Effects of Climatic Conditions on Performance of Polycrystalline Silicon Solar Photovoltaic Modules in Puebla, México / *Efectos de las Condiciones Climáticas en el Desempeño de Módulos Fotovoltaicos de Silicio Policristalino en Puebla, México*

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Abstract:
Solar photovoltaic (PV) continued to be one of the fastest-growing renewable electricity technologies; power plants are ideally located in regions with high insolation levels. Crystalline silicon (Si) solar cells and modules have dominated PV technology since the beginning. Recently polycrystalline Si (p-Si) based solar cells have reported high record efficiencies above 22%, making them possible competitors to conventional single crystal silicon solar cells. These PV systems present an attractive proposal and the alternative of using resources that are non-polluting and abundant. Mexico has a privileged situation in terms of solar irradiation, with an annual average of 5.3 kWh/m^2 per day, this has allowed the installed capacity and the generation of PV electric power increased in four years (2011 – 2015) 30 MW and 39 GWh/a to 170 MW and 190 GWh/a (SENER 2017). On the other hand, Puebla City (19° 03´ north latitude, 98° 10´ west longitude, altitude 2179 masl) receives on average 5.4 kWh per m^2 of solar radiation, which is slightly above the national average. Because of this advantage, the use of solar PV array was incorporated in the Universidad Tecnológica de Puebla (UTP), and contributes to the generation of ~ 650 kWh photovoltaic electric power monthly. Nevertheless there are several factors affecting the energy yield, the most important is the incident solar radiation on the modules, and since solar cells are semiconductors, they are also very sensitive to temperature. This work tries to estimate the loss of generated energy caused by the effects of climatic conditions on the performance analysis of p-Si solar PV modules, monitoring of energy gain and processing climatic data in two periods; January – March and August - October to obtain information.

Keywords: solar cells, efficiency, climatic conditions.

Resumen:
La energía solar fotovoltaica (FV) sigue siendo una de las tecnologías de energía eléctrica renovable de más rápido crecimiento; Las plantas de energía están ubicadas idealmente en regiones con altos niveles de insolación. Las celdas y módulos solares de silicio cristalino (Si) han dominado la tecnología fotovoltaica desde el principio. Recientemente, las celdas solares basadas en Si - policristalino (p-Si) han reportado eficiencias por encima del 22%, lo que las hace posibles competidoras de las celdas basadas en silicio monocristalino. Estos sistemas fotovoltaicos presentan una propuesta atractiva y la alternativa de utilizar recursos no contaminantes y abundantes. México tiene una situación privilegiada en términos de irradiación solar, con un promedio anual de 5.3 kWh / m^2 por día, lo que ha permitido aumentar la capacidad instalada y la generación de energía fotovoltaica en cuatro años (2011 - 2015) 30 MW y 39 GWh. / a hasta 170 MW y 190 GWh / a (SENER 2017). Por otro lado, la ciudad de Puebla (19 ° 03´ de latitud norte, 98 ° 10´ de longitud

oeste, altitud de 2179 msnm) recibe en promedio 5.4 kWh por m^2 de radiación solar, ligeramente por encima de la media nacional. Debido a esta ventaja, el uso de paneles fotovoltaicos solares se incorporó a la Universidad Tecnológica de Puebla (UTP) y contribuye a la generación de energía eléctrica fotovoltaica de ~ 650 kWh por mes. Sin embargo, hay varios factores que afectan el rendimiento de energía, el más importante es la radiación solar incidente en los módulos, y como las celdas solares son semiconductores, son muy sensibles a la temperatura. Este trabajo trata de estimar la pérdida de energía causada por los efectos de las condiciones climáticas en el análisis de rendimiento de los módulos solares fotovoltaicos de p-Si, se realizó el monitoreo de la ganancia energética y el procesamiento de datos climáticos en dos períodos; Enero - Marzo y Agosto - Octubre para obtener la información.

1. Introduction

Solar radiation is a composition of many wavelengths, waves of different length carry different amount of energy. Many authors propose the quantification of this energy using three techniques to calculate its intensity: by means of instrumentation, with satellite images, and using physical and empirical irradiance models; as well as combinations of these, however quantifying the incident solar radiation on a surface requires analyzing other important variables as geometric, geographical, astronomical, physical properties and their dependence to the meteorological variables (Gutierrez-Trashorras, et al., 2018). Solar modules work best in certain weather conditions, but, since the weather is not constant, most solar photovoltaic modules do not work under constant operating conditions. The performance of a PV system depends not only on its basic characteristics but also on the environmental conditions. The ambient temperature, pluvial precipitation, humidity and wind velocity plays an important role in the photovoltaic conversion process. All these issues affect the most important parameter of any solar cell, its efficiency, i.e. how much of the sunlight energy is converted into electrical energy through the PV effect.

