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Modeling Wind–Solar Complementarity under Heatwave Conditions: A Copula-Based Study for Southern Spain

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Abstract. The increasing penetration of variable renewable energy sources has raised critical challenges for power system planning, particularly under extreme climatic conditions. In Southern Europe, heatwaves have become more frequent and intense, with the potential to alter the joint behavior of wind and solar power generation. This study investigates how heatwave conditions affect the dependence structure between wind and solar generation in the Andalusia region of Spain using a copula-based modeling framework. Monthly aggregated wind and photovoltaic solar generation data from January 2015 to November 2025 are combined with climatic information from the ERA5 reanalysis dataset. Heatwave months are identified using a climatological threshold based on the 90th percentile of monthly mean temperature. Marginal distributions are selected through goodness-of-fit tests, and the joint dependence structure is modeled using bivariate copulas estimated by maximum likelihood and selected via the Bayesian Information Criterion. The results indicate weak negative dependence between wind and solar generation in the baseline scenario, suggesting moderate complementarity on average. However, this structure changes substantially when conditioning on heatwave occurrence: months without heatwaves exhibit near independence between sources, whereas heatwave months display a stronger negative dependence, captured by a rotated Clayton copula. Scenario simulations further show that heatwaves reshape the joint distribution of renewable generation, reinforcing complementarity under extreme thermal conditions. These findings highlight the importance of incorporating climate extremes into multivariate renewable energy modeling and provide relevant insights for energy planning and risk assessment in regions increasingly exposed to heatwaves.

Key words. Wind–solar complementarity; Heatwaves; Copula models; Renewable energy systems

1. Introduction

The ongoing energy transition, driven by global decarbonization targets and energy security goals, has promoted a rapid expansion of intermittent renewable energy sources, particularly wind power and solar photovoltaic energy (IEA, 2023; Olauson, 2018). Although these sources play a central role in mitigating greenhouse gas emissions, their intrinsic variability poses significant challenges to power system planning, operation, and reliability (Brown, 2018). In this context, understanding not only the individual behavior of these sources but also the structure of their joint dependence becomes essential to assess the degree of energy complementarity or synergy and its impacts on supply stability (Grothe & Schnieders, 2011).

In addition to the natural variability associated with renewable resources, recent climate change has intensified the frequency and severity of extreme events, such as heatwaves, particularly in southern Europe (Perkins-Kirkpatrick & Lewis, 2020). Spain, and especially the Andalusia region, stands out as one of the territories most vulnerable to these phenomena, exhibiting a persistent upward trend in average temperatures and more pronounced thermal extremes (Lemus-Canovas et al., 2021). Heatwaves directly affect atmospheric regimes, potentially altering both solar radiation patterns and wind circulation simultaneously, which suggests that the dependence between solar and wind generation may change substantially under extreme climatic conditions (Bloomfield et al., 2020). However, such changes in the dependence structure remain underexplored in the literature, particularly from a multivariate probabilistic perspective.

A large share of existing studies assesses the complementarity between renewable sources using linear correlation measures or aggregated indicators, which assume constant and symmetric dependence over time (Jerez et al., 2013). While informative, these approaches are limited in capturing nonlinear relationships, asymmetries, and regime shifts induced by extreme climatic events. In this regard, copula theory provides a robust and flexible statistical framework that allows modeling the marginal distributions of variables separately from their joint dependence structure, including across different climatic regimes (Nelsen, 2006; Joe, 2014). The use of copulas enables the identification of variations in the sign and strength of dependence, as well as the investigation of tail dependence, a crucial aspect for the assessment of extreme risks in power systems (Grothe & Schnieders, 2011).

The main objective of this study is to investigate how heatwaves modify the dependence structure between wind and solar power generation in the Andalusia region using bivariate copula models. Specifically, the study aims to: (i) characterize the average dependence between the sources under a reference (baseline) scenario; (ii) compare this structure during months classified as with and without heatwave occurrence; and (iii) identify potential changes in the sign, strength, and asymmetry of dependence associated with extreme thermal conditions. By segmenting the analysis according to climatic regimes, this study advances beyond the assumption of stationary dependence, contributing to a more realistic understanding of the joint behavior of renewable energy sources (Bloomfield et al., 2020).

The analysis is conducted using monthly wind and solar power generation data for the period from 2015 to 2025, combined with climatic information derived from the ERA5 reanalysis dataset (Hersbach et al., 2020). Heatwave classification is based on a robust climatological criterion, defined using the 90th percentile of monthly mean temperature calculated over the reference period from 1981 to 2014, allowing for the consistent identification of months with anomalously high temperatures (Perkins-Kirkpatrick & Lewis, 2020). The choice of Andalusia is justified both by its substantial contribution to Spain's renewable energy mix and by its recurrent exposure to thermal extremes, making the region a natural laboratory for investigating the effects of heatwaves on wind–solar complementarity (Lemus-Canovas et al., 2021).

