Analysis of Spatiotemporal Balancing between Wind and Solar Energy Resources in the Southern Iberian Peninsula

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ABSTRACT

Electricity from wind and, to a lesser extent, solar energy is intermittent and not controllable. Unlike conventional power generation, therefore, this electricity is not suitable to supply base-load electric power. In the future, with greater penetration of these renewable sources, intermittency and control problems will become critical. Here, the authors explore the use of canonical correlation analysis (CCA) for analyzing spatiotemporal balancing between regional solar and wind energy resources. The CCA allows optimal distribution of wind farms and solar energy plants across a territory to minimize the variability of total energy input into the power supply system. The method was tested in the southern half of the Iberian Peninsula, a region covering about 350 000 km². The authors used daily-integrated wind and solar energy estimates in 2007 from the Weather Research and Forecasting (WRF) mesoscale model, at a spatial resolution of 9 km. Results showed valuable balancing patterns in the study region, but with a marked seasonality in strength, sign, and spatial coverage. The autumn season showed the most noteworthy results, with a balancing pattern extending almost over the entire study region. With location of reference wind farms and photovoltaic (PV) plants according to the balancing patterns, their combined power production shows substantially lower variability than production of the wind farms and PV plants separately and combined production obtained with any other locations. Atmospheric circulations associated with the balancing patterns were found to be significantly different between seasons. In this regard, synoptic-scale variability played an important role, but so did topographic conditions, especially near the Strait of Gibraltar.

1. Introduction

It is expected that worldwide primary energy demand will increase by 45%, and demand for electricity will increase by 80% between 2006 and 2030 (IEA 2008). Consequently, without decisive action, energy-related greenhouse gas (GHG) emissions will more than double by 2050, and increased oil demand will intensify concerns over the security of supply. There are different paths toward stabilizing GHG concentrations, but a key issue in all of them is the replacement of fossil fuels by renewable energy sources. In this scenario, solar and wind electricity will play a key role. There are two main solar electricity technologies: the direct conversion of sunlight into electricity [photovoltaic (PV)] and concentrating solar power (CSP). PV systems enable direct conversion of sunlight into electricity through semiconductor devices, through their receipt of global horizontal irradiance (GHI). Today, PV provides 0.2% of total global electricity generation. Germany is the highest producing country in the world, with 17.3-GW installed capacity, followed by Spain with above 4 GW (about 4% of the installed capacity) (IEA 2010b). While its use is small today, PV power has a particularly promising future, as it is projected to provide around 5% of global electricity consumption by 2030, increasing to 11% by 2050 (IEA 2010b). CSP plants concentrate direct normal irradiance (DNI) to produce electricity based on the thermodynamic cycle. In addition, this technology has the advantage of being able to store the solar energy. Current penetration of this technology is low, about 1-GW capacity (mostly in Spain), but it is expected to contribute about 5% of annual global electricity production by 2050 (IEA 2010a). Wind energy is the fastest growing renewable. In 2008, wind energy provided nearly 20% of...
electricity consumption in Denmark, more than 11% in Portugal and Spain, over 4% in the entire European Union (EU), and nearly 2% in the United States (IEA 2009). By 2030, wind electricity is estimated to contribute about 9% of global electricity production, growing to 12% by 2050 (IEA 2009). In the EU, regulations set a binding target of 20% of final energy consumption from renewable sources by 2020, along with a commitment to achieve at least a 20% reduction of greenhouse gases by 2020, compared to 1990 (European Directives 2009/28/EC and 2009/29/EC). For Spain, to achieve this 20% final consumption goal, a substantial increase in the contributions of wind and solar energy to electricity production is necessary, from the current 15% to more than 45% (Gómez et al. 2010). Most of this increment will be located in the southern Iberian Peninsula (the study region here; Ruiz-Arias et al. 2012). Similar target increases in the share of these renewables are expected in other regions (Jacobson and Delucchi 2009).

A major challenge will be the integration of these large-scale wind and solar yields into existing energy supply infrastructure. The challenge comes from the fluctuating nature of the solar and wind resources and their sensitivity to indeterminate weather patterns, as compared to the relatively stable and predictable sources of conventionally generated electricity. These characteristics make the cost of these renewables less competitive for power generation systems, because intermittent production creates negative externals that translate into grid integration costs. Short-term wind and solar power forecasting is the primary requirement for efficient integration of renewables into power systems and for the reduction of grid integration costs (Saintcross et al. 2005; Kariniotakis et al. 2006; Lorenz et al. 2011; Lara-Fanego et al. 2012). Unexpected generation must be accommodated by system reserves. Therefore, as wind and solar power contributes a higher proportion of all generation, it will become more difficult for electrical system operators to effectively integrate such additional fluctuating power input. Thus, solutions that reduce power fluctuations are important if wind and solar electricity is to significantly displace other electricity technologies and will contribute reliable power similar to base load of conventional plants.

One of the most promising ways to reduce the power fluctuation from renewables is to take advantage of the spatial variability of these resources. Since the spatial correlation of wind and (to a lesser extent) solar energy resources diminishes with distance, interconnection of wind and solar power in a region will reduce fluctuations in total production. That is, a balancing effect can be achieved because of variable weather and climate conditions across a region. When this balancing is reached, the combined output of numerous, widely spaced renewable energy plants, based on the same or different resources (but mainly wind and solar), would be smoother than the output of individual power plants. In addition, such dispersed generation is expected to reduce forecast error, thereby reducing grid integration cost.

Kahn (1979) and Landberg (1997) conducted the earliest analyses on smoothing or spatial balancing of wind energy resources. More recently, Archer and Jacobson (2007) studied a reduction of wind power production fluctuation through the interconnection of 19 wind farms in the midwestern United States. They found a significant decline in the fluctuation of total production, compared to single wind farms. Consequently, they demonstrated that interconnected wind farms could supply reliable base-load power. Cassola et al. (2008) proposed a method for optimal distribution of wind farms at 10 locations in Corsica (France), to reduce temporal variability of total wind power production. They concluded that, based on this distribution, around 16% of yearly average wind power could be used as reliable base load. Kempton et al. (2010) analyzed the benefits of interconnecting offshore wind farms along the east coast of the United States, concluding that aggregation of production considerably reduces wind power fluctuation.

