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Classification of days according to DNI profiles using clustering techniques

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ABSTRACT

A methodology to classify days as a function of the state of the sky for Concentrated Solar Power (CSP) plant operation is proposed. For this purpose, three indexes are used to characterize the energy, variability and time distribution of the DNI and to define the type of days by means of clustering techniques. Two sets of indexes are tested and compared. The energy of days is represented by the transmittance index, k_b. Two indexes are used to characterize the variability of the DNI: persistence index of the instantaneous k_b values (POP_D) and Variability Index (VI). Equivalent indexes have been previously used to classify the types of days using Global Horizontal Irradiation (GHI). A novel index to define the time distribution of the DNI daily energy is introduced. Clustering analysis is applied to thirteen years (2000–2012) of 10-min DNI measurements recorded in Seville (37.40°N, 6.01°W) by the Group of Thermodynamics and Renewable Energy (GTER) at the University of Seville. The k-medoids algorithm is used for cluster analysis. Through the use of well-known internal validity indexes and with the help of the L-method, the optimum number of clusters (types of days) is found to be 10. The results are compared with the assessment carried out by five experts on a reference set composed of DNI daily curves from two years (2010 and 2011). This comparison reveals a better coincidence when the clustering is performed using *VI*.

1. Introduction

The solar resource assessment for a feasibility analysis of a Concentrated Solar Power (CSP) plant is usually based on annual, monthly and, in some cases, daily Direct Normal Irradiation (DNI) data (Cebecauer and Suri, 2015; Pagola et al., 2010; Wilcox and Marion, 2008). The aim of these studies is to characterize statistically the solar resource of the location in these temporal scales. This information is used at different stages of a CSP plant project, from the feasibility analysis to the daily or hourly electricity generation forecast. However, the production of a CSP plant is not directly proportional to the energy radiation received; it depends on when (time of the day) and how (with a low or high variability) is received. A day with highly variable DNI because of the frequent passage of clouds can have the same energy as another with very stable DNI during a fraction of the day and yet the electricity generation can be very different because the operation of the plant will be very different, too. Therefore, a methodology to classify the days that takes into account the intraday variability and temporal distribution, besides the daily energy, could help to better characterize the solar resource from a CSP plant standpoint. Since temporal distribution and variability affect the performance of CSP plants, this characterization can be useful from the design stage to the definition of the operation strategy of the plant regarding different aspects like the thermal storage dispatch or the commercialization of the electricity generated. For example, Kraas et al. (2013) have shown that the DNI forecasting error increases with variability, resulting in penalties derived from incorrect power generation forecasts in the electricity market.

The classification of the days according to the solar radiation can be approached from a qualitative or quantitative standpoint (Kang and Tam, 2013). From a quantitative standpoint, the quantity of daily energy recorded in a location is evaluated. This approach follows the TMY3 methodology (Wilcox and Marion, 2008) and the majority of methodologies used to characterize the long-term behaviour of the solar radiation for feasibility analyses of CSP plants (Cebecauer and Suri, 2015; Fernández Peruchena et al., 2016; Pagola et al., 2010). The qualitative classification has been studied for decades by means of the clearness index. Liu and Jordan introduced this concept in 1960 (Liu and Jordan, 1960). The clearness index is the ratio between the global and

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Nomenclature

k_b	transmittance index	I_{cs}	direct normal irradiance in clear sky conditions
k_t	clearness index	I_{sc}	solar constant
H^d_{bn}	daily direct normal irradiation	ε_0	the Earth-Sun distance correction factor
H^d_{cs}	daily direct normal irradiation in clear sky conditions	α	solar elevation angle
I_{bn}	direct normal irradiance		

the extra-terrestrial radiation on a horizontal surface. This index has been widely used in different intervals of temporal integration (Perez et al., 2011; Skartveit and Olseth, 1992; Tovar-Pescador, 2008). The daily clearness was initially used as a classification criterion to categorize the days into three types: clear days, cloudy days, and overcast days (Lam and Li, 1996; Li and Lam, 2001). This classification proved insufficient for solar energy applications. The operation and the production of two days with similar k_t can be very different.

