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Comparative analysis of the conversion performance of a grid-connected photovoltaic system

Análisis comparativo del rendimiento de conversión de un sistema fotovoltaico conectado a la red

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Abstract

A performance study of a photovoltaic system installed in an eco-house on the campus of the University of Calgary in Canada is presented. The panels of the photovoltaic array installed on the roof have different azimuth and tilt angles, therefore, the solar energy incident on them is different. The effects of orientation on the efficiency of electrical energy production in individual photovoltaic modules are analyzed. The conversion efficiency is determined by means of measurements of the energy produced by the modules, supported by the RETScreen software, but also independently, it is calculated using the radiation data from the university weather station (WRS). These results are compared with those of a previous study, carried out with PVSyst, where the orientation angles of the system are simplified. Average results of energy produced, and efficiency are shown. It is observed that the efficiencies from the simulations are very similar, although of lower value. The results obtained with WRS are considered more realistic and of greater magnitude.

Solar energy production, Solar radiation measurements, Simulation efficiencies comparison

Resumen

Se presenta un estudio de rendimiento de un sistema fotovoltaico instalado en una casa ecológica en el campus de la Universidad de Calgary en Canadá. Los paneles del arreglo fotovoltaico instalados en el techo, tienen diferentes ángulos de acimut e inclinación. Se analizan los efectos de la orientación en la eficiencia de producción de energía eléctrica en los módulos fotovoltaicos individualmente. Se determina la eficiencia de conversión por medio de mediciones de energía producida por los módulos, apoyándose con el software RETScreen, pero también de forma independiente, se calcula utilizando los datos de radiación de la estación meteorológica de la universidad (WRS). Estos resultados, se comparan con los de un estudio previo realizado con PVSyst, donde se simplifica los ángulos de orientación del sistema. Se muestran resultados promedio de energía producida, y de eficiencia. Se observa que las eficiencias a partir de las simulaciones son muy parecidas, aunque de menor valor. Los resultados obtenidos con WRS se consideran más realistas y de mayor magnitud.

Comparación de simulación de eficiencias, Mediciones de radiación solar, Producción de energía solar

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Introduction

There are several research studies where the importance of studying the efficiency of photovoltaic systems (PVS) is shown, proposing techniques, algorithms, or models to maximize it. For example, one of the techniques that allows increasing performance in a PVS is the maximum power point tracking (MPPT). Various proposals have been made, experimenting with the combination of already existing algorithms for the control of the MPPT, demonstrating its effectiveness in simulation-based implementations (Manas M. et al., 2023).

Furthermore, in other works the authors validate their proposals in hardware, applying techniques and addressing topics related to artificial intelligence, such as neural networks and machine learning (Jena R. et al. 2023). In (Song Y. et al, 2023), a mixed power generation system, where the inclusion of a PVS is a substantial part, is proposed. In addition, the authors establish a model that optimizes or allows the most appropriate conditions for better efficiency in energy production. On the other hand, in (N. Kahar N. et al., 2023) the authors carried out a comparative study, where they demonstrate through simulation, that the use of PV systems with bifacial panels increases the efficiency in PVS.

Nevertheless, initially the investment cost could be significant. In (Galicia R, et al., 2023) the authors implement a study of a photovoltaic (PV) panel to observe how the specific environmental conditions of a geographical point affect it. The author mention that the influence of temperature, solar radiation, humidity, and wind speed on the efficiency of the solar panel was the main research motivation. In the current paper, a performance study of a photovoltaic system installed in an eco-house on the campus of the University of Calgary in Canada is presented. There is a roof made up of 37 PV panels, where two of them are horizontal, while the rest are oriented according to a certain curvature of the roof design, resembling a tortoise shell. Moreover, there are seven rows of five modules connected in a parallel configuration, each with an individual inverter (microinverter) that can record the electricity production of each PV module in real time.

This research focuses on the determination of the performance of this PV system, analyzing the figure of merit of conversion efficiency (the division of electrical energy produced at the output of the module between the energy that affects the module through solar radiation). There is already an analysis of this system based on simulation (Team Canada, 2011) where the PVSyst software is used, and it is validated with SAM-NREL. Although both previous results are very approximate, certain considerations were made in the study due to limitations in the database device data (PV modules). The authors are even aware that, owing to the design, there is a variation in the orientation of the panels in terms of azimuth, which according to their calculations is 9.5° on average, but for simulation purposes they establish 9° in average for the entire PV generator. In the present work, the performance is reviewed if more realistic conditions are considered.

