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The use of a sky camera for solar radiation estimation based on digital image processing

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ABSTRACT

The necessary search for a more sustainable global future means using renewable energy sources to generate pollutant-free electricity. CSP (Concentrated solar power) and PV (photovoltaic) plants are the systems most in demand for electricity production using solar radiation as the energy source. The main factors affecting final electricity generation in these plants are, among others, atmospheric conditions; therefore, knowing whether there will be any change in the solar radiation hitting the plant's solar field is of fundamental importance to CSP and PV plant operators in adapting the plant's operation mode to these fluctuations. Consequently, the most useful technology must involve the study of atmospheric conditions. This is the case for sky cameras, an emerging technology that allows one to gather sky information with optimal spatial and temporal resolution. Hence, in this work, a solar radiation estimation using sky camera images is presented for all sky conditions, where beam, diffuse and global solar radiation components are estimated in real-time as a novel way to evaluate the solar resource from a terrestrial viewpoint.

1. Introduction

Renewable energy systems are presented as a pollution-free form of electricity generation providing an alternative to traditional systems [1–3]. Accordingly, solar energy is listed as the cleanest [4] and most important source of energy, at least for the next few years [5–7].

The current expansion in solar energy applications is making it necessary to study those factors related to system efficiency improvement and final production. It is essential that meteorological conditions are optimal in order to maximize electricity production, which relies on high incident solar radiation values. Therefore, possessing information with regard to atmospheric conditions is one of the main requirements for solar power plants to improve system performance, allowing plant operators to adapt their plant's operation modes to the meteorological conditions [8].

Satellite images have been used by several authors to study atmospheric features. Clouds are the highest solar attenuation factor. According to cloud presence, the sky is generally classified into three categories: cloudless, partially-cloudy and overcast [9]. Moreover, clouds are presented at different heights: high, medium and low [10], to better study their motion using correlation procedures such as the maximum cross-correlation method [11]. Cloud cover has been widely studied in different places around the world [12,13], above all to examine the role of clouds in solar radiation measurements [14]. Measuring the solar radiation hitting the ground is one of the most important objectives in cloud studies, as it is especially required for solar power plant management. For this reason, many studies have been carried out on solar radiation estimation using different satellite devices, which have been used to estimate solar radiation [15–18]. Using Meteosat satellite images, the cloud cover index was calculated for estimating global solar radiation, presenting RMSE (root-mean-square error) values in the testing period higher than 230 Wm^{-2}, and an R^2 value of about 0.40 [19]. Different atmospheric models were combined with satellite images for estimating global and direct radiation [20]. In this work, the authors shown the results for multiple combinations, where direct radiation presented an RMSE value higher than 220 Wm^{-2} for overcast sky conditions. ANN (Artificial neural network) and MLR (multiple linear regression) models were compared to estimate global irradiance under cloudless skies in

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73 different locations over Turkey [21], where the results shown different RMSE values varying this statistical parameter between 2 and 4 MJ m^{-2}. Furthermore, solar radiation estimations have even been tasked with solar radiation forecasting using satellite images [22] from 15 min to 3 h with satisfactory results.

Nonetheless, there has recently been an increase in technology studying sky conditions from a different perspective to that of satellites. Sky cameras provide a hemispherical view of the sky with higher spatial resolution and lower temporal resolution than satellite images. Different factors have been evaluated with this emerging technology. An estimation of PAR (photosynthesis active radiation) was made using a digital fisheye camera, where the authors show RMSE values higher than 100 Wm^{-2} under clear skies [23]. Cloud coverage was studied using a TSI camera [24]; clouds were also classified into different groups through the use of direct radiation data [25]. In general, the problem presented by sky cameras is image pixel saturation around the sun [26–28] this was overcome using direct normal irradiance [29]. With the aforementioned problem resolved, the authors carried out digital image processing to identify the clouds satisfactorily [30]. Combining satellite and sky camera imagery, cloudiness was predicted for the next 3 h, with sky camera predictions (whenever prediction was possible) providing better results than satellite predictions on days with cloud presence [31]. Consequently, sky cameras are one of the most accurate technologies in detecting short-term cloud situations. Therefore, a further step using this technology (against satellite and statistical models) could be to quantify the total solar radiation incident in the solar fields, forecasting cloudy situations that might affect electricity-generating solar power plants; meaning precise information to adapt the solar plant's strategic operation to the meteorological conditions – fundamental for better integration of generated electricity into grid-integration systems.