The benefits of solar energy aggregation have received less attention. In general, the spatial variability of the solar resource is significantly less than that of wind energy (Archer and Jacobson 2003; Papadimas et al. 2010; Gueymard and Wilcox 2011; Wideń 2011). Nevertheless, clouds produce substantial spatial variability in solar energy production. Wiemken et al. (2001) analyzed spatial variability of PV production in Germany. Similarly, this spatial variability across the United States was addressed by Mills and Wiser (2010). They reported variability similar to that of wind energy.

Since solar and wind energy will contribute more to total electricity production in the future, it is worth analyzing the combined effect of the spatial distribution of these two sources. In our context, a balancing effect becomes effective when and where strong solar energy compensates weak wind energy, and vice versa. From a meteorological and climatological point of view, the balancing effect between solar and wind resources can be easily anticipated, given a large enough region. Over Europe, wind resources tend to be higher in winter and lower in summer, the opposite for solar resources. Balancing seems very dependent on the temporal and spatial scales considered (Pozo-Vázquez et al. 2011). Although some projects intended for very high renewable penetration are founded on the idea of balancing (Trieb et al. 2005; Tröster et al. 2011), there has been little research in this new field. Heide et al. (2010, 2011) analyzed the optimal mix between solar (PV) and wind energy in Europe.
within a scenario of very high penetration (100%) of these renewables. Their analyses were based on meteorological model estimates and were carried out on seasonal time scales, with a constraint of reducing storage needs as much as possible. They gave an optimal seasonal mix of 55% wind and 45% solar. Widén (2011) analyzed balancing between solar and wind resources in Sweden, based on meteorological station data. He reported a negative correlation between solar and wind resources (and thus balancing) on all time scales at a national scale; monthly totals provided the highest negative correlations (seasonal variability). He also showed a greater hour-to-hour variability when the solar share increases.

We explore here the use of canonical correlation analysis (CCA) for assessing the spatiotemporal balancing between the solar and wind energy resources over a region. The CCA decomposes two sets of space–time-dependent variables into pairs of spatial patterns (canonical modes), such that they are maximally correlated. Therefore, the CCA will eventually highlight the existence of balancing between solar and wind energy resources, depending on the nature (sign and strength) of the canonical patterns. In this sense, the CCA finds the optimal distribution of wind farms and solar energy plants over a territory, to minimize the variability of total energy input into the power supply system. The methodology was tested in the southern half of the Iberian Peninsula, a region covering about 350 000 km². The varied topographic and geographic conditions of the region lead to an anticipation of the existence of balancing effects between solar and wind energy resources. In addition, this region produces a substantial part of the wind energy (more than 40%) and solar energy (90%) in Spain (UNESA 2010). We used daily-integrated wind and solar energy estimates from 2007, based on the Weather Research and Forecasting (WRF) mesoscale model (Skamarock et al. 2008), at a spatial resolution of 9 km. These studies were done seasonally and for the complete period. Atmospheric conditions associated with the balancing pattern were also examined.

This paper is organized as follows. Section 2 presents the study area and methodology, including the dynamical downscaling setup. Results are presented in section 3. A summary and some conclusions are presented in section 4.

2. Methods and study area

a. Study area

The study region (Fig. 1) corresponds roughly to the southern half of the Iberian Peninsula, covering about 350 000 km². Henceforth, the word “region” or “regional” will refer to the entire study region, whereas “parts,” “areas,” and geographic directions will refer to subregions within that larger region. The region is located in a transition zone from temperate to subtropical climates, bounded on the south by the Atlantic Ocean and Mediterranean Sea. Several areas within the region can be characterized by their dominant topographic features. The southwest, corresponding to western Andalusia and the south of Portugal, is an almost homogeneous area, open to the Atlantic Ocean. The central and northern parts have an intermediate topographic complexity. In particular, central Spain is a plateau with a mean elevation of about 700 m. Transition from this area to central Portugal is relatively smooth. Finally, complex topography dominates the east and southeast parts of the region. This area contains several mountain ranges and includes the Sierra Nevada National Park, with a maximum elevation of 3482 m (highest on the Iberian Peninsula). Since the region borders both the Mediterranean Sea (at the south) and the Atlantic (at the west), there are extensive coastal areas where local thermal contrasts strongly influence the wind energy resource.

The large-scale circulation over the region is mainly driven by a semipermanent subtropical high pressure center over the Azores islands, which varies in location and intensity during the year. During winter, this high is situated at lower latitudes, allowing the Iberian Peninsula to be affected by zonal circulations from the west, while in summer it migrates northward, blocking the westerlies over most of the peninsula (Trigo et al. 2002, 2004). The Azores subtropical high is the southern part of the North Atlantic Oscillation (NAO) dipolar atmospheric variability pattern (Hurrell et al. 2003), which is linked to
large-scale atmospheric dynamics and the modulation of the strength of the westerlies over the European region (Pozo-Vázquez et al. 2000, 2001; Castro-Díez et al. 2002; Gámiz-Fortis et al. 2008).

Although the entire region is under the influence of the Azores subtropical high, the region experiences a wide range of climate conditions. This range is related to orography (Fig. 1) and numerous synoptic disturbances of Atlantic origin, which cause enormous spatial variability in precipitation and other climate variables (Trigo and DaCamara 2000; Trigo et al. 2004). For example, the eastern part is less influenced by the Azores high, and more affected by the Mediterranean Sea. In fact, annual precipitation values across the region range from 300 mm yr$^{-1}$ in the coastal semidesert southeast to more than 2500 mm yr$^{-1}$ in the mountains near the Strait of Gibraltar (Romero et al. 1998; Ramos-Calzado et al. 2008). Since mesoscale spatial variability of solar radiation is mainly related to cloudiness, this variability is relatively high in the region (Pozo-Vázquez et al. 2004; Alsamamra et al. 2009; Pozo-Vázquez et al. 2011).