In fact, each row of modules presents different orientations and therefore variations in azimuth. For this reason, in (Bueno R, 2015), information about the PV system has been collected, as part of the work developed in an international summer stay at the University of Calgary. The information collected consists of the physical characteristics of the PV system and the energy production data, which allow obtaining the efficiency of each module. In addition, the free software RETScreen is considered, which provides data such as irradiance, which is required to calculate the energy produced by the modules per day, as well as the efficiency. The above is validated; that is, the calculation is carried out again, but now with meteorological information obtained directly from the university's meteorological station (WRS).

On the one hand, this information is taken up and a comparative analysis is accomplished between the efficiency results obtained from the use of RETScreen and that obtained from the WRS information’s. On the other hand, these results are compared with the information from the previous analysis, where the PVSyst is used (Team Canada, 2011). It is considered that this study allows to have a more realistic performance behavior of the PV array than in the previous study, by considering the real azimuth angles instead of a single average value.

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Moreover, it is considered that, by determining the efficiency from data taken directly from the meteorological station located very close to the study system, it allows obtaining information with greater accuracy. The rest of the article is made up of the following sections: section 2 presents the physical and electrical characteristics of the photovoltaic system; the methods used to assess conversion performance are explained in section 3; the results and discussion are in section 4; finally, in section 5 the conclusions are shown.

Study PV system

Physical characteristics

Figure 1 shows the installation of the arrangement of 35 PV modules on the roof of the house, forming a somewhat elliptical silhouette. Seven groups of five PV modules with the same geometric characteristics are formed. The panels of the different sections have a very similar inclination, but their azimuth angle does vary significantly, especially for the modules installed in sections that are further apart. Therefore, to carry out an analysis of the performance in energy production, it is necessary to consider seven flat surfaces with different geometric characteristics, since, due to the difference in angles, the irradiance incident on them will also vary. Section one is called the section that is furthest to the West and section seven is the one that is furthest to the East (as shown in Table 1).

Figure 1 Spo'pi house on the campus of the University of Calgary
Source: Own elaboration

Direction	West ----------------------------> East						
Section	1	2	3	4	5	6	7

Table 1 Distribution of PV array sections
Source: Own elaboration

Therefore, it is necessary to know the azimuth angle and the inclination that each of the sections has. The design of the house was made by computer, and it has a 3D drawing. From this, the desired angles can be determined, since all the measures defined in the design were respected, both for accommodation in the direction of the house towards the south and in the structure that supports the arrangement.

Determination of the azimuth angle with the CAD model

To determine the angles, we work with the Revit model of the project (see figure 2).

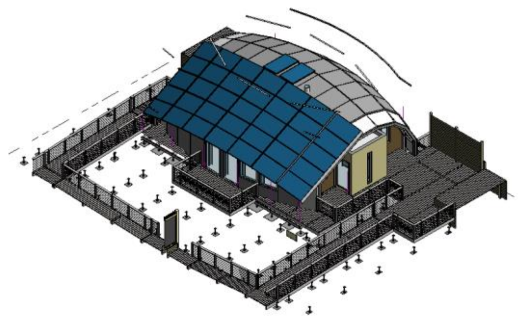

Figure 2 Revit model of the Spo'pi house, Canada Solar Decathlon

To carry out the calculations and the desired measurements, this model has been exported to AutoCAD. When making this format change, the Revit model works with many lines for details. Figure 3 shows the already exported drawing again.

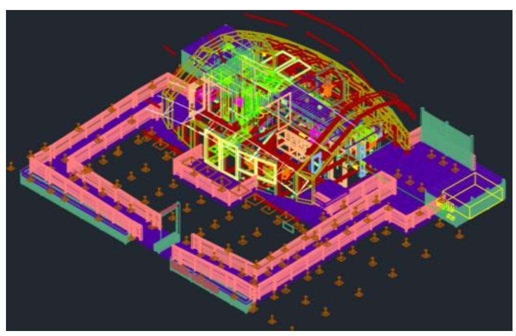

Figure 3 Autocad model of the Spo'pi house, Canada Solar Decathlon

Of the elements included in the drawing, only those corresponding to the installation of the photovoltaic modules are of interest.

