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Photovoltaic simulation considering building integration parameters

Simulación fotovoltaica considerando parámetros de integración en edificaciones

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Abstract

This research calibrates and validates a model for monocrystalline photovoltaic systems in SAM (System Advisor Model) for power generation simulation, considering the meteorological characteristics of Cuenca, Ecuador, close to the equatorial line. The electrical performance is calculated by arranging photovoltaic systems with specific characteristics, with inclinations that respond to conventional local roofing and different orientations. Efficiency is calculated with *in situ* measurements over a period of 18 days. Meteorological data were used to calibrate a weather file for the year 2016. Annual yields are estimated according to inclination and orientation, and technical characteristics of the photovoltaic system. Losses are detected due to dirt accumulation and increase in temperature of the panels. The model is validated by linear regression, by comparing the simulated values with the data obtained from *in situ* measurements of a reference panel deployed horizontally. The results show an average efficiency loss of 2.77% for dirt conditions and up to 30% for temperature increases.

Resumen

Esta investigación calibra y valida un modelo de sistemas fotovoltaicos monocristalinos en la herramienta computacional System Advisor Model (SAM) para simulación de generación eléctrica, considerando las características meteorológicas en Cuenca (Ecuador), ciudad en altura próxima a la línea ecuatorial. Se obtiene el rendimiento eléctrico al desplegarse paneles fotovoltaicos de características específicas, con inclinaciones que responden a techumbres típicas locales y distintas orientaciones. Se calcula la eficiencia con mediciones *in situ* durante un período de 18 días, para que, con datos meteorológicos se calibre un archivo climático para el año 2016. Se estiman rendimientos anuales acorde a inclinación y orientación, y a características técnicas de los fotovoltaicos. Se detectan pérdidas por acumulación de suciedad e incremento de temperatura de las placas. Se valida el modelo mediante una regresión lineal, al comparar los valores simulados con los datos obtenidos de mediciones *in situ* de un panel en posición horizontal. Los resultados indican una pérdida promedio de eficiencia de 2,77 % por condiciones de suciedad y de hasta el 30 % por incremento de temperatura.

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The validation of the model showed a determination coefficient R^2=0.996 and a normalized Root Mean Square Error (RMSE) of 8.16%. It is concluded that because of the particular latitude of the study site, unlike most of the planet, the provision of photovoltaic panels in any orientation considering low slopes does not significantly reduce the annual power generation performance.

Keywords: Monocrystalline, Photovoltaic Simulation, SAM, Renewable Energies

La validación del modelo mostró un coeficiente de determinación R^2 = 0,996 y un RMSE normalizado de 8,16 %. Se concluye además que, por la latitud particular del sitio en estudio, a diferencia de la mayor parte del planeta, la disposición de paneles fotovoltaicos en cualquier orientación considerando pendientes bajas, no reduce significativamente el rendimiento en la generación de energía eléctrica anual.

Palabras clave: energías renovables, monocristalino, SAM, simulación fotovoltaica.

1. Introduction

The increasing energy demand and the anthropogenic processes that cause the climatic change have made necessary to consider alternative sources of energy which are clean, renewable and of lower impact expansion potential [1]. In addition, it is also an ideal condition that they can be deployed in buildings and urban environments [2,3]. The photovoltaic (PV) solar technology is undoubtedly one of the main alternatives to face the global energy problematic, due to its existent potential for expansion and more convenient costs [4,5].

Due to its geographic location, Ecuador is at a latitude with important solar potential [6,7]. Ecuador is a developing country with increasing energy consumption and mostly invariant seasonality along the year [8,9]. As a consequence, there exist relatively constant high levels of insolation [10] that provide a high potential for utilizing solar energy as an alternative for effectively reducing atmospheric contaminants and the global effects of climatic change [11–13].

Nevertheless, since each city has particular characteristics regarding resources and energy demand [11], [14], it is necessary to determine the variable potential for energy generation in every urban environment, prior to establishing urban [15] and infrastructure [16] regulations. The International Renewable Energy Agency (IRENA) suggests taking advantage of vast building surroundings and roof areas to locate energy capture systems as a complement to energetic efficiency measures in buildings, and for implementing distributed energy production schemes [12].

Some aspects with urban impact must be considered in the case of photovoltaic or thermal solar technologies. For instance, capture surfaces should be placed coplanar in the building, taking part of the architectural surroundings [17]. In addition, they should be deployed according to the consumption of each building [18].