Surface wind speed variability is associated not only with mesoscale circulations but also with other more localized factors. Many of these are related to topographic characteristics (elevation, aspect, slope, surface roughness, etc.) and others with thermal contrast near water bodies (Hutchinson et al. 1984; Weber and Furger 2001; McVicar et al. 2008). The complex topography and the influence of the Atlantic Ocean and the Mediterranean Sea combine to produce marked spatial variability in regional wind speeds (Alsamamra et al. 2011, manuscript submitted to Meteor. Appl.). In particular, when winds associated with strong thermal contrast between the Mediterranean Sea and Atlantic Ocean are channeled and accelerated through the Strait of Gibraltar, strong easterlies (known as levante) are produced. In summary, the interaction of mesoscale circulations, topographic and geographic features generates substantial spatial variability in wind speed and solar radiation in the region, despite its relatively small size.

b. Mesoscale model configuration

The Weather Research and Forecasting (WRF) model v3.0 has been used in this work. The domain is shown in Fig. 2. The outer domain has a spatial resolution of 27 km, covering the Iberian Peninsula and parts of northern Africa. The inner domain has a spatial resolution of 9 km and covers the southern Iberian Peninsula. Topography, land use, and land–water mask datasets were interpolated from U.S. Geological Survey (USGS) land cover, with appropriate spatial resolution for each domain (5′ and 2′, respectively). A two-way interaction was used for both domains, with 27 vertical levels, 7 of which are within the first 1000 m above the ground. The second level was used to obtain wind speed estimates and corresponding wind energy values. Since the height of this second level fluctuates with pressure, we have computed the mean and standard deviation over the study period and entire inner domain. The mean value was 28.96 m above ground level (AGL) with standard deviation 0.4 m. Therefore, this second level provides estimates of wind energy around 30 m AGL.

Parameterization schemes for the WRF were selected on the basis of several parameterization evaluation studies in the region (Fernández et al. 2007; Borge et al. 2008; Ruiz-Arias et al. 2008, 2011; Argüeso et al. 2011). For the longwave radiation, we selected the Rapid Radiation Transfer Model (RRTM) scheme (Mlawer et al. 1997). For the shortwave solar radiation, we used the Dudhia scheme (Dudhia 1989). The Kain–Fritsch scheme (Kain and Fritsch 1990, 1993) was used for cumulus, the Yonsei University Planetary Boundary Layer (YSU PBL) scheme (Hong et al. 2006) was used for the boundary layer, and Thompson graupel was used (Thompson et al. 2004) for the microphysics. The Noah land surface model (Chen and Dudhia 2001) was used. Argüeso et al. (2011), using a setup similar to the one here, proved that the WRF model was able to correctly reproduce the climate of the study region.

Initial and boundary conditions were generated from Global Forecast System (GFS) model output, with spatial resolution of 0.5°. In particular, the analysis provided by this system every 6 h were used to upgrade the boundary conditions. Simulations were conducted for the year 2007. Following Hahmann et al. (2010), integration periods of
eight days, with a spinup of 24 h, were used, and outputs were saved every hour. The balancing analysis computed daily-integrated wind and solar energy values based on WRF modeled solar radiation and wind speed, within the inner domain (9-km spatial resolution). Wind speed estimates at 30 m AGL (second vertical level) at 1-h intervals were used to estimate daily-integrated wind energy values based on

\[ E_{\text{daily\_wind}} = \sum_{i=1}^{24} \left( \frac{1}{2} \rho v_i^2 \right) \times 1 \text{ h}, \quad (1) \]

where \( v \) is the wind speed every hour and \( \rho \) is air density at sea level. Similarly, daily integrated solar energy estimates were obtained based on hourly estimates of shortwave downward solar radiation (GHI) at the surface:

\[ E_{\text{daily\_solar}} = \sum_{i=1}^{24} \text{GHI}_i \times 1 \text{ h}. \quad (2) \]

Raw daily solar and wind energy time series were normalized for each season, taking January through March to be winter, April through June spring, July through September summer, and October to December autumn. This standardization ensures that all elements possess temporal stationarity and are weighted equally.

c. Balancing analysis methodology

Spatiotemporal balancing between solar and wind energy resources in the region was analyzed based on the CCA (Barnett and Preisendorfer 1987; Bretherton et al. 1992; Von Storch and Zwiers 2001). CCA is a multivariate statistical model that facilitates study of interrelationships among sets of multiple dependent variables and multiple independent variables. Whereas multiple regressions predict a single dependent variable from a set of multiple independent variables, CCA simultaneously predicts multiple dependent variables from multiple independent variables. Here, the dependent and independent sets of variables are the solar energy and wind energy fields in the study region. To this end, CCA explores the association between different composites of variables in the two sets. Particularly, CCA derives a set of weights for each set variables, so the resulting composite variables (pairs of canonical variables) are maximally correlated (canonical correlation). This results in the first canonical mode. The procedure can be repeated, attaining successive canonical modes derived from residual or leftover variance from earlier modes. That is, the second pair of canonical variables is derived so that they exhibit the maximum correlation, but are derived based on variance not accounted for by the first canonical mode. Since successive pairs of canonical variables are based on residual variance, each of the pairs of variables is orthogonal and independent of all other variables derived from the same set of data. The maximum number of canonical variables (and therefore canonical modes) that can be extracted from the sets of variables equals the number of variables in the smallest dataset. The strength of relationship between each pairs of canonical variables is reflected by the canonical correlation. When squared, the canonical correlation represents the amount of variance in one canonical variable accounted for by the other canonical variable. This also may be called the amount of shared variance between the two canonical variables.