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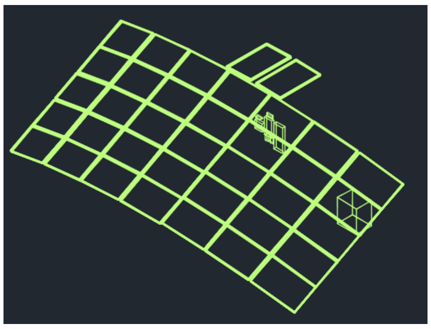

Figure 4 Drawing in autocad for the calculation of azimuth
Source: Own elaboration

For this reason, we proceed to hide all the other layers of the drawing, until only the block of lines that forms the photovoltaic array is shown (figure 4). Autocad has a method to measure the azimuth angle of a line, it calculates it with respect to the normal of the line and its projection towards the south, in the drawing records. When doing the export, the data of the geographic position with respect to the south are also sent. Therefore, parallel lines are drawn to each one of the sections to be able to use this method, until obtaining a drawing like the one shown in figure 5. As can be seen, there are already parallel lines to the different sections of the array, so the method can be applied. This consists of selecting one of the lines, right clicking with the mouse on it and writing the Field command. This command opens a dialog box in which object is subsequently chosen in field names and angle in property. With this selection the calculation of the azimuth angle is made showing it in the preview box.

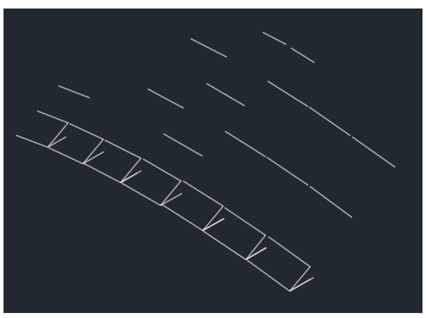

Figure 5 Drawing in autocad for the calculation of the azimuth
Source: Own elaboration

The same procedure is repeated for every section of the PV array. To check that the angle remained the same for the five elements, the same measurement was made in the different panels of each section. Table 2 shows the values of inclination and azimuth angle of each of the sections.

Section	Inclination	Azimuth
1	27.062°	351.14°
2	27.167°	354.16°
3	27.306°	356.90°
4	27.445°	0
5	27.584°	3.09°
6	27.700°	5.81°
7	27.823°	8.85°

Table 2 Inclination and azimuth angles for each section, own elaboration
Source: Own elaboration

Electrical characteristics

The 35 photovoltaic panels are made of polycrystalline silicon, Conergy brand P230PA model. The modules have a nominal power of 230 Wp under standard test conditions (STC, Standard Test Conditions) (Conergy, 2011). The system also has a microinverter for each panel for the conversion of electric power from DC to AC. These devices are of the Enphase brand M 190 72 240 model, with a conversion efficiency of 95%. The 35 modules are connected in parallel. The installation has a nominal capacity of 7.2 kW AC. The PV system is equipped with a data acquisition system. The inverters have a logic card that monitors the amount of energy produced and can transmit the information to a hub. This uploads the information to a database that can be reviewed online, on the manufacturer's website, Enphase Enlighten. Figure 6 shows a basic schematic of a photovoltaic solar system with an Enphase data acquisition system, which represents the study scenario in this paper.

Figure 6 PV system and data acquisition, Enphase energy.

The elements that allow the acquisition of data are presented below:

1) Microinverter that is responsible for the conversion of DC energy produced by the photovoltaic panels to AC to be consumed or transported to the network.

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2) Wiring that transmits the AC electrical energy converted by the inverters to a load center, and the production data signal.

3) Envoy data acquisition card that is responsible for uploading the information to the web page.

4) Router or modem to provide Internet connection.

5) Information system hosted on Enphase Enlighten's website.

This data acquisition system allows for a greater degree of confidence in the measurements made, since it avoids human errors in measurement and taking results.

Performance evaluation

Power production analysis

In this section an analysis of the electrical energy production of the modules is carried out according to their orientation, and for each of the panels. This analysis is based on radiation data provided by the RETScreen software and on solar radiation measurements made during the month of June on the University of Calgary campus.

