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Analysis of the intra-day solar resource variability in the Iberian Peninsula

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ABSTRACT

The intra-day modes of variability of the solar resources in the Iberian Peninsula, their associated weather patterns and their impact on the solar power output are assessed in this work. The analysis is performed for yearly and seasonal variability. Firstly, the modes of variability are identified by means of hierarchical cluster analysis. It is computed with two years of measured global horizontal irradiance (GHI) and direct normal irradiance (DNI) data gathered at four stations. Notably, three-hour statistics describing mean and variability of solar radiation are used as input to the cluster analysis. Secondly, synoptic weather patterns associated with each group resulting from the cluster analysis are assessed using sea level pressure and cloudiness data. Finally, the solar PV power yield associated with each mode is evaluated. The yearly analysis reveals the existence of four modes of variability of the solar resource in the study area. The four modes are shown to have a distinctive weather pattern and also specific impacts on solar power generation in the study area. Seasonal analyses show results similar to the annual analysis, but with marked seasonal differences.

1. Introduction

Great efforts have been made along the last decades to make renewable energy a plausible alternative to conventional energy generation system. In particular, the European Council has committed to achieving at least 27% renewable energy penetration in the European Union by 2030 (Commission and Secretariat-General, 2016).

One of the most important drawbacks of integrating high levels of renewable generation in the electricity system, particularly solar energy, is the variability of the resource. Unlike conventional power generation, solar power is conditioned by weather, and is thus intermittent. The power system operators try to keep the balance between generation and load in the grid. Due to the fact that the forecasts of generation and load are not completely accurate, power system operators rely on reserves to manage the anticipated and non-anticipated variability (Yang et al., 2018). The incorporation of the solar energy adds additional uncertainty to the power system from the generation side (Renné, 2014). As a consequence, an increase in the amount of balancing reserves is necessary to keep the grid stable. This increase is related to the historical solar power forecasting error distribution (Matos et al., 2017). Another consequence is the existence of specific economic costs for the integration of the solar energy. The reduction in operation reserves (on average), and consequently the integration costs, through the improvement of the solar forecast, was addressed by Zhang et al. (2015). As solar energy penetration increases, the effect of the resource variability in power grid operation will be more challenging. The case of the Iberian Peninsula grid is particularly interesting, mainly because this grid, constituted by the Portuguese and Spanish grids, is largely isolated from the rest of Europe (General Court, 2015).

A better understanding of solar resource variability and its causes at various spatial and temporal scales would be helpful to develop efficient mitigation solutions (Coker et al., 2013; Engeland et al., 2017). Solar irradiance varies at a wide range of temporal scales (from seconds and minutes to years and decades), associated with processes that operate at spatial scales from thousands of kilometers to a few meters (solar cycle, synoptic-related cloud variability, convection and orographic clouds, aerosol load, etc.).

In general, temporal scales from seconds to minutes are related to local processes, such as convective or orographic clouds, whose area of influence is limited. These scales are relevant for optimal management of a solar power plant (or set of plants) in a limited area (Lave et al., 2012). Temporal scales from tens of minutes to hours (intra-day variability) are often associated with distinct synoptic weather patterns. As the area of influence of these patterns usually reaches hundreds of square kilometers, these time scales are relevant to grid integration objectives (Perez et al., 2016). Finally, climatic time scales (seasons to years), characteristic of the solar cycle, are more appropriate for plant project development (Lohmann et al., 2006; Pozo-Vázquez et al., 2004;

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Pozo-Vazquez et al., 2011; Ruiz-Arias et al., 2016; Santos-Alamillos et al., 2017). On this matter, Gutiérrez et al. (2017) analyzed spatial and interannual variability of the solar PV yield of the Iberian Peninsula.

The temporal variability of solar irradiance as a function of temporal resolution was extensively analyzed (Gueymard and Wilcox, 2011; Lave et al., 2017; Moreno-Tejera et al., 2016; Perez et al., 2011). Moreover, analyses of its spatial variability and the relationship between temporal and spatial scales of variability was addressed in several papers (Barnett et al., 1998; Perez et al., 2012). A common feature emerging from this work is an increment in the correlation with reducing distance and with increasing temporal aggregation (Hoff and Perez, 2012; Mills and Wiser, 2010; Perez et al., 2016). A byproduct of the spatial variability of solar resources is the smoothing effect on PV plant output caused by the aggregation of geographically disperse PV plants (Lave et al., 2012; Marcos et al., 2012; Hoff and Perez, 2012; Wiemken et al., 2001; Zagouras et al., 2014).

Although clouds are the most important factor in solar resource variability, very few papers addressed the relationship between this variability and cloud type and coverage (Kasten and Czeplak, 1980; Salgueiro et al., 2016; Tzoumanikas et al., 2016). The main issue is the lack of appropriate observational records. Instead of observation, Reno and Stein (2013) used cloud categories derived from satellite images to understand and model the spatial variability of solar radiation. Similarly, McCandless et al. (2016) used satellite-derived cloud information to improve short-term solar radiation forecasting.