There are no generally accepted guidelines regarding suitable sizes for canonical correlations, and thus for the number of canonical modes to analyze (Anderson et al. 1998). Rather, the decision is usually based on the contribution of the findings to better understanding of the research problem under study. In this work, and as a first approach, the statistical significance of canonical correlations was analyzed based on the \( F \) statistic (Bartlett 1941). Only canonical modes with canonical correlation statistically significant at the 0.05 level were retained for subsequent interpretation. In a second approach, only canonical modes with canonical correlations values above 0.4 were considered. This arbitrarily selected and stringent value allows retention of only the most important balancing modes for further analysis. The rest of the canonical modes, with considerable lower canonical correlation, do not provide valuable information regarding the coupling of wind and solar resources in the region.

Homogeneous canonical loadings have been used as a basis for interpretation of the canonical modes. Particularly, homogeneous canonical loadings are the simple linear correlation between the original observed variables in the field and their corresponding canonical variables. By mapping these correlations, the spatial pattern associated with the corresponding canonical mode can be analyzed. The canonical loading reflects the variance that the observed variable shares with the canonical variable, and can be interpreted as a factor loading in assessing the relative contribution of each variable to each canonical mode. The larger the coefficient is, the more important it is in deriving the canonical mode.

The CCA eventually highlights the existence of balancing between solar and wind energy resources, depending on the nature (sign and strength) of canonical correlation and canonical loading patterns. For the purposes here, we look for canonical modes whose associated canonical patterns indicate areas in which solar and wind energy are meaningfully anticorrelated. The CCA was applied to the daily-integrated, seasonally standardized wind and solar energy fields. Data analysis was done
for each season of the year and for the entire year. First, to avoid computational problems with the sample size, the daily data were prefiltered using a principal component analysis (PCA) (Barnett and Preisendorfer 1987). This is a widely used method to analyze spatiotemporal variability of an environmental variable. In particular, this method allows reduction of the initial dataset dimension into a few representative variables (modes). The new variables called principal components (PCs) and often referred to as modes of variability, are obtained as linear combinations of the initial variables. These combinations are obtained such that the new variables account for the maximum fraction of the variance contained in the original dataset. The number of modes retained in the PCA analysis is a compromise between the need to retain as much as possible of the signal and the requirement of noise reduction. The number of retained modes was determined such that an increase by one would minimally change the canonical correlation results (Von Storch 1999). In all analyzed cases (seasonal and annual data), five modes proved to be a good compromise. These five modes explained between 75% and 93% of solar energy variance, and between 70% and 80% of wind energy variance. Second, the CCA analysis was performed based on the retained modes. Next, the canonical modes were projected again into the original dataset based on the PCA, to represent their associated spatial patterns.

Finally, mesoscale atmospheric conditions associated with each canonical pattern were analyzed. To this end, we computed composite maps of daily-mean horizontal wind components at 30 m AGL and daily-mean solar radiation anomalies at the surface, associated with the 15 (30 for the annual analysis) maximum and minimum values of wind energy canonical time series. Data for these composites were taken from the WRF integration outer domain (Fig. 2), which covers the entire Iberian Peninsula and northwest Africa at a spatial resolution of 27 km.

3. Results

In this section, the results of the CCA analyses are presented. These analyses were done for each season of the year and for the entire year, independently. Only the canonical modes that produced a canonical correlation higher than 0.4, were analyzed. To understand the nature and strength of the coupled wind–solar energy modes, a brief description of the associated mesoscale atmospheric conditions is presented for each mode. Table 1 summarizes the principal results of the CCA analyses. The canonical correlation and the associated explained variances are presented, for the selected modes and for each period.

### Table 1. Summary of results of the CCA. In particular, the table shows, for the seasonal and annual analysis, the solar and wind field explained variance (Var.) associated with each canonical mode. The last column shows canonical correlation values. Only canonical modes with a canonical correlation higher than 0.4 were analyzed.

<table>
<thead>
<tr>
<th>Season</th>
<th>Mode</th>
<th>Var. solar energy (%)</th>
<th>Var. wind energy (%)</th>
<th>Canonical correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Mode 1</td>
<td>38.1</td>
<td>31.0</td>
<td>0.55</td>
</tr>
<tr>
<td>Winter</td>
<td>Mode 2</td>
<td>26.3</td>
<td>7.4</td>
<td>0.51</td>
</tr>
<tr>
<td>Spring</td>
<td>Mode 1</td>
<td>6.0</td>
<td>7.0</td>
<td>0.61</td>
</tr>
<tr>
<td>Spring</td>
<td>Mode 2</td>
<td>9.3</td>
<td>16.0</td>
<td>0.52</td>
</tr>
<tr>
<td>Summer</td>
<td>Mode 1</td>
<td>26.5</td>
<td>17.0</td>
<td>0.73</td>
</tr>
<tr>
<td>Summer</td>
<td>Mode 2</td>
<td>12.8</td>
<td>8.6</td>
<td>0.64</td>
</tr>
<tr>
<td>Summer</td>
<td>Mode 3</td>
<td>12.2</td>
<td>10.3</td>
<td>0.52</td>
</tr>
<tr>
<td>Autumn</td>
<td>Mode 1</td>
<td>23.2</td>
<td>25.7</td>
<td>0.51</td>
</tr>
<tr>
<td>Autumn</td>
<td>Mode 2</td>
<td>6.6</td>
<td>23.2</td>
<td>0.45</td>
</tr>
<tr>
<td>Annual</td>
<td>Mode 1</td>
<td>42.2</td>
<td>6.5</td>
<td>0.46</td>
</tr>
<tr>
<td>Annual</td>
<td>Mode 2</td>
<td>8.3</td>
<td>13.3</td>
<td>0.40</td>
</tr>
</tbody>
</table>

