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Artículo Original

Short term generation forecast for photovoltaic farms connected to the National Power Grid

Pronóstico a muy corto plazo para parques solares fotovoltaicos conectados a la Red Eléctrica Nacional

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Israel Borrajero Montejo, Miguel Hinojosa Fernández, Juan Carlos Peláez Chávez, Krystine Naranjo Villalón*, Alfredo Roque Rodríguez

Centro de Física de la Atmósfera, Instituto de Meteorología, La Habana, Cuba

ABSTRACT: A very short term forecast (15 min) of photovoltaic generation from solar farms connected to the National Power Grid in Cuba is presented. The approach described here is based, on one side, on the Heliosat II method for the estimation of solar radiation from meteorological satellites visible images and on the other, on the Cloud Motion Vectors algorithm, which allows to produce an image extrapolated to a near future time based on two consecutive images already received. Both methods are combined to produce an irradiance forecast that is used to estimate the power generation for a given location. In this case, a sample of the available farms. With the available satellite images and processing power, this implementation allows to produce a 15 minutes forecast every 5 minutes achieving a correlation of 0.835 between predicted and reported values in the farms and a mean square error of 0.51 Mw.

Keywords: Cloud Motion Vector, Solar Radiation, Forecasting, Short Term Forecast, Satellite Images.

RESUMEN: Se presenta un pronóstico a muy corto plazo (15 min) de generación fotovoltaica a partir de parques solares conectados al Sistema Eléctrico Nacional en Cuba. El enfoque aquí descrito se basa, por un lado, en el método Heliosat II para la estimación de la radiación solar a partir de imágenes visibles de satélites meteorológicos y, por otro, en el algoritmo Cloud Motion Vectors, que permite producir una imagen extrapolable en el futuro próximo basado en dos imágenes consecutivas. Ambos métodos se combinan para producir un pronóstico de irradiancia que se utiliza para estimar la generación de energía para un lugar determinado. En este caso, una muestra de los parques disponibles. Con las imágenes satelitales disponibles y la potencia de procesamiento, esta implementación permite producir un pronóstico de 15 minutos cada 5 minutos logrando una correlación de 0,835 entre los valores predichos y reportados en las fincas y un error cuadrático medio de 0,51 MW.

Palabras Clave: Vector de movimiento de nubes, Radiación Solar, Pronóstico, Pronóstico a Corto Plazo, Imágenes de satélite.

INTRODUCTION

As photovoltaic generation increases its share in the total power output of many countries, the need for accurate forecast methods that allow to take into account the often fluctuating nature of solar radiation arises, so proper compensation actions can be put in effect in due time.

Two main forecast ranges are requested mostly by the power companies or institutions that manage electric power generation and distribution. First, a one day ahead forecast is needed to match the power to generate to the estimated demand, which depends on a wide variety of issues, ranging from whether it is a working day or holiday to several meteorological variables. These 24 to 48 hours forecast is accomplished most often with numerical weather prediction models (NWP) which deliver maps of forecasted solar radiation, among many other meteorological variables. The values taken from these maps are interpolated to the PV plants positions and different statistical, analytic or IA based methods can be applied to obtain the power generation (Lorenz *et al.*, 2007)

*Author of correspondence: Krystine Naranjo Villalón. E-mail: krystinenaranjo@gmail.com
Israel Borrajero Montejo. E-mail: israel.borrajero@insmet.com
Miguel Hinojosa Fernández. E-mail: miguel.hinojosa@insmet.com
Juan Carlos Peláez Chavéz. E-mail: jcpozone@yandex.com
Alfredo Roque Rodríguez. E-mail: alfroquerodriguez@gmail.com
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While NWP models can give a reasonable estimation of the behavior of solar radiation at PV farms, they can't provide an accurate forecast so far, less than 5-6 hours in advance (Lorenz *et al.*, 2007, Pérez et al., 2007, 2010, Mathiesen *et al.*, 2013) due to significant sudden changes in the conditions of specific PV facilities, so a much more accurate and shorter term forecast is needed to compensate quick fluctuations that could take place, for instance, as a cold front cloud band sweeps across the territory making several PV plants change from sunny to cloudy conditions.

