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Comparison of Irradiance Decomposition and Energy Production Methods in a Solar Photovoltaic System

Tisciane Perpetuo e Oliveira, Dante Inga Narvaez, Marcelo Gradella Villalva

Abstract—Installations of solar photovoltaic systems have increased considerably in the last decade. Therefore, it has been noticed that monitoring of meteorological data (solar irradiance, air temperature, wind velocity, etc.) is important to predict the potential of a given geographical area in solar energy production. In this sense, the present work compares two computational tools that are capable of estimating the energy generation of a photovoltaic system through correlation analyzes of solar radiation data: PVsyst software and an algorithm based on the PVlib package implemented in MATLAB. In order to achieve the objective, it was necessary to obtain solar radiation data (measured and from a solarimetric database), analyze the decomposition of global solar irradiance in direct normal and horizontal diffuse components, as well as analyze the modeling of the devices of a photovoltaic system (solar modules and inverters) for energy production calculations. Simulated results were compared with experimental data in order to evaluate the performance of the studied methods. Errors in estimation of energy production were less than 30% for the MATLAB algorithm and less than 20% for the PVsyst software.

Keywords—Energy production, meteorological data, irradiance decomposition, solar photovoltaic system.

I. INTRODUCTION

THE interest of studies on solar radiation measurement has become higher due to the increased use of solar energy and climate changes. Currently, the acquired data are more accurate and have increased temporal and spatial resolution [1].

The following are definitions of terms utilized in the literature in relation to solar radiation. Irradiation (Wh/m^2) is the incident energy per unit area in a surface and is found by integration of the radiation at a given time (usually 1 hour or 1 day). On the other hand, irradiance (W/m^2) is the radiant energy rate incident on a surface by unit of area.

Solar radiation is radiant energy received from the sun, either directly, or in a diffuse way (by spreading in the sky and reflection from the ground). Radiosity (W/m^2) is the rate at which radiant energy leaves a surface per unit area by combined emission, reflection and transmission. Finally, extraterrestrial radiation is solar radiation received on a surface at the edge of Earth's atmosphere [1]-[3].

The global horizontal irradiance (GHI, in W/m^2), which is utilized in this study, is hemispherical solar radiation received

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by a horizontal plane, i.e., the total direct and diffuse radiation. Direct normal radiation (DNI, in W/m^2) is the solar radiation falling on a given direction on a plane. In turn, diffuse horizontal irradiance (DHI, in W/m^2) is the sun's radiation scattered by the atmosphere and ground [1]-[3], as it is shown in Fig. 1.

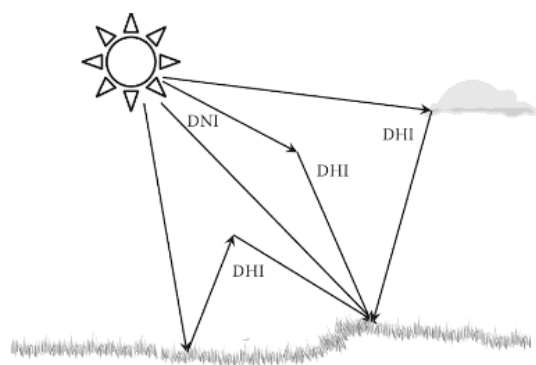


Fig. 1 Components of solar radiation reaching the earth's surface [1]

Estimation of energy production by a solar photovoltaic system involves several steps, and each step has a variety of methods that have been developed through the years:

- Irradiance decomposition: To calculate the direct normal and diffuse horizontal irradiance models from global horizontal irradiance data.
- Irradiance transposition: To obtain the normal and diffuse equivalent irradiances in a fixed inclined plane (photovoltaic modules with a different orientation from the horizontal).
- Device modeling: To estimate the energy production of the oriented photovoltaic modules at fixed azimuth and inclination angles, by means of some modeling method of the solar array and inverter.

In this paper, performance of irradiance decomposition and energy production methods is analyzed through simulations in PVsyst software and an open-source-library based program, so the results are compared with 15-day measured data on a solar power plant in Campinas, Brazil.