In this study, the amount of energy produced by the panels daily is compared with the amount of solar energy they receive or average daily incident irradiance for the month of June 2014. The following method is applied in the analysis:

1) The daily average radiation is calculated using RETscreen, for each of the sections.

2) An energy production report is prepared for the month of June 2014, from the inverter's data acquisition system.

3) A table is made showing the production of the panels, average incident irradiance and the conversion efficiency (the latter is calculated taking the information of the production of the panels and the incident irradiance).

4) The efficiency obtained is compared with the nominal efficiency indicated by the manufacturer.

5) Steps one through four are repeated but using data from the University of Calgary Weather Station (WRS).

Method using RETScreen

RETScreen allows the analysis of different types of renewable energy projects. To start using it, the type of system to be analyzed is configured. Figure 7 shows the main RETScreen window, it shows the type of project, the application, the type of analysis, etc. These values are predetermined for each type of project, the current analysis project corresponds to a photovoltaic energy system.

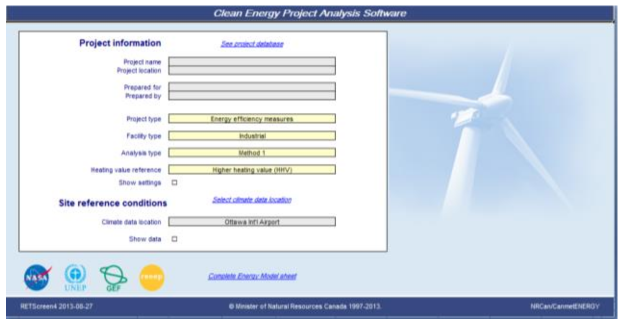

Figure 7 RETScreen main window
Source: Own elaboration with RETScreen.

To configure the analysis project, click the See Project database option, opening a dialog box (see figure 8) in which the following parameters are selected: Project type: Power; Type: Photovoltaic; Project name: 100 kW. Subsequently, click on the confirm button, which returns to the main window, but now shows the values of the selected project. Next, the local climate is selected (RETScreen has climate values from different parts around the world). A point is searched for and selected in the city of Calgary, which opens a new dialog box (see figure 9).

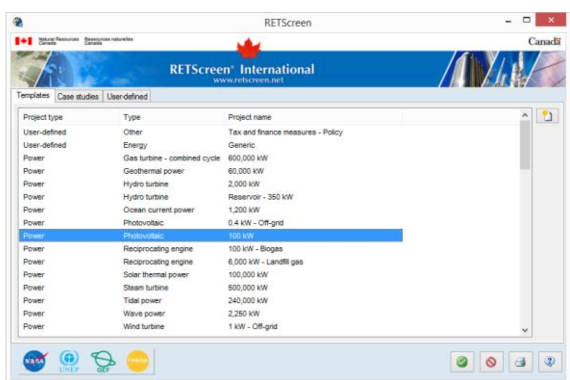

Figure 8 RETScreen window to select the project
Source: Own elaboration with RETScreen.

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Journal Electrical Engineering
December 2023, Vol.7 No.19 15-24

In this window, the location parameters to determine the meteorological values are selected. For the city of Calgary, there are values for the international airport, therefore, the parameters to be selected are the following:

- Country – región: Canada
- Province / State: Alberta
- Climate data location: Calgary Int'l. Airport

When selecting those parameters, the values corresponding to the international airport of the city of Calgary, a place very close to the University, are established.

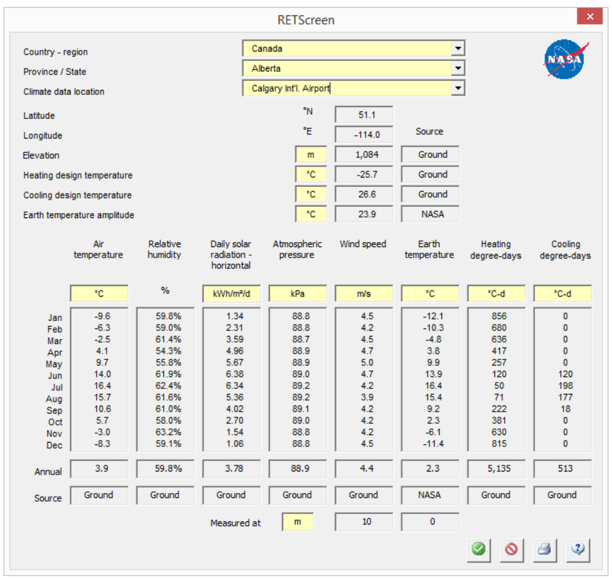

Figure 9 RETScreen window for locality selection, Own elaboration with RETScreen.

