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A methodology for evaluating the spatial variability of wind energy resources: Application to assess the potential contribution of wind energy to baseload power

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ABSTRACT

We propose a method for analyzing the potential contribution of wind energy resources to stable (baseload) power within a region. The method uses principal component analysis (PCA) to analyze spatiotemporal balancing of wind energy resources and then assesses the optimal wind farm location to reduce wind power fluctuations. The ability of different reference wind turbines, alone or interconnected, to provide stable power is ultimately evaluated at selected locations. The method was tested in the southern Iberian Peninsula, including offshore areas. We used hourly wind energy estimates from the WRF mesoscale model at 3-km spatial resolution for the period 2008–2010. First, results show a valuable spatial balancing pattern between the wind energy resources in the northeast study region and Strait of Gibraltar area. The pattern was found to result from the interaction of mesoscale zonal flow with the complex topography of the region. Second, the results indicate that by taking advantage of the spatial balancing pattern, the optimal allocation and interconnection of wind farms across the region, can substantially reduce wind power fluctuations. This optimal allocation can in some cases generate stable power, thereby contributing to baseload power.

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1. Introduction

In the next decades, wind energy is expected to play a major role in the replacement of fossil fuels by renewable energy sources [1,2]. Given the fluctuating nature of wind resources and their sensitivity to weather patterns, the integration of major wind yields into the existing energy supply infrastructure will be a challenge [3,4]. One way to reduce this power fluctuation of wind energy is to take advantage of the strong spatial variability of this resource. The idea is that since the spatial correlation of wind speed diminishes with distance, the combined output of numerous widely-spaced wind farms should be smoother than the simple output of an individual wind farm. There are numerous studies in the literature that analyze the spatiotemporal variability of the wind energy resource and its consequence for wind power integration [5–9]. In addition, numerous studies have analyzed the benefits of combining wind and hydropower to provide stable power [10–12], but only a few have addressed if, by interconnecting advantageously-distributed wind farms, it may be possible to guarantee a certain amount of wind power output all the time, eventually transforming wind energy into a reliable supply. There is no clear consensus in the literature for evaluating the contribution of wind toward reducing the conventional capacity of power systems. In general, two parameters for describing this contribution have been used: capacity credit and firm capacity. Capacity credit is a measure of the ability of a wind farm or a solar plant to contribute to the peak demands of a power system, maintaining the same security of supply as conventional power plants [13]. This parameter is usually expressed in %. Obtaining the capacity credit is no easy task, since full modeling of the power system is necessary. Several studies have analyzed the wind energy capacity credit, in individual countries and for all Europe [13–15]. The main conclusion was that wind power has capacity credit but is highly dependent on the supporting electric system, wind load factor and penetration level. On average, for a penetration around 20%, the wind energy capacity credit could

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approach 20% of installed power [13]. The firm capacity is defined as the fraction of installed wind capacity that is available with the same probability as that of a thermal plant [14]. With this definition, the firm capacity of wind energy can be used to analyze the potential contribution of wind to provide baseload power, that is defined as the minimum amount of power that must be available to the final customers in all moment. Unlike capacity credit, firm capacity can be assessed relatively easily from pure wind data [6]. In contrast to the capacity credit, the ability of wind energy to provide firm capacity in central and northern Europe has been shown to be limited [16–18]. Underpinning these results are the relatively homogeneous weather conditions and limited topographic features across this area. Studies in other regions of Europe and the world are more encouraging. For instance, Archer and Jacobson [19] showed the existence of wind power firm capacity in the Midwestern United States, Cassola et al. [20] in the isle of Corsica (France) and Kempton et al. [21] in offshore areas along the east coast of the United States. In this study, a method for analyzing the potential contribution of wind energy to stable power in the Andalusian region of southern Spain is proposed and evaluated. The method is based on Principal Component Analysis (PCA) to obtain spatiotemporal variability patterns of wind energy in the region. Based on analysis of these patterns, the best wind farm locations to reduce wind power fluctuations through their interconnection are then assessed, to optimally reduce the wind power fluctuations. Data for the analysis consist of 3-km spatial resolution gridded wind energy time series across the Andalusian region, including offshore areas, derived from mesoscale Numerical Weather Prediction (NWP) model simulations. Finally, the firm capacity provided by different combinations of offshore and onshore wind farms is estimated. Although relatively small, the study region is characterized by varied topographic, geographic and weather conditions. This fact anticipates the existence of considerable wind speed spatial variability and, ultimately, spatial balancing of wind energy resources. This paper is organized as follows: Section 2 deals with the study area, data and method. Section 3 describes the results. Finally, in Section 4, a summary and conclusions are presented.