II. GENERAL FLOW DIAGRAM

Fig. 2 shows the flow diagram used by several commercial computational tools to estimate the energy output of a solar photovoltaic system [4]. Irradiance, temperature and other meteorological data can be imported from a database (in the form of monthly averages of several years previously measured) or from field-measured meteorological data. In

addition, the normal direct and horizontal diffuse irradiance data can be modeled from decomposition methods or imported from data measured in the field by solarimetric stations.

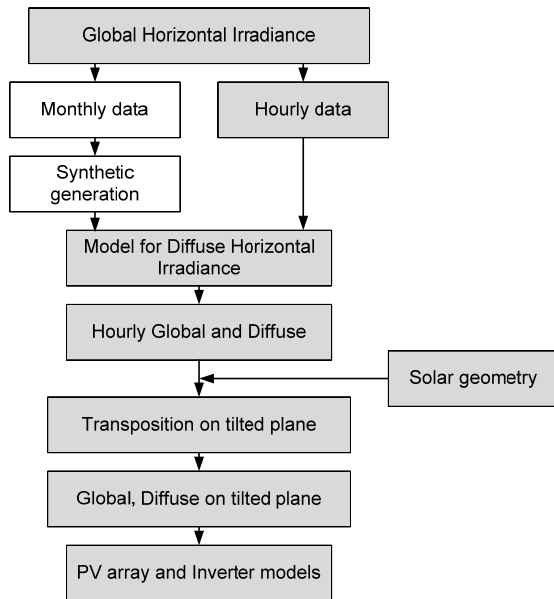


Fig. 2 Flow diagram for estimation of photovoltaic solar energy production

III. IRRADIANCE DECOMPOSITION

The components of the global horizontal irradiance GHI (direct normal DNI and diffuse horizontal DHI irradiances) can be calculated through the use of data decomposition methods.

In the open-source-library based program, the Maxwell direct irradiance (DISC) simulation code [5] is used to calculate the normal direct irradiance DNI from the global horizontal irradiance GHI, usually in hourly mean values, through empirical relationships between the global and direct clearness indexes, according to the formula:

$$DNI = I_0 \tau(z) [g(K_t, m) + y(K_t, x)] \quad (1)$$

I_0 is the normal direct extraterrestrial irradiance, $K_n = DNI / I_0$ is the normal direct brightness index, $K_t = GHI / (I_0 \cos z)$ is the horizontal global clearness index, $g(K_t, m)$ represents the incremental relationships between $K_n / \tau(z)$ for each month m , $y(K_t, x)$ is a statistical distribution function to reach K_n with random x . $\tau(z)$ is a function of the zenith angle, that is fitted with experimental data and is defined as:

$$\tau(z) = 0.8847e^{-0.1061p \sec(z)} \quad (2)$$

z is the solar angle of zenith, p is pressure measured at the station, at atmospheres, $h = 1$ for alt <1150 ft and $h = p^2$ otherwise.

The decomposition method of Erbs [6] was used in the developed program for the calculation of the diffuse horizontal irradiance DHI from the horizontal global GHI and direct

normal DNI irradiances, according to the relation:

$$DHI = GHI - DNI \times \cos(z) \quad (3)$$

GHI is the global irradiance on the horizontal plane, DNI is the normal direct irradiance, z is the zenith solar angle.

IV. DATA TRANSPOSITION

Meteorological data transposition methods are used to calculate the equivalent irradiances in a tilted plane (direct DBI, diffuse DTI, and in consequence global GTI) from the horizontal plane irradiances and the fixed angular orientation of the photovoltaic modules (β).

A. Direct Irradiance

The geometric method for the calculation of the direct irradiance in a tilted plane (DBI) considers the projection of the direct normal irradiance (DNI) in the fixed tilted plane in which the PV modules are installed, that is to say:

$$DBI = DNI \times \cos(AOI) \quad (4)$$

DNI is the normal direct irradiance, AOI is the angle of incidence of sunlight on the tilted plane.