By adopting a copula-based approach grounded in observed data, this study provides quantitatively relevant evidence for energy planning under climate warming scenarios. The expected results contribute to the debate on the resilience of power systems heavily reliant on renewable energy sources, highlighting the importance of incorporating extreme climate variability into the joint modeling of energy resources (Brown et al., 2018). In this way, the study offers methodological and empirical insights for policymakers, system operators, and researchers interested in the secure and efficient integration of renewable energy sources in increasingly challenging climatic contexts.

2. Literature Review

The complementarity between variable renewable energy sources has been widely discussed in the literature as a fundamental mechanism for mitigating the inherent intermittency of wind and solar power generation. Seminal studies have demonstrated that the spatial and technological combination of these sources can reduce the aggregated variability of electricity production and enhance power system reliability, particularly in systems with high shares of renewables (Jerez et al., 2013; Brown et al., 2018). In the European context, the joint integration of wind and solar energy has been identified as a key element for achieving carbon neutrality targets while preserving energy supply security (Bloomfield et al., 2020).

A large portion of early research on renewable complementarity relied on simple metrics, such as Pearson or Spearman correlation coefficients, complementarity factors, and seasonal indicators (Jerez et al., 2013; François et al., 2016). Although these indicators provide useful insights, they implicitly assume linear, symmetric, and stationary relationships between energy sources, which may obscure more complex behaviors, particularly under extreme climatic conditions. More recent studies have emphasized that dependence between renewable resources can vary substantially over time and across different meteorological regimes, thereby limiting the validity of analyses based solely on average correlation measures (Bloomfield et al., 2020).

Regarding climatic impacts, robust evidence indicates that the frequency, duration, and intensity of heatwaves have increased consistently in recent decades, especially in southern Europe and the Iberian Peninsula (Perkins-Kirkpatrick & Lewis, 2020; Lemus-Cánovas et al., 2021). These extreme events are associated with persistent atmospheric patterns characterized by high-pressure systems, subsidence, and atmospheric stability conditions that tend to favor high solar irradiance while often suppressing near-surface wind speeds. Consequently, heatwaves have the potential to simultaneously affect solar and wind power generation, suggesting structural changes in the joint dependence between these sources (Bloomfield et al., 2020).

Despite the relevance of thermal extremes, most of the literature on renewable energy resources continues to focus on average or seasonal analyses, largely neglecting explicit segmentation by extreme climatic events. Some recent studies have begun to investigate periods of joint low renewable generation—such as so-called dunkelflaute events demonstrating that persistent episodes can simultaneously compromise multiple renewable sources (Olauson et al., 2018; van der Wiel et al., 2019). However, these analyses often adopt deterministic approaches or rely on univariate statistics, thereby limiting the understanding of the joint probabilistic structure under extreme regimes.

In this context, copula-based methods have gained prominence as suitable tools for modeling complex dependencies between energy and climatic variables. The main advantage of copulas lies in their ability to model marginal distributions separately from the dependence structure, allowing the capture of nonlinear relationships, asymmetries, and tail dependence (Nelsen, 2006; Joe, 2014). In energy-related applications, copulas have been employed to analyze spatial dependence of wind resources, joint production risk, and optimal capacity allocation, consistently demonstrating superior performance compared to approaches based solely on linear correlation (Grothe & Schnieders, 2011; Morales et al., 2010).

Studies specifically addressing wind solar complementarity using copula models remain relatively scarce but indicate promising results. Recent works suggest that dependence between these sources may exhibit significant asymmetries, with regimes in which complementarity strengthens or weakens depending on prevailing meteorological conditions (François et al.,

2016; Zhang et al., 2019). Nevertheless, few studies explicitly examine how extreme events such as heatwaves influence this dependence structure, representing a relevant gap in the current literature.
Furthermore, the choice of the study region plays a central role in the interpretation of results. Andalusia stands out as one of the regions with the highest solar potential in Europe and a substantial share of wind power generation, in addition to its high exposure to thermal extremes (Jerez et al., 2013; Lemus-Cánovas et al., 2021). Despite these characteristics, there remains a lack of studies that jointly assess wind–solar dependence in this region from a multivariate probabilistic perspective, particularly at monthly time scales that are relevant for medium-term energy planning.
Against this backdrop, a clear gap emerges in the literature regarding the probabilistic modeling of wind–solar dependence conditioned on heatwave occurrence, especially using observed data and flexible methodologies such as copulas. The present study seeks to contribute to this debate by combining renewable generation data and climate reanalysis information with bivariate copula models, enabling an explicit comparison between regimes with and without heatwaves. In doing so, the paper advances the state of the art by integrating extreme climate variability into the analysis of renewable complementarity, providing relevant evidence for energy planning and risk assessment in power systems increasingly dependent on intermittent renewable sources.