So the second kind of forecast that is required, is the so called "Very short term forecast", with a range from 15 minutes up to a few hours. The most common mechanism of this kind of forecast is the extrapolation of clouds positions in series of cloud images which can be obtained from high resolution geostationary satellites or from wide lens cameras located at the PV sites (Hao et al., 2013, Tiwari et al., 2019, 6H. Escrig et al., 2013). The most scalable approach would be using satellite images due to reduced logistic and maintenance costs. This avoid the need for dedicated hardware and stable communications between each solar park location and the data processing center. However this comes at the cost of a reduced accuracy due to the low resolution of current satellite data. For this reason some hybrid techniques using both techniques has been proposed (Zaher et al., 2018)

There has been a lot of experiences with the estimation of solar radiation using satellite data with the Heliosat II Method and its different revisions as one of the most reliable and simple method for calculating irradiance from a cloud index.(Cano et al., 1986, Albarelo et al., 2014). A combination of Heliosat and cloud motion forecast has been used before in (Hammer et al., 1999) But in this case, the satellite used was European Meteosat and a previous version of the cloud index estimation algorithm.

The National Load Management Office keeps several sets of diesel generators groups connected to the power grid, which are kept at about 50 percent of their full capacity, this allows to quickly add or remove power generation capacity in response to peaks or sudden changes in the power demand, which can't be matched by the large power plants as they most follow a stable generation regime. The Very short term generation forecast can supply information on sudden changes in the photovoltaic contribution with enough anticipation, so the diesel generators can be added or withdrawn in time to avoid power fluctuations.

The purpose of this work is to present a very short-term forecast of power generation at photovoltaic parks connected to the national power grid, by applying the Heliosat II method to satellite images, extrapolated or forecasted by the Cloud Motion Vectors Method (CMV), based on the hypothesis that these extrapolated (or linearly predicted) images offer the best approximation of the spatial distribution of the future cloudiness index for a short time interval (less than 30 minutes)

MATERIALS AND METHODS

For this work, Level 2 type images from geostationary satellite GOES 16 (Figure 1) were used, which contain the reflectance values rectified by the sun-earth distance, the angle of incidence of the sun on the surface and the aging of the sensor. They are files in netCDF format with a spatial resolution of 2 km^2.

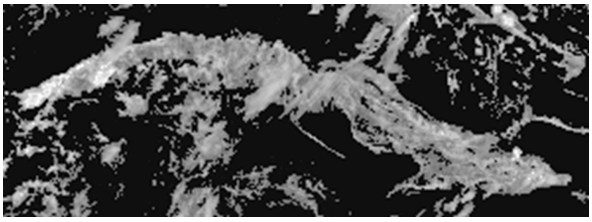

Figure 1. Channel 2 image from GOES 16, 0.62 µm

The original resolution of the images in the band that is being used (visible) is 0.5 km^2, but the "Level 2" product only offers 2 Km^2, the frequency of the images is 5 minutes, this allows to produce a forecast of 15 minutes every 5 minutes. The satellite is located at a fixed position, 0.0 latitude, 75.0W longitude, 36000 Km above the surface of the Earth, providing thus a very good coverage of the territory of Cuba.

Heliosat (Cano et al., 1986, Albarelo et al., 2014) is a long time known method for the estimation of global solar radiation based on visible images from meteorological satellites. It first calculates the clear sky radiation map for a given region at a given time, based on the position of the sun and the ordinary components of the atmosphere, air, absorbing gases, absorbing or reflecting aerosols and surface albedo, then a cloud index map is calculated from a visible satellite image corresponding to the same time. This cloud index map has the cloud density normalized to a range between 0 (no clouds) and 1 (dense heavy clouds) with all geographic details present in ordinary visible images removed. Then the clear sky radiation is modulated by this index, producing a map of estimated solar global radiation.

The application of the Heliosat method allows for the elaboration of very much updated radiation maps, in this case, every 5 minutes a new map can be obtained, but this is not a forecast. If it is assumed that for short intervals of time (less than 30 minutes) the cloud motion is approximately linear, then a set of cloud motion vectors can be calculated between two successive images, these CMV give an estimation of the speed and the direction of the clouds motion. If each point in an image is displaced according to the direction and speed (multiplied by an arbitrary time interval) of the motion vector corresponding to its original position, a new image is created which contains the estimated positions of the clouds by the chosen arbitrary time interval in the future, as long as the time interval is short enough, to remain within the linear approximation.

There are several methods for motion vector calculation. The Open Computer Vision (OpenCV) is an open source library which contains a huge collection of image processing routines, it is implemented in C++ language, with different interfaces that allow developers to use these tools from different computer languages. In particular, two motion vectors algorithms are implemented, the Farneback (Farneback et al., 2003) and the Lucas - Kanade (Lucas and Kanade, 1981) methods. The first one calculates motion vectors for every point in the images while the second uses the most relevant details in the scene to calculate the vectors and then interpolates to the rest of the image. From a previous work experience, the Lucas - Kanade method yielded slightly better results, so this was the method used here.