There are currently being developed architectural constructive elements, such as cover slabs, glasses, solar filters and even tiles, which are photovoltaic (PV) panels, i.e. they have energy generation capacity. These elements preserve the geometry and take part of the surroundings, thus satisfying the concept of architectural integration [PV Building Integrated Photovoltaics (BIPV)] [19–21].

This work is intended to determine the electrical efficiency of PV monocrystalline solar panels as a function of the inclination and orientation, in order to provide a methodological foundation for the development of a model for predicting the performance of other PV technologies suitable for adaptation or integration to the building surroundings; this requires measuring the performance for different orientations and inclinations.

There are not clearly established criteria regarding optimal inclination and orientation of PV panels for cities such as Cuenca, and any inclination close to the horizontal and oriented opposite to its latitude is considered appropriate [22]. However, this empirical guideline does not take into account aspects such as the coplanar adaptation to the buildings, and the losses due to accumulation of dirt, which may vary between 5% [23] and 35% [24] and affect the performance of the system.

Besides the aforementioned issues, the surface temperature of the PV modules also affect the overall system efficiency in PV facilities [25–28]. In addition, it is necessary to consider economic aspects and energy demand, in order to maximize the production during periods of higher demand or cost [29].

This study proposes a methodology to build a simulation model in the software SAM (System Advisor Model) [30], to estimate the production of electricity of PV monocrystalline panels. The model is calibrated considering the impact of factors such as orientation, inclination, and efficiency losses due to the accumulation of dirt and temperature increments. The model and the corresponding climatic file are implemented in SAM. The resulting model is valid for simulating real values of production [31] and determining the PV performance, without requiring *in situ* measurements along periods of one year or longer, and preventing the use of models with more uncertainty and which are not freely available to the user. In this manner, the methodology for model calibration can be replicated in other locations.

2. Materials and methods

This study is focused in calibrating and validating a simulation model of a monocrystalline PV system, using short periods of *in situ* measurements. In addition, a local climatic file in readable format (SAM CSV) is generated by the software SAM. Performance losses due to parameters such as accumulation of dirt and increments of temperature as a function of weather and global irradiance, are also considered.

The *in situ* measurements were carried out during December 2016 and January 2017. Three monocrystalline PV panels were installed next to a meteorological station located at (-2.901691°S, -79.010151° E). Each panel has a nominal power of 100 W, 36 cells and dimensions 0.54 m wide and 1.2 m long (Figure 1), and is electrically connected to the HIOKI PW 3337-03 measurement equipment and to variable load resistances, which were adjusted between 1 and 100 Ω in order to obtain the maximum power (Figure 2) for a specific irradiance. Data of DC voltage, current and power were collected, with a sampling period of five minutes, which were further converted to hourly intervals.

In particular, the measurements were taken according to the inclination and orientation of the panels, along 12 days of December 2016 between the hours of 7:30 and 17:00. Data were obtained from the horizontal panel and panels with inclinations 14.00°, 18.26° and 26.56° (with all orientations: N, S, E, W), to validate the model in SAM. These inclinations correspond to typical roof pitches in low-rise buildings and residential housings in the city of Cuenca [32]. The methodology shown in Table 1 was used for measuring performance according to inclination and orientation.

Figure 1. Monocrystalline solar panels with different inclinations

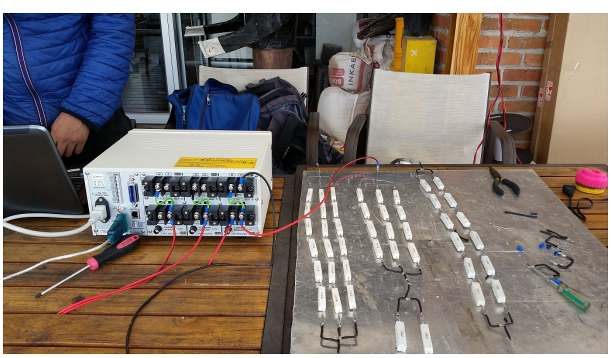

Figure 2. HIOKI PW 3337-03 equipment and load resistors

Then, the efficiency was calculated as:

$$\eta = \frac{P}{E \times Ac} \times 100 \quad (1)$$

where η is the efficiency of the panels, P is the output power, E is the irradiance of the sun, and Ac is the capture area or area of the panel. For each orientation, the inclination which resulted in the best performance (among the three proposed) was chosen, and additional measurements were taken along three days of January 2017 to determine the optimal configuration (both inclination and orientation) for this time of the year, according to the methodology shown in Table 2.

