Effect of Environmental Factors on the Performance of Photovoltaic Solar Modules Arrays

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Abstract : Identifying how soiling affects the performance of photovoltaic systems, would help us to optimize their cleaning cycles and reduce their indirect carbon footprint. For this reason, a photovoltaic system installed in Barranquilla (Colombia) was analyzed; calculating their performance considering the climatic factors and comparing it with the real performance of the system. Differences were noted between actual and calculated performances referable to soiling, what increase the system's indirect carbon footprint because the non-generated energy must be supply by a conventional energy source (fossil fuels); these differences change depending on the rains. The characterization of the rains would allow to know a model to estimate the soiling.

Key words : Solar irradiance, environmental factors, photovoltaic (PV) solar module, soiling, indirect carbon footprint.

Introduction

Every year, the world energy consumption increases dramatically because the increase of the world population. Nowadays the most of the electrical energy is generated from fossil fuels which also generate greenhouse gases, GHG. Therefore, the use of renewable energy sources like the solar energy is a clean solution for the electrical energy generation and thus to reduce the GHG emissions (1).

The solar energy can be transformed using PV solar modules that transform the solar energy into electrical energy directly. The performance of PV solar modules depends of environmental factors like the available solar irradiance, the wind speed and direction, ambient temperature, cell temperature, relative humidity, the pollution and the solid particles that deposit on the surface of the PV solar modules (2, 3 and 4).

So, to estimate the technical and economic performance of a PV solar generation facility, is necessary to have a model that allow us to evaluate the operational performance of the modules with the specific conditions of the installation (3). This paper searches to establish a method to calculate the performance of a PV solar modules array installed in Barranquilla, using the relation between the efficiency, the climate factors and the soiling. This location has one of the better average irradiance of the region (5).

The soiling affects the performance of the PV solar generation systems because it reduces the glass protector transmittance of the module and reduce the exploitation of the solar incident irradiance. The soiling can reduce the generated power of the PV solar system till 50% (2). In 1940 decade, was realized the first

researches about the soiling effect on the performance of solar systems; these researches worked over the flat-plate thermal solar collector technology, getting 4.7 % of performance reduction as result; this small effect could be possible because the researches were made during the rainy season and the module's tilt was 30° what helped the natural cleaning of the surface (3).

In 1970 decade, it was realized studies in Saudi Arabia and Kuwait what showed that the soiling reduced the performance of PV modules till 33.5 % after one month without a cleaning routine and till 65.8 % after six months (3). Since 1990 decade, they have been realized a lot studies about the effect of the soiling on the performance of the PV modules, in general terms, every study identified the soiling as one of the key factors in the reduction of the PV modules performance and also as one of the factors that can be corrected through maintenance actions. Recent studies have been showed that the reduction on the PV modules performance is strongly related with the particulate material composition (1 and 2).

Though the PV solar system are environmental friendly, its efficiency reduction could generate an indirect carbon footprint because the non-generated energy must be supply by other energy sources of the energy grid that are fossil fuels commonly.

Experimental

In this study, it was taken as data source a solar energy plant located in Barranquilla, Colombia. The plant has 150 PV 315 Wp polycrystalline modules and three 14kW invertersbut only was taken data from 104 PV modules and two inverters because the data from the other inverter were incomplete. Furthermore, the plant has a weather station where is logged the next variables: ambient temperature, dew point, relative humidity, rain, atmospheric pressure, speed and direction wind and solar irradiance. In the Table 1 and in the Fig. 1, can find a PV modules technical data and plant pictures.

Table 1. Technical data of PV modules. Taken from PV module datasheet.

Reference	CHSM661P-315
Maker	Astronergy
Nominal power	315.0 Wp
Voltage at maximum power	35.83 V
Open-Circuit voltage	45.55 V
Short-Circuit current	9.02 A
Current at maximum power	8.71 A
Technology	Si-Poly (72 cells)
Dimensions	0.994m x 1.956m

(a)   (b)

Fig. 1. (a) PV solar modules array; (b) Weather station.

(a)

