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Comparison of the Representativeness of Solar Radiation Type of Days from the Viewpoint of the Production of Parabolic Trough and Central Receiver Plants

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Abstract. The classification of days according to the solar radiation features is one of the tools frequently used for the solar resource assessment, modelling or forecasting. Recent studies discuss the appropriate classification method or number of types of days, but these studies usually don't take into account, at least in an explicit way, the relation between the types of days and the yield of solar plants. In this work, we compare the representativeness of the types of days defined by two classification methods from the viewpoint of the production of a Central Receiver (CR) and a Parabolic Trough (PT) solar plant. The selected classification methods are based on the daily solar radiation features: energy, variability and temporal distribution. So, in a first step, the days of a period of 16 years of measurements recorded in Seville (Spain) are classified by these two methods. In a second step, the daily gross productions of both CSP plants are estimated using System Advisor Model program. Then, the representativeness of the types of days of each classification method is evaluated according to the production of the CR and the PT plant by means of a methodology based on the clear sky yield index or k_p index. Finally, the ARE and the annual relative RMSE and the MAE for the plants and classification methods analyzed are compared. Then, we can conclude, that the representativeness of the types of days of a classification method has a certain dependence on the plant that depends on the classification method applied.

INTRODUCTION

The classification of days according to the solar radiation features is one of the tools frequently used for the solar resource assessment, modelling or forecasting [1]. Recent studies discuss the appropriate classification method or number of type of days [2], but these studies usually don't take into account, at least in an explicit way, the relation between the types of days and the yield of solar plants.

In a previous study, Moreno-Tejera et al. [3] compare the behaviour of two classification methods from the viewpoint of the production of two Parabolic Trough (PT) solar plants with different configuration finding certain differences. In this work, the representativeness of the types of days of the solar radiation classification methods applied by Moreno-Tejera et al. [3] is evaluated from the perspective of the production of a Central Receiver (CR) and a Parabolic Trough (PT) solar plant. To this end, in a first step, the days of a period of 16 years of measurements recorded in Seville (Spain) are classified by these two methods: the clustering classification method of Moreno-Tejera et al. [4] and a classification method based on the daily k_t index [5]. In a second step, the daily gross productions of the CSP plants are estimated using System Advisor Model programme (SAM, https://sam.nrel.gov/). The CSP plants modelled are similar to two real plants currently in operation: the PT plant Andasol 3 (Spain) (https://solarpaces.nrel.gov/andasol-3) and the CR plant NOOR III (Morocco) (https://solarpaces.nrel.gov/noor-iii) Then, the representativeness of the types of days of each classification method is evaluated according to the production of the CR and the PT plant by means of a methodology based on the clear sky yield index or k_p index previously published by Moreno-Tejera et al. [3]. Finally, the Annual Relative Error (ARE), the Mean Absolut Error (MAE) and

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the Root Mean Square Error (RMSE) metrics for the plants and classification methods analyzed are compared in order to assess the influence of suitability of the classification methods for each type of plant.

INPUT DATA AND CLASSIFICATION METHODS

The meteorological database used for the evaluation of the classification methods covers sixteen years (2000-2015) of DNI and GHI measurements recorded every 5 seconds in Seville (37.40° N, 6.01° W) by the Group of Thermodynamics and Renewable Energy (GTER) of the University of Seville. These records are averaged every 10-minutes and used as input to simulate the modelled plants. Each day of these sixteen years is classified by means of two classification methods according to DNI and GHI features.

The first selected classification method is based on the daily clearness index. This method is frequently used in the literature [3] to help to identify the state of the sky due to its simplicity. The daily clearness index or kt is defined as the ratio between the daily GHI and the daily extraterrestrial horizontal radiation:

$$k_t = \frac{H_{g0}^d}{H_0^d} \tag{1}$$

where H^d_{g0} is the daily horizontal global radiation and H^d_0 is the daily horizontal extraterrestrial radiation.