### a. Winter

Only two modes with a canonical correlation higher than 0.4 were found for winter (Table 1). The time series of the leading mode (Fig. 3) have a canonical correlation of 0.55. Both solar and wind energy canonical time series show a positive trend, ending in high positive anomalies during March (Fig. 3c). Also remarkable is that solar energy exhibits greater variability than wind energy. The leading mode accounts for around 38% of the variance of solar energy and 31% of the wind energy fields. Their respective spatial patterns (Figs. 3a,b) show a coupling between solar energy in the west (especially in Portugal, where correlation reaches 0.8) and wind energy in the Gulf of Cádiz and western Strait of Gibraltar area (where correlation values approach 0.7). This coupling is associated with a marked meridional circulation over the western Iberian Peninsula. Positive wind speed and solar radiation anomalies, and therefore positive wind energy and solar energy anomalies, are found in central and southern Portugal (Fig. 3d), areas of high positive loadings in Figs. 3a,b. These positive anomalies are associated with northerly winds (usually cold and dry during winter). The unique topographic features in the Strait of Gibraltar area turn this northerly flow into strong westerly winds (called poniente), generating high positive wind speed anomalies (and therefore high positive wind energy anomalies) in this area, with high positive loads (Fig. 3b). In contrast, negative wind speed and solar radiation anomalies (Fig. 3e), and therefore negative wind and solar energy anomalies, are associated with southwesterly flows. This circulation usually brings relatively warm and humid air into the western study area, fostering more cloudiness and resultant
negative solar energy anomalies. In particular, over the Gibraltar strait area (which shows high positive loads in Fig. 3b), this circulation brings weaker-than-normal winds that cause high negative wind energy anomalies. Interpretation of wind speed anomalies in Figs. 3d,e requires information from Figs. 3a–c and consideration of the normalization period, here 3 months. Finally, this leading mode of winter CCA analysis does not show areas where balancing between solar and wind energy resources occurs.

The time series of the second mode (Fig. 4) have a canonical correlation of 0.51. Both the wind and solar time series exhibit considerable variability. A spectral analysis reveals that this variability is mainly associated with a 3–6-day range, and therefore is related to synoptic activity. This was further confirmed by analysis of the synoptic maps associated with this mode. This second mode accounts for around 26% of the solar energy field variability and around 8% of the wind energy field variability. Their spatial patterns (Figs. 4a,b) are much more interesting from the balancing point of view. On the one hand, this second mode presents negative loads on the solar energy field in almost the entire region, particularly over Andalusia, were values reach $-0.6$. On the other hand, positive loads are found in the wind energy field near the Strait of Gibraltar, with values up to 0.5. Therefore, this second mode accounts for a balancing effect between the wind energy in the latter area and solar energy in most of the region. The mesoscale atmospheric circulations associated with this balancing are presented in Figs. 4d,e. Notably, positive solar and negative wind energy anomalies are associated with relatively high pressure over the Gulf of Cádiz, which brings stable conditions to the study area (positive solar energy anomalies) and weaker westerly winds over the Strait of Gibraltar area.

Alternatively, negative solar and positive wind energy anomalies are associated with low pressure to the west of this area. In the latter scenario, frontal activity brings cloudiness to most of the region, and in the former scenario, strong easterly winds (levante) to the Strait of Gibraltar area.

b. Spring

During spring, two canonical modes were selected (Table 1) for further analysis. The time series of the leading mode (Fig. 5c) have a canonical correlation of 0.61. Both series exhibit clear variations with monthly
and synoptic time-scale variability. This leading mode of the spring CCA analysis accounts for only about 6%–7% of the variability of the solar and wind energy fields. Nevertheless, this mode is remarkable because it locally explains more than 35% of the variance (correlations higher than 0.6), and because the spatial pattern indicates a balancing effect. For the solar energy field (Fig. 5a), negative correlations ($\leq 0.6$) are observed in the eastern Strait of Gibraltar area. For wind energy (Fig. 5b), relatively high positive correlations are observed in the central strait area and regional mountain ranges (correlations above 0.5). Therefore, the leading mode of the spring analysis accounts for a weak (but statistically significant) balancing effect between solar and wind energy in the region. Positive solar energy anomalies over southern Portugal (and negative anomalies in eastern Strait of Gibraltar, an area of interest here) and positive wind energy anomalies over the central strait area are associated with an easterly flow over the entire southern Iberian Peninsula, intensified near the strait (Fig. 5d). This easterly flow brings cloudy conditions to the coastal areas of the southern part of the region, reducing solar energy availability. Alternatively, negative solar energy anomalies over southern Portugal (and positive anomalies at the eastern Strait of Gibraltar), along with negative wind energy anomalies over the central strait area, are associated with westerly winds over the strait area (Fig. 5e). These winds have weaker than average speeds over this area, decreasing wind energy.

The time series of the second mode (Fig. 6) have a canonical correlation of 0.52, and exhibit high variability at synoptic time scales (Fig. 6c). This second mode of the spring CCA analysis accounts for around 9% of the variability of solar energy and 16% of wind energy. The corresponding spatial patterns (Figs. 6a,b) indicate a weak (but statistically significant) balancing between solar energy in the western part of the region and wind energy in its central and eastern parts. This balancing is relatively weak, because correlation between the canonical mode and the solar field (homogeneous correlation) is relatively low. Figures 6d,e present the mesoscale atmospheric conditions associated with this balancing. Positive solar energy anomalies over the eastern part of the region (and therefore negative ones over the western part, an area of interest here) and positive wind energy anomalies over the central and eastern parts (Fig. 6d) are associated with a southerly flow over the southeastern peninsula. This circulation usually advects warm and humid air and therefore generates more cloudiness, resulting in negative solar energy anomalies across this area. Wind speeds are intensified (mainly by topographic features) in some parts of the central and eastern region, producing positive wind energy anomalies. In contrast, negative solar energy anomalies in the east (and therefore positive ones in the west), along with negative wind