Table 1. Parametric variation for measuring the performance of monocrystalline panels according to their inclination and orientation

East			
Day	Panel 1	Panel 2	Panel 3
1	0°	14,00°	18,26°
2	0°	18,26°	26,56°
3	0°	26,56°	14,00°
South			
Day	Panel 1	Panel 2	Panel 3
4	0°	14,00°	18,26°
5	0°	18,26°	26,56°
6	0°	26,56°	14,00°
West			
Day	Panel 1	Panel 2	Panel 3
7	0°	14,00°	18,26°
8	0°	18,26°	26,56°
9	0°	26,56°	14,00°
North			
Day	Panel 1	Panel 2	Panel 3
10	0°	14,00°	18,26°
11	0°	18,26°	26,56°
12	0°	26,56°	14,00°

Table 2. Optimal configuration of monocrystalline panels for January 2017

Day	**Panel 1**	**Panel 2**	**Panel 3**
1	S 26,56°	E 14,00°	N 18,26°
2	S 26,56°	N 18,26°	W 18,26°
3	S 26,56°	W 18,26°	E 14,00°

Of the four analyzed configurations, the optimal was selected based on the average energy production during the days of measurement.

On the other hand, to estimate the energy losses due to accumulation of dirt, weekly measurements of the performance of the PV panel were carried out, from January 11th to February 1st 2017, using the optimal inclination and orientation. In this case, one of the panels was used for control purposes and was cleaned during the days of measurement, while the two remaining panels did not have any intervention; however, since precipitation events are frequent in Cuenca, the panels that did not receive any manual maintenance showed changes on the surface since such events cleaned them. It is necessary to consider that rainfall is high locally, with precipitations all year long such that no rain periods of more than one month are unusual [33].

In order to estimate the losses due to increments of temperature, the output power and the temperature on the surface of the monocrystalline panels were measured. Then, the efficiency was calculated by means of equation (1) using the irradiance data obtained from the meteorological station, and average values of efficiency losses were established by irradiance ranges. Then, the model was calibrated in SAM using data of average performance losses due to accumulation of dirt; the data was organized by irradiance ranges. The information was obtained from in situ measurements, and consisted of a climatic file generated during 2016, with hourly values of direct, diffuse and global radiation (all given in W/m^2), relative humidity (%), zenithal angle (°), precipitation (mm), wind direction and velocity (° and m/s, respectively). Thus, the climatic file of the site under study is not obtained by interpolating values of climatic variables between two locations, which results in greater degree of uncertainty in the predictions of the models, but by contrast results are validated through a real comparison between measurements of PV production and instantaneously detected climatic conditions.

In addition, technical data (in Table 3) of the utilized PV panels was incorporated to the software.

Table 3. Specifications of the simulated PV panel

Specifications			
Tipe of cell	Monocrystalline Silicium	Voc	21,6 V
Area of the module	0,645 m^2	Coefficient Voc Temperature	-0,38 %/°C
NOCT	46 °C	Coefficient Isc Temperature	0,1%/ °C
Vmp	17,3 V	Coefficient MPP Temperature	-0,41 %/°C
Imp	5,78 A	Number of cells in serie	36

Since this study defines aspects related to energy processing, the point of maximum power of the panel was considered in each estimation. The losses of the system were established based on *in situ* efficiency measures for irradiance intervals of 200 W/m^2 and for losses due to accumulation of dirt; for calculation purposes a base loss of 5% is established in the program by defect. With the simulated data of performance, a database was generated with values similar to the in situ measurements, and the following metrics were calculated: Determination coefficient R^2 (equation 2), root of the mean squared error (RMSE) (equation 3), mean bias error (MBE) (equation 4); at last, the 90% confidence interval was established (CI 90%) (equation 5), for time intervals suggested by some validation studies in SAM [34, 35], for this period of the year. The values of RMSE and MBE were normalized with respect to the maximum value among the *in situ* measurements.

$$R^2 = \frac{\sum_i^N (SAM_i - Measured_{avg})^2}{\sum_i^N (SAM_i - SAM_{avg})^2} \qquad (2)$$

$$RMSE = \sqrt{\frac{\sum_i^N (SAM_i - Measured_i)^2}{N}} \qquad (3)$$

$$MBE = \frac{\sum_i^N (SAM_i - Measured_i)^2}{N} \qquad (4)$$

$$IC_{90\%} = 1.645 \times [Std(SAM_i - Measured_i)] \qquad (5)$$

3. Results and discussion

After using the parameter variation for measuring the performance and calculating the efficiency in December, the results shown in Table 4 were obtained.