(b)
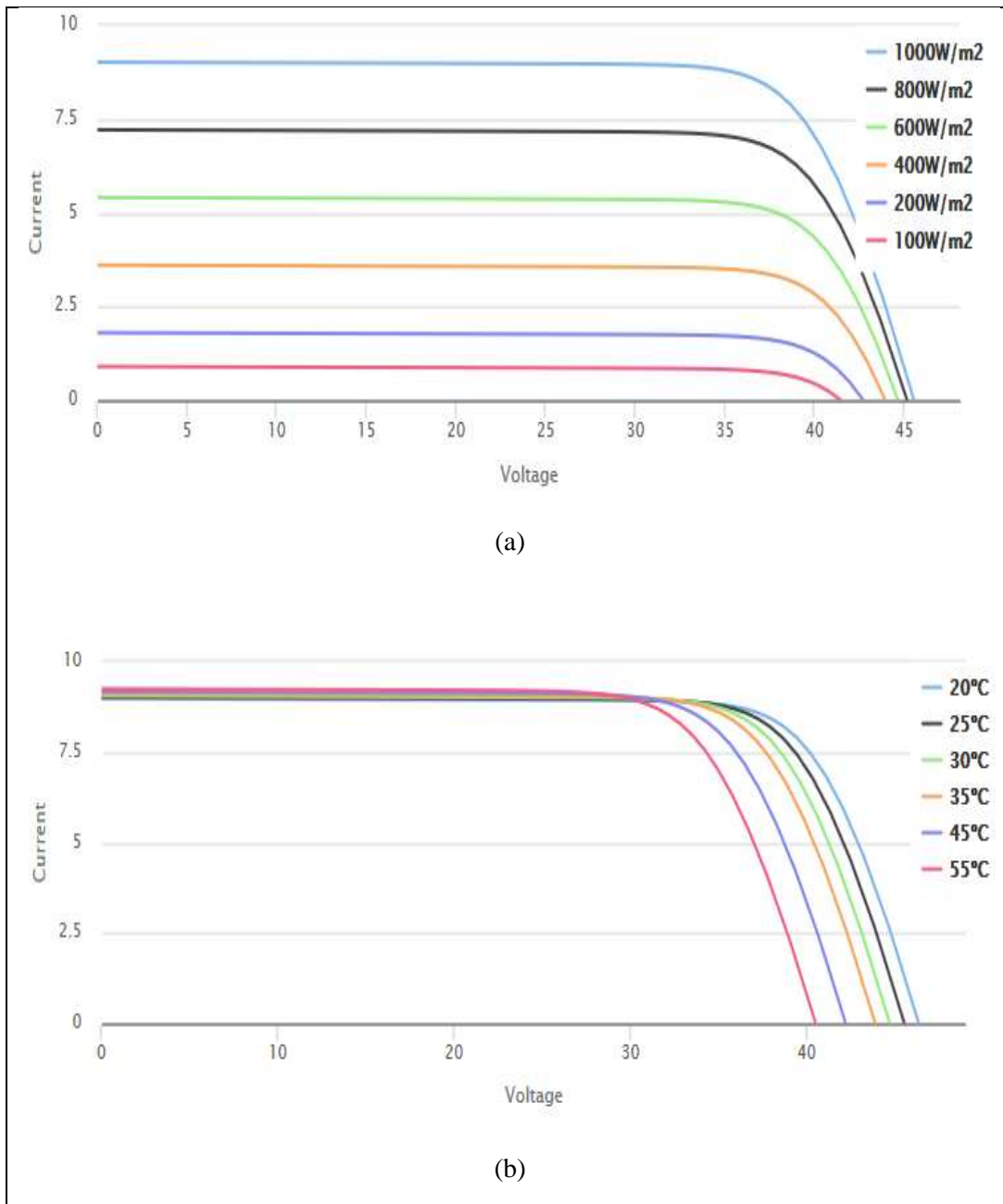
Fig. 2. (a) PV module I-V curve at constant temperature (25 °C); (b) PV module I-V curve at constant solar irradiance (1000 W/m^2). Taken from Helioscope database.

The PV modules nominal performance is described by their I-V curve what is unique for every kind of PV module. The behavior of this curve is function of two weather factors: The solar irradiance [W/m^2] and the cell temperature [°C], as is showed in Fig. 2. In typical operation conditions, these factors vary so it is necessary to get a mathematical model that estimate the behavior of the PV modules output power in function of these factors (6 and 7). It was used a nonlinear second order polynomial model, as is showed in Eq. 1.

$$P = A \cdot G_{eff}^2 + B \cdot G_{eff} + C \cdot T_{cell}^2 + D \cdot T_{cell} + E \cdot G_{eff} \cdot T_{cell} + F \cdot G_{eff}^2$$
$$\cdot T_{cell} + G \cdot G_{eff} \cdot T_{cell}^2 + H$$
Eq. 1

Where P is the PV module output power [W], G_{eff} is the effective irradiance on the plane of the PV module [W/m^2], T_{cell} is the PV module temperature [°C] and; A, B, C, D, E, F, G and H are the weights of the model.

To calculate the effective irradiance on the plane of the PV module, it is necessary to make the correction of the irradiance with respect to the tilt angle of the modules; in this case, 10° south. The Eq. 2 to Eq. 5 show how to calculate the effective irradiance.

$$\cos\theta = \cos(\phi - \beta)\cdot\cos\delta\cdot\cos\omega + \sin(\phi - \beta)\cdot\sin\delta \qquad \text{Eq. 2}$$
$$\cos\theta_z = \cos\phi\cdot\cos\delta\cdot\cos\omega + \sin\phi\sin\omega \qquad \text{Eq. 3}$$
$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad \text{Eq. 4}$$
$$G_{eff} = R_b\cdot I \qquad \text{Eq. 5}$$