Within the region of Puebla City were installed at UTP (in the faculty of Renewable Energies in May 2013) 24 p-Si PV panels facing the south with a tilt angle of 45°. This work illustrates the study on commercially available photovoltaic modules used at UTP under real operating conditions, in order to investigate the effects of environmental conditions on their energy production. It has been reported that the characteristic power curve is affected significantly by the module temperature. The open-circuit voltage decreases significantly with increasing PV module temperature (values are up to -0.45 % / K for crystalline silicon) whereas the short circuit current increases only slightly (values range between 0.04 and 0.09 % / K) (Green, 1981). The electrical performance is primarily influenced by the absorbent semiconductor of solar cell used. Solar panels made of polycristalline materials, are slightly less efficient than those made up of monocrystalline materials, this is due to the nature of production, the silicon is not grown as a single ingot but as a block of crystals, we can recognise the p-Si solar panel for the blue speckled colour. According to manufacturer (*cnbm solar*) the PV modules used in the UTP converts between 14 to 17% of the incident solar radiation into electricity, depending upon to the climatic conditions. The rest of the incident solar radiation is converted into heat, which significantly increases the temperature of the PV module and reduces the PV efficiency of the module. In this work we will try to estimate the energy gain generated in 2018, comparing climatic data effects of solar global radiation, temperature and wind velocity of two seasons in the year; January to March vs August to October.

2. Data and methodology

2.1 Study area

The study region is located in the central region of México in Puebla State in the city of Puebla. The daily total global solar radiation, temperature, wind velocity, humidity and energy data used in this work were provided by the following weather stations (Valdes-Barróna, et al., 2014):

- The *Instituto Nacional de Investigaciones Forestales, Agropecuarias y Pecuarias* (INIFAP; National Institute for Forestry, Agriculture and Livestock) (http://clima.inifap.gob.mx/redinifap)
- The *Servicio Meteorológico Nacional* (SMN; National Meteorological Service). The SMN operates a network of 187 automatic stations (http://smn.cna.gob.mx/productos/emas/emas.html).
- The *Comisión Federal de Electricidad* (CFE; Federal Electricity Commission) (www.cfe.gob.mx)

2.2 Materials

The p-Si solar cells and panels used for this work have important electrical parameters: the photogenerated current, *Iph*; the short-circuit current, *Isc*; the open-circuit voltage, *Voc*; the maximum power, *Pmax*; the fill factor, *FF*; the efficiency, η; the series resistance, *R*s; and the shunt resistance, *Rsh*. The specifications are listed in Table 1 and 2 below. An image of solar panels is shown in Figure 1:

Module dimensions (mm x mm)	1655 X 992
Cell dimensions (mm x mm)	156 X 156
Cells per module (units)	60
Cell area per module (m^2)	1.46
Electrical specifications	
Maximum power Pm (W)	245
Voltage at maximum power Vmp (V)	31.1
Open circuit voltage Voc (V)	37.4
Current at maximum power Imp (A)	7.89
Short circuit current Isc (A)	8.65

Table 1. Panel specifications
Bibliographic source: cnbmsolar.com

Efficiency (%)	Pmpp (W)	Vmpp (V)	Impp (A)	Voc (V)	Isc (A)	FF (%)
17.27	4.197	0.524	7.992	0.620	8.458	80.03
17.02	4.137	0.524	7.876	0.619	8.353	80.01

16.77	4.076	0.522	7.810	0.617	8.286	79.73
16.52	4.015	0.518	7.746	0.613	8.215	79.73
16.27	3.955	0.515	7.683	0.610	8.144	79.61
16.02	3.894	0.512	7.613	0.608	8.075	79.31
15.77	3.833	0.510	7.534	0.605	8.058	78.62
15.52	3.772	0.508	7.453	0.604	8.02	77.87
15.27	3.711	0.505	7.350	0.604	7.997	76.83
15.02	3.649	0.503	7.271	0.604	7.989	75.64
14.52	3.529	0.499	7.067	0.604	7.988	73.14
14.02	3.407	0.499	6.833	0.604	7.833	72.01

Table 2. Cell Electrical characteristics
Bibliographic source: cnbmsolar.com

The input power for efficiency calculations is 1000 W/m^2, thus the input power for a 156 × 156 mm^2 cell is 24.3 W. These PV modules were rated at standard test conditions (STC: 1000W/m^2, AM 1.5, 25°C).

