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A multi-step scheme for spatial analysis of solar and photovoltaic production variability and complementarity

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ABSTRACT

Renewable energy resources are variable by nature. Due to this fact conventional electricity systems, which were designed for centralized generation, have to follow a different management approach when a big share of these technologies take part into the system. The space-time variability characteristics of solar radiation, wind and precipitation are very different and a detailed understanding of them is important for an adequate planning and management of the electricity system.

This paper is focused on solar irradiation as source of energy for photovoltaic (PV) generation, but the proposed scheme can generally be applied to other renewable resources and different solar irradiation applications. A comprehensive methodology to analyze variability and complementarity of solar resource and PV production among sub-regions of a wide area is developed. The photovoltaic energy yield is defined as kWh per kW installed, which facilitates the comparison among sub-regions and allows a comparison with other renewable energies like solar thermoelectric or wind energy. The multi-step approach facilitates the spatial evaluation and comparison among areas and it could be applied to different time resolutions, from a short term analysis to climatological perspective as well as a climate change projections analysis.

The main steps of the method are the application of an objective clustering method for performing a regionalization of the whole domain, the analysis of the temporal variability of solar radiation and photovoltaic energy yield, and the intercomparison of the obtained clusters for examining their complementarity.

As an implementation example, we make use of 30 years of daily satellite data, which is usually considered as the time for defining a climatology, and a long-term overview of solar variability is analyzed over the Iberian Peninsula (IP). In this region, the internal interconnections of the electrical system are strong, but the external interconnections are rather limited. The spatial distribution and variability of photovoltaic (PV) power yield is calculated for different tracking systems. The variability is analyzed on an interannual time scale, which is relevant for energy supply security and year-to-year price stability. The interannual variability shows robustness and stability of solar radiation and PV production on average for the whole domain, but with significant differences among clusters that could allow spatial compensation of PV production. The relationship between the variability of solar irradiation and of PV yield is not uniform among the different clusters. Areas where solar irradiation is higher are more sensitive to tracking type.

The whole process described in the article provides the information of how solar resource and the PV energy yield perform in a limited area and provide the tools to analyze the relationships between sub-areas and their variability. In this sense, this method can be applied for isolated or nearly isolated electric systems located in regions with a variety of climates, or for interconnected systems involving several countries.

1. Introduction

In the past few decades, there has been an increase in the renewable energies installed capacity. Renewable technology prices have decreased rapidly attracting investors to the sector, and political agreements such as the requirements of the European Commission for 2020 are also driving this trend. For photovoltaic (PV) energy a large growing trend is expected in the next years (Eurostat Statistics

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Nomenclature

$B(0)$	direct (beam) irradiance on the horizontal plane
$B_0(0)$	direct (beam) extra-terrestrial irradiation
$B_{0d}(0)$	daily direct (beam) irradiation
$B_d(0)$	daily direct (beam) extra-terrestrial irradiation on the horizontal plane
c	number of clusters where the 2 fit-lines split
c_j	centroid of the cluster j
CH	Calinski-Harabasz validity index
CV	coefficient of variation
$D(0)$	diffuse irradiance on the horizontal plane
$D_d(0)$	daily diffuse irradiation on the horizontal plane
$F_{D,d}$	diffuse fraction
$G(0)$	global irradiance on the horizontal plane
G_{ef}	global effective irradiation
$G_d(0)$	daily global irradiation on the horizontal plane
I_m	intensity from the photovoltaic module
IP	Iberian Peninsula
J	objective function of the Kmeans clustering method: summation over euclidean distances
k	number of clusters
k_i^o	coefficients of the efficiency curve of a inverter
K_{Td}	clearness index
P_{out}	power output from the photovoltaic module
P_{inv}	nominal power of the inverter
p_o	normalized output power of a inverter
PV	photovoltaic
$RMSE_{left}$	root mean squared error of the left-side linear regression
$RMSE_{right}$	root mean squared error of the right-side linear regression
$RMSE_T$	total root mean square error
T_a	ambient temperature
T_c	cell temperature
V_m	voltage of a photovoltaic module
x_i	each point in the cluster, where the point is a vector with elements comprising the daily irradiation time series values at a pixel obtained from satellite images

Explained, 2014).