B. Diffuse Irradiance

The diffuse equivalent irradiance in a tilted plane (DTI) is calculated in the developed program using the isotropic sky model [7], according to the formula for the global irradiance in the tilted plane GTI (with components direct DBI and diffuse DTI, DTA):

$$GTI = DNI \times R_n + DHI \left(\frac{1 + \cos \beta}{2} \right) + DHA \left(\frac{1 - \cos \beta}{2} \right) \quad (5)$$

DNI is the normal direct irradiance, $R_n = \cos(AOI)$ is the variable geometric factor, DHI is the diffuse horizontal irradiance, β is the angle of inclination of the photovoltaic modules, DHA is the diffuse horizontal irradiance by reflections on the ground (albedo).

V. ENERGY PRODUCTION

The Sandia Advanced Model [8] model for photovoltaic modules and inverters has four sub-models for the modules and three sub-models for the inverters. For example, the simple efficiency sub-model is represented as follows:

$$P_{dc,m} = G \times \eta_m \times A_m \times \frac{\gamma_{mp,ref}}{100} \times (T_c - 25) \quad (6)$$

$G = G_b + f_d(G_d + G_a)$ is the total effective irradiance in a tilted plane, f_d is the diffuse irradiance utilization factor, η_m is the conversion efficiency of the module, A_m is the module area in squared meters, $\gamma_{mp,ref}$ is the maximum temperature coefficient in power, T_c is the temperature of the cells of the photovoltaic modules. On the other hand, the Sandia model with the option inverter with manufacturer data is expressed in the form:

$$P_{ac} = \frac{P_{ac,0}}{P_{dc,0} - P_{s,0}} (P_{dc} - P_{s,0})^2 \quad (7)$$

$P_{ac,0}$ is the maximum AC power, $P_{dc,0}$ is the maximum DC power, $P_{s,0}$ is the power consumption during operation.

The calculation of the energy produced at the end of a day was added to the program as the integral of the power curve, which facilitates the calculation of the energy, due to the fact that they are hourly means of power, as a cumulative sum of the hourly power values (*cumsum* function of MATLAB), where T can be 1h or less (sampling period in the studied case is 30s = 1/120h):

$$E_{kWh} = \sum_{n=1}^N P_{ac}(nT) \times T \quad (8)$$

VI. DEVELOPED PROGRAM AND HARDWARE SETUP

The program developed to simulate grid-connected photovoltaic solar systems is based on the Sandia National Laboratory's open-source library PV_LIB [9], which is composed of a set of functions for the decomposition and transposition of meteorological data, as well as the modeling of photovoltaic modules and inverters. The PV_LIB library is available for MATLAB and Python, and the MATLAB environment is chosen due to the existence of other functions and libraries that facilitates the analysis and evaluation of the energy production simulation.

For this purpose, the PV_LIB codes were modified, and a graphical interface was developed in the MATLAB environment, in order to facilitate the use of the program. The interface developed in MATLAB Graphical User Interface Development Environment (GUIDE) is presented in Fig. 3.