Where θ is the angle of incidence of the irradiance on the PV modules array, ϕ is the latitude angle of the location, β is the slope angle of the PV modules array, δ is the declination angle of the location, ω is the hour angle, θ_z is the zenith angle, R_b is the ratio of total irradiance on the tilted surface to that on the horizontal surface and I is the solar irradiance on the horizontal surface [W/m^2] (8). The PV module temperature depends of the heat transfer by radiation from the sun and heat transfer by convection (9, 10, 11and 12).

$$T_{cell} = T_{amb} + \frac{G_{eff}}{U_0 + U_1 W_s} \qquad \text{Eq. 6}$$

Where T_{amb} is the ambient temperature [°C], U_0 is the heat transfer coefficient by radiation [W/m^2-K], U1 is the heat transfer coefficient by convection [W-s/m^2-K] and W_s is the wind speed [m/s].

So, if it is replaced Eq. 5 and Eq. 6 on Eq.1, it is gotten the generated power of the PV modules array. This generated power must be corrected by the PV modules aging that is 2.5 % in the first year (data from the PV module datasheet). On other hand, the actual generated power by the PV modules array is gotten from the DC voltage and DC current registers of the inverters. Finally, it is possible compare the daily performance of the model and the actual system (13). Also it is possible calculate the indirect carbon footprint of the system by performance derate.

Results

For this analysis, were taken the data of the weather and the electrical variables from May 15, 2017 to September 15, 2017.

It was defined a nonlinear regression model that describe the behavior of a PV module using its specific I-V curve for effective irradiance upper 50 W/m2 and temperature among 20 °C and 55 °C, with an adjusted R-Square of 99.993 %. In the Eq. 7 and the Fig. 3 is shown the estimated model.

$P = (-7.45E-6)\cdot G_{eff}^2 + (3.56E-1)\cdot G_{eff} + (-5.31E-5)\cdot T_{cell}^2$ $+ (1.01E-2)\cdot T_{cell} + (-1.19E-3)\cdot G_{eff}\cdot T_{cell}$ $+ (5.90E-9)\cdot G_{eff}^2\cdot T_{cell} + (-1.74E-7)\cdot G_{eff}$ $\cdot T_{cell}^2 + 2.80$	E q. 7

In the Fig. 4, it is shown the linear behavior between effective irradiance and the incident irradiance, with a correlation of 98.98 %. In Eq. 8, is presented the linear model used.