The natural variability of renewable energy resources like solar radiation and wind presents some challenges for the management of electricity systems, which were designed for conventional technologies like nuclear or thermal power plants. For that reason a thorough knowledge and understanding of space-time features of solar radiation is needed. In the case of solar PV energy, its variability (Widén et al., 2015) can be studied from the perspective of the resource or from the perspective of the PV power output, that includes some aspects of the PV generators involved in variability, like inverters or tilted and tracking panels which increase the complexity of the assessment. There are many studies focused on the short-term variability (Zamo et al., 2014) that analyzed PV production ramps due to changes in solar incident irradiation associated with cloud motion (Cros et al., 2014; Remund et al., 2015). Also, the smoothing effect that a well-spread site planning has on the PV production is being investigated (Marcos et al., 2012; Perpiñán et al., 2013).

Not only short-term scales are important to address renewable resources intermittency but also longer time scales are relevant in order to make the system more efficient and reliable (Davy and Troccoli, 2012). Due to that reason, stakeholders can take advantage of climatological studies of renewable energy resources. Operation and management of the system is done in the short-term and in the long run as well. Consequently, policymakers and operators of the electricity system need an accurate evaluation of resources availability in present and future climate conditions for their mid and long-term planning. The analysis of interannual variability has a particular importance in order to assess stability of the resource and the financial viability of renewable energy plants (Pryor et al., 2006), as well as the likelihood of strong electricity price oscillations like the ones associated for example with the large interannual variations of hydroelectric production.

Regarding that perspective of long-term variability of solar resources, there are studies focused on long series from stations (Sanchez-Lorenzo et al., 2009; Sanchez-Lorenzo et al., 2013; Vázquez et al., 2012) or reanalysis data that identify low frequency changes in solar radiation, as the "dimming" and "brightening" periods (Wild et al., 2005), that show relationship between solar irradiation and anthropogenic aerosols (Nabat et al., 2014). Some studies examine the influence of large-scale circulation atmospheric modes like the NAO (North Atlantic Oscillation) on solar radiation (Pozo-Vázquez and Tovar-Pescador, 2004; Jerez et al., 2013), while others study the spatial variability instead of the temporal variability (Gueymard and Wilcox, 2011).

Some authors make use of regionalization techniques for atmospheric variables in order to analyze them from a climatological point of view (Argüeso et al., 2011) or for solar energy purposes, mainly for

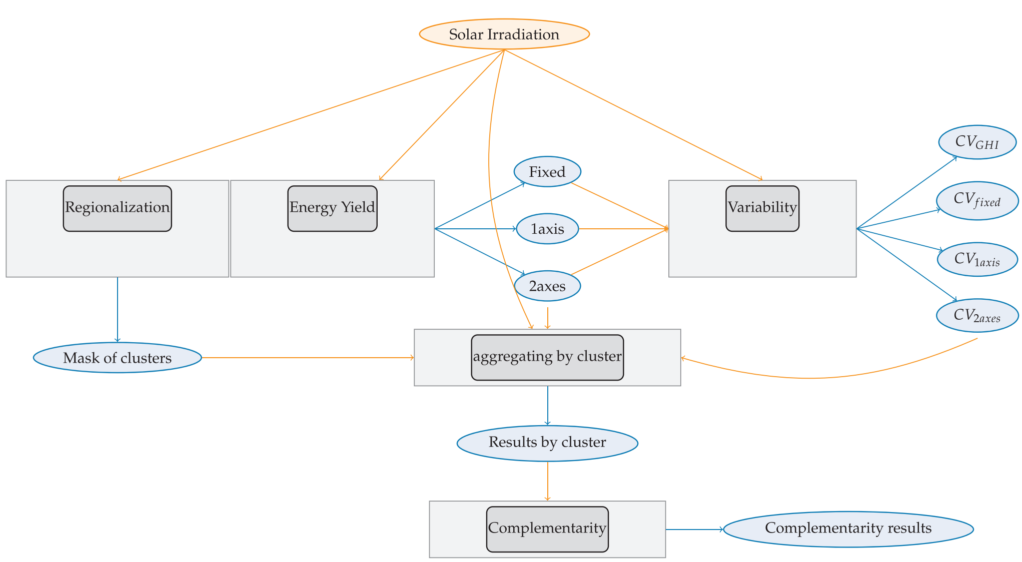

Fig. 1. Scheme: Each gray block represents each of the operations needed to get the variability and complementarity results. Orange ellipses are the data employed and blue ellipses are the results of each stage. If the results of one of the blocks are used as input for another stage, connectors are represented in orange color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)