Energy Conversion and Management 105 (2015) 1166–1177

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Solar irradiance forecasting at one-minute intervals for different sky conditions using sky camera images

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ARTICLE INFO

Article history:
Received 28 May 2015
Accepted 1 September 2015
Available online 14 September 2015

Keywords:
Solar irradiance forecasting
Sky camera
Image processing
CSP plants
PV plants

ABSTRACT

In the search for new techniques to predict atmospheric features that might be useful to solar power plant operators, we have carried out solar irradiance forecasting using emerging sky camera technology. Digital image levels are converted into irradiances and then the maximum cross-correlation method is applied to obtain future predictions. This methodology is a step forward in the study of the solar resource, essential to solar plant operators in adapting a plant's operating procedures to atmospheric conditions and to improve electricity generation. The results are set out using different statistical parameters, in which beam, diffuse and global irradiances give a constant normalized root-mean-square error value over the time interval for all sky conditions.

The average measure is 25.44% for beam irradiance; 11.60% for diffuse irradiance and 11.17% for global irradiance.

1. Introduction

One of the main aims of systems designed to generate electricity using renewable energy is to exploit fully free energy sources by adapting them to atmospheric conditions and thus improving their electricity-generating operation. This is the case for CSP and PV plants, which are designed to convert solar energy into electricity [1–4]. Consequently, any alteration in energy reception from this resource can vary the resultant output. For this reason, many researchers have studied the different atmospheric properties to provide mechanisms for determining the best sites to install solar power plants as well as systems for improving the plant's operation according to meteorological conditions [5].

Analyzing the atmospheric properties, one finds that aerosols modify sunlight and cause solar radiation dispersion [6]. Aware of the effect of aerosols in the atmosphere, many authors have studied their properties, where satellite images provide sufficient information to characterize aerosol-column characteristics at different geographical locations [7,8], as well as using other terrestrial sky camera techniques [9,10].

However, clouds are the most attenuating factor altering the sun's energy, reducing the amount of solar radiation that hits the ground and causing fluctuations in the different subsystems involved in electricity generation. As a result, clouds have been widely studied. Escrig et al. [11] used satellite images to classify clouds into low, medium and high using the optical image properties from spectral channels. In this way, sky camera images have been processed to identify clouds present in the sky [12–14]. Following this, a methodology was implemented to combine satellite and sky camera images to produce a cloudiness prediction system in real time over the short- and medium-term [15–17].

Some of the aforementioned methodologies were used to study solar irradiance using different techniques and for different purposes [18]. Solar radiation has also been studied using statistical and parametric models [19], as was the case with a study in Algeria, where a total of 17 models were compared so as to determine the most accurate for estimating DNI – the most suitable models being those that require fewer inputs [20]. Besides, the solar resource has been widely studied using different techniques [21–23], mainly to estimate global irradiance. Generally, many studies have been conducted on solar radiation estimation using various satellite devices. This was the case with a study in Vietnam, where satellite images, solar radiation data and a variety of other atmospheric information were combined to generate solar radiation maps to study the sun's behavior at that geographical location [24]. Satellite images have likewise been used to estimate solar radiation [25–28] and have even been utilized for solar radiation forecasting. Geostationary satellite images were used to predict solar irradiance from 30 min

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http://dx.doi.org/10.1016/j.enconman.2015.09.001
0196-8904/

Nomenclature

α	solar altitude (°)
$\sigma_{R_{est,mea}}$	covariance of the two input data sets (the estimated and measured irradiances) [dimensionless]
$\sigma_{R_{est}}$	standard R_{est} deviation (dimensionless)
$\sigma_{R_{mea}}$	standard R_{mea} deviation (dimensionless)
ANN	artificial neural networks
BL	blue channel
CIESOL	Solar Energy Research Center
CMV	cloud motion vector
CSP	concentrated solar power
DNI	direct normal irradiance (W m^{-2})
ESSS	exponential smoothing state space
GR	green channel
H	hue channel
HSV	hue, saturation, value
JPEG	joint photographic expert group
MBE	mean bias error (W m^{-2})
MSG	meteosat second generation
N	total number of estimations
ND	digital correlation of image channels based on the solar altitude
nMBE	normalized mean bias error (%)
nRMSE	normalized root-mean-square error (%)
PV	photovoltaic
R	correlation coefficient (dimensionless)
R_{est}	irradiance estimation (W m^{-2})
R_{max}	maximum of irradiance measured (W m^{-2})
R_{mea}	irradiance measured (W m^{-2})
R_{min}	minimum of irradiance measured (W m^{-2})
RD	red channel
RGB	red, green, blue
RMSE	root-mean-square error (W m^{-2})
S	saturation channel
sin	sine function
TSI	total sky imager
V	value channel