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**Fig. 4.** As in Fig. 3, but for the second mode of the CCA resulting from the winter analysis. The cross and triangle in (a) and (b) indicate the grids selected for the analysis presented in section 3f.
energy anomalies (Fig. 6e), are caused by a low pressure center covering almost the entire peninsula. This low pressure center brings north winds (usually cold and dry) to the eastern part of the region, producing positive solar energy anomalies there. This low causes weak winds (negative wind energy anomalies) in the central and eastern parts of the region, however.

c. Summer

For summer, three canonical modes were selected (Table 1). The time series of the leading mode (Fig. 7c) have a canonical correlation of 0.73, and exhibit a decrease from July to the beginning of September. In addition, considerable variability is observed at synoptic time scales. This leading mode of the summer CCA analysis accounts for around 26% of the solar field variability, and 17% of the wind energy field. The corresponding spatial patterns (Figs. 7a,b) show a positive coupling between the solar energy in the entire region and the wind energy in its eastern part. No balancing is observed. This mode resembles the leading mode of the winter analysis (Fig. 3). Mesoscale atmospheric conditions (Figs. 7d,e) are similar to those of Fig. 3. The coupling seems to be associated with meridional circulations in the eastern Iberian Peninsula. Positive (negative) wind and solar energy anomalies are associated with northerly (southerly) winds over the east and south of the peninsula.

The times series of the second summer mode (Fig. 8c) have a canonical correlation of 0.64, and have considerable temporal variability at synoptic time scales. This second mode accounts for around 13% of the solar field variability, and 9% for wind energy. The corresponding spatial patterns (Figs. 8a,b) indicate balancing between the solar energy over nearly the entire region and the wind energy in the south and east. Relatively high and positive correlations are observed for solar energy over nearly the entire study region, within highest values (around 0.7) in the east. Negative correlations (around −0.7) are observed in the wind energy field along coastal areas to the south and east. On one hand, positive solar radiation anomalies in the entire region and negative wind energy anomalies in the east and south are associated with westerly winds over the central peninsula, and weak southwesterly winds over the south and east (Fig. 8d). On the other hand, negative solar radiation anomalies and positive wind anomalies in the east and south are associated with a low pressure center in the eastern peninsula (Fig. 8e). This center strengthens the wind over the eastern and southern peninsula, giving rise to those positive wind anomalies, but its associated frontal activity brings cloudiness to central and eastern areas, reducing solar energy availability.

The third mode (Fig. 9) gives a canonical correlation of 0.52. Both wind and solar energy time series (Fig. 9c) show considerable variability at both monthly and synoptic time scales. This mode accounts for around 12% of the variability of solar energy, and about 10% of wind energy. The corresponding spatial patterns resemble those...
of the springtime leading mode (Fig. 5). In particular, positive correlations are observed in the solar energy pattern of coastal areas of the southern and eastern region, although values are relatively weak (about 0.4). For the wind energy pattern, positive correlations are found in southwestern areas and to the east of the Strait of Gibraltar. Negative loads are observed in northeastern areas. Mesoscale atmospheric conditions are

Fig. 6. As in Fig. 3, but for the second mode of the CCA resulting from the spring analysis.

Fig. 7. As in Fig. 3, but for the first mode of the CCA resulting from the summer analysis.
similar to those observed for the spring leading mode (Fig. 4). On one hand, positive solar radiation and wind anomalies in the southeast are associated with southwesterly and westerly winds (Fig. 9d). On the other hand, negative solar radiation and wind anomalies are associated with easterly flow over the entire southern peninsula, intensified near the Strait of Gibraltar (Fig. 9e). This easterly flow brings cloudy skies to the eastern part of the region, reducing solar energy availability.

d. Autumn

The autumn analysis showed probably the most interesting results for the balancing between solar and wind energy resources, region-wide. The first two canonical modes had canonical correlation values over 0.4 (Table 1) and were analyzed in more depth. The time series of the leading mode (Fig. 10c) had a canonical correlation of 0.51. A spectral analysis of these time series revealed that this variability is mainly associated with synoptic-scale activity. Moreover, there is a noticeable decrease during October and November. This leading mode accounts for about 2% of the solar energy field variability and for about 25% of the wind energy field variability. The spatial patterns show a balancing effect between the solar and wind energy resources almost regionwide. Relatively high positive correlations are observed for the solar energy field across the entire region (Fig. 10a), reaching 0.8 in the west, near the Gulf of Cádiz. Large negative correlations are observed for the wind energy field across the entire region, except the very southeast. Minimum values (−0.8) are again observed in the western area, near the Gulf of Cádiz. Therefore, the leading mode of the autumn CCA analysis indicates a general balancing between solar and wind energy, nearly extending over the entire region. Positive solar and negative wind energy anomalies are associated with westerly winds in the region (Fig. 10d), while negative solar and positive wind energy anomalies are associated with a low pressure center west of Portugal (Fig. 10e). This low pressure center brings southerly winds over most of the region, and associated frontal activity brings cloudiness (negative solar energy anomalies) and relatively high wind speeds (positive wind energy anomalies).