3. Methodology

This study adopts a quantitative approach based on the integration of observed renewable generation data and climatic information derived from atmospheric reanalysis, with the aim of investigating the joint dependence structure between wind and solar power generation under different thermal regimes. The analysis focuses on the Andalusia region in southern Spain, selected due to its high relevance in the context of the European energy transition, its substantial share of wind and solar sources in the regional electricity mix, and its recurrent exposure to extreme heat events. The proposed methodology combines climate data processing techniques, descriptive statistical analysis, and multivariate modeling through bivariate copulas.
The wind and solar generation data used in this study consist of aggregated monthly time series for the Andalusia region, covering the period from January 2015 to November 2025. This temporal resolution was chosen because it is particularly suitable for medium-term energy planning analyses and allows for direct compatibility with monthly climatic data.
The wind and solar generation data were obtained from publicly available energy statistics provided by official national and European energy platforms, ensuring consistency and reliability of the information. The dataset covers the period from January 2015 to November 2025 without temporal gaps, allowing for a continuous analysis of the joint behavior of renewable generation over time.
The aggregation of data at the monthly level was performed by summing total energy generation within each calendar month, ensuring consistency between wind and solar series. Climatic variables were aggregated by computing spatial averages over the study region, preserving coherence between meteorological and energy data.
Pre-processing procedures included the verification of missing values, consistency checks, and alignment between datasets. No significant data gaps were identified, and the resulting dataset is temporally complete and suitable for multivariate statistical analysis.
While the use of monthly aggregated data is appropriate for medium-term planning analyses and ensures consistency with climatological datasets, it is important to acknowledge its limitations when analyzing extreme events such as heatwaves. Heatwaves are inherently short-term meteorological phenomena, often lasting from a few days to a couple of weeks, and are characterized by high-frequency dynamics that may not be fully captured at the monthly scale.
As a consequence, the aggregation process may smooth intra-month variability and partially dilute the intensity and temporal alignment between wind and solar generation responses to extreme thermal conditions. This implies that the dependence structures identified in this study should be interpreted as representing average regime effects rather than short-term operational dynamics.
Nevertheless, the monthly framework remains highly relevant for planning-oriented applications, as it captures persistent climatic anomalies and their cumulative impact on renewable generation. Importantly, the dependence structures identified in this study reflect consistent regime-dependent patterns that are expected to persist across temporal scales, even if their short-term dynamics may exhibit additional variability. In this sense, the results provide robust insights into the structural relationship between wind and solar generation under different thermal conditions. Future research may extend this framework by employing higher-frequency data (e.g., daily or hourly), enabling a more detailed characterization of short-term interactions without altering the fundamental dependence patterns identified at the monthly level.
Climatic information was obtained from the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Atmospheric reanalyses are datasets that combine observations from multiple sources—such as meteorological stations, satellites, and buoys—with numerical atmospheric models through data assimilation techniques. This process yields spatially and temporally consistent climatic fields that are widely used in climate and energy studies. In this work, the air temperature at 2 meters was employed, provided as monthly averages, as it represents a robust indicator of near-surface thermal conditions associated with the occurrence of heatwaves.
The extraction of climatic data was performed for a geographic area corresponding to the territorial extent of Andalusia, defined using geographic coordinates that delimit the region in terms of latitude and longitude. The use of a spatial bounding box allows for an adequate representation of regional thermal variability while preserving spatial coherence between climatic data and the analyzed energy generation area. After data retrieval, monthly temperature fields were spatially aggregated by computing the mean over all grid points within the defined area, resulting in a single time series of regional mean monthly temperature.

To identify heatwave events, a percentile-based climatological criterion widely adopted in the literature on thermal extremes was applied. First, a climatological reference period spanning from 1981 to 2014 was defined, from which the 90th percentiles of monthly mean temperature were computed for each calendar month. This approach accounts for the natural seasonality of the climate, avoiding the use of a fixed threshold throughout the year. Subsequently, observed monthly mean temperatures during the study period (2015–2025) were compared against the corresponding monthly thresholds, classifying each month as a heatwave month when the temperature exceeded the respective 90th percentile, or as a non-heatwave month otherwise.

Following the climatic classification, an integrated dataset was constructed containing, for each month of the analysis period, wind generation, solar generation, mean monthly temperature, the climatological threshold (90th percentile), and a binary indicator variable (dummy) representing the occurrence or absence of a heatwave. The merging of generation and climate datasets was performed based on year and month variables, ensuring proper temporal alignment between the series. This procedure resulted in a final, internally consistent dataset suitable for multivariate statistical analysis and comparison across distinct climatic regimes.