Of the values obtained in this table, the values for the month of June, the month for which the analysis is being carried out, are highlighted. For this month there are global and historical values of average radiation on a horizontal flat surface of 6.38 kWh/m^2/day, which is equal to 6380 Wh/m^2/day. The radiation values that are obtained are for horizontal surfaces; however, the study surfaces are not all horizontal. Due to the above, it is necessary to carry out the calculations for the average radiation for inclined surfaces. The advantage of this software is that it already has a programmed method. To calculate the radiation from inclined surfaces, click on the main window on Complete Energy Model Sheet, which is located at the bottom. This opens a tab of the program in which it is necessary to select method two, since it is the one that is programmed for this calculation.

For this method, it is necessary to introduce three parameters, one of them is the system tracking method, which in this case, being a fixed system, is selected as fixed. The other two parameters to set are the inclination and the azimuth for each panel or for each section. The angle values used are those shown in table 2. As an example, the calculations for section 1 are carried out with the following parameters:

1) Solar tracking mode: Fixed
2) Slope: 27.1
3) Azimuth: 351.1

The result, for all the sections corresponding to the inclined surface for the month of June, is shown in Table 3. The analysis for each section is made on this value.

Section	Irradiation (I) (kWh/m^2/day)
1	6330
2	6320
3	6320
4	6320
5	6320
6	6310
7	6310

Table 3 Irradiation results per section with RETScreen
Source: Own elaboration

Knowing the irradiation that reaches each one of the panels, a comparison can be made of the electric energy produced against the solar energy that it receives. For this, it is necessary to use the generated energy data saved on the server of the Enphase Enlighten website. The procedure, to calculate the average production of the panels for the month of June, consists first in downloading the total production data for each day of the month. Subsequently, the average for the 30 days of the month is obtained. This is achieved for each module. Although there is another factor to consider for this calculation, such as the area of the modules. From Table 3, an effective area of 1.65 m^2 (Conergy, 2011) must be considered to obtain the total radiation that reaches the modules. The efficiency (η) is calculated as the ratio between the average daily electrical energy production ($\bar{E}_s$) and the average solar energy ($\bar{E}_d$) that affects the modules during the month of June.

$$\eta = \frac{\bar{E}_d}{\bar{E}_s} \quad (1)$$

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The $\bar{E}_d$ is calculated by subtracting 5% of the measured energy from the inverter output. The $\bar{E}_s$ is calculated by multiplying the irradiation value (I) of the corresponding section (table 3) by the effective area (A_e) of the modules, this is done for each section.

$$\bar{E}_s = \mathrm{I} \times A_e \quad (2)$$

Method using WRS

The data provided by RETScreen are also an average of historical data from different databases, such as NASA, the departments of ecology of Canada and the United States, mainly. That is why the obtained results are lower than expected. For this reason, the study is also carried out, but using data that was measured in the field.

The irradiation data provided by the WRS are direct radiation values on a horizontal surface, distributed in 1-min intervals; therefore, it is necessary to average them per day and then per month to assess the daily production that the modules had during the month of June. The average radiation value according to the data was 5647.79 Wh/m^2, which is less than the value found in the RETScreen database by approximately 800 Wh/m^2. From this point it can be inferred that the efficiency of the modules is a little above what was measured previously. Based on the values obtained, the ratio of radiation that reaches the inclined surface to that which reaches the horizontal surface is calculated. The resulting ratio is called the radiation factor (RF), unique for each section. Table 4 shows the RF results.

Section	RF	Irradiation (kWh/m^2/day)
1	0.992	5603.52
2	0.990	5594.67
3	0.990	5594.67
4	0.990	5594.67
5	0.990	5594.67
6	0.980	5585.82
7	0.980	5585.82

Table 4 Ratio of inclined plane with the horizontal and irradiance by section
Source: Own elaboration

PVSYST

In (Project manual, 2011) they carry out a simulation study using PVSyst. Based on this information provided in their study, it follows that the efficiency of the photovoltaic array can be calculated from equation (3) and the results for the month of June are verified.

$$\text{EffArrR} = \frac{EArray}{GlobInc \times Area} = \frac{1238kWh}{190\frac{kW}{m^2} \times 61.05\ m^2} \quad (4)$$

Where (in accordance with their terminology): EffArrR is the efficiency of the PV array; EArray is the received energy in the PV array; GlobInc is radiation factor and area is the area of the PV panel. For the month of June, it gives a result of EffArrR = 10.67 %.