$$G_{eff} = 0.9357\cdot I + 0.2549$$

q. 8

In the Fig. 5, the model is validated with data from September 16 to September 25, 2017; getting a correlation between the validation set and the model of 98.73 %.
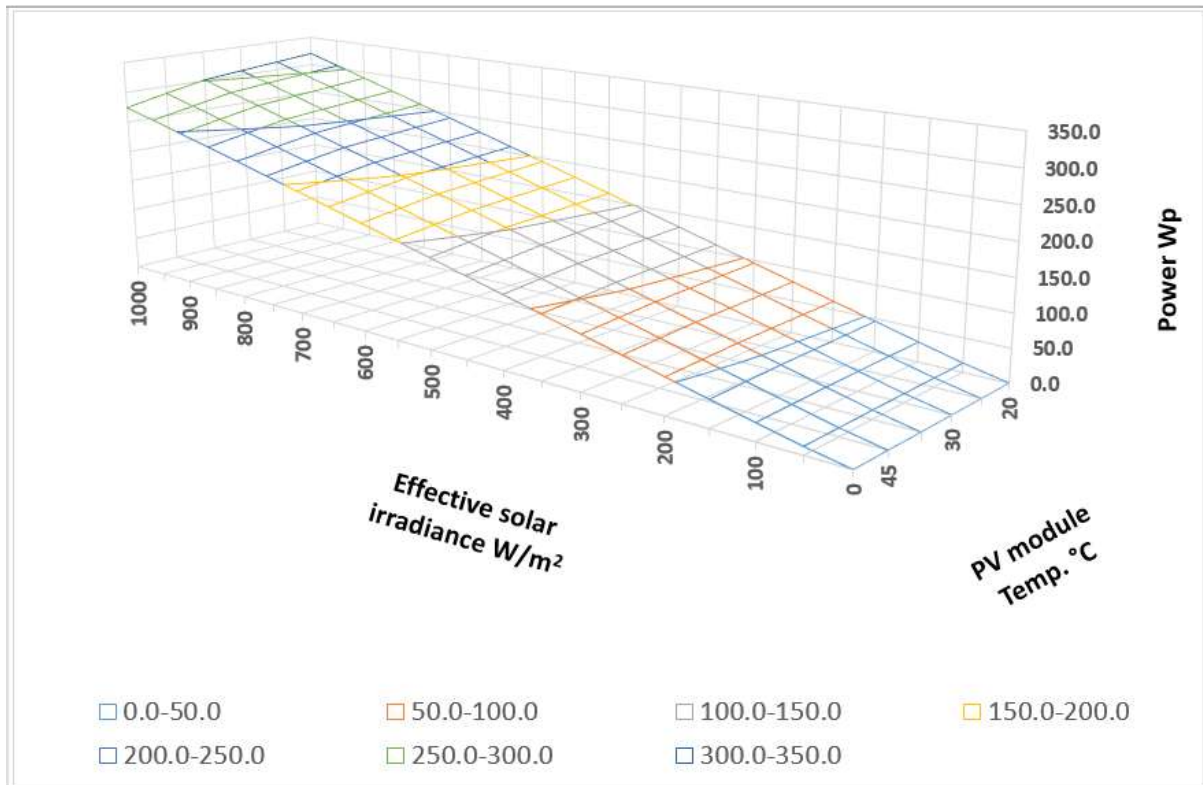
Fig. 3. PV module power model in function of effective irradiance and its temperature.
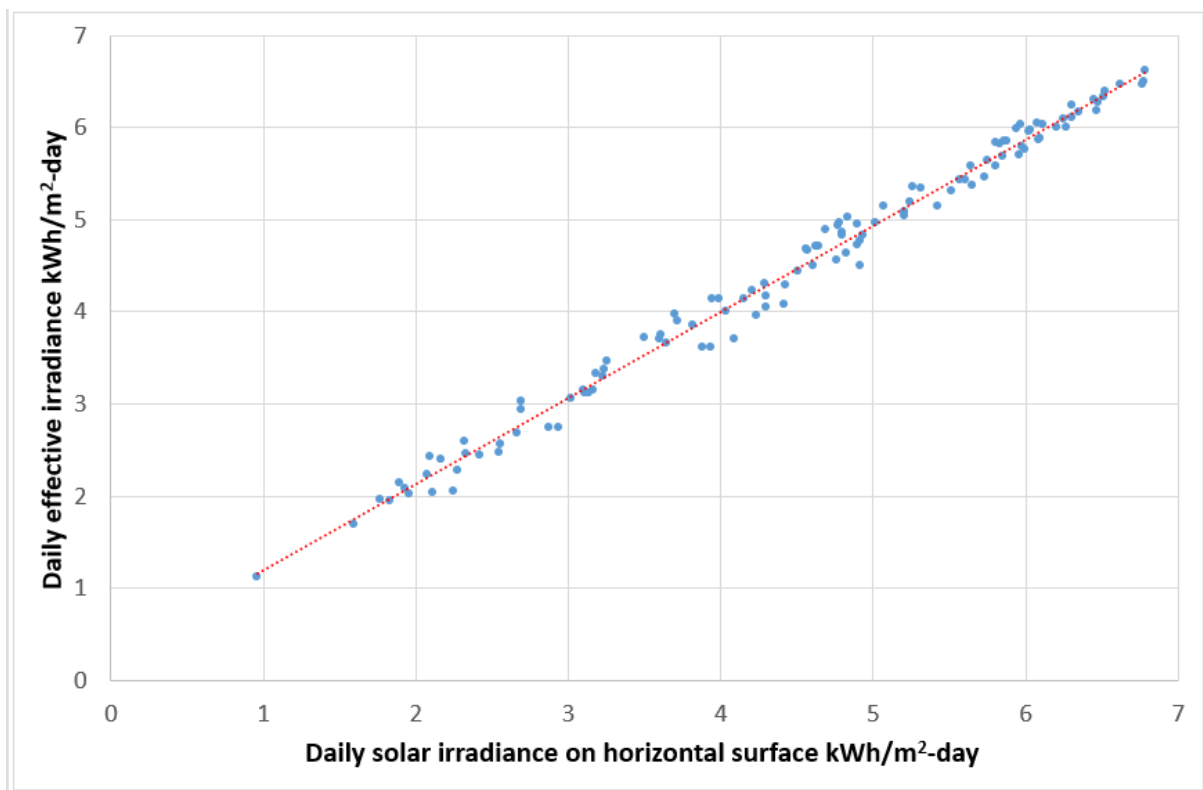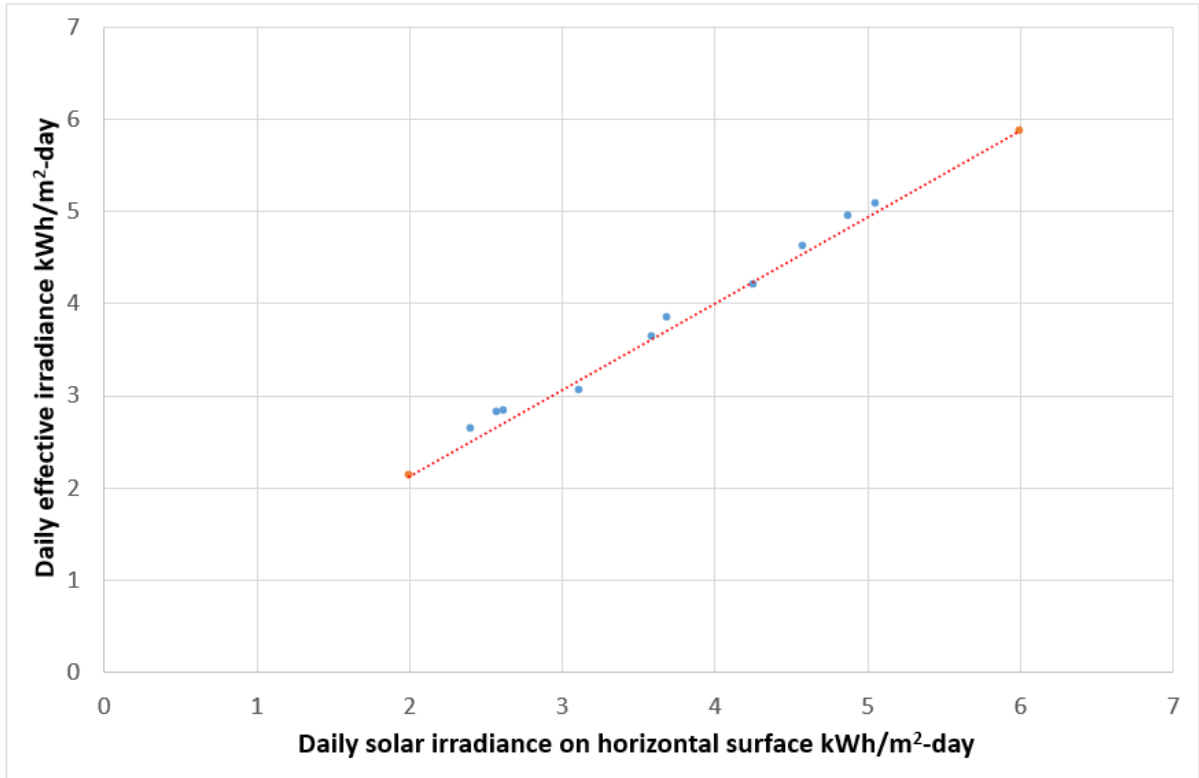