Several boundaries have been proposed in the literature to classify the sky conditions usually, in three types of days: clear sky (CS), partially cloudy sky (CL) and cloudy sky (OV). In this study, we have selected the boundaries proposed by Lam [5]:

$$\begin{aligned} &a)\ overcast\ to\ cloudy\ sky && if\ \ k_t^d \leq 0.3 \\ &b)\ cloudy\ to\ partly\ cloudy\ sky && if\ \ 0.3 < k_t^d \leq 0.65 \\ &c)\ partly\ cloudy\ to\ clear\ sky && if\ \ k_t^d > 0.65 \end{aligned} \tag{2}$$

The second classification method is proposed by Moreno-Tejera et al. [4] and uses three dimensionless indexes defined from DNI measurements to classify the days. These indexes take into account three relevant features of the DNI curves from a CSP viewpoint: 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 index used to characterize the daily energy of the DNI is the transmittance index (k_b) introduced by Skartveit and Olseth [5]. This index is defined as:

$$k_b = \frac{H_{bn}^d}{H_{CS}^d} \tag{3}$$

where H_{bn}^d is the daily DNI and H_{CS}^d is the daily DNI irradiation under clear sky conditions. To calculate the DNI in clear sky conditions, the ASHRAE clear sky model [6] is used. The parameters of this model have been empirically fitted with the instances of lowest atmospheric attenuation for every day of the year recorded in Seville [4].

The variability index, or VI, represents the daily DNI variability. The VI, introduced by Stain et al. [7] for the GHI, is applied by Moreno-Tejera et al. [4] for the DNI and defined as the ratio between the length of the DNI curve and the length of the maximum enveloping clear sky day curve:

$$VI = \frac{\sum_{k=2}^{j} \sqrt{\left(I_{bn_k} - I_{bn_{k-1}}\right)^2 + \Delta t^2}}{\sum_{k=2}^{j} \sqrt{\left(I_{cs_k} - I_{cs_{k-1}}\right)^2 + \Delta t^2}} \tag{4}$$

where I_{bn} is the DNI average every 10 minutes, *Ics* is the maximum clear sky DNI average every 10 minutes, Δt refers to an interval of 10 minutes, and *n* is the number of 10-minute intervals of the considered day. This index is normalized dividing by the maximum VI obtained for using in the classification method.

Finally, Moreno-Tejera et al. [4] propose a new index that informs about the fraction of energy concentrated during the morning. The *morning fraction* is defined as the ratio between the accumulated DNI in the first half of the day and the accumulated DNI for the whole day. This index allows knowing if the daily radiation is concentrated in the first or the second part of the day:

$$F_m = \frac{H_{bn\_m}^{d}}{H_{bn}^{d}} \tag{5}$$

According to these three indexes, the Method 2 classifies the days applying clustering techniques in 10 types of days from the solar radiation viewpoint. A detailed description about the clustering techniques applied can be found in [4]. The *medoids* (or centers of the clusters) of each cluster or type of day are represented in Fig. 1. In this figure, the *medoids* of the clusters are grouped by similar temporal distribution in columns. Within each column, the *medoids* are grouped by variability and energy levels. Note that one balanced day (central column) with medium energy could have more energy than a morning day (left column) with high energy. To help to identify each type of day with its features, each cluster is called with the first letter of its type of temporal distribution ("M" morning, "B" balanced and "A" afternoon) and the first letter of its level of energy ("H" high, "M" medium, "L" low and "N" null).