The statistical modeling of dependence between wind and solar generation was conducted using bivariate copulas, allowing for the separation between marginal distribution fitting and the estimation of the joint dependence structure. Initially, the marginal distributions of the generation series were fitted using Lognormal and Weibull distributions, which are commonly employed in the renewable energy literature, with selection based on the Bayesian Information Criterion (BIC). The marginally transformed series into the uniform (0,1) space were then used for copula estimation, enabling the analysis of the sign, strength, and asymmetry of dependence through Kendall's τ coefficient and, when applicable, tail dependence measures.

Finally, the analysis was performed separately for three data subsets: (i) a reference (baseline) scenario including all months of the study period; (ii) months classified as non-heatwave periods; and (iii) months classified as heatwave periods. This segmentation allows for an explicit assessment of how extreme thermal events affect the dependence structure between renewable energy sources, providing a more realistic and regime-conditioned view of the joint behavior of wind and solar generation. By integrating observed data, climate reanalysis information, and flexible probabilistic models, the proposed methodology offers a robust framework for analyzing the impacts of climate extremes on renewable energy systems.

4. Theoretical Framework: Copula Theory

Statistical modeling of dependence among random variables is a central element in applications involving renewable energy systems, as variables such as wind and solar power generation often exhibit nonlinear, asymmetric relationships that depend on specific climatic conditions. Traditional approaches based on correlation coefficients such as Pearson, Spearman, or Kendall provide only aggregated measures of association and implicitly assume constant dependence structures over the entire domain of the variables. These limitations become particularly relevant when the focus is on extreme behaviors or regime changes, such as those induced by severe climatic events (Joe, 2014; Nelsen, 2006).

Copula theory offers a flexible mathematical framework for modeling multivariate dependence, allowing an explicit separation between the modeling of marginal distributions and the joint dependence structure. Formally, a copula is a multivariate distribution function defined on the unit hypercube $[\mathbf{0},\mathbf{1}]^d$ with uniform marginals. The theoretical foundation of copulas is established by Sklar's Theorem, which states that for any joint distribution function $\boldsymbol{F_{XY}(x,y)}$ with continuous marginals $\boldsymbol{F_X(x)}$ and $\boldsymbol{F_Y(y)}$, there exists a copula $\boldsymbol{C(.,.)}$ such that:

$$\boldsymbol{F_{X,Y}(x,y) = C\big(F_X(x), F_Y(y)\big)}, \qquad (1)$$

and, conversely, any copula combined with valid univariate marginals defines a multivariate joint distribution (Sklar, 1959; Nelsen, 2006). This decomposition allows the dependence between variables to be modeled independently of the shapes of their marginal distributions, which is particularly advantageous in energy applications, where different sources often exhibit distinct statistical distributions.

In the bivariate case, which is the focus of this study, the joint density function can be expressed in terms of the copula density $\boldsymbol{c(.,.)}$ and the marginal densities $\boldsymbol{f_X(x)}$ and $\boldsymbol{f_Y(y)}$ as:

$$\boldsymbol{f_{X,Y}(x,y) = c\big(F_X(x), F_Y(y)\big)\, f_X(x) f_Y(y)}, \qquad (2)$$

where

$$\boldsymbol{c(u,v) = {\delta^2 C(u,v)}/{\delta u \delta v}}. \qquad (3)$$

This formulation highlights that all information related to the dependence between X and Y is contained in the copula, while the marginal distributions describe only the individual behavior of each variable. In renewable energy studies, this separation is crucial, since wind and solar generation often follow asymmetric distributions—such as Weibull or Lognormal—whereas their joint dependence may assume complex forms (Grothe & Schnieders, 2011).

Several parametric families of copulas have been proposed in the literature, each associated with specific dependence properties. Among the most commonly used are the Gaussian copula, which captures symmetric dependence without tail dependence; the Student's t copula, which allows symmetric dependence with heavy tails; and the so-called Archimedean copulas, such as Clayton, Gumbel, and Frank, which enable the modeling of asymmetries and dependence concentrated in specific regions of the distribution (Joe, 2014). For instance, the Clayton copula exhibits lower-tail dependence, whereas the Gumbel copula concentrates dependence in the upper tail. Rotated versions of these copulas allow the representation of negative dependence or additional asymmetric regimes.

In the context of energy studies, the application of copula-based methods has grown steadily. Recent works demonstrate that copula models are able to adequately represent the spatial and temporal dependence of wind resources, as well as the joint dependence between different renewable sources, outperforming approaches based solely on linear correlation (Grothe & Schnieders, 2011; François et al., 2016). However, studies that employ copulas to investigate changes in dependence structures conditioned on extreme climatic events—such as heatwaves—remain scarce, motivating the adoption of this approach in the present work.