Figure 1. PV panels used in the UTP
Bibliographic source: Own elaboration

The electricity produced for the PV panels is direct current (DC) and must be converted to alternating current (AC). The photovoltaic inverter turns the DC electricity generated by the solar panels into 120-volt AC that can be put to immediate use by connecting the inverter directly to a dedicated circuit breaker in the electrical panel.

3. Results and discussion

3.1 Climatic

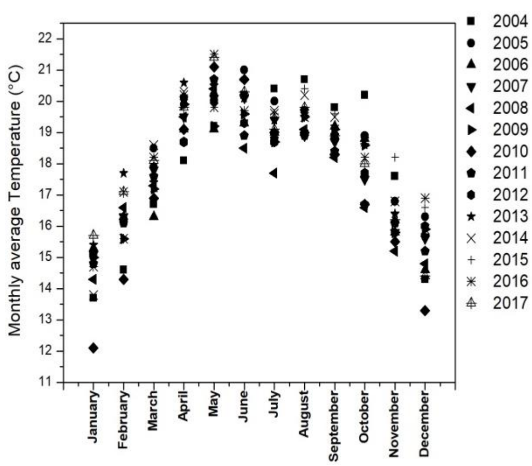
The ambient temperature, solar radiation, wind velocity and pluvial precipitation are key factors in understanding climate variability; for example, the temperature variation is important due to the high sensitive in an absorbent semiconductor, it is known that efficiency and output power decrease with temperature due to increased thermal activation of carriers over the p-n junction barrier (which leads to higher recombination current hence lower V_{oc})

(Sing, 2013, Sing, et al., 2012, Skoplaki, et al., 2009) however, others increase, such as the I_{sc}, which slightly increases (Dupre, et al., 2016).

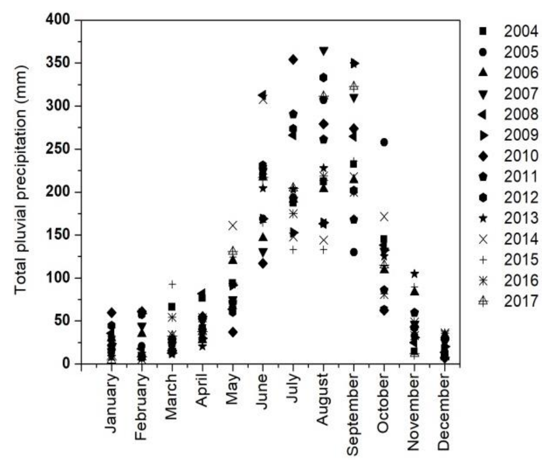
Knowing the ambient temperature and pluvial precipitation, climatic dates along the years is useful in the understanding of climatic conditions in the zone of study. Figure 2 A indicates the monthly average variation of ambient temperature and the total pluvial precipitation for the period of 13 years in Puebla State (2004 – 2017). For temperature we can observe an annual pattern indicating almost the same behavior in these years. 18°C was the average annual temperature. The ambient temperature had maximum values for the months April, May and June (~ 20°C) and the minimum values of ambient temperature were reported in December and January (~ 15°C).

Total pluvial precipitation shows that the rainy season usually occurs between June and October (Figure 2 B). Between 2004 and 2017 the total annual precipitation was 1309 mm on average, meanwhile in 2015 it reached 1185 mm and in 2007 1410 mm; these were the minimum and maximum total precipitation values for that period respectively. The pluvial precipitation data were more dispersed mainly between May and October.

Taking as reference the temperature and rainfall between 2004 and 2017 in Puebla State, this work will use the climatic effects reported with meteorological data for Puebla City in 2018.



A)



B)

Figure. 2 Monthly Average Temperature in Puebla State
Bibliographic source: Own elaboration with CONAGUA data,
http://smn.cna.gob.mx/productos/emas/emas.html

According to Figure 3, in the first 90 days of the year (period January to March) the average, maximum and minimum values reported for average daily global solar radiation were 482.38, 587.35 and 275.63 W/m^2 respectively. On the other hand, the average, maximum and minimum values reported for average daily temperature in the same period were 15.97, 20.98 and 8.21°C respectively. From figure 3 A) and B) it is observed a sligthly correlation between global radiation and temperature. The wind velocity in this period it was 5.82 km/h on average but with an atipycal behavior in January 29 with a maximum value of 19.49 km/h on average, the minimum value reported it was 3.28 km/h on average. One day was reported in this period with significant rainfall (March 7), however it was another 6 days with very slightly precipitation from 0.2 to 2.2 mm.