Table 4. Best inclination per orientation

Orientation	Best inclination
East	14,00°
South	26,56°
West	18,26°
North	18,26°

The results in Table 4 are due to the position of the sun this time of the year (close to the solstice), for which the south orientation is greater than the north orientation in any inclination; however, the east orientation of 14° results in a greater efficiency due to mornings of high irradiance and cloudy afternoons, and thus was selected for further analysis of the influence of dirt.

In this analysis, during the first week of measurements there were no performance losses due to the amount of weekly accumulated rainfall (41.8 mm); during the second week of monitoring there was a total rainfall of 6 mm, which resulted in dirt spots on the surface and a little significant reduction in the efficiency of the panels (0.7 %).

Since in the third week there were no rain events, the presence of material on the surface of the panels was evident; as a consequence, the corresponding measurements exhibited an average efficiency reduction of 2.77%, with a maximum of 3.68% and a minimum of 1.87%. A week later, the accumulated rainfall (13.4 mm) removed a significant amount of particles from the surface, thus resulting in negligible losses. Since this average value of efficiency loss was very small, the predefined value of 5 % was used for the simulation in SAM. As it was stated before, in this place long no rain periods are seldom, as it is for high Andean cities.

From the generated data it was possible to establish a comparative criterion for calibrating and validating the model in SAM, based on the parameters specified in the methodology. The results estimated by the model were compared with the horizontal panel *in situ* measurements, thus obtaining the statistical data shown in Table 5.

Table 5. Calculated metrics

Metric	Value	Unit
R^2	0,996	-
RMSE	5,263	W
NRMSE	8,156	%
MBE	-1,04	W
NMBE	-1,616	%
IC 90 %	8,522	%

The *in situ* and simulated data are compared graphically in Figure 3. There is an evident strong linear correlation, as confirmed by the calculated value of the R^2 coefficient. The RMSE and NRMSE values, which indicate the error of the data estimated by the model compared to the real measurements, are very acceptable in this case [36].

The MBE and its normalized value are employed to determine the model underestimation or overestimation; it was found that the model underestimates the system performance by 1.61%. Figure 4 shows the real behavior of the system and the estimated by the model in SAM for 12 days of measurement, considering as reference short-period validations carried out in TRNSYS by [36, 37], where the maximum generation values show a trend; a slight underestimation by the model could be observed. In addition, previous studies analyze the temporal resolution with intervals smaller than one hour [38], and compare simulated and *in situ* values for a two-day period [39].

The 90% CI (confidence interval) in Table 5 indicates that 90% of the simulated values are within ± 8.522% of the *in situ* measured values, which is really close to the ± 8% that has been obtained in the validation of seven baseline studies with SAM [34]. It is important to remark that this value is smaller in an annual simulation, exhibiting a better fit of the linear model and more validity.