Thus, copula theory provides the necessary mathematical foundation to rigorously and flexibly analyze how the dependence between wind and solar generation behaves under different thermal regimes. By enabling the comparison of dependence structures estimated for months with and without heatwaves, this approach contributes to a deeper understanding of the impacts of climate warming on renewable complementarity and on the risks associated with the operation of power systems that are increasingly reliant on intermittent energy sources.

5. Results

This section presents the empirical results obtained from the application of the proposed methodology to analyze the joint dependence between wind and solar power generation in the Andalusia region. The analysis is based on aggregated monthly data of wind and photovoltaic solar generation, expressed in megawatt-hours (MWh), covering the period from January 2015 to November 2025. Initially, descriptive results of the generation series are presented, along with nonparametric correlation measures, in order to provide a preliminary assessment of the joint behavior of renewable sources. Subsequently, the results of the bivariate copula modeling are discussed, considering both the reference (baseline) scenario and the segmentation by climatic regimes, distinguishing months with and without heatwave occurrences. This framework allows for a systematic evaluation of how extreme thermal events influence the sign, strength, and structure of dependence between wind and solar generation.

Figure 1 depicts the monthly evolution of wind and solar energy generation in the Andalucía region from January 2015 to November 2025. The wind generation series is characterized by pronounced variability throughout the entire period, with substantial month-to-month fluctuations and no clear long-term upward or downward trend. This behavior reflects the intrinsically intermittent nature of wind resources, which are strongly influenced by short-term atmospheric dynamics such as synoptic circulation patterns and regional wind regimes. In terms of magnitude, monthly wind generation remains predominantly within the order of several hundred thousand megawatt-hours (MWh).

In contrast, solar generation exhibits a markedly different temporal pattern, combining a well-defined seasonal cycle with a strong and persistent upward trend over time, particularly from 2019 onward. This sustained increase reflects the rapid expansion of installed photovoltaic capacity in the region, as well as improvements in technology and deployment intensity. Monthly solar generation reaches peak values exceeding one million megawatt-hours (MWh) in the most recent years of the sample. The comparison between the two series highlights the distinct structural characteristics of each renewable source: wind generation displays relatively stable magnitude but high short-term variability, whereas solar generation shows pronounced growth and regular seasonal behavior. These contrasting dynamics provide initial empirical evidence of the relevance of joint analyses to assess the dependence structure and potential complementarity between wind and solar generation in Andalucía.

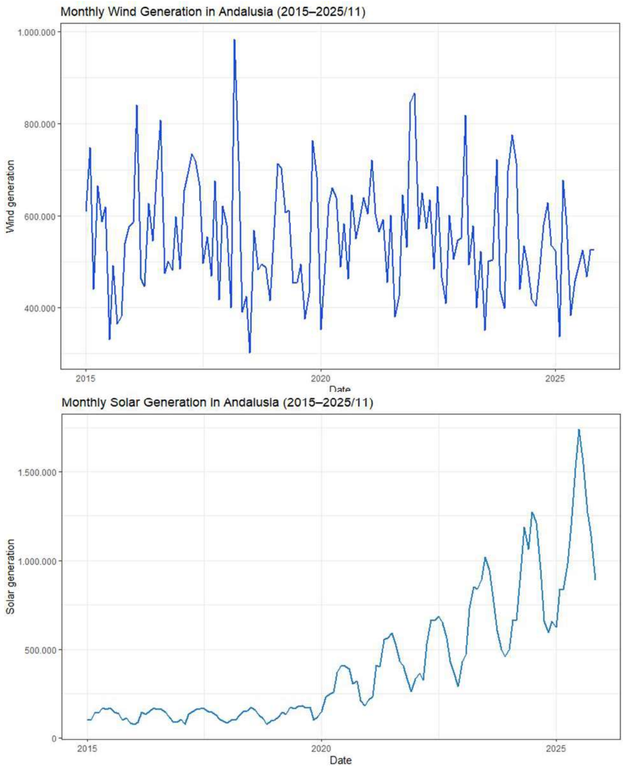


Fig. 1. Wind and solar power generation

As shown in Figure 2, the kernel density estimates of the empirical distributions of monthly wind and solar generation in Andalusia reveal distinct probabilistic characteristics for each energy source over the analyzed period. The density associated with wind generation exhibits moderate asymmetry, with a concentration of probability mass around intermediate values and a relatively elongated upper tail, a pattern consistent with distributions commonly used to model wind-related processes. In contrast, the density of solar generation displays a more pronounced positive skewness, characterized by a high concentration of observations at lower generation levels and a long right tail, reflecting the combined effects of seasonality, structural growth in installed capacity, and increased interannual variability in solar output.