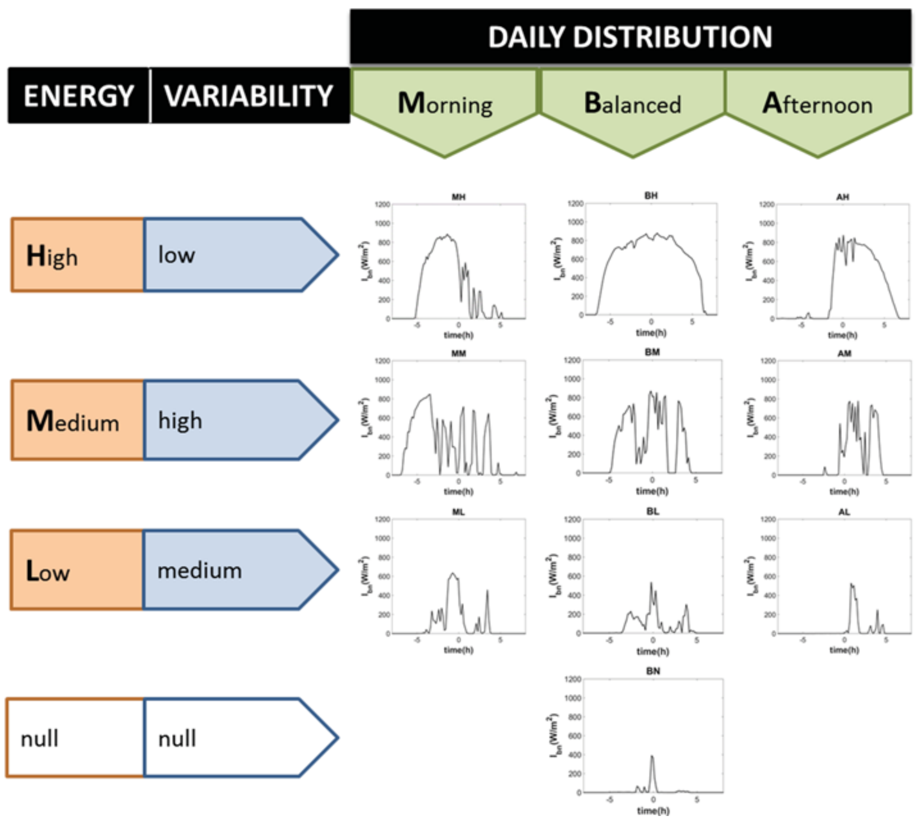

FIGURE 1. DNI representation of the days corresponding to the cluster medoids (Figure from:[3])

METHODOLOGY

Plants Models and Simulation

Two CSP plants with different technologies have been selected to compare the adequacy of the classification methods: a parabolic trough (PT) plant and a central receiver (CR) plant. Both have the same storage capacity in terms of equivalent hours (seven and a half hours). The PT plant has an installed net capacity of 50 MWe and is modelled with the same main characteristics as the solar plant Andasol 3, sited in Spain. The CR plant has an installed net capacity of 150 MWe and is modelled with the same main characteristics as the solar plant NOOR III, sited in Morocco.

TABLE 1. Main technical data used in SAM to model the selected plants

Parameter	PT	CR
Storage capacity (h)	7.5	7.5
Installed Net capacity (MWe)	50	150
Reference ST plant:	Andasol 3	Noor III

Both plants have been modelled in System Advisor Model programme (SAM, https://sam.nrel.gov/) to estimate their gross electrical production for the sixteen years of 10-min DNI measurements for the location of Seville, Spain.

The operation strategy of the plants has been defined to provide full power output during the maximum possible time. The purpose of defining this operating strategy is to use all the remaining energy in the storage tanks after the sunset, so that the TES is empty at sunrise of the next day. The large capacity of the storage system permits the generation of electricity during the first hours of the next day. So, to avoid the effect of the energy collected during a given day on the assessment of the next day, the electricity yield is computed from 4:00 a.m. to 3:50 a.m. of the next day.