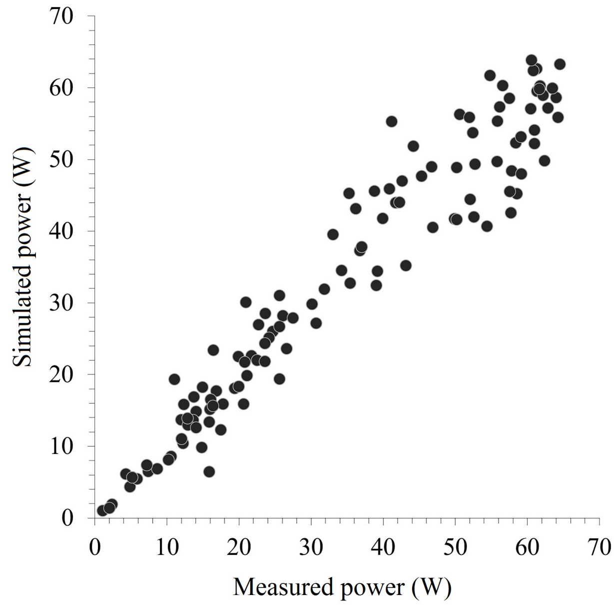

Figure 3. Scatter plot of measured vs. simulated power

In addition, the estimated values of temperature of the PV cells are different than the *in situ* measurements. Therefore, the average annual temperature from the model database was used instead for comparison purposes, since for the same levels of radiation the temperature seems to behave in a similar manner along the year, as opposed to the *in situ* measurements which are one-time values registered at the particular day of measurement. An important average difference of 13.33 °C can be observed in the data shown in Table 6, where the cells with no values indicate that during that day the radiation levels were not within those intervals. It is also assumed that the difference may be greater, since the model estimates the temperature of the cells, while the measurements were taken on the panel glass which is lower than the surface temperature of the cells [40]. This temperature variation can be also due to the intensity of the UV rays, since it is a high location [41]. Thus, it is recommended that measurements are taken in the lab to confirm the increment in the surface temperature of the cells.

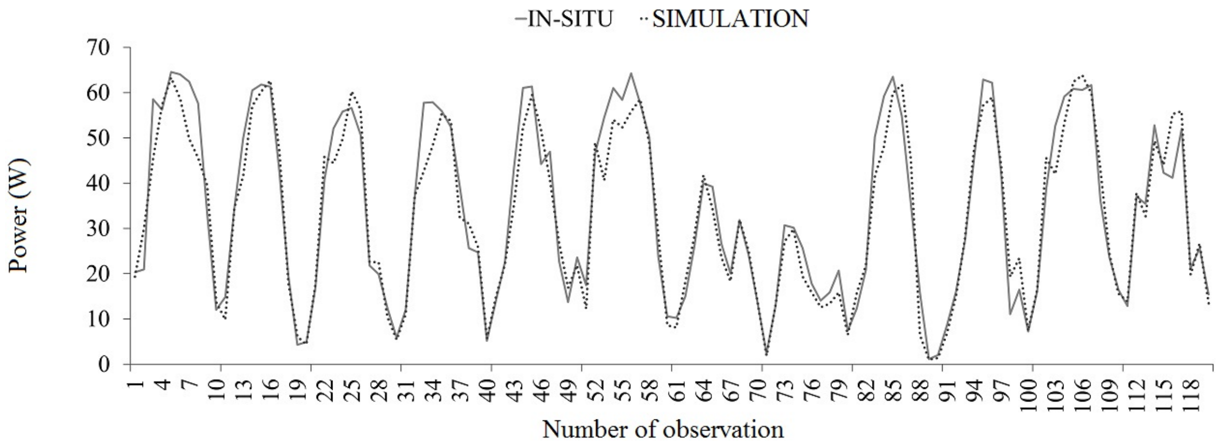

Figure 4. Performance comparison

Table 6. Comparison of the simulated and measured temperature

Irradiance (W/m^2)	Anual average temperature (°C)	Measured temperature (°C)
0-200	15,81	-
200-400	21,05	33,5
400-600	24,56	-
600-800	27,02	40
800-1000	30,33	43
1000-1200	34,08	49,33

Based on the values of these metrics, it was determined that the model is valid, and thus can be used to estimate the production of energy along longer periods, having available the climatic file. The values of performance in Table 7 were obtained after carrying out a simulation for one year (expressed in kWh/year) for a 100 W module, considering orientation and inclination parameters.

Thus, the horizontal is the configuration with the greater generation. However, such configuration cannot be deployed in inclined roofs and, in addition, it is does not take advantage of the cleaning due to the rainfall.

Table 7. Annual production of energy (kWh/year)

Angle	North	South	East	West
0°	119,16			
14°	116,5	116,94	117,21	116,24
18,26°	114,66	115,24	115,63	114,35
26,6°	109,76	110,64	111,35	109,5