**Fig. 4. Effective solar irradiance Vs. Irradiance on horizontal surface.**

Fig. 5. Comparison between validation set and the model.

To calculate the module temperature, it was used Eq. 6; taking as coefficients U_0 and U_1, 30.02 W/m^2-K and 6.28 W-s/^{m3}-K, respectively. These coefficients were specified for polycrystalline solar PV modules in (12). In the Fig. 6, it is shown the difference between the ambient temperature and module temperature.

So having the effective solar irradiance and the module temperature, it is possible to use the Eq. 1 to calculate the modelled generated power and the modelled efficiency. Finally, it is applied the aging correction to the model.

The actual generated power is calculated with the DC current and DC voltage registers from the inverters.
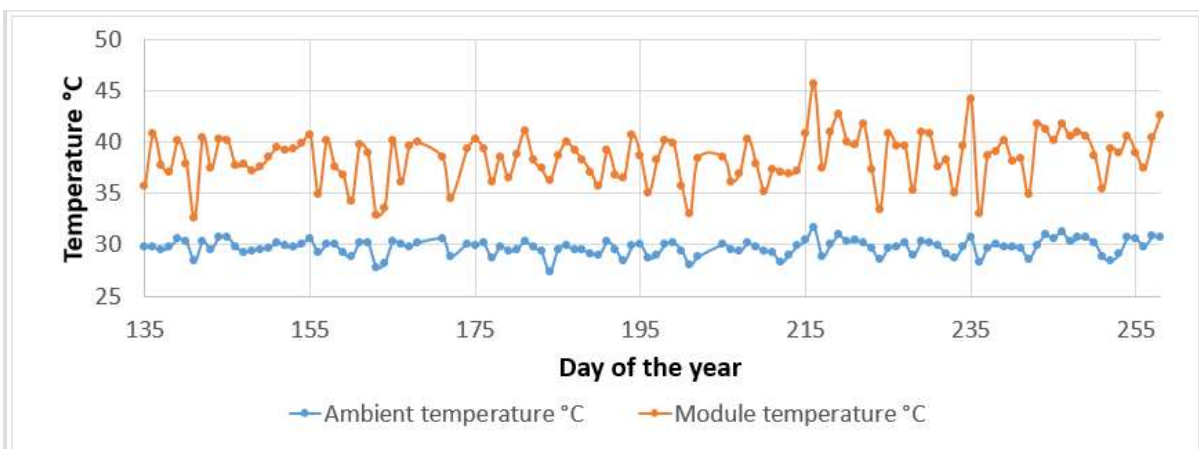
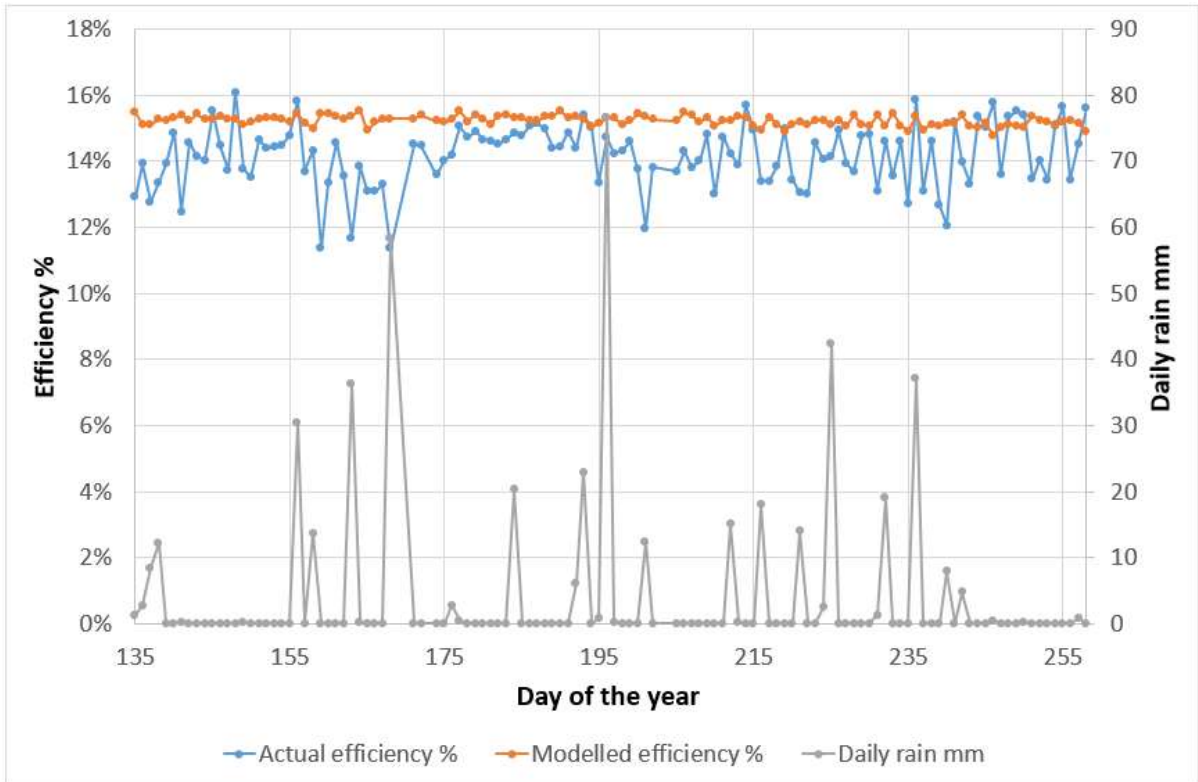**Fig. 6. Ambient temperature and module temperature comparison.**

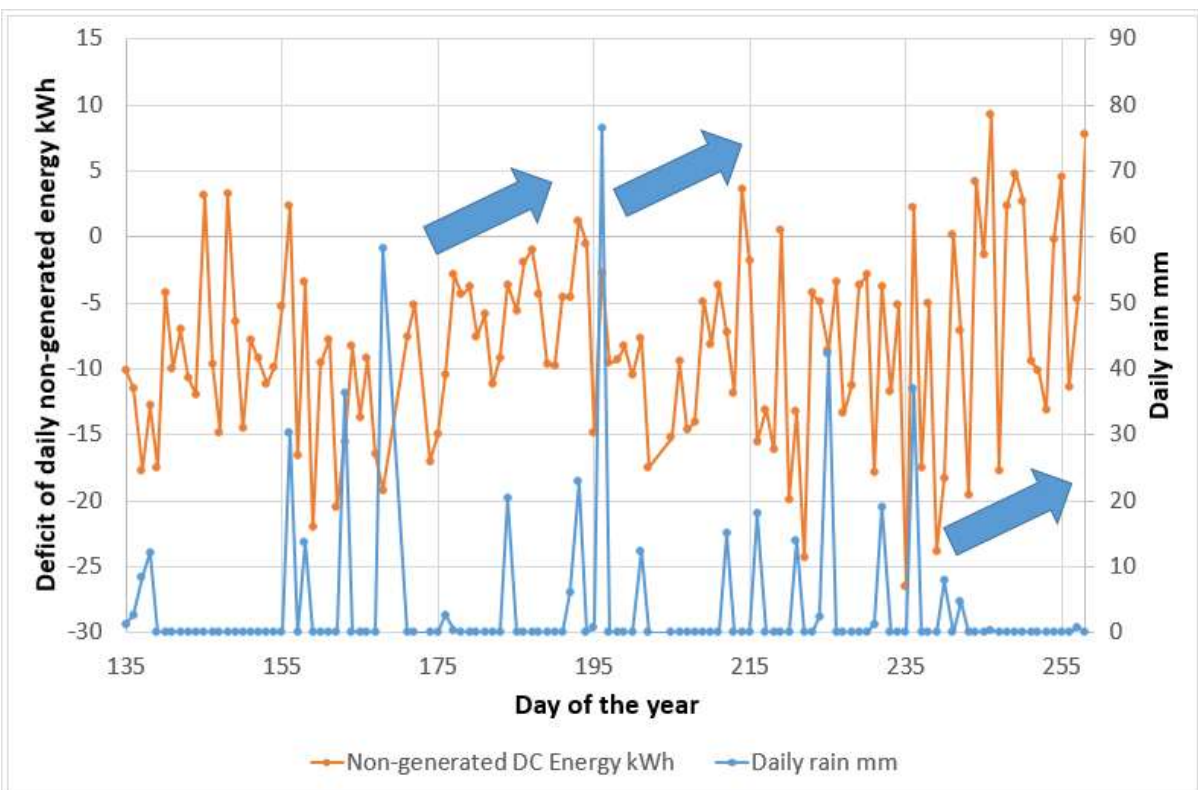**Fig. 7. Actual efficiency and modelled efficiency comparison.**

