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Short and medium-term cloudiness forecasting using remote sensing techniques and sky camera imagery

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ABSTRACT

The increasingly widespread use of CSP (concentrated solar power) plants to produce electricity has generated a constant search to improve and optimize final production. These plants are looking for new technologies and methodologies that offer significant, reliable strategies which can be applied to their systems. Clouds are hydrometeors which affect solar radiation, decreasing its value and, consequently, electricity production. Knowing when solar radiation is obstructed by clouds provides useful information to CSP operators to adapt electricity production to the cloud presence, optimizing electricity production processes. As a result of this necessity to study cloud cover, short and medium-term cloudiness forecasting is presented here, where cloudiness is predicted for the following three hours.

1. Introduction

Electricity generation in CSP (concentrated solar power) plants has increased over recent decades. Up to now, studies have been carried out relating to electricity production [1,2] or focused on production schemes, Oak et al. [3]. Other works have studied electricity demand attending to factors involved in production such as the study developed by An et al. [4].

In CSP plants, the energy obtained from the sun and the subsequent electricity transformation is conditioned by the presence of clouds. Suitable atmospheric conditions are desired for the collection system to operate correctly the plants, avoiding also some technological problems as the presented by Zidanšek et al. [5]. Clouds over an area may remain for a long period or just for a few minutes. Therefore, it is important for CSP plant operators to know when the solar field provides acceptable conditions (clear skies) to produce electricity. Accordingly, it is vitally important to adapt electricity production to cloud presence in order to maximize CSP plant production.

Traditional cloudiness studies appear to improve and optimize the management of these CSP plants using different technologies to identify clouds. Satellite technology, amongst other applications, is used to study atmospheric features (cloudiness, aerosols, rain, etc.); this is the case in Zarzalejo et al. (2005) [6], where the authors used satellite images and artificial intelligence techniques to estimate cloud cover, whereas Kisi [7] employed these techniques to estimate solar irradiance. Artificial neural networks have frequently been utilized in solar radiation estimation. A study about this issue was presented by López et al. [8], in which the network input parameters were chosen to model direct irradiance. A global solar irradiation estimation was made by Rusen et al. [9], where two different models were combined: one focused on the satellite-based HELIOSAT method and the other on a ground-based linear-type model. A special use for satellite images is the validation of traditional models in terms of solar radiation estimations. Such utilization was applied in a work presented by Moreno et al. [10], in which the authors showed a validation of daily global solar irradiation estimations in Spain with good results. Furthermore, satellite images have been used to classify sky conditions, a case in point being the study by Ghosh et al. [11], where the authors split the sky into three different types: cloudless, partially-cloudy and overcast. In a recent study, Escrig et al. [12] used Meteosat satellite images to study cloud cover, classifying the clouds into three different layers (high, medium and low), so as to study their motion based on the Maximum Cross-Correlation method presented in Refs. [13–16].

Nevertheless, satellite imagery is not the only technology related to the study of cloudiness. Increasingly, hemispheric sky cameras are emerging devices used as a ground view approach to

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cloud cover studies. Authors such as Gueymard [17] used these cameras to study the impact of aerosols on solar radiation. Olmo et al. [18] used an all-sky (charge-coupled device, CCD) camera to determine aerosol optical depth. As is shown in Refs. [18], sky cameras have great potential in monitoring atmospheric features such as cloud detection, cloud classification, aerosol properties etc. Cloud cover was also studied by Kassianov et al. [19], who established a model representing cloud coverage using a TSI (total sky imager) sky camera. In the research set out by Cazorla et al. [20], the authors used the red/blue reasoning in sky camera images along with a KNN (K nearest neighbor) classification algorithm to estimate cloud cover. Applying a KNN classification algorithm, Heinle et al. [21] made a sky classification, dividing the sky into seven groups; this technique had a success rate of about 75%. Martínez-Chico et al. [22] combined DNI (direct normal irradiance) and sky camera imagery to perform a cloud classification (into four groups) aiming to show the attenuation of radiation based on cloud type. Furthermore, Thuillier et al. [23] used a sky camera to associate solar irradiance enhancement with thin cloud presence. However, sky cameras have a problem related to image processing. In Refs. [20,21,24–26] the authors stated that the solar disk area appeared saturated. Some authors, conversely, removed or blocked this area [20,21,25] and yet others Long et al. [24], mistakenly classified the solar disk area. Kazantzidis et al. [26[proposed the use of DNI to solve this problem. In an attempt to tackle this problem, Alonso et al. [27] developed a methodology to identify the pixel saturation in the solar disk area using radiometric data. Consequently, a full-sky camera image processing was carried out by Alonso et al. [28], where clouds were identified and the saturation problem in the solar disk area was solved.