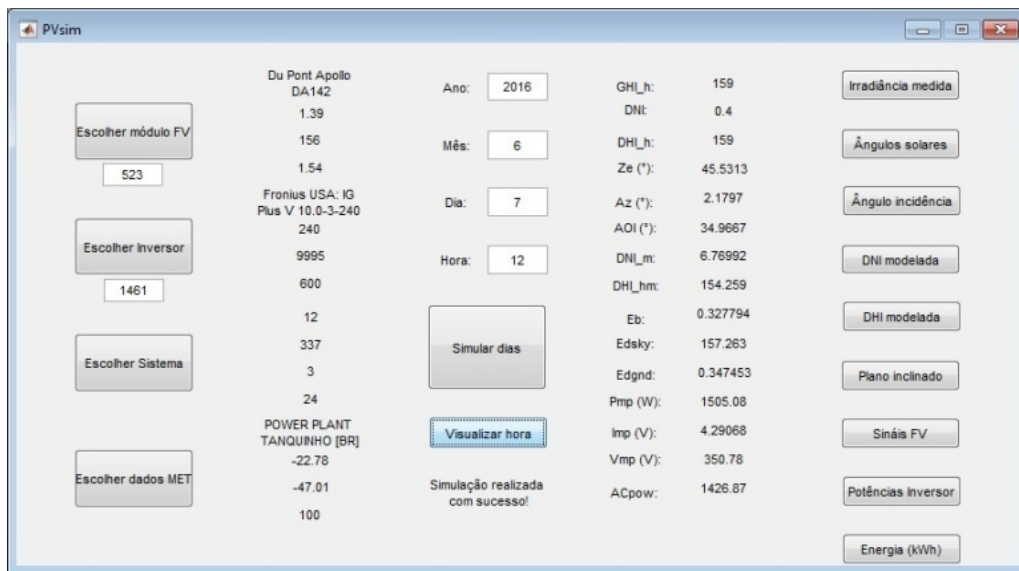


Fig. 3 Home screen of the photovoltaic system simulator



Fig. 4 Energy meter connected to the output of a three-phase solar inverter in Tanquinho solar power plant, Brazil

In order to validate meteorological data decomposition and photovoltaic energy production, measurements of meteorological data and produced energy were performed in

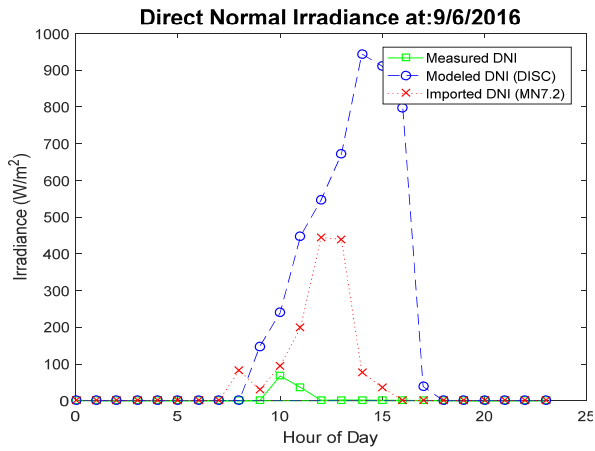
part of the Tanquinho Solar Photovoltaic Power Plant in Campinas, Brazil. The studied photovoltaic system uses 24 strings of three thin-film modules from Dupont-Apollo and a 10-kW three-phase inverter from Fronius.

To carry out the measurements, within the short time available to do the task, one of the string inverters of the plant was chosen, which had its output power monitored every 30 seconds by an energy meter between days 7th June and 21st June, in 2016. Fig. 4 shows the meter connected to the output of the photovoltaic inverter in one of the power distribution boards of the plant.

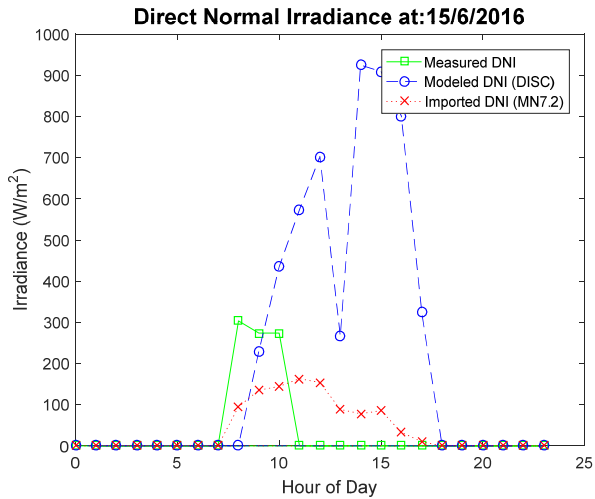
VII. RESULTS AND COMPARISON

In this section, we show the results of the developed program in relation to the normal direct irradiance (DNI) modeled from measured global horizontal irradiance (GHI) data and using the DISC method, which is compared to the DNI calculated from the Meteonorm database (using the PVsyst program) and the DNI measured in the field, for the