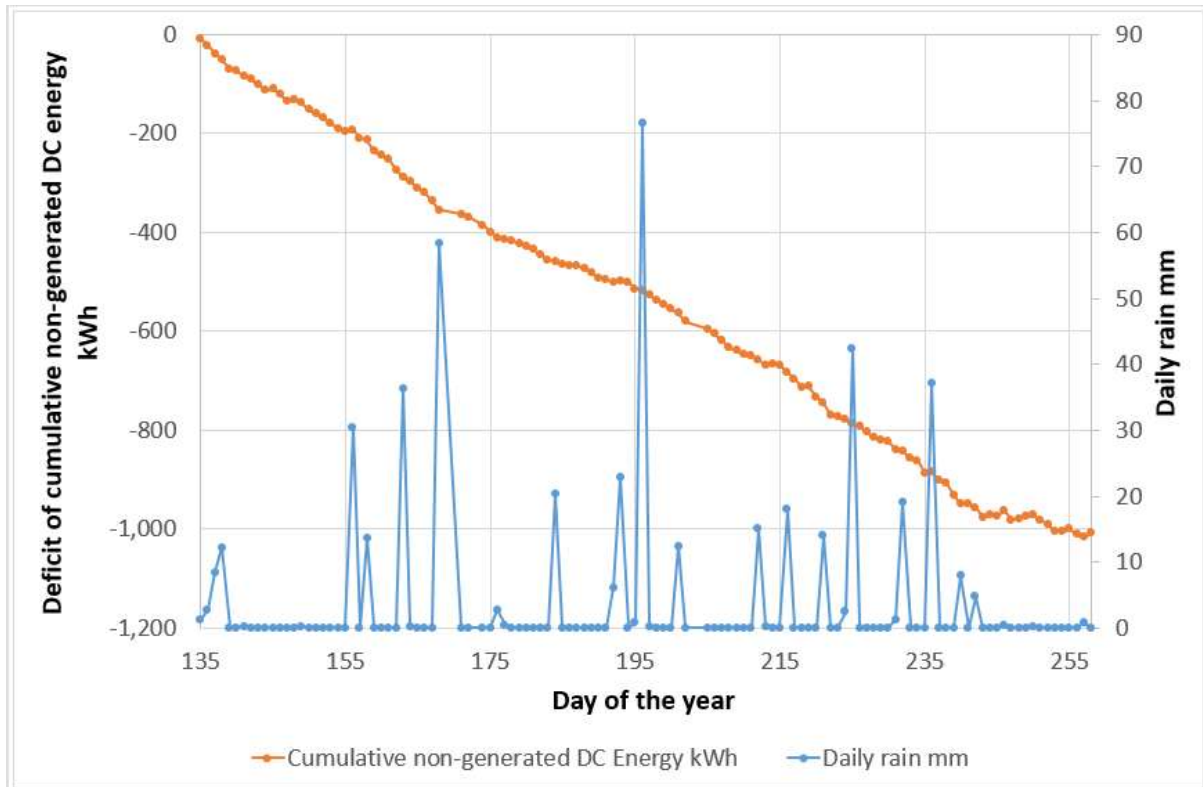**Fig. 8. Deficit of non-generated DC energy and daily rain.**

