc, D.A.; de León Aldaco, S.E.; Aguayo Alquicira, J. Trends in Hybrid Renewable Energy System (HRES) Applications: A Review. *Energies* **2024**, *17*, 2578. [CrossRef]

4. Giedraityte, A.; Rimkevicius, S.; Marciukaitis, M.; Radziukynas, V.; Bakas, R. Hybrid Renewable Energy Systems—A Review of Optimization Approaches and Future Challenges. *Appl. Sci.* **2025**, *15*, 1744. [\[CrossRef\]](#)
5. Shahnazian, F.; Das, K.; Yan, R.; Sørensen, P. Aspects of Relevance of Hybrid Power Plants in Control and Stability of Weak Grids. *Energies* **2024**, *17*, 6353. [\[CrossRef\]](#)
6. Ferreira, M.M.; Santos, J.A.; da Silva, L.R.; Abrahao, R.; Gomes, F.d.S.V.; Braz, H.D.M. A New Index to Evaluate Renewable Energy Potential: A Case Study on Solar, Wind and Hybrid Generation in Northeast Brazil. *Renew. Energy* **2023**, *217*, 119182. [\[CrossRef\]](#)
7. Winsly, B.W.; Ramalingam, V.K.; Santhappan, J.S.; Maria, A.J.; Chokkalingam, M.P.; Rajendran, V. Optimal Sizing and Techno-Economic-Environmental Evaluation of Biomass-Solar-Wind-Grid Hybrid Energy System: A case study of an institute in South India. *Energy Convers. Manag.* **2025**, *325*, 119352. [\[CrossRef\]](#)
8. Lv, F.; Tang, H. Assessing the Impact of Climate Change on the Optimal Solar–Wind Hybrid Power Generation Potential in China: A Focus on Stability and Complementarity. *Renew. Sustain. Energy Rev.* **2025**, *212*, 115429. [\[CrossRef\]](#)
9. Zhou, Q.; Li, H. Knowledge Mapping of Hybrid Solar PV and Wind Energy Standalone Systems: A Bibliometric Analysis. *Energy Eng. J. Assoc. Energy Eng.* **2024**, *121*, 1781–1803. [\[CrossRef\]](#)
10. Hassan, Q.; Algburi, S.; Sameen, A.Z.; Salman, H.M.; Jaszczur, M. A Review of Hybrid Renewable Energy Systems: Solar and Wind-Powered Solutions: Challenges, Opportunities, and Policy Implications. *Results Eng.* **2023**, *20*, 101621. [\[CrossRef\]](#)
11. Hajou, A.; El Mghouchi, Y.; Chaoui, M. A New Solar-Wind Complementarity Index: An Application to the Climate of Morocco. *Renew. Energy* **2024**, *227*, 120490. [\[CrossRef\]](#)
12. Harrison-Atlas, D.; Murphy, C.; Schleifer, A.; Grue, N. Temporal Complementarity and Value of Wind-PV Hybrid Systems across the United States. *Renew. Energy* **2022**, *201*, 111–123. [\[CrossRef\]](#)
13. Hajou, A.; El Mghouchi, Y.; Chaoui, M. Novel Approaches for Wind Speed Evaluating and Solar-Wind Complementarity Assessing. *Renew. Energy Focus* **2024**, *48*, 100547. [\[CrossRef\]](#)
14. Arribas, L.; Cano, L.; Cruz, I.; Mata, M.; Llobet, E. PV-Wind Hybrid System Performance: A New Approach and a Case Study. *Renew. Energy* **2010**, *35*, 128–137. [\[CrossRef\]](#)
15. Denis, A.; Xydis, G. Exploring the Feasibility of Solar and Wind Energy Utilization in Poland: A Hybrid Energy Mapping Approach. *Tech. Ann.* **2023**, *1*. [\[CrossRef\]](#)