Evaluation of the Production

To evaluate the types of days from the viewpoint of the production of both plants, we use a methodology previously published [8]. This methodology is based on a dimensionless index called the clear sky yield index or k_p. This index compares the production of a plant for a period (one day in our case) to the production that could be generated for the same period under clear sky conditions.

$$k_p = \frac{P^d}{P^d_{cs}} \tag{6}$$

where P^d is the daily electric energy produced by the plant and $P_{CS}{}^d$ the daily electric energy produced by the plant under clear sky conditions.

To evaluate both classification methods, first the statistical characterization of the k_p values of each type of day is analysed comparing its distribution to the rest. The aim of this comparison is to suggest some improvements in the number of groups proposed, merging or subdividing groups. Then, the median k_p value of each type of day is selected to estimate the daily production of each day of the database.

The daily differences between the production estimated by the median k_p value and the production of the plants obtained by SAM are compared by means of the Annual Relative Error (ARE), Mean Absolut Error (MAE) and Root Mean Square Error (RMSE) metrics.

RESULTS

To evaluate and compare the results of both CSP plants, we calculate the ARE and the annual relative RMSE and the MAE for each plant and classification method. Considering that the installed net capacity of the plants is quite different, the annual relative RMSE and MAE metrics are defined as the ratio between the metrics and the mean daily production of the whole dataset. In Fig. 2, 3 and 4, we represent the relative RMSE, the relative MAE and the ARE for the different classification methods evaluated: method 1 (M1) based only on the k_t index; method 2 (M2) based on the k_b, *VI* and F_m indexes and methods 3 (M3) and 4 (M4), also based on k_b, *VI* and F_m but dividing in two and three subgroups, respectively the group with more variability. In Fig. 2, we can observe that, for both plants, M4 shows the best performance in terms of RMSE, although closely followed by M3 and M2, while M1 provides the worst results. In general, the results for the CR plant are better than those for the PT plant, except in the case of M1, in which case they are similar. The figures of Fig. 2 also show that the difference between the relative RMSE of the M1 and M2 is 14 % for the PT plant and 20 % for the CR plant and these differences increase when the number of subgroups of BM type of day increase. The difference between the M1 y M4 is 23% for PT plant and 32% for CR plant.

As shown Fig. 2 and 3, the annual averaged relative RMSE and MAE values follow similar behaviors. As in RMSE case, MAE values achieve lower values for the CR plant. We also can observe that the percentage relative difference between the annual averaged RMSE value of M3 and M4 (using M3 as reference) is 3% for the CR plant and 6% for the PT. In the MAE case, the percentage relative differences obtained are similar to those obtained for RMSE both for CR and PT plants.

Finally, in Fig. 4, the ARE values for the M1 show a behavior less steady than other methods along the period, overestimating in some years and underestimating in others the annual production of the plants more significantly than the other methods. In the methods based on the k_b, *VI* and *Ft* indexes, the ARE values just exceed the 5 % in the year 2002, showing the best results for the M3 and M4, among which differences are not appreciated.

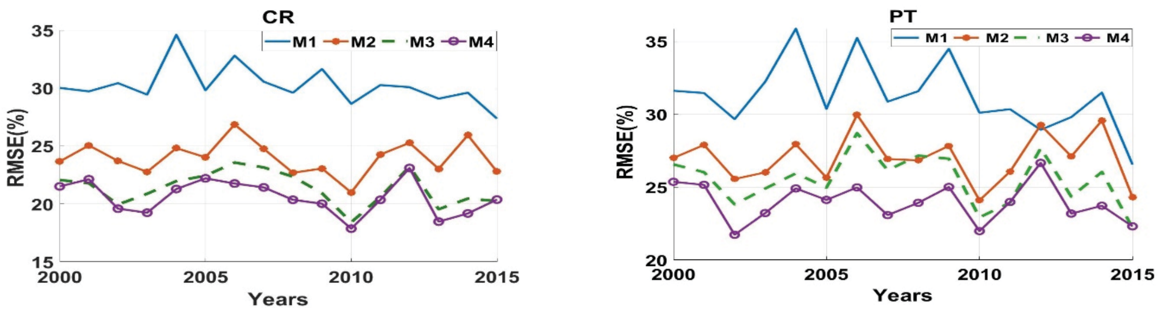

FIGURE 2. RMSE of the estimation of the daily gross production for the CR (left) and PT (right) plants through the k_p median values of the type of days for each classification method