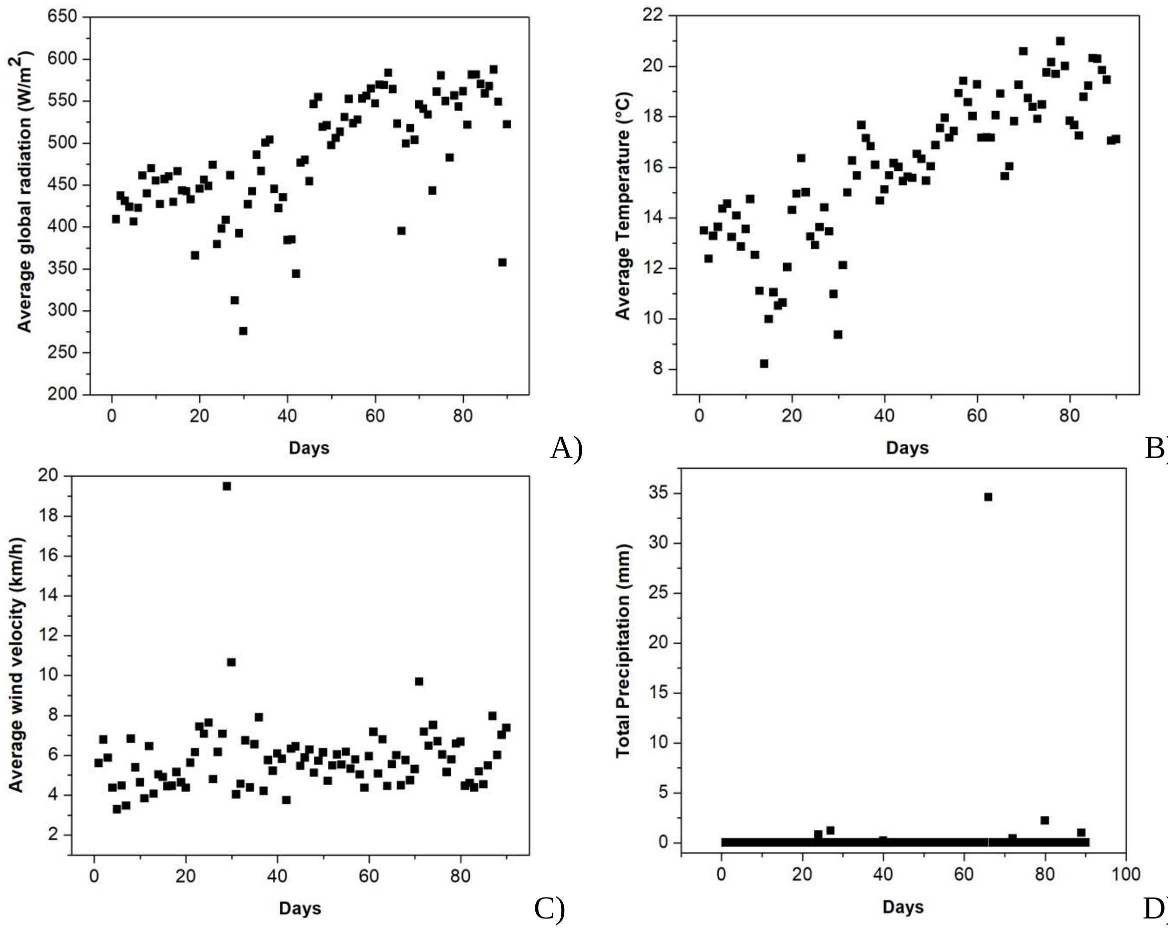


Figure. 3 Climatological data in the first 90 days of the 2018 year (INIFAP)
Bibliographic source: Own elaboration with INIFAP data, http://clima.inifap.gob.mx/redinifap

Figure 4 shows the climatological data for the period from August to October (day 213 to day 304) the average, maximum and minimum values reported for average daily global solar radiation were 441.75, 612.03 and 246.26 W/m^2 respectively, on the other hand, for average daily temperature the average, maximum and minimum values reported for this period were 17.84, 19.91 and 15.61°C respectively. The wind velocity remained almost constant with an average value of 4.34 km/h, the maximum and minimum values were 8.64 and 2.29 km/h on average respectively. In contrast with first period, during this period there were 48 rainy days (8 times more than in the first period); 15 days with a total precipitation between 10.2 to 35.2 mm, 25 days between 1.2 to 9.2 mm and 8 days with slightly precipitation between 0.2 to 0.6 mm. The rain caused that the global radiation modify drastically in comparison with the first period. In this second period no one correlation was observed between climatic values of temperature and global radiation.