16. Asadi, M.; Pourhossein, K.; Noorollahi, Y.; Marzband, M.; Iglesias, G. A New Decision Framework for Hybrid Solar and Wind Power Plant Site Selection Using Linear Regression Modeling Based on GIS-AHP. *Sustainability* **2023**, *15*, 8359. [\[CrossRef\]](#)
17. Effat, H.A.; El-Zeiny, A.M. Geospatial Modeling for Selection of Optimum Sites for Hybrid Solar-Wind Energy in Assiut Governorate, Egypt. *Egypt. J. Remote Sens. Space Sci.* **2022**, *25*, 627–637. [\[CrossRef\]](#)
18. Martinez, A.; Iglesias, G. Hybrid Wind-Solar Energy Resources Mapping in the European Atlantic. *Sci. Total Environ.* **2024**, *928*, 172501. [\[CrossRef\]](#)
19. Costoya, X.; deCastro, M.; Carvalho, D.; Gómez-Gesteira, M. Assessing the Complementarity of Future Hybrid Wind and Solar Photovoltaic Energy Resources for North America. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113101. [\[CrossRef\]](#)
20. Monforti, F.; Huld, T.; Bódis, K.; Vitali, L.; D’Isidoro, M.; Lacal-Arántegui, R. Assessing Complementarity of Wind and Solar Resources for Energy Production in Italy. A Monte Carlo approach. *Renew. Energy* **2014**, *63*, 576–586. [\[CrossRef\]](#)
21. Couto, A.; Estanqueiro, A. Assessment of Wind and Solar PV Local Complementarity for the Hybridization of the Wind Power Plants Installed in Portugal. *J. Clean. Prod.* **2021**, *319*, 128728. [\[CrossRef\]](#)
22. Santos-Alamillos, F.J.; Jiménez-Garrote, A.; Pozo-Vázquez, D. Meteorological Assessment of Coupled Wind–Solar Power Generation Regimes in Spain. *Complement. Var. Renew. Energy Sources* **2022**, 215–243. [\[CrossRef\]](#)
23. Graça Gomes, J.; Jiang, J.; Chong, C.T.; Telhada, J.; Zhang, X.; Sammarchi, S.; Wang, S.; Lin, Y.; Li, J. Hybrid Solar PV-Wind-Battery System Bidding Optimisation: A Case Study for the Iberian and Italian Liberalised Electricity Markets. *Energy* **2023**, *263*, 126043. [\[CrossRef\]](#)
24. Robaina, M.; Oliveira, A.; Lima, F.; Ramalho, E.; Miguel, T.; López-Maciél, M.; Roebeling, P.; Madaleno, M.; Ferreira Dias, M.; Meireles, M.; et al. Analysis of NECP-based Scenarios for the Implementation of Wind and Solar Energy Facilities in Portugal. *Energy* **2025**, *324*, 135734. [\[CrossRef\]](#)
25. Arribas, L.; Domínguez, J.; Borsato, M.; Martín, A.M.; Navarro, J.; Bustamante, E.G.; Zarzalejo, L.F.; Cruz, I. The Potential of Utility-Scale Hybrid Wind–Solar PV Power Plant Deployment: From the Data to the Results. *Wind* **2025**, *5*, 16. [\[CrossRef\]](#)
26. Blair, N.; Dobos, A.P.; Freeman, J.; Neises, T.; Wagner, M.; Ferguson, T.; Gilman, P.; Janzou, S. *System Advisor Model, SAM, 2014.1.14: General Description*; Technical Report NREL/TP-6A20-61019; NREL: Golden, CO, USA, 2014.