A set of scripts was developed in Python language that calculates the cloud index maps by the Heliosat method, applies to them the CMV algorithm and calculates the 15 minutes ahead global radiation forecasts, the procedure is applied to images at every exact hour minus 15 minutes, for the following 19 days to obtain the forecasts for the exact hours:

Table 1. Days with available data

Month	Days	Year
March	31	2021
April	01 - 14	2021
April	24 - 28	2021
August	05	2021 [1]

For each of these days there is a set of images that covers the entire daytime interval. Forecasts produced consist of 1100 x 400 point maps with their lower left corner at 19.0 degrees North latitude and 85.0 degrees West longitude. Although the resolution of this map is of 0.01 degree (approximately 1 Km^2), the values are actually interpolated from the GOES 16 Level 2 images with a resolution of 2 Km^2. To obtain the generation forecasts in a set of photovoltaic parks, it is first necessary to obtain the interpolated radiation values of the map at the positions of the parks and from these radiation values, calculate the photovoltaic generation. The conversion equations that allow calculating the power generation in each park based on the predicted solar radiation are obtained by least square regression using hourly data series of solar radiation measured at the parks and generation data taken simultaneously, these data are supplied on a daily basis by the National Load Management Office of the Ministry of Energy and Mines. Although they have an hourly frequency, taking series of 60 days prior to the day on which the forecasts are being made, produces sufficiently robust fittings for the calculation of power generation. The regression coefficients are calculated anew, every day, for each PV plant. The regression equation has the form:

$$G = \sum_{i,\, j\, =\, 0}^{2} Cr_{ij} Rad^{i} Shs^{j} \quad (1)$$

Where:

G- Electric generation (Mw)

Cr_{ij}- Regression coefficients

Rad- Solar radiation w/m^2

Shs- Sine of the solar height angle

As it shows in equation 1, the generation is not made to depend only on radiation, but also on the sine of the solar height angle, the inclusion of this variable improves the percent of explained variance as it provides means to include the effect of some processes that affect the relation between generation and radiation, such as the shift of the solar spectrum towards shorter wavelengths at higher sun height angles, and the higher temperature of the panels near noon.

Figure 2 shows the graphics of power generation values estimated by equation 1 versus reported generation for two PV plants with capacities of 2 Mw and 4 Mw respectively. The regression model "takes care" of issues such as the park total capacity, aging, or the current state of maintenance for each park.

Among the set of images from the 19 days referred earlier, those received at exact hours minus 15 minutes and exact hours minus 20 minutes were chosen to derive the cloud index maps and have the cloud motion vectors calculated, then these cmv's were applied to the exact hour minus 15 minutes images with an extrapolation time of 15 minutes to produce forecasts

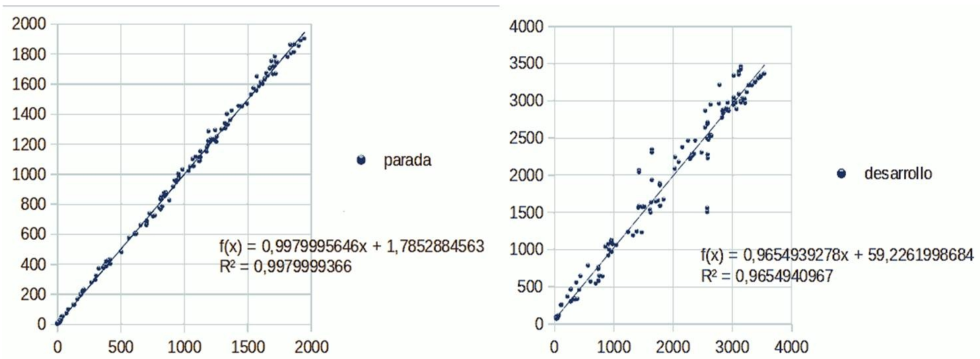

Figure 2. Relations between electricity generation values estimated from the least square adjustment and reported in 2 photovoltaic parks

of the cloud index maps for each exact hour. The Heliosat method was applied to obtain the forecasted solar radiation maps, then the radiation values were interpolated to the positions of 34 operational PV plants all over the National Territory, and the values of generation estimated using the regression equation 1, these forecasted generation values were compared to the corresponding hourly reported values from the National Load Management Office. Considering these 34 PV parks, the 19 days with available images and an average of 10 hours of daylight per day, a total of 6700 pairs of forecasted - reported values were obtained.