To formally identify the most appropriate marginal distributions for each variable, goodness-of-fit tests were conducted for a broad set of parametric distributions frequently applied in energy studies, including the Normal, Lognormal, Weibull, Gamma, and Exponential distributions. The assessment relied on statistical goodness-of-fit procedures, notably the Kolmogorov–

Smirnov test, complemented by information-based criteria such as the Bayesian Information Criterion (BIC), ensuring a balance between statistical adequacy and model parsimony.

The results indicate that wind generation is best described by a Weibull distribution, in line with well-established findings in the literature on wind resource and power generation modeling. Conversely, solar generation was found to be more accurately represented by a Lognormal distribution, capturing its strong positive skewness and the occurrence of extreme values associated with periods of high solar irradiance and rapid capacity expansion. The identification of these marginal distributions is a crucial step for the subsequent copula-based analysis, as it ensures an appropriate transformation of the variables into the uniform domain and supports a robust estimation of the joint dependence structure between wind and solar generation.

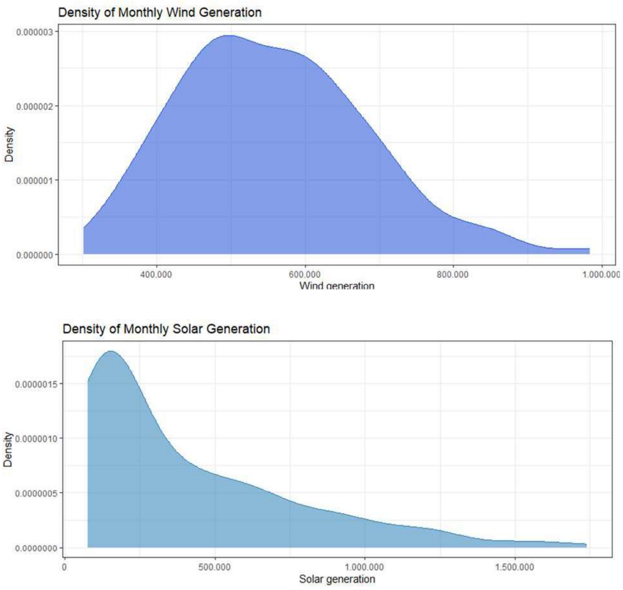


Fig. 2. Wind and solar density

After identifying the marginal distributions that best describe the historical behavior of wind and solar generation, a bivariate copula was estimated to represent the joint dependence structure between these sources in the baseline period. Marginal distributions were selected based on goodness-of-fit tests, using the p-value as the decision criterion, ensuring an adequate representation of the empirical behavior of the series prior to joint modeling. Copula parameters were estimated using maximum likelihood, and model selection was conducted according to the Bayesian Information Criterion (BIC).

For the baseline scenario, covering the period from January 2015 to November 2025 and comprising 131 monthly observations, the dependence structure between wind and solar generation was adequately captured by a Gaussian copula. The estimated correlation parameter was negative ($\rho \approx -0.16$), corresponding to a Kendall's τ of -0.10. This result indicates the presence of weak negative dependence, suggesting a moderate degree of complementarity between the two sources when analyzed over the full sample without explicit conditioning on extreme climatic regimes.

The series were subsequently segmented according to the occurrence of heatwaves, yielding two distinct subsets: months without heatwaves (HW = 0), totaling 88 observations, and months with heatwaves (HW = 1), totaling 43 observations. This segmentation allowed for a direct assessment of how the dependence structure between wind and solar generation changes under different thermal conditions.

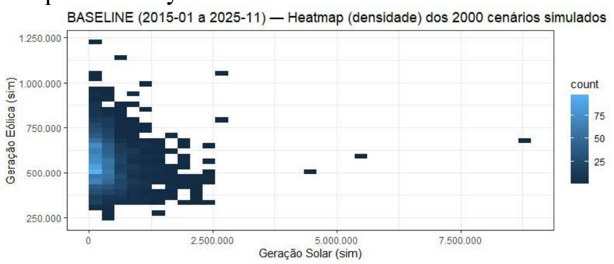
For the subset of months without heatwaves, the selected model indicated an independence structure between wind and solar generation, with Kendall's τ statistically equal to zero. This finding suggests that, under thermally normal conditions, there is no evidence of significant probabilistic dependence between the two sources. A plausible explanation is that, in the absence of persistent thermal extremes, the atmospheric processes governing wind regimes and solar irradiance tend to operate in a relatively decoupled manner. Furthermore, seasonal heterogeneity and intra-annual variability may dilute systematic associations when aggregated, leading to a dependence structure close to independence.