With the development of solar technologies, new classification methods introduce the combination of the daily clearness index with other parameters or parameters based on the clearness index in other temporal scales. The latter parameters provide more qualitative information to classify the days by considering the state of the sky. Muselli et al. (2000) characterize classes of typical days according to some parameters elaborated from hourly clearness index profiles. One parameter estimates the perturbation state of the hourly k_t values by considering the integral of the squared second derivative of the hourly clearness profile. Harrouni et al. (2005) uses the fractal dimension of Global Horizontal Irradiance (GHI) curves along with the daily clearness index as classification indexes. Rahim et al. (2004) and Baharuddin and Rahim (2010) classify the days using the cloud fraction and the sunshine duration applied to building design, finding similar results in both cases.

With the inclusion of new parameters, some studies propose increasing the number of the types of days or the states of the sky. Soubdhan et al. (2009) identify 4 different types, analysing instantaneous clearness indexes by means of the combination of Dirichlet distributions that model the clearness index distribution curves. Calbó et al. (2001) try to classify the days into 5 and 9 groups, testing different parameters derived from GHI and Diffuse Horizontal Irradiance (DHI) measurements. The best results are found for the 5 types of days compared with human observations. Umemiya and Kanou (2008) integrate the 15 classes proposed by the CIE standard in 7 classes, using the atmospheric turbidity, the clearness index, the brightness and the normalized global illuminance as classification parameters. Kang and Tam (2013) assess the probability of persistence of the instantaneous clearness index and, with the help of the daily clearness index, suggest classifying the days into 10 types. In the literature, there is neither a clear consensus about the number of types of the states of the sky, nor the most proper parameters to identify them.

Most of the parameters used to classify the days are calculated from the global component. Calbó et al. (2001) suggest that the diffuse component is a better discriminant factor than the global radiation. The DNI seems to be a better discriminant factor, too, given its higher sensitivity to cloud passages and the absence of geometrical effects. Perez et al. (2011) use the transmittance index, calculated from hourly DNI values, as an input to characterize the intrahourly variability of the GHI. M Gastón-Romeo et al. (2011) classify the days into 4 classes through clustering techniques that use the morphology of the DNI curves. This methodology is oriented to establish a classification of days useful for CSP. The use of the Mathematical Morphology-based technique maintains the dynamic pattern of the DNI curves, which is what helps characterize the variability of the DNI, but the temporal distribution of the energy is lost.

In this work, we propose a methodology to classify the state of the sky from DNI measurements, which can be useful for CSP plant analysis and operation. For this purpose, two combinations of parameters that represent the energy, the variability and the temporal distribution of the DNI are tested. Conventional clustering techniques are used to define the number and identify the features of the types of days. The parameters are calculated from 13 years (2000–2012) of DNI measurements recorded in Seville (Spain). Both options are validated by comparison with the visual classification carried out by 5 experts from two years of DNI curves.

2. Experimental data

The database used for this work corresponds to thirteen years (2000–2012) of DNI measurements recorded in Seville (37.40° N, 6.01° W) by the Group of Thermodynamics and Renewable Energies (GTER) of the University of Seville. These measurements were recorded every 5 s with an Eppley Normal Incidence Pyrheliometer (NIP) mounted on a Kipp & Zonen 2AP 2-axis tracker. This pyrheliometer is considered a secondary standard device according to ISO specifications. The hourly and daily uncertainty specified by the manufacturer is ±1%, assuming proper maintenance of the instruments. The GTER station follows a maintenance and calibration procedure according to the recommendations from the instrument manufacturers. The database passed a quality control check (Moreno-Tejera et al., 2015), and it was filled by applying gap filling techniques (Moreno-Tejera et al., 2016). The DNI database was averaged every 10 min for this implementation.

3. Methods

3.1. Classification indexes

From a CSP plant point of view, there are three useful features of the DNI to take into account for grouping the days: the daily energy, the distribution over time of this energy and the variability (high frequency changes) of the instantaneous values caused by the passage of clouds throughout the course of the day. The aim of this work is to identify a good combination of indexes that help classify the days as a function of these features.

3.1.1. Daily energy characterization index

The first methods proposed in the literature to classify the state of the sky were based on the daily clearness index, k_t (Iqbal, 1983; Kudish and Ianetz, 1996). The k_t index is defined (Liu and Jordan, 1960) as the ratio of the global radiation and the solar extraterrestrial radiation on the horizontal surface in instantaneous values or for an interval of time. If we are interested only in the direct component, we can find in the literature a similar index that relates the daily DNI with the value of this component in the absence of atmosphere (Tovar-Pescador, 2008) or in an ideal clear sky condition. This is the definition of the transmittance index (k_b) introduced by Skartveit and Olseth (1992):