RESULTS

Figure 3 shows the dispersion diagram of the predicted values against those reported in the PV parks for all periods when both values are present. The grouping of most of the points in the vicinity of the line **Y = X** can be appreciated. More overestimated than underestimated values are observed, which may result from a tendency shown by the Heliosat II method, as currently implemented, to slightly underestimate the attenuation of global solar radiation by cloudiness. Table 3 shows the values of the calculated statistics.

Table 2. List of operational PV parks used in this work

Park	Province	Power(MW)
Troncoso II	Pinar del Río	1.4
Pinar 220 C	Pinar del Río	2.2
Pinar 220 A-2	Pinar del Río	3.88
Paso Real	Pinar del Río	2.2
Santa María	Pinar del Río	2.2
Cortes	Pinar del Río	2.2
Naranjito	La Habana	0.5
Cardenas III	Matanzas	2.2
Cardenas I	Matanzas	3.5
Yaguaramas	Cienfuegos	5
Caguaguas	Villa Clara	2.2
CAGUAGUAS II	Villa Clara	4.4
Universidad (UCLV)	Villa Clara	1
Marrero	Villa Clara	2.2
Guasimal	Sancti Spíritus	4.4
Yaguajay	Sancti Spíritus	2.2
Venegas	Sancti Spíritus	1.25
Venezuela	Ciego de Avila	2.2
Ceballos	Ciego de Avila	4.4
Imías	Camaguey	2.2
Planta Mecánica	Camaguey	2.2
Parada II	Las Tunas	4.4
Parada	Las Tunas	2.2
Yuraguanal 1	Holguín	2.2
Yuraguanal 2	Holguín	2.2
Desarrollo	Granma	4.4
Mártires de Artemisa	Granma	4.4
Yarey 2	Granma	2.2
Siboney	Granma	1.1
Payares	Granma	4.4
Río Grande	Santiago de Cuba	4.4
Santa Teresa 4	Guantánamo	1.1
La Yaya	Guantánamo	1
Guantánamo 110kV	Guantánamo	2.2

Table 3. Calculated statistics, Bias, Root Mean Square Error and Correlation between forecasted and reported generation values.

Bias	RMSE	Corr
0.139	0.51	0.835

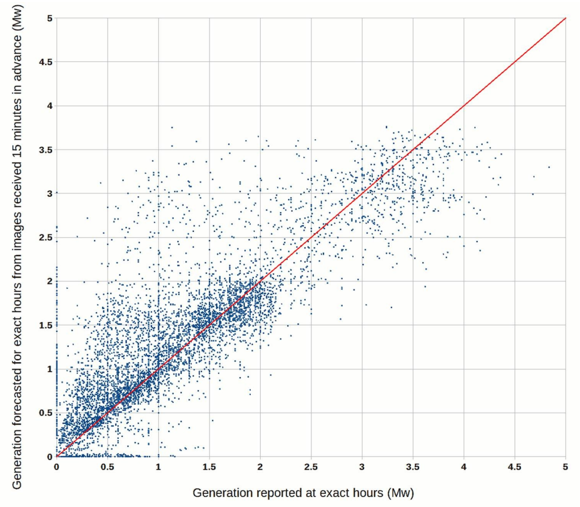

Figure 3. Scatterplot of forecasted versus reported values of generation at PV parks

As a way of assessing the added value of the cloud forecasting mechanism, values of generation were calculated for the images at exact hours minus 15 minutes and compared to the hourly reports at exact hours, which could be considered as a forecast by permanence. The set of statistics obtained is shown on Table 4, with RMSE and Correlation values showing poorer correspondence.

Table 4. Calculated statistics, Bias, Root Mean Square Error and Correlation between generation values calculated at exact hours minus 15 minutes, and reported values at exact hours.

Bias	RMSE	Corr
0.114	0.872	0.7

CONCLUSION

The use of the Cloud Motion Vector method for forecasting cloud movement together with the Heliosat-II method for estimating solar radiation can be used with good results for the very short-term forecasting of electricity generation at PV Parks installed in the country. The mean value of the correlation between predicted and reported values in the parks is 0.835 and the mean square error is 0.51 Mw. This endorses its implementation as a very useful service for the National Load Management Office to plan the entries or withdrawals from the power grid system of diesel generator sets that avoid instabilities caused by sudden increases or decreases in photovoltaic generation.

DATA AVAILABILITY STATEMENT

The data presented in this study for generation and solar irradiance are available on request from the corresponding author. The data are not publicly available due to these datasets being provided by a national entity that has not publicly released this information. Satellite datasets were obtained from the NOAA here https://www.noaa.gov/information-technology/open-data-dissemination.

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