The time series of the second mode (Fig. 11c) have a canonical correlation of 0.45. Both wind and solar time series vary considerably, at both synoptic and monthly time scales. This second mode accounts for considerably lower solar energy variability than the leading mode (about 6%), but a similar value for wind energy (23%). The spatial patterns (Figs. 11a,b) show strong positive correlations in the solar field (greater than 0.6) over the eastern part of the region. Negative correlations in the wind energy field are found over nearly the entire region, although minimum values (0.8) are observed over...
eastern, central, and northern areas. This second mode again indicates a balancing effect between the wind energy in the aforementioned areas and solar radiation in the very east of the region. On one hand (Fig. 11d), positive solar and negative wind energy anomalies are associated with a meridional circulation over the eastern Iberian Peninsula. Weak southerlies are observed over central and southeastern areas, generating positive solar
and negative wind anomalies in those areas. On the other hand, negative solar and positive wind anomalies are associated with a low pressure center in the southeast of the region, over the Mediterranean Sea (Fig. 11e). This center brings northeasterly winds over the eastern part of the region, leading to positive wind energy anomalies, while the frontal activity of this low brings cloudiness to very eastern areas, reducing solar radiation.

e. Annual period

Previous results differ according to the season studied, further emphasizing the seasonal dependence of coupling between the wind and solar energy resources in the region. Therefore, the annual analysis, which averages all seasonal characteristics, produced only two pairs of statistically significant canonical patterns (Table 1). The leading mode time series (Fig. 12c) have a canonical correlation of 0.46, and a clear annual cycle is apparent, with higher values during summer. Monthly and synoptic-scale variability is also evident. This mode accounts for 42% of the solar energy variability, but only about 7% of the wind energy. The spatial patterns show positive correlations in the solar field almost region-wide, with higher values to the west and north (Fig. 12a). For wind energy, positive correlations (about 0.5) are found near the Strait of Gibraltar and mountainous zones of the central part of the region. There is negative correlation (about −0.5) over some southern areas, along the Mediterranean coast near the strait, and in the east. Therefore, the leading annual mode indicates weak but statistically significant annual balancing between solar and wind energy in the aforementioned areas. This mode resembles the leading mode of the spring analysis (Fig. 5), and the third mode of the summer analysis (Fig. 9). The associated atmospheric circulations also resemble the corresponding modes from spring and summer. On one hand, positive solar radiation anomalies in the entire study region and positive wind anomalies at the Strait of Gibraltar (and therefore, negative wind anomalies along the coastal Mediterranean near Gibraltar) are associated with easterly flow over the entire southern peninsula, intensified in the strait area (Fig. 12d). This easterly flow brings cloudiness to the entire study region, reducing the solar radiation availability. On the other hand, negative solar radiation anomalies in the whole study area and negative wind anomalies at the Strait of Gibraltar (and therefore, positive wind anomalies at the coastal areas of the Mediterranean near Gibraltar) are associated with southerly flow at the western part of the Iberian Peninsula (Fig. 12e).

The time series of the second mode have a canonical correlation of 0.4 (Fig. 13c), and demonstrate considerable monthly variability. This second mode accounts for 8% of the variance of the solar field and 13.5% of the wind field. Spatial patterns show weak positive correlations in solar energy over Portugal and the Mediterranean coast (Fig. 13a). Positive wind energy correlations are also
observed (Fig. 13b) in these areas, but values are higher. Therefore, no balancing effect is observed. Atmospheric conditions show that positive solar and wind energy anomalies are associated with southwesterly flow over the western part of the region, which turns into westerly flow in the eastern part. On the other hand, negative wind anomalies are associated with high pressure over the Gulf of Cádiz, which produces weak winds over the region.

f. Balancing times series analysis

Based on the results of the previous section, we further analyzed the balancing between solar and wind energy resources in the study region. In particular, solar and wind energy time series at various locations were compared in cases of noteworthy resource balancing (Fig. 14). The locations were selected on the basis of their correlation (loading factor) values on the wind and solar map, that is, the highest ones (one negative and other positive). The time series were extracted directly from the raw, daily-integrated, and normalized wind and solar energy database, and they were detrended based on linear regression. Figure 14a shows wind and solar energy time series for locations highlighted with a cross in Fig. 4, which are therefore representative of balancing observed during the second canonical mode of winter. Correlation between the time series was $-0.53$, and the percentage of days during winter with opposite sign anomalies was $63\%$. Similarly, Fig. 14b shows wind and solar energy time series for locations highlighted in Fig. 8 (second summer mode). Similar results emerged in this case, with a correlation around $-0.34$, and a percentage of cases with opposite sign anomalies of $62\%$. Figures 14c,d represent locations highlighted in Fig. 10 (first autumn canonical mode) and Fig. 11 (second autumn canonical mode), respectively. The autumn season showed the greatest balancing between solar and wind resources in the region. This is further confirmed by this particular analysis; that is, the time series in Fig. 14c has a correlation of $-0.46$ and a percentage of days with opposite sign anomalies of $63\%$. The time series in Fig. 14d have a correlation of $-0.56$, and a percentage of days with opposite sign anomalies of $71\%$. Figure 14e shows wind and solar energy time series for locations highlighted in Fig. 12 (first annual mode). For this annual case, correlation of these time series is $-0.32$ and the percentage of days with opposite sign anomalies was $58\%$.