2. Methods and study area

2.1. Study area

The study region (Fig. 1) of Andalusia is in the southern Iberian Peninsula (IP), and covers an area of 87.000 km^2. From a topographic point of view, the region may be split into two different parts. The western part is a nearly homogeneous flat area, open to the Atlantic Ocean. The eastern part has very complex topography and is isolated from the Atlantic influence by the Sierra Nevada and Cazorla mountain ranges (Fig. 1). Atmospheric circulation across the study region is dominated by a semi-permanent subtropical high-pressure centre over the Azores islands. The position and intensity of this centre changes through the year [22]. The study region is bounded on the south by the Atlantic (western part) and Mediterranean (eastern part), with about 900 km of coastline. One of the most important features regarding wind energy is the existence of strong, semi-permanent winds near the coast of the Strait of Gibraltar. Low-speed winds are channeled and accelerated through this 11 km-wide topographic feature. Despite the relatively small size of the region, there is a remarkable surface wind speed spatial variability across it, caused by interaction of mesoscale circulations with the topographic features [23]. The geographic, topographic and climatological characteristics of the study are fully discussed in Refs. [24,25]. The study region has areas of great significance for offshore wind energy, especially near the Strait of Gibraltar [26,27]. Although development of offshore wind farms in these areas is in its early stages, the offshore wind energy resource is addressed herein.

2.2. Data

Region-wide wind energy resources at 80 m above ground level (m.a.g.l.) were obtained from integrations with the WRF (Weather Research and Forecasting) NWP (Numerical Weather Prediction) model [28]. Simulations were conducted for three years (2008–2010). The model configuration included three nested domains, with 27, 9 and 3 km spatial resolutions (Fig. 2). We used 36 vertical levels, 8 levels within the lowest 1000 m.a.g.l. The five lowest vertical levels, which are important for wind energy applications, were approximately located at 4, 18, 43, 64 and 80 m.a.g.l. Hourly data from this last level in the third nested domain, with 3-km spatial resolution and centered on the study region, were used in the study. The analysis included offshore areas as much as 20 km from the coast, a distance considered feasible for offshore wind energy projects [29]. The physical configuration of the model was selected based on results of an evaluation study of WRF model performance in the study region [25], and we used initial and

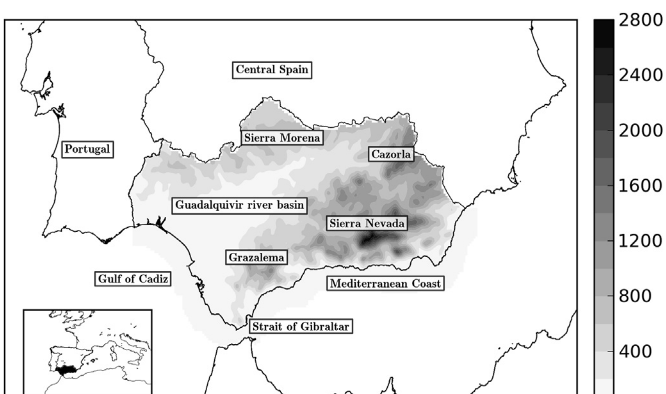

Fig. 1. Location (inset, bottom right) and principal topographic and geographic characteristics of study region. Gray scale colors indicate elevation based on the 3-km spatial resolution Digital Elevation Map used in the model simulation to derive study data. Scale at right indicates elevation in meters above sea level.

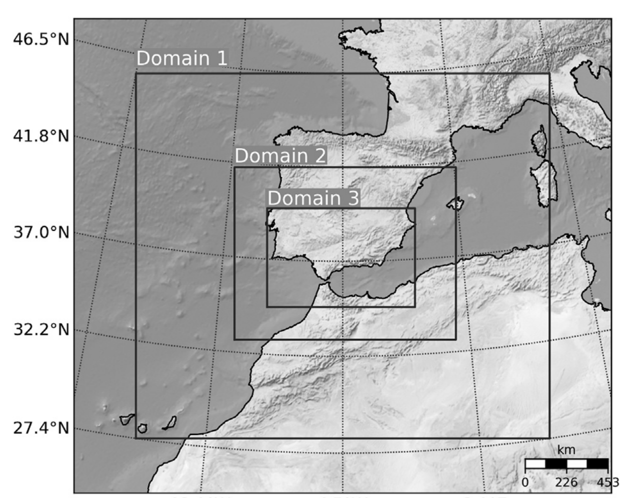

Fig. 2. Spatial configuration of domains for numerical simulation: three nested domains with 27, 9 and 3 km horizontal resolutions. Data from the inner domain (3 km) were analyzed.

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