27. Bahramara, S.; Moghaddam, M.P.; Haghifam, M.R. Optimal Planning of Hybrid Renewable Energy Systems Using HOMER: A Review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 609–620. [\[CrossRef\]](#)
28. Huld, T.; Paietta, E.; Zangheri, P.; Pinedo Pascua, I. Assembling Typical Meteorological Year Data Sets for Building Energy Performance Using Reanalysis and Satellite-Based Data. *Atmosphere* **2018**, *9*, 53. [\[CrossRef\]](#)

29. Müller, R.; Pfeifroth, U.; Träger-Chatterjee, C.; Cremer, R.; Trentmann, J.; Hollman, R. *Surface Solar Radiation Data Set -Heliosat (SARAH)-Edition 1*; Satellite Application Facility on Climate Monitoring: Frankfurt, Germany, 2015. [\[CrossRef\]](#)
30. Amillo, A.; Huld, T.; Müller, R. A New Database of Global and Direct Solar Radiation Using the Eastern Meteosat Satellite, Models and Validation. *Remote Sens.* **2014**, *6*, 8165–8189. [\[CrossRef\]](#)
31. Huld, T.; Müller, R.; Gambardella, A. A New Solar Radiation Database for Estimating PV Performance in Europe and Africa. *Sol. Energy* **2012**, *86*, 1803–1815. [\[CrossRef\]](#)
32. Urraca, R.; Gracia-Amillo, A.M.; Koubli, E.; Huld, T.; Trentmann, J.; Riihelä, A.; Lindfors, A.V.; Palmer, D.; Gottschalg, R.; Antonanzas-Torres, F. Extensive Validation of CM SAF Surface Radiation Products over Europe. *Remote Sens. Environ.* **2017**, *199*, 171–186. [\[CrossRef\]](#)
33. Urraca, R.; Gracia-Amillo, A.M.; Huld, T.; Martinez-de-Pison, F.J.; Trentmann, J.; Lindfors, A.V.; Riihelä, A.; Sanz-Garcia, A. Quality Control of Global Solar Radiation Data with Satellite-Based Products. *Sol. Energy* **2017**, *158*, 49–62. [\[CrossRef\]](#)
34. Jensen, A.R.; Anderson, K.S.; Holmgren, W.F.; Mikofski, M.A.; Hansen, C.W.; Boeman, L.J.; Loonen, R. Pvlb Iotools—Open-Source Python Functions for Seamless Access to Solar Irradiance Data. *Sol. Energy* **2023**, *266*, 112092. [\[CrossRef\]](#)
35. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 Global Reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [\[CrossRef\]](#)
36. Gualtieri, G. Analysing the Uncertainties of Reanalysis Data Used for Wind Resource Assessment: A Critical Review. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112741. [\[CrossRef\]](#)
37. Olauson, J. ERA5: The New Champion of Wind Power Modelling? *Renew. Energy* **2018**, *126*, 322–331. [\[CrossRef\]](#)
38. Masoud, A.A. Hybrid Wind-Solar Energy Potential Modeling Using ERA5 and Solar Irradiation Data in Google Earth Engine. *Renew. Energy* **2024**, *232*, 121042. [\[CrossRef\]](#)
39. Byers, L.; Friedrich, J.; Hening, R.; Kressig, L.X.; McCormick, C.; Malaguzzi Valeri, L. *A Global Database of Power Plants*; World Resources Institute: Washington, DC, USA, 2021. Available online: <https://www.wri.org/research/global-database-power-plants> (accessed on 22 July 2025).
40. Freeman, J.; Jorgenson, J.; Gilman, P.; Ferguson, T. *Reference Manual for the System Advisor Model's Wind Power Performance Model*; National Renewable Energy Laboratory: Golden, CO, USA, 2014.
41. Dobos, A.P. *PVWatts Version 5 Manual-Technical Report NREL/TP-6A20-62641*; National Renewable Energy Laboratory: Golden, CO, USA, 2014.
42. PySAM Version 5.1.0. Available online: <https://github.com/nrel/pysam> (accessed on 22 January 2025).
43. Nebey, A.H.; Taye, B.Z.; Workineh, T.G. Site Suitability Analysis of Solar PV Power Generation in South Gondar, Amhara Region. *J. Energy* **2020**, *2020*, 3519257. [\[CrossRef\]](#)
44. de Luis-Ruiz, J.M.; Salas-Menocal, B.R.; Pereda-García, R.; Pérez-Álvarez, R.; Sedano-Cibrián, J.; Ruiz-Fernández, C. Optimal Location of Solar Photovoltaic Plants Using Geographic Information Systems and Multi-Criteria Analysis. *Sustainability* **2024**, *16*, 2895. [\[CrossRef\]](#)
45. Ren, G.; Wan, J.; Liu, J.; Yu, D. Spatial and Temporal Assessments of Complementarity for Renewable Energy Resources in China. *Energy* **2019**, *177*, 262–275. [\[CrossRef\]](#)
46. Liu, L.; Wang, Z.; Wang, Y.; Wang, J.; Chang, R.; He, G.; Tang, W.; Gao, Z.; Li, J.; Liu, C.; et al. Optimizing Wind/Solar Combinations at Finer Scales to Mitigate Renewable Energy Variability in China. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110151. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.