Searching the improvement of devices and technologies related to solar radiation estimation, the aim of this work is to present the methodology to obtain an estimation of the three solar radiation components (beam, diffuse and global) in real-time using a total sky camera, over 1 min periods and under all sky conditions, as an optimal alternative of traditional systems to estimate the solar resource. To do this, we have only used the digital image levels, supposing a new procedure to estimate the solar radiation from a ground view. The process consists of estimating the three solar radiation components at pixel-level, for obtaining the final radiation values, averaging the different image areas according to each solar radiation component.

2. Materials and methods

2.1. Data collection

A total sky camera with a rotational shadow band (namely a *TSI* 880 model) was used for the solar radiation estimation in real time. The hemispheric vision was represented in JPEG (joint photographic expert group) images, with a 352 × 288 pixel-image resolution. Each pixel can have a value between 0 and 255 supposing a pixel resolution of 8 bits. All images were collected over 1-min periods when the solar altitude (in degrees) was higher than 5° - this was to avoid image processing problems derived from atmospheric variations.

Additionally, irradiance data were collected for each minute that a TSI image was acquired. Diffuse and global irradiance measurements were taken from two *CMP11 Kipp & Zonen* pyranometers, and direct irradiance from a *CH1 Kipp & Zonen* pyrheliometer; these were installed on a two-axes solar tracker.

Both the sky camera and the solar tracker are 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. Periodic maintenance is carried out to ensure the correct utilization of the data.

2.2. General schema for obtaining the solar radiation estimation

After making a historical dataset with sky camera images and solar radiation data, an estimation value of beam, diffuse and global irradiance is obtained, using the value of the solar altitude α (in degrees) and ND value as the best correlations of digital image levels based on the solar altitude. The general process for this is shown in Fig. 1:

The historical dataset for analyzing the digital image values has been obtained according to sky conditions, as shown in Fig. 2, where the digital image values were treated and modelled separately for cloudless and overcast skies. For that purpose, different DDBB (data bases) were created to collect data.

2.3. Division of the image into three areas

The digital pixel levels in the image behave differently depending on their proximity to the solar area. Therefore, knowing the distance between each pixel and the "sun pixel" is key to processing the digital values. The solar pixel is obtained using solar height and azimuth functions. These two geographic variables define the sun's position in the image. So, to measure the distance from the pixels in the image to the "sun pixel", the Euclidean distance is calculated from each point in the image to the point where the sun is situated. In Fig. 3 the process is represented graphically, where the Euclidean distance is calculated according to the Function 1.

$$dis = \sqrt{a^2 + b^2} \qquad (1)$$

Since this distance has been calculated for all image pixels, the result is a matrix made up of distances. An example of the distance matrix for the day of May 20th, 2014, at 12:00 UTC (coordinated universal time) is shown in Fig. 4:

As presented in another work, the area around the sun appears more saturated, progressively diluting out to the rest of the image [29]. After observing different times of day, different dates and different times of the year, it was determined that this area varied depending on the time of day. For this reason, area identification is performed within the image. This identification determines areas with a homogeneous appearance, all with reference to the sun pixel. Consequently, centered at the pixel site, a total of three different areas within the image are represented. Fig. 5 shows how this space has been defined in a particular image.

As shown in Fig. 5, the demarcated zones often have an apparently similar appearance. The radius that defines them is dynamic and depends on solar altitude. After an adjustment is made for

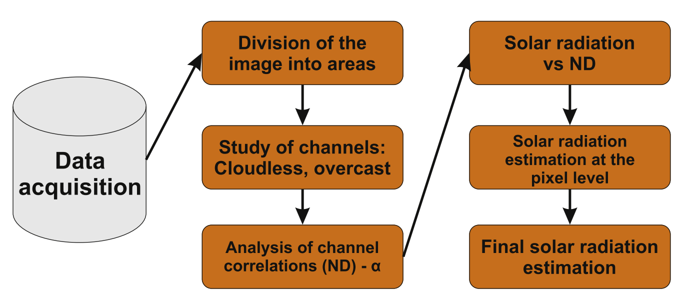

Fig. 1. Flowchart of the process used to obtain the solar radiation estimation.