to 5 h [29]. Hourly solar irradiance time series using satellite image analysis and a hybrid ESSS model together with ANN were combined to forecast solar irradiance in the tropics [30]. In this work, the nRMSE varies between 20.65% and 43.69%. Furthermore, MSG satellite images were used for solar irradiance forecasting, where Heliosat-2 method was adapted to MSG images and was combined with cloud motion vectors to determine the irradiance from 15 min to 3 h, with satisfactory results [31]. In that article, the best results were obtained for cloudless skies for the three solar radiation components, oscillating the nRMSE values between 5% and 15%.

The main problem that satellite images present is the simultaneous appearance of different cloud layers. Under these conditions, only the higher layers are seen by the satellite when modeling the atmosphere, the lower layers remaining hidden. Consequently, on making the prediction, only the higher clouds are taken into account, highlighting the need for information about the presence of other cloud layers below.

In this work, a total sky camera (TSI 880 model) was used to conduct solar irradiance forecasting over the short- and medium-term for all sky conditions (cloudless, partially-cloudy and overcast skies) at one-minute intervals, investigating its potential as a tool for making the prediction from a terrestrial view, using only digital image levels. With this solar irradiance forecasting, a new step is given in the prediction of solar resource for optimizing the current technologies responsible for providing the future sky conditions, increasing also the temporal resolution for giving the prediction at one-minute intervals.

2. Materials and methods

2.1. Data collection

We used a total sky camera with a rotational shadow band (namely a *TSI* 880 model) for solar irradiance estimation in real time. The hemispheric vision was represented in JPEG 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 one-minute periods when the solar altitude (in degrees) was higher than 5° – this was to avoid image processing problems derived from atmospheric variations. With a frequency of 3 times a week, the glass dome is washed using a soft cloth with water. This maintenance work is carried out with distilled water. At least once a month, the glass dome is waxed, thus avoiding oxidation and corrosion of glass especially in a place so close to the sea.

Additionally, we collected irradiance data for each minute that a TSI image was acquired. Diffuse and global irradiance measurements were taken using two *CMP11 Kipp & Zonen* pyranometers, and direct irradiance using a *CH1 Kipp & Zonen* pyrheliometer; these were installed on a two-axes solar tracker. Daily maintenance consists of cleaning pyranometers, pyrheliometer and solar sensor with a soft cloth moistened with ethyl alcohol. This will solve the problems caused by the generation of condensation, causing the appearance of several drops of water on the glass sensor. Every two months, it will be necessary to check the solar tracking makes the follower, and annually will be calibrated complete station.

Both the sky camera and the solar tracker are located at the 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 uncertainties-errors of experimental data is lower than 5% in all cases.

2.2. General schema

Solar irradiance forecasting using sky camera images is carried out by following two steps: the first is to obtain a solar irradiance estimation at pixel level and the second consists of calculating the pixel motion that will be applied to each image pixel. Fig. 1 shows the general schema for obtaining the solar irradiance estimation, where digital image levels are only used to predict solar irradiance over the short- and medium-term.

When the image was collected, we processed it to obtain the solar irradiance at the pixel level. After that, we calculated the cloud motion vectors and applied them to the last image to move the image pixels. Finally, we obtained the solar irradiance values for each motion, allowing solar irradiance forecasting at each minute of the prediction.

2.3. Determination of CMVs

Following the steps detailed in Fig. 1, when the three sky images were collected, the next step consisted of obtaining the cloud motion vectors to determine the pixel motions. To do this, we followed the methodology proposed in Ref. [16], where the spherical image is split into different sectors to study the cloud motion of