An interesting distinctive feature is established in Table 7 with respect to the orientation and slope of the PV in the context of this study. The horizontal configuration effectively yields the maximum production, but it only exceeds by 8.8% the annual generation of the minimum production obtained in this work (West orientation with an inclination of 26.56°). Therefore, due to the aforementioned limitations, the horizontal layout is not recommended. In the comparison of the performance for the inclined and oriented cases, it was observed that a smaller slope effectively yields a better average production, 5.8% higher for the case of 14° with respect to the 26.56° case, and 4.2% more for 18° compared to 26.56°. Analyzing the one-time performances, the maximum production was obtained for the East orientation with 14°, and the minimum for the West orientation with 26.56°, with the former more efficient by 7 %. The losses measured in this study are smaller, considering for instance the PV performance estimations for a condition of moderate seasonal weather (36° of latitude), in which a deviation of 90° with respect to the optimal orientation results in a 17% reduction of the performance [42]. As expected, greater deviations opposite to the solar path and latitudes more distant to the Equator, should result in larger reductions in the PV performance. The better performance for the case of East orientation is because of morning with less clouds.

A more significant difference can be observed in monthly values, which vary between 7.33 kWh/month for July (month with minimum irradiance) and 12.19 kWh/month for November (month with maximum irradiance) (Figure 5). This is an indication of a uniform production along the year in this location, as opposed to PV supply studies carried out in moderate seasonal weather (38° south latitude) in which the generation during the summer months can be the triple of that for the winter months [43]; and in strong seasonal weather, such as Helsinki (Finland), in extreme latitude (60° north latitude), where the summer production can be more than ten times the winter production. This represents an obvious advantage of the equatorial zones, since it is more adaptable to face urban demands.

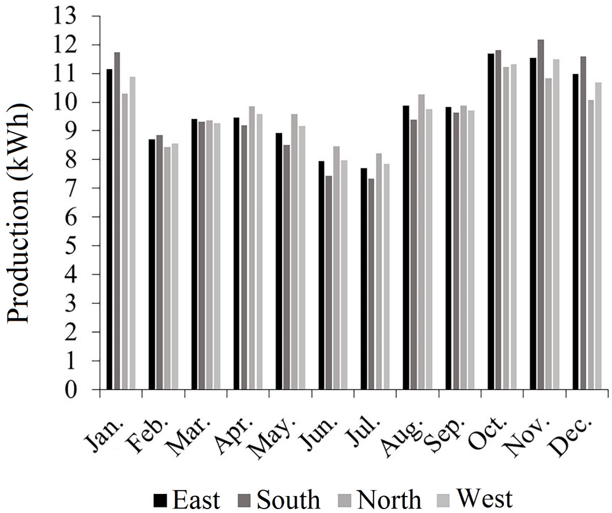

Figure 5. Estimated monthly production by simulation in SAM

4. Conclusions

An important step towards exploiting the potential of a particular city to generate renewable energy, is to validate tools that can be used to reduce the estimation and simulation uncertainties, of PV production in this case. This study showed that, by means of specific adjustments in different parameters, the SAM model can be used with low uncertainty in the city of Cuenca (Ecuador), this providing a reliable model for forecasting a possible PV electric generation. For other locations a similar calibration can be carried out, validating the model with *in situ* performance measurements.

Among the results of the study, the efficiency loss due to accumulation of dirt was measured, obtaining an average of 2.77%, which is not significant and indicate that a recurrent cleaning of the PV panels is not necessary, since the continuous rainfalls are enough to recover the efficiency. On the other hand, losses due to the temperature are important for high irradiance, which might be due to the constructive features of the cells or to elevated indices of UV rays. This became a relevant parameter during model calibration.

The estimation performance of the model was evaluated using statistical metrics, to compare the model estimates with in situ measurements. The values obtained were R^2 = 0,996, NRMSE = 8,156 y NMBE = -1,616%, which demonstrate that although the model underestimated such measurements, it is appropriate for forecasting future scenarios in annual simulations, since it exhibits a strong linear trend with respect to the *in situ* measurements. A methodology and a validated tool were delivered, which are useful for estimating the electric generation employing monocrystalline solar panels.

Regarding performances detected in the particular location, a higher annual generation can be obtained facing the PV systems to the East with a slope inclination close to the horizontal. However, no significant differences were found with respect to other orientations with similar inclinations, due to the geographic location of the area under study which results in mainly uniform levels of irradiance along the year. Likewise, although it was observed that, depending on inclination and orientation, the expected production during June-July (minimum irradiance) is 40% less than the production of November (maximum irradiance), the annual production is significantly more stable as compared to other latitudes. This results in an excellent potential of connection to a smart grid under a distributed generation scheme, or storage for self-supply.

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