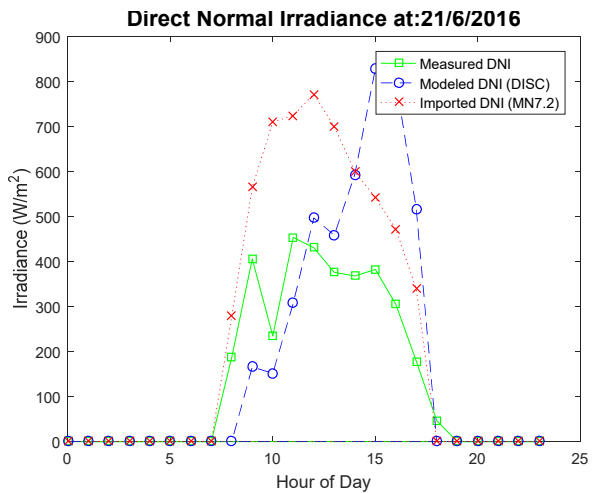
days 9th June (average day), 15th June (clean day) and 21st June (cloudy day) in 2016 by the solarimetric station of the Tanquinho solar power plant, see Fig. 5.



(a) June 9th, 2016

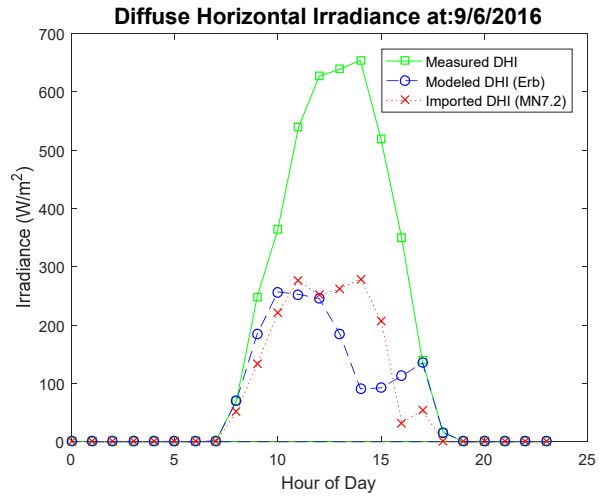


(b) June 15th, 2016

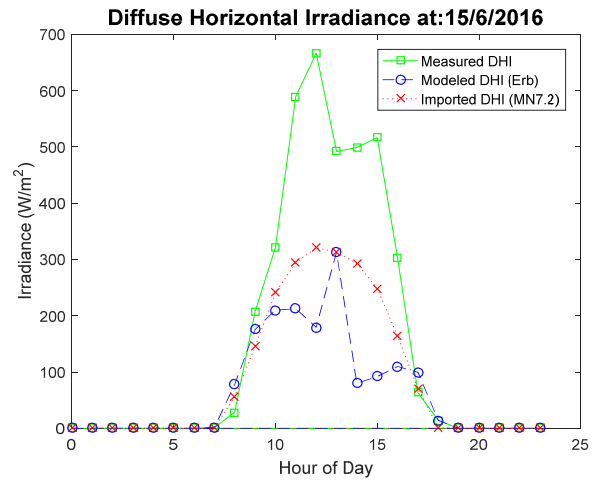


(c) June 21st, 2016.

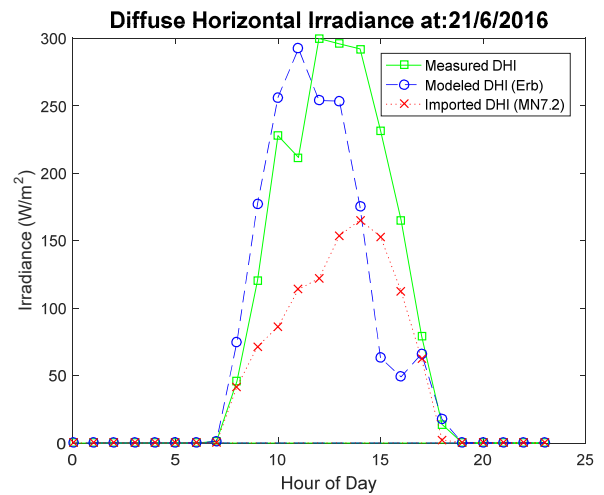
Fig. 5 Estimation of DNI for three typical days