Results and discussion

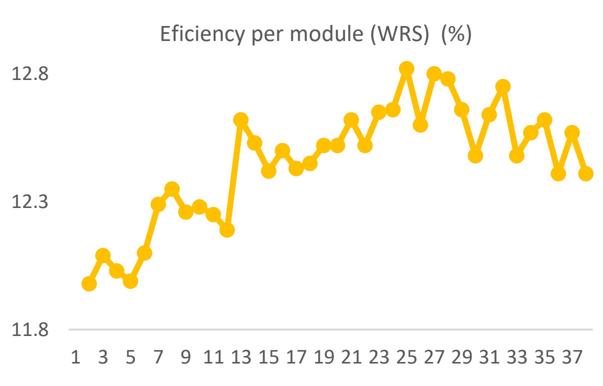
Firstly, a section is presented where the results obtained with the two methods seen (WRS and RETScreen) are presented and compared. Subsequently, in a following section, the comparison with the PVSyst results is performed.

WRS vs RETScreen comparison

The first comparison that is made is that of efficiency, but graphs are also analyzed where the energy received, and the energy produced per module per section are broken down.

PV modules efficiencies

Graphic 1 shows the efficiency results, in percentage, obtained with the WRS procedure. It is observed that the efficiency increases as the position of the panels is located further to the East, according to their corresponding section (table 2).



Graphic 1 Efficiency per PV module (WRS procedure)
Source: Own elaboration

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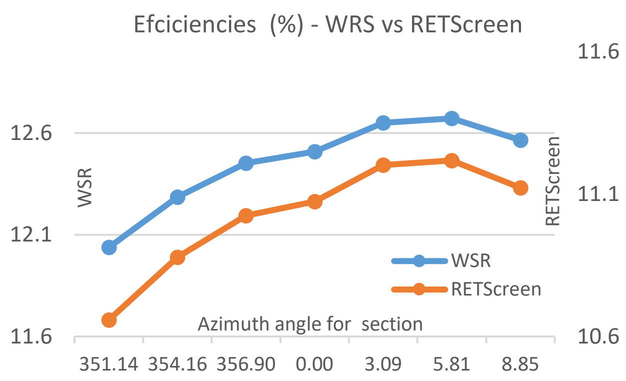
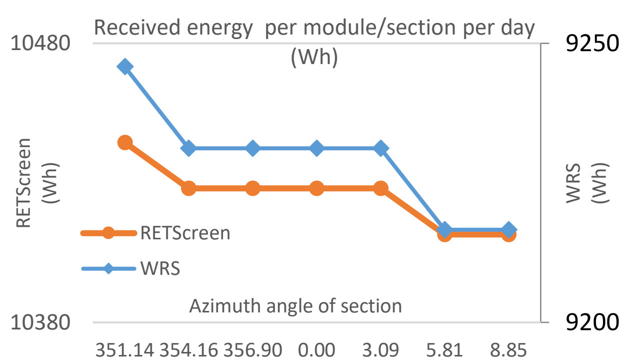
On the other hand, graphic 2 shows the results of average efficiency per module section, for both procedures (WRS and RETScreen). For both methods, a profile can be observed where there is a tendency to increase the efficiency of the modules of the sections further east.



Graphic 2 Average efficiency per section (WRS and RETScreen procedure)
Source: Own elaboration

Received energy vs produced energy by the PV modules

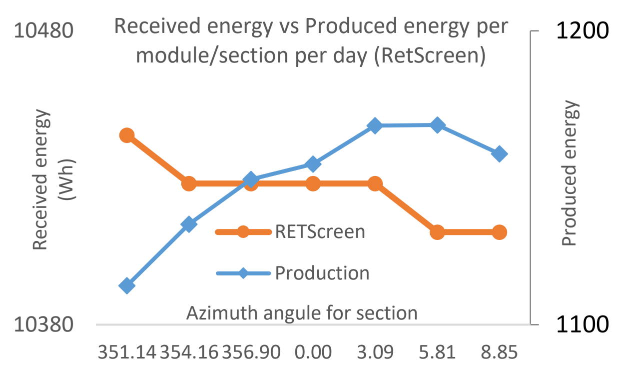
An interesting exercise is to carry out the breakdown of the energies considered in the calculation of efficiency. In this way, graphic 3 shows the results of the energy received on average for each section of the module set. That information is shown for both methods (WRS and RETScreen).