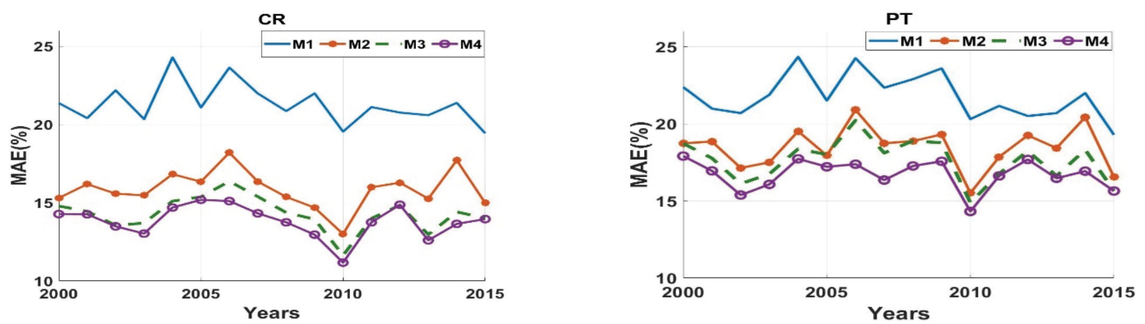

FIGURE 3. MAE of the estimation of the daily gross production for the CR (left) and PT (right) plants through the k_p median values of the type of days for each classification method

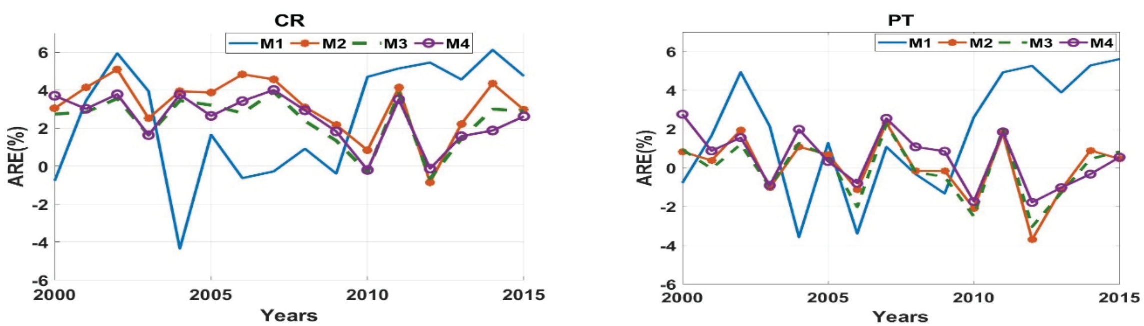

FIGURE 4. ARE of the estimation of the daily gross production for the CR (left) and PT (right) plants through the k_p median values of the type of days for each classification method

CONCLUSIONS

In this work we conclude that the representativeness of the types of days of a classification method has a certain dependence on the plant technology. The method based only on the k_t index results in the highest RMSE values for the two technologies compared, since this method uses a low discrimination in cloudy type of days. The results reached with the classification method based on k_b, *VI* and F_m indexes are better in both cases. The results also show that the classification obtained by direct application of this classification method works better for the CR technology, since the further refinement by subdivision or merging of certain groups based on the distribution of k_p only requires the subdivision of one type of days (the type of day with maximum variability) in two subgroups to obtain a substantial improvement of the results, whereas a greater number of modifications (subdivision of the type of day with maximum variability into three groups and the merger of three type of days with temporal distribution not balanced) is required to obtain a comparable improvement in the case of the PT technology.

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