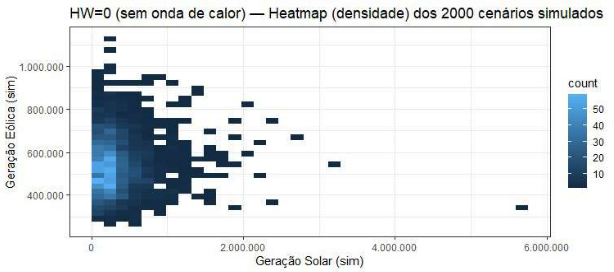
In contrast, for the subset of months characterized by heatwave conditions, the estimated dependence structure differs markedly. In this regime, the selected copula was a rotated Clayton copula (270 degrees), with an estimated parameter $\theta \approx -0.75$, yielding a Kendall's τ of -0.27. This value indicates a moderate negative dependence, substantially stronger than that observed in the baseline scenario.

The strengthening of negative dependence during heatwave months reflects an intensification of conditional complementarity between wind and solar generation. This behavior can be interpreted in terms of the physical mechanisms associated with extreme heat events, which are typically linked to persistent high-pressure systems and enhanced atmospheric stability. Under such conditions, solar generation is favored by increased incoming radiation, while wind generation may be reduced due to weakened pressure gradients and near-surface circulation. This asymmetric response of the two sources is captured by the more pronounced negative dependence structure identified for heatwave periods.

To assess plausible joint realizations of wind and solar generation in Andalusia under distinct thermal regimes, 2,000 synthetic scenarios were generated for each subset (baseline, non-heatwave months, and heatwave months). Simulations were conducted within a bivariate copula modelling framework, which explicitly separates the dependence structure from the marginal behaviour of each variable. First, parametric marginal distributions for wind and solar generation were fitted using the historical monthly dataset (2015–2025/11), selecting the most adequate forms for each subset. The observed series were then mapped to the unit interval through the fitted cumulative distribution functions, yielding pseudo-observations in (0,1). Within this transformed space, the copula family describing the joint dependence between wind and solar generation was estimated by maximum likelihood, and the best specification for each regime was retained. Finally, paired draws (Usolar, Uwind) were sampled from the fitted copula and mapped back to the original domain (MWh) via the fitted marginal quantile functions, producing simulated scenarios that are jointly consistent with both marginal variability and the estimated dependence structure.

Figure 3 summarises these results by displaying heatmaps of the density of the 2,000 simulated scenarios in the "solar vs. wind" plane for: (i) the baseline, (ii) non-heatwave months (HW=0), and (iii) heatwave months (HW=1). Conceptually, each heatmap highlights where simulations concentrate most frequently, i.e., which wind–solar combinations are most probable under the fitted joint distribution within each regime. Under the baseline, the simulated cloud is relatively dispersed, yet it concentrates mainly around moderate wind output and low-to-moderate solar output, reflecting the overall joint variability across the full sample. For non-heatwave months (HW=0), the simulated pattern appears more "diffuse", in line with the selection of an independence copula for this subset: the density does not reveal a strong systematic co-movement between the sources, indicating that, under typical thermal conditions, high (or low) outcomes in one source do not impose statistically meaningful constraints on the other. In contrast, during heatwave months (HW=1), the heatmap geometry changes more markedly, displaying increased asymmetry and a support consistent with stronger negative dependence (i.e., enhanced complementarity). In this regime, it becomes relatively more likely to observe combinations where higher solar generation is not accompanied by simultaneously higher wind generation, and vice versa. From an applied perspective, this implies that heatwaves not only affect marginal properties (notably by elevating and widening the distribution of solar generation), but also reconfigure the joint dependence, thereby altering the probability of specific renewable supply combinations relevant for system planning, adequacy, and operational risk assessment. Hence, Figure 3 provides a key result by showing that, conditional on heatwaves, the simulated joint distribution shifts and reorganises, reinforcing that purely average-based assessments may overlook material regime-dependent changes in wind–solar complementarity.





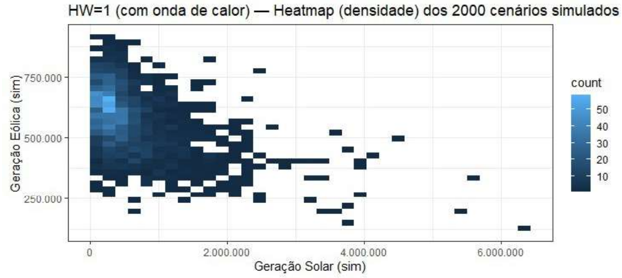


Fig 3. Joint density of simulated wind–solar generation scenarios (N=2,000) in Andalusia under non-heatwave and heatwave regimes.

Table 1 reports the estimated monthly probabilities of heatwave occurrence associated with a representative simulated year, labeled as "2026" for interpretative purposes. These probabilities do not correspond to a deterministic forecast for the calendar year 2026. Instead, they are derived from the ensemble of simulated scenarios generated from the historical distributions and dependence structures estimated in this study.