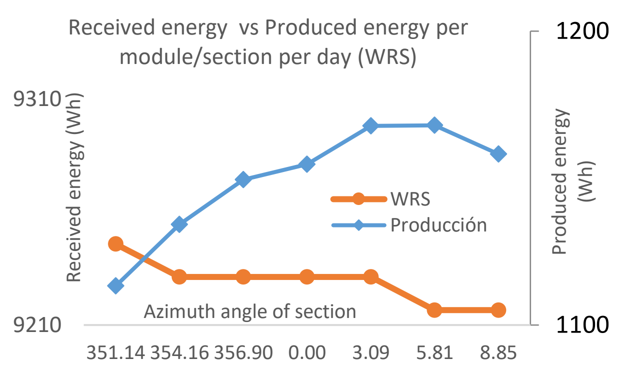
Graphic 3 Average received energy per section of PV modules for both methods (WRS and RETScreen)

From graphic 3, the results obtained for energy received using the method that involves the use of WRS data are lower (scale on the right) compared to those obtained by the method where the information is used. from RETScreen (scale on the left). On the other hand, a general trend can be seen in which the modules that receive more energy are those located in the sections further to the West.

According to graphic 2 and graphic 3, it can be commented that a behavior with a tendency to be inversely proportional is observed, where the sections that receive more energy are those that produce less. Given the above, the curves of energy received against energy produced are plotted, for the RETScreen and WRS method. These curves are presented in graphic 4 and graphic 5, respectively.



Graphic 4 Received energy vs energy produced per module (RETSCreen)
Source: Own elaboration



Graphic 5 Received energy vs produced energy (WRS),
Source: Own elaboration

From graphic 4 and graphic 5, the highest efficiency can be seen with the WRS procedure, where for a certain amount of received energy, the energy production is greater, observing a more efficient conversion capacity. The other interesting behavior is the one that has been observed in the sense that an inverse relation in the energy conversion. This is very noticeable in graphic 4, where the westernmost sections receive more solar energy, but produce less (left of the graph), while the easternmost sections receive less solar energy, but have a higher production (right of the graphic). Clearly, these behaviors are due to various factors, one of which may be the effect of the temperature of the panels on the conversion efficiency.

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Comparison with PVSYST

The average efficiency results obtained with the WRS and RETScreen methods are then compared with the efficiency value obtained in (1) with PVSyst. In addition, the nominal efficiency of the PV modules (Datasheet) is placed.

PVSyst	RETScreen	RWS	Maximum nominal efficiency
10.67 %	11.03 %	12.46 %	13.9 %

Table 5 Average efficiencies for the month of June
Source: Own elaboration

In the case of the efficiency obtained from RETScreen, it is quite close to the value obtained with PVSyst in the previous study. This would indicate that both simulators tend towards a very similar value. However, these are values that tend to be conservative in magnitude. The most accurate value is considered to correspond to the efficiency obtained from the WRS information, where the efficiency value is higher than in the case of the simulators.

Acknowledgment

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Conclusions

The electrical energy conversion performance of a photovoltaic array is evaluated. For the evaluation, the RETScreen software (free software from the Canadian government) was used to analyze the average efficiency of the panels for a month. An evaluation was also made with radiation values measured on the campus of the University of Calgary, which allowed obtaining greater precision and very similar results with a small difference of approximately 0.6%, so the data delivered by this software is very reliable and serve to make projections with a small error. In the results it can be observed that the panels of sections 5-6 had a higher yield (approximately 0.5%).

Making a comparison between the modules that produced more energy and those that produced less, it was found that those that were facing east had the best yields with an average difference of 0.6% more than those that were oriented to the west, the equivalent of approximately 60-65 Wh and which allows a fluorescent bulb to be on for 5 hours.

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