In this work, a methodology for forecasting cloudiness in the short- and medium-term (1–180 min) is presented, using remote sensing techniques in MSG (Meteosat Second Generation) satellite imagery and TSI-880 model sky camera imagery combined with radiometric data.

2. Materials and methods

2.1. Data collection

Data from the years 2010 and 2011 have been used. Cloudiness forecasting was carried out separately using satellite and sky-camera images.

With respect to cloudiness forecasting, earth pictures were taken every 15 min. From a total of 12 spectral channels from the MSG satellite, five were used in this work (VIS 0.6, VIS 0.8, IR 3.9, IR 10.8 and IR 12.0) [29].

For each of the five chosen channels, a 121x161 pixel raster image, centred on the University of Almería, was saved and used via the algorithm whenever the solar altitude was higher than 10° - in order to avoid mistakes in cloud detection due to the low brightness in the images.

For prediction using the total sky camera, images from a sky camera, with a rotational shadow band (namely a *TSI*880 model) were collected every minute and the solar altitude was higher than 5° - in order to avoid the pyranometer's cosine effect. Additionally, diffuse and global irradiance measurements were taken from two *CMP* 11 *Kipp&Zonen* pyranometers, and direct irradiance from a *CH* 1 *Kipp&Zonen* pyrheliometer; these were installed on a two-axes solar tracker.

The testing facility is located at the Solar Energy Research Center (CIESOL) at the University of Almería, Spain (36.8°N, 2.4°W, at sea level), which has a Mediterranean climate and a high maritime aerosol presence.

The methodology used for the cloudiness forecasting and presented here is divided in two main blocks: one centred on cloudiness forecasting using remote-sensing techniques (MSG satellite imagery) and the other on forecasting using sky-camera images and radiometric data.

2.2. Cloudiness forecasting using MSG satellite imagery

Using satellite images, cloudiness is predicted for up to 3 h ahead. Firstly, the clouds are detected. Then, an algorithm analyzes and detects the cloud motion in three different layers (low, medium and high clouds).

2.2.1. Cloud detection in satellite imagery

Cloud detection was carried out following the methodology presented in Ref. [12] obtaining a cloud identification (clouds which attenuate the DNI below 400 Wm^{-2} – based on the optimal operating value for CSP plants, as the case of Gemasolar plant (collaborator in this work), and following the methodology presented in the article cited in this paragraph. Fig. 1 shows an original and a processed satellite image.

2.2.2. Cloud motion in satellite imagery

When the cloud motion was calculated. Each raster image (or slot) was divided into three layers: low, medium and high [30]. Additionally, each layer was divided into five sectors to determine the cloud motion more accurately as Fig. 2 shows.

Three consecutive slots are required to study the cloud trajectory for each sector, obtaining the cloud motion vectors for the sectors. This motion vectors are calculated studying the cloud motion between the sectors from the first and the second slot, second and third slot and, finally, the first and third slot. For this study, the Maximum Cross-Correlation method was applied, calculating the representative cloud motion vectors. This method produces, between two consecutive slots (at sector level), a maximum in the pixel where the two compared sectors are more similar, obtaining the representative cloud motion [13–16].

2.2.3. Short- and medium-term cloudiness forecasting with MSG satellite imagery

The cloudiness forecasting was the outcome of the above subsections. As the motion vectors were obtained for each sector and for the three layers, we applied the corresponding displacement to all sectors of the last slot received. A total of 12 displacements were carried out, providing a displacement for the following 180 min (15 min for each displacement). From then onwards, the future cloud position is determined. Nevertheless, we did not know if the reference point (image center pixel) was affected by clouds. So, we determined the pixels affected by the sunbeams in the different layers (0–15 km, representing all cloud heights) for each displacement and the cloud top height using thermal channel information. Therefore, knowing the cloud height and position in the future, we could determine if the sunbeam trajectory pixel/s matched with a certain cloud.

2.3. Cloudiness forecasting using sky-camera images

The cloudiness forecasting using sky-camera images follows the same proceeding than satellite images, above explained, to make the cloudiness forecasting. Firstly, the images are processed to identify clouds. Three consecutive images were taken to study the cloud motion. With the cloud motion, we reproduced future scenarios to identify the cloud presence over the next three hours.