(a) June 9th, 2016



(b) June 15th, 2016



(c) June 21st, 2016

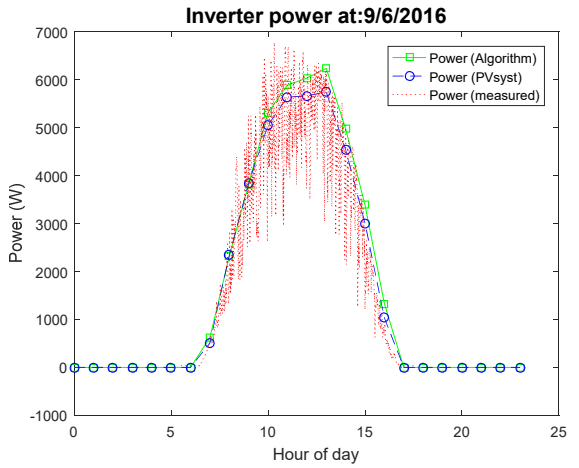
Fig. 6 Estimation of DHI for three typical days

The horizontal diffuse irradiance (DHI) component was also modeled from measured horizontal global irradiance

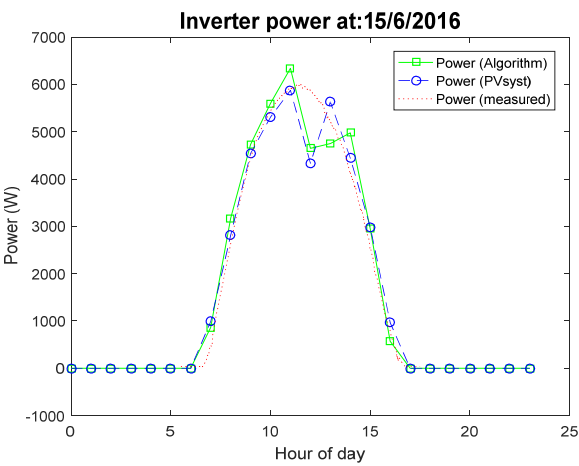
(GHI) data by the Erbs method. The results were compared with the Meteonorm database and the measured DHI in the field for the available measurement days. Results for a normal day (9th June), a clean day (15th June) and a cloudy day (21st June) are depicted in Fig. 6.

Fig. 7 presents the simulation results of power at the inverter output compared to PVsyst simulation and measured power data on normal, clean and cloudy days.

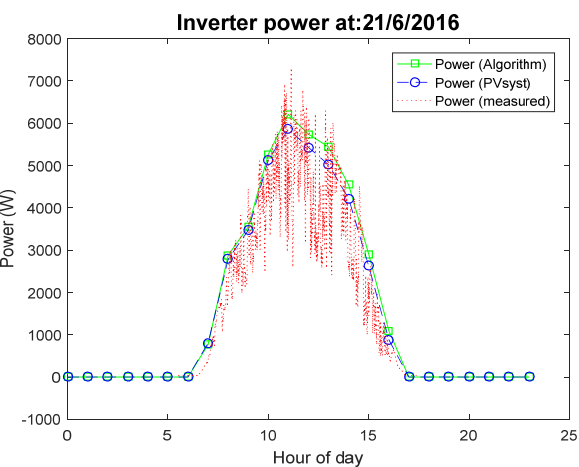
The energy curves produced between June, 7th and 21st, 2016 were simulated in the developed program with measured global horizontal, direct normal and diffuse horizontal irradiances and using geometric and isotropic sky decomposition methods. The curves were compared with simulations in PVsyst using measured irradiance and geometric and Perez transposition methods, as well as with produced energy data that were measured in the photovoltaic power plant. The results for average, clean and cloudy days are shown in Fig. 8.