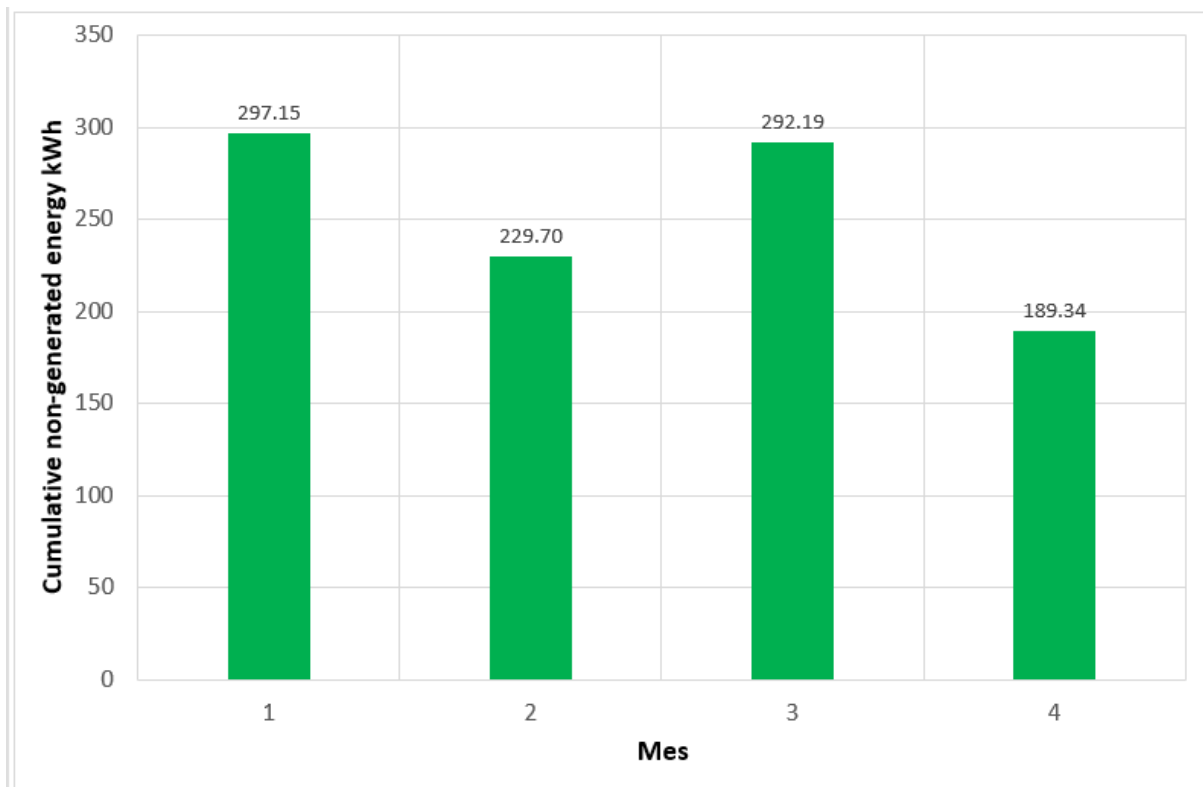**Fig. 9. Deficit of cumulative non-generated DC energy and daily rain.**

Fig. 10. Monthly non-generated energy.

In the Fig. 7, it is shown that the modelled efficiency has a stable behavior while the actual efficiency presents important variations, some of these variations could be associated to rain events. In the Fig. 8, it is

shown how the actual efficiency improve after some rainy events (8). However, no every rain events have the same effect over the actual efficiency of the plant.

In the Fig. 9 and Fig 10, it is shown that que trend of plant is to decrease the efficiency, though some rain events can improve the efficiency, those in not enough to change the trend but in month with more rain the reduction of efficiency is less accelerated.

This information could help to define a cleaning program centered in the condition of the PV modules having as factors: Cleaning cost, reduction of PV modules array efficiency, available solar irradiance, cost of kWh generated and PV module efficiency by area (14 and 15).

To calculate the indirect carbon footprint generated by the efficiency reduction, was used the emission factor proposed by UPME, 0.374 TCO_2/MWh (16).In the Table 2, it is shown the indirect carbon footprint as result of the system efficiency reduction.

Table 2. Indirect carbon footprint of the efficiency reduction.

Month	Monthly non-generated energy kWh	Month indirect carbon footprint $kgCO_2$	Month indirect carbon footprint $kgCO_2$/kWp
1	297.15	111.13	3.39
2	229.70	85.91	2.62
3	292.19	109.28	3.34
4	189.34	70.81	2.16

Discussion

The development of a mathematical model for the estimation of the behavior of a PV module in function of weather factors is a very important tool to evaluate the performance of the PV modules array system because allows to compare the actual PV module behavior with a model and identify possible external factors like the soiling that could affect the PV module performance.

The difference between the modelled and the actual data, it can be attribute to factors that was not used in the model development such as relative humidity, wind direction, soiling characterization and rain characterization. In the rain case, it is necessary to realize a characterization that allows to quantify its effect on the PV modules soiling (17). Also, the weather factors that were not consider by the model, are related with the soiling so it could consider that non-generated energy presented on Fig.10 is result of PV module soiling.

This study starts the way to the development of a model to improve the cleaning cycles for PV modules (Efficiency Centered Maintenance, ECM) because the soiling effect on the PV module efficiency was isolated indirectly and was possible calculated the non-generated energy. So it is possible calculate the economic and environmental costs of the efficiency reduction.

In other hand, there are many work to do for the adjustment of the model for example: experimental measurement to determine the coefficients U0 y U1 for the specific location, measure the quantity of material that deposit on the PV module to establish a soiling measurement and to develop a rain model that include factor like rain rate, rain duration, wind direction and speed, and other factor that allow measure the effect of the rain over the PV module soiling.

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