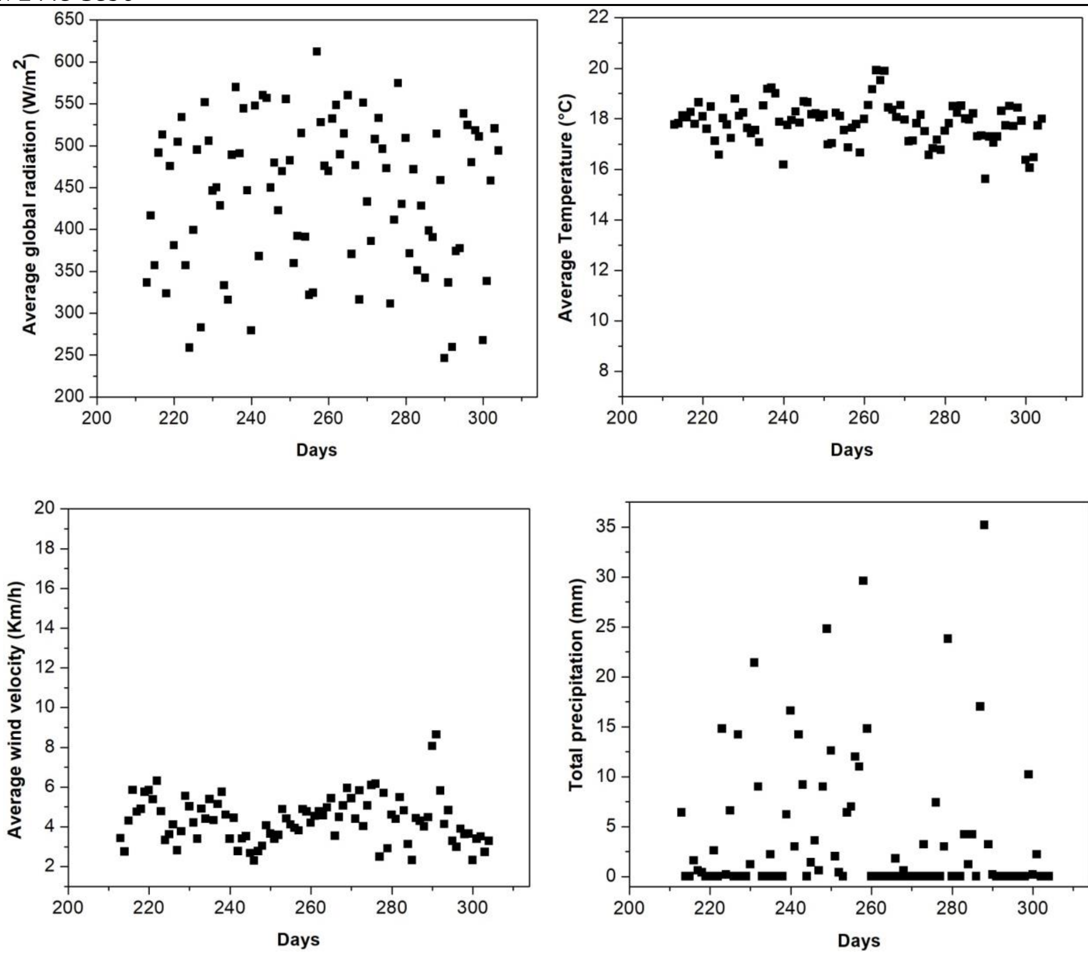


Figure. 4 Climatological data days 213 - 204 of the 2018 year (INIFAP)
Bibliographic source: Own elaboration with INIFAP data, http://clima.inifap.gob.mx/redinifap