(a) June 9th, 2016

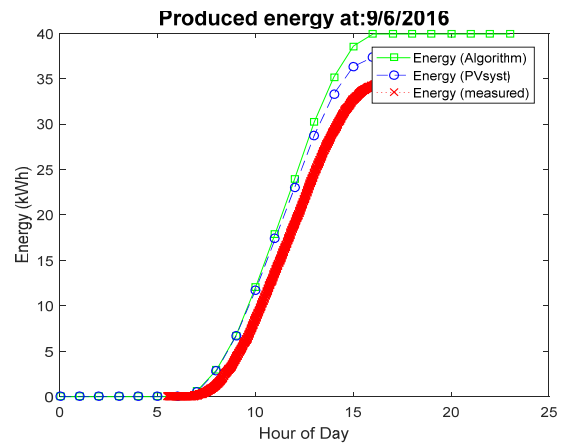


(b) June 15th, 2016

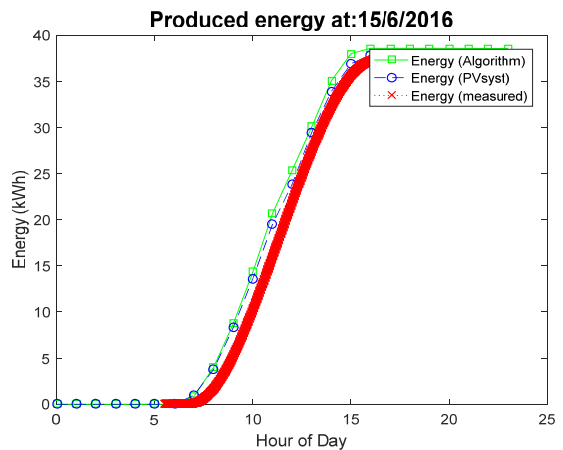


(c) June 21st, 2016

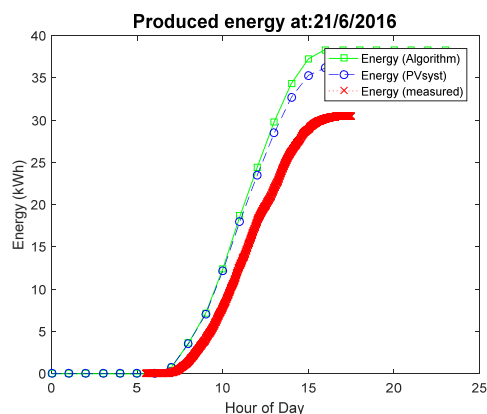
Fig. 7 Output power for three typical days



(a) June 9th, 2016



(b) June 15th, 2016



(c) June 21th, 2016

Fig. 8 Energy produced in three typical days

Finally, to verify the performance of the simulation tools used, the percentage error $E_p = 100\% (E_{mod} - E_{mea}) / E_{mea}$ of energy production at the end of the day was evaluated in the period between June 7th and 21st, 2016. The results are shown in Table I, in which it can be observed that the simulation in PVsyst has a result that is closer to the one measured. That is probably due to the fact that shading and dirt of the photovoltaic modules were not considered in this work. Moreover, it is possible to improve the performance of the developed program by testing other transposition methods for meteorological data, and by adjusting the parameters of the photovoltaic module and inverter according to the datasheet of the manufacturer.

TABLE I
 PERCENTAGE ERROR IN ENERGY PRODUCTION

Day	Algorithm error	PVsyst error
07-June	21.2 %	15.1 %
08-June	10.2 %	3.95 %
09-June	15.7 %	8.29 %
10-June	21.4 %	14.2 %
11-June	16.8 %	8.90 %
12-June	11.7 %	4.53 %
13-June	19.2 %	10.0 %
14-June	31.6 %	19.4 %
15-June	2.83 %	0.94 %
16-June	30.2 %	17.6 %
17-June	30.7 %	18.0 %
18-June	31.2 %	18.7 %
19-June	29.9 %	18.5 %
20-June	27.5 %	17.9 %
21-June	25.8 %	18.8 %

VIII. CONCLUSION

A MATLAB program based on the open source library PV_LIB allowed us to enter PV system data using a graphical interface and obtain the hourly energy and meteorological data for an entire year, with the advantage of being able to test several methods within the same program.

The estimation procedure of photovoltaic energy explained in this work can be used to simulate a wide variety of systems

and to evaluate performance when there is access to field-measured energy data. New technologies of photovoltaic modules and inverters can be inserted from the manufacturer's data, as well as meteorological data from solarimetric stations or databases available on the internet.

Comparisons show that the open-source based algorithm used in this work has lower precision than commercial software, especially for cloudy days. Tests with more measured meteorological and energy data will be considered in future work.

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