Cloud regimes are linked to specific weather patterns. Therefore, analysis of these patterns is an important step toward understanding solar resource variability. The relationship between wind power output variability and weather patterns was addressed in several papers (Brayshaw et al., 2011; Correia et al., 2017; García-Bustamante et al., 2013; Ohba et al., 2016; Steiner et al., 2017). These studies indicated that synoptic weather patterns associated with large-scale atmospheric circulations are important to understand wind power variability and can be effective predictors of wind generation variability. Unlike the case of the wind, very few papers addressed the relationship between weather patterns and solar power variability. Recently, Köhler et al. (2017) identified critical weather patterns for solar power integration in Germany. As a consequence, understanding the influence of weather patterns on solar radiation resource variability remains limited.

The present work aims at contributing to the understanding of intra-day modes of variability of the solar resource in the central and southwestern parts of the Iberian Peninsula. A better understanding of this variability and its underlying causes may provide mitigation solutions for solar energy grid integration in the study area, which is characterized by the best solar resources in Europe (Santos-Alamillos et al., 2017). For instance, the knowledge of the atmospheric circulation patterns may help in estimating and forecasting available resources and their intermittency in the coming hours, aiding operation of the system (McCandless et al., 2015). We hypothesize the existence of specific modes of solar radiation intra-day variability in the study area associated with specific weather regimes.

Firstly, hierarchical cluster analysis is performed to obtain the modes of variability of the solar resource. This type of analysis allows the classification of a set of solar radiation values into specific regimes. The analysis is based on global horizontal irradiance (GHI) and direct normal irradiance (DNI) data collected at four stations representative of the study area over a two-year period. Given the objectives of our work, choosing the appropriate temporal scale for the cluster analysis is a critical issue. Here, following Perez and Hoff (2013), three-hour mean and variability statistics computed with 15-min averages based on GHI and DNI values are obtained. These statistics are used as input to the cluster analysis.

Secondly, synoptic weather patterns responsible for the different intra-day modes of solar resource variability are obtained. To this end, we perform composite analyses of pressure reduced to mean sea level (MSLP) and cloudiness data. The solar resource modes are analyzed in the light of their associated weather patterns and cloud regimes. Finally, the aggregated solar PV power yield in the study area associated with each analyzed mode is assessed. Yearly and seasonal analyses are conducted independently.

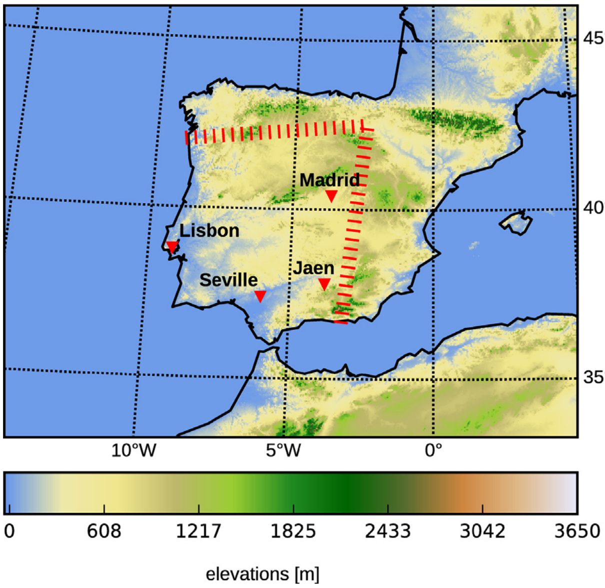

Fig. 1. Digital elevation map showing the location of the four analyzed stations. The red dashed lines delimits the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The work is organized as follows. Section 2 describes the study area while Section 3 describes the dataset and the methodology. Results are presented and discussed in Section 4, while in Section 5 some concluding remarks are proposed. The results of the seasonal analyses are detailed in Appendix A.

2. Study area

This study is based on the analysis of data collected at four radiometric stations, namely, Jaen, Lisbon, Madrid and Seville, located in the central and southwestern Iberian Peninsula (see Fig. 1). The study area accounts for the majority of the currently installed solar power in the Iberian Peninsula.

From a climatic point of view, the study area is located in a transition zone from temperate to subtropical climates. Several studies showed that the atmospheric circulation over the study area is ruled by the semi-permanent Azores Islands anticyclone (Castro-Díez et al., 2002; Trigo et al., 2002; Trigo et al., 2004). As a consequence, the study area shows the same climatic regime regarding cloudiness (Trigo et al., 2002) and solar radiation (Pozo-Vázquez et al., 2004; Pozo-Vazquez et al., 2011; Sancho Ávila et al., 2012; Santos-Alamillos et al., 2012). The position and intensity of the Azores anticyclone changes throughout the year, giving rise to a marked seasonality in their influence area.

From a topographic point of view, the study area may be split into two different parts. The western area is a nearly flat region, with many wide valleys open to the Atlantic Ocean. The Lisbon and Seville stations are located in this part. On the other hand, the central and southern area shows a more complex topography, with several mountain ranges in the south (where the Jaen station is located) and a plateau in the center (where the Madrid station is located). As a consequence of these different topographic characteristics, certain spatial variability in the cloudiness and solar radiation can be anticipated associated with local features (Lauret et al., 2016). In addition, in coastal areas, as for Lisbon,