Finally, an additional and quantitative study of the balancing was done. At grid points highlighted in Fig. 12 (first annual mode) by crosses, and that correspond to grids with maximum balancing (negative correlation), the energy production of a reference PV plant (grid point with a cross in Fig. 12a) and reference windmill (grid point with a cross in Fig. 12b) were evaluated. The
wind speed and solar radiation time series were extracted directly from the raw data at these locations, and were used for estimating the hourly energy production over the study period (2007). For wind energy, we computed the energy produced by a Vestas Wind Systems A/S V90–2.0 MW windmill, with a rated nominal power of 2 MW. Since the hub of this windmill is at 80 m AGL, wind speed derived from the model was accommodated to this altitude by vertical interpolation using splines. The resulting wind power energy hourly series were normalized, dividing by the respective nominal power, obtaining corresponding wind energy hourly capacity factor time series. Similarly, the hourly production of a reference PV plant was computed following Ruiz-Arias et al. (2012). Specifically, the PV potential for electricity production was calculated based on a traditional fixed PV system with panels inclined 30° over the horizontal and permanently oriented southward. Production was normalized by the nominal power to obtain an hourly capacity factor. Finally, the wind and PV hourly capacity factors were combined in a single series, representative of the combined power. Normalization was also used for this combined time series, for proper evaluation. Then, the standard deviations of the hourly wind and PV capacity factor time series were compared with those of the combined wind and solar capacity factor time series. The standard deviation is a measure of intermittency in production, and therefore may be used to evaluate the balancing between solar and wind energy. Figure 15 shows wind, PV and combined capacity factor time series for selected periods of the year. Balancing is clearly observed in these representative time series, notably those of winter and autumn (Figs. 15a,d). In general, it is clear that combination of wind and solar power smooths the variability of power output. Notably for the entire year, the standard deviations of wind energy and PV capacity factor time series were 0.33 and 0.31, respectively. On the other hand, for the combined capacity factor time series, standard deviation declined to 0.21. To have a reference for the benefit of balancing, we computed the average of standard deviation of combined capacity over the entire study region, assuming the windmill and solar PV plants are located at the same site. The value obtained is 0.24. Finally, we calculated standard deviation of combined capacity factor for the grid points with highest correlation (and least balancing) (highlighted by triangles in Figs. 12a,b), obtaining a value of 0.27. The former analysis was also conducted for the second winter mode (Fig. 4), one of the most significant balancing patterns obtained in the CCA. For this winter case, standard deviation of combined capacity factor is 0.18 at the points of greatest balancing (grid with crosses in Figs. 4a,b). The average value for the entire study region, assuming collocated windmill and solar PV plants, is 0.22, while the value for the grid points with least balancing (highest positive correlation, highlighted by triangles in Figs. 4a,b) is 0.26. In both cases, annual and winter, a substantial reduction in standard deviation of combined capacity.
factor is obtained when locating wind farm and PV plants based on the CCA results. As may be expected, the reduction is greater for the winter case (which shows a noteworthy balancing pattern) than for the annual case (which shows a weaker pattern).

4. Summary and conclusions
In the present work, we have proposed and evaluated a method for analyzing the spatiotemporal balancing between the solar and wind energy resources in a region. The method attempts to find the optimal distribution of wind farms and solar energy plants over a territory, to minimize the variability of energy input into the power supply system. The methodology applies a canonical correlation analysis to solar and wind energy fields in the region, and then analyzes the corresponding coupled spatiotemporal canonical patterns. The method was tested in the southern half of the Iberian Peninsula, covering about 350,000 km². The study region, though
relatively small, possesses considerable spatial variability in the main climate variables, owing to varied topographic features and the influence of the adjacent Mediterranean Sea and Atlantic Ocean. We used wind and solar energy estimates from the Weather Research and Forecasting mesoscale model. Daily-integrated solar and wind (at 30 m AGL) energy fields from 2007 were analyzed, at a spatial resolution of 9 km. Independent seasonal and annual analyses were done, and the atmospheric circulations associated with each coupled canonical mode were investigated.

Results show the existence of valuable balancing between the solar and wind energy resources in the region, but with a marked seasonality. In particular, during winter, a noteworthy balancing was observed between the solar energy resources over almost the entire study region and the wind energy resources near the Strait of Gibraltar. During spring, weak balancing was observed between solar energy near the eastern Strait of Gibraltar and wind energy in the central strait area and mountainous interior of the region, and between solar energy in the southwestern Iberian Peninsula and wind energy in the central and eastern peninsula. Important balancing was evident in summer between the solar energy over almost the entire region and wind energy in the south and east. Finally, the autumn season turned out to have the

![Fig. 15. Capacity factor time series for a PV plant (dashed line), windmill (continuous line), and the combination of both (shaded areas) for selected period along the year 2007. Values were computed for the locations highlighted in Fig. 12a (solar energy) and Fig. 12b (wind energy) using a reference windmill and PV plant. Figures correspond to 10 days selected in each season. In particular, (a) 22 Feb–2 Mar was used as representative of the winter season, (b) 26 May–6 Jun for spring, (c) 16–26 Jul for summer, and (d) 1–11 Dec for autumn.](image)
most important balancing effect. During this season, balancing between the solar and wind energy resources extended over the entire region, although it was more important in the southwestern and southeastern areas. Atmospheric circulations associated with these coupled patterns showed a marked seasonal dependence. Synoptic scale variability greatly influenced the balancing, but so did topography, especially near the Strait of Gibraltar.

The annual analysis, which represents an averaging of the seasonal results, showed only a weak balancing between region-wide solar energy and coastal wind energy near the Strait of Gibraltar and in the eastern part of the region. These relatively poor results from the annual analysis compared to the seasonal ones can be attributed to averaging. That is, coupling between wind and solar energy resources varied considerably in strength, sign, and spatial coverage through the year, resulting in a null effect from seasonal averaging. On the basis of the CCA analysis, we further analyzed time series of the wind and solar energy resources at locations of the greatest balancing. The most important results were found for the second mode during autumn. Wind and solar energy time series representative of this mode showed a correlation of $-0.56$, and $71\%$ of the time the sign of the anomalies was opposite. Finally, when locating reference wind farms and PV plants according to the balancing patterns, their combined power production showed substantially lower variability than production of wind farms and PV plants separately or than the combined production achieved by any other locations.

Our procedure can be easily applied to areas of arbitrary size, to optimize the grid power output. The method facilitates planning of the location of future wind and solar energy plants across a region, so that total electricity production (solar plus wind) will have smaller fluctuations. This may result in greater use of renewables as reliable, base-load electric power. Currently, renewable projects are developed in locations with either maximum wind or sun. In the future, project locations should also take into account the fluctuation of power supply from each renewable. To inform this endeavor in the future, we will augment the present analysis of meteorological balancing with an investigation of load demand.

It should be emphasized that we only attempted a seasonal analysis, to highlight the existence of balancing patterns over the year. This seasonal analysis should be extended to the reference climatic period (i.e., 1981–2010). This would permit evaluation of the stability of the presented seasonal balancing patterns over this reference period, and would make our results more useful for deciding power plant placement. In addition, our results were constrained by the use of model estimates instead of measurements.

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