In this context, the values of $\hat{p}$ represent empirical probabilities of heatwave occurrence across the simulated scenarios, reflecting the underlying climatological patterns captured by the model rather than a specific predictive outcome for a given future year.The results reveal a marked seasonal pattern in heatwave probabilities. The highest probabilities are observed during the summer months, with July and August exhibiting the largest values, both equal to 0.636. This indicates that, in the simulated scenarios, heatwave conditions occur in approximately 63.6% of realizations during these months. Such behavior is fully consistent with the climatological characteristics of Andalusia, a region known for intense and persistent summer heat driven by high solar radiation, subsidence associated with subtropical anticyclones, and limited atmospheric instability.

Intermediate probabilities are identified in May (0.455), October (0.364), and December (0.400). These values suggest a non-negligible likelihood of heatwave conditions during late spring, early autumn, and, to a lesser extent, winter months. In the Andalusian context, this pattern reflects the increasing frequency of anomalously warm episodes outside the core summer season, which has been documented in recent decades and is often associated with large-scale circulation anomalies and background warming trends.

Lower probabilities are observed in June, September, and November (0.182), indicating transitional periods in which heatwave occurrence is less frequent but still possible. The lowest probability is found in March (0.091), corresponding to early spring, when atmospheric conditions in southern Spain are typically more influenced by mid-latitude disturbances and milder temperature regimes.

Overall, the monthly probability structure displayed in Table 1 aligns well with the known seasonal climatology of Andalusia. The concentration of high probabilities in July and August, combined with reduced likelihood in late winter and early spring, supports the physical plausibility of the simulated scenarios. These results provide a coherent probabilistic characterization of heatwave risk throughout the year, which is particularly relevant for assessing the conditional impacts of extreme temperature events on renewable energy generation dynamics.

Year	Month	p hat
2026	Jan	0,273
2026	Feb	0,273
2026	Mar	0,091
2026	Apr	0,273
2026	May	0,455
2026	Jun	0,182
2026	Jul	0,636
2026	Aug	0,636
2026	Sep	0,182
2026	Oct	0,364
2026	Nov	0,182
2026	Dec	0,400

Table I. - Probability of Heat Waves

6. Conclusion

This study investigated how heatwave conditions modify the dependence structure between wind and solar power generation in Andalusia, Southern Spain, using a copula-based modeling framework. By combining observed monthly generation data with climate reanalysis information, the analysis demonstrated that the joint behavior of renewable sources is not stationary over time, but rather strongly conditioned by extreme thermal regimes. The baseline results revealed weak negative dependence between wind and solar generation, indicating a modest degree of complementarity when all months are considered jointly. However, this average behavior conceals substantial regime-dependent differences that become evident once heatwave and non-heatwave periods are analyzed separately.

The segmentation of the dataset according to heatwave occurrence provided clear evidence that extreme thermal conditions significantly alter the dependence structure between renewable sources. During non-heatwave months, the dependence between wind and solar generation was best described by an independence copula, suggesting that, under thermally normal conditions, the stochastic drivers of wind and solar resources operate largely independently at the monthly scale. In contrast, during heatwave months, a rotated Clayton copula captured a markedly stronger negative dependence, reflecting enhanced complementarity. This finding is consistent with the physical mechanisms associated with heatwaves, which tend to favor solar generation while simultaneously suppressing near-surface wind speeds due to atmospheric stability and weakened pressure gradients.

The simulation of 2,000 joint wind–solar scenarios for each climatic regime further reinforced the relevance of a regime-conditioned approach. The resulting joint distributions highlighted pronounced differences in the shape, dispersion, and concentration of probable generation combinations across regimes. In particular, heatwave-conditioned simulations exhibited more asymmetric and constrained joint outcomes, emphasizing that extreme climatic events not only affect marginal generation levels but also reshape the probabilistic structure of joint renewable supply. These results have direct implications for power system planning and adequacy assessment, as they suggest that reliance on average dependence measures may underestimate risks associated with extreme climate conditions.

Despite its contributions, this study has some limitations that open avenues for future research. The analysis was conducted at a monthly temporal resolution, which is appropriate for medium-term planning but may mask short-term dynamics relevant for operational studies. Future work could extend the framework to higher temporal resolutions or incorporate spatial dependence across multiple regions. Additionally, integrating climate model projections could allow the assessment of how wind–solar dependence under heatwave conditions may evolve under future warming scenarios. Nonetheless, the copula-based methodology proposed here provides a robust and flexible foundation for incorporating extreme climate variability into the joint modeling of renewable energy sources, contributing to more resilient energy system planning in a warming climate.

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