3.2 Electrical properties of solar panels

For calculate the electrical characteristics of the UTP photovoltaic system, it was used the Shockley single diode equation, which describes the *I–V* characteristic of the ideal PV cell (Sze, 2007):

$$I = I_s \left[e^{\left(\frac{qV}{\alpha KT}\right)} - 1 \right] \qquad [1]$$

Where *I* is the diode current, I_s is the reverse bias saturation current, *q* is the electron charge (1.60217646 × 10^{-19} C), *V* is the voltage across the diode, *K* is the Boltzmann constant (1.3806503 × 10^{-23} J/K), *T* (in Kelvin) is the temperature of the *p–n* junction, and α is the diode ideality factor. To calculate the effect of temperature and solar radiation on the PV system there are various methods to express variations of the I_{SC} in function of solar radiation (G) and temperature (T), as can be seen in the following linear empirical relation (Ibrahim, et al., 2017, González-Longatt, 2005, Savita Nema, et al., 2010):

$$I_{sc}\,(G, T) = \frac{G}{G_{STC}} \left[I_{sc,STC} + \mu_{Isc} (T - T_{STC}) \right] \qquad [2]$$

Where I_{sc} and $I_{sc,STC}$ are the short-circuit current of a PV module and its value at standard test conditions (A), G and G_{STC} are the solar global radiation (W/m^2) and global radiation at STC, μ_{ISC} is the thermal coefficient of the short-circuit current (A/°C).

3.3 Effect of climatic conditions

Solar panel temperature is proportional to solar radiation and ambient temperature; however, when operating in the normal conditions they typically operate at variable temperature and solar radiation. To determine the power output of the solar cell, it is necessary to determine the expected operating temperature of the PV module. The nominal operating cell temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under STC (in this case ambient temperature of 20 °C at AM 1.5 and global radiation of 800 W/m^2 and wind speed not greater than 1 m/s). In order to calculate the PV module operating temperature, there is an approximate expression (Stuart, et al., 2006):

$$T_m = T_{amb} + (NOCT - 20)(\frac{G}{800}) \qquad [4]$$

Where T_m is the module temperature, T_{amb} is the ambient temperature and G is the global radiation in [W/m^2] (Kotlay, et al., 1998, Malik, et al., 2003). This equation was used to estimate in a simple way the module temperature in a typical day along the two periods evaluated in 2018.

On the other hand, Skoplaki et al., 2008 and Schwingshackl, et al., 2013, suggest an advanced model to integrate wind data in the NOCT - standard equation. This model considers, in addition to the ambient temperature and the in-plane solar radiation, also wind speed and specific solar panel properties, such as efficiency, temperature coefficient of maximal power, transmittance of the cover system and absorption coefficient of the p-type semiconductor of the cells.

$$T_m = T_{amb} + (NOCT - 20)\left(\frac{E}{800}\right)\left(\frac{h_{w,NOCT}}{h_w}\right)[1 - \frac{\eta_{STC}}{\tau * \alpha}(1 - \beta_{STC} * T_{STC})] \qquad [5]$$

Where η_{STC} and β_{STC} are efficiency and temperature coefficient of maximal power under STC, values for η_{STC} and β_{STC} for the p-Si PV technologies are between 14 to 17 % and -0.4336 % / °C respectively; $(\tau * \alpha)$ is usually assumed as 0.9; h_w is the wind convection coefficient, which is typically a linear function of the wind velocity.

In the case of h_w, there are different parameterizations, in this work it was used the following approximation (Armstrong, et al., 2010, Sharples, et al., 1998):

$$h_w = 5.7 + 2.8\, v_w \qquad [6]$$

Where V_w is the local wind velocity close to the module, $h_{w,NOCT}$ is the wind convection coefficient for wind speed at NOCT conditions, i.e. $V_w = 1$ m/s.

The I-V and Power-V curves were plotted using equations 1 and 2 in function of average module temperature (considering wind effect) and average global solar radiation for every month of the two periods compared in this work. The data used are shown and compared in Table 3:

Period	**Average ambient temperature (°C)**	**Average module temperature (°C)**	**Average module temperature (wind effect) (°C)**	**Average global radiation (W/m²)**	**Efficiency (%)**
1					
January	12.79	26.06	22.98	424.33	7.22
February	16.6	31.88	27.92	488.93	8.37
March	18.55	35.24	30.96	534	9.24
2					
August	17.93	31.49	29.23	433.85	7.50
September	18.09	32.7	31	467.33	8.06
October	17.5	30.78	28.92	424.89	7.34

Table 3. Climatic data used for the calculations (INIFAP)
Bibliographic source: Own elaboration with INIFAP data, http://clima.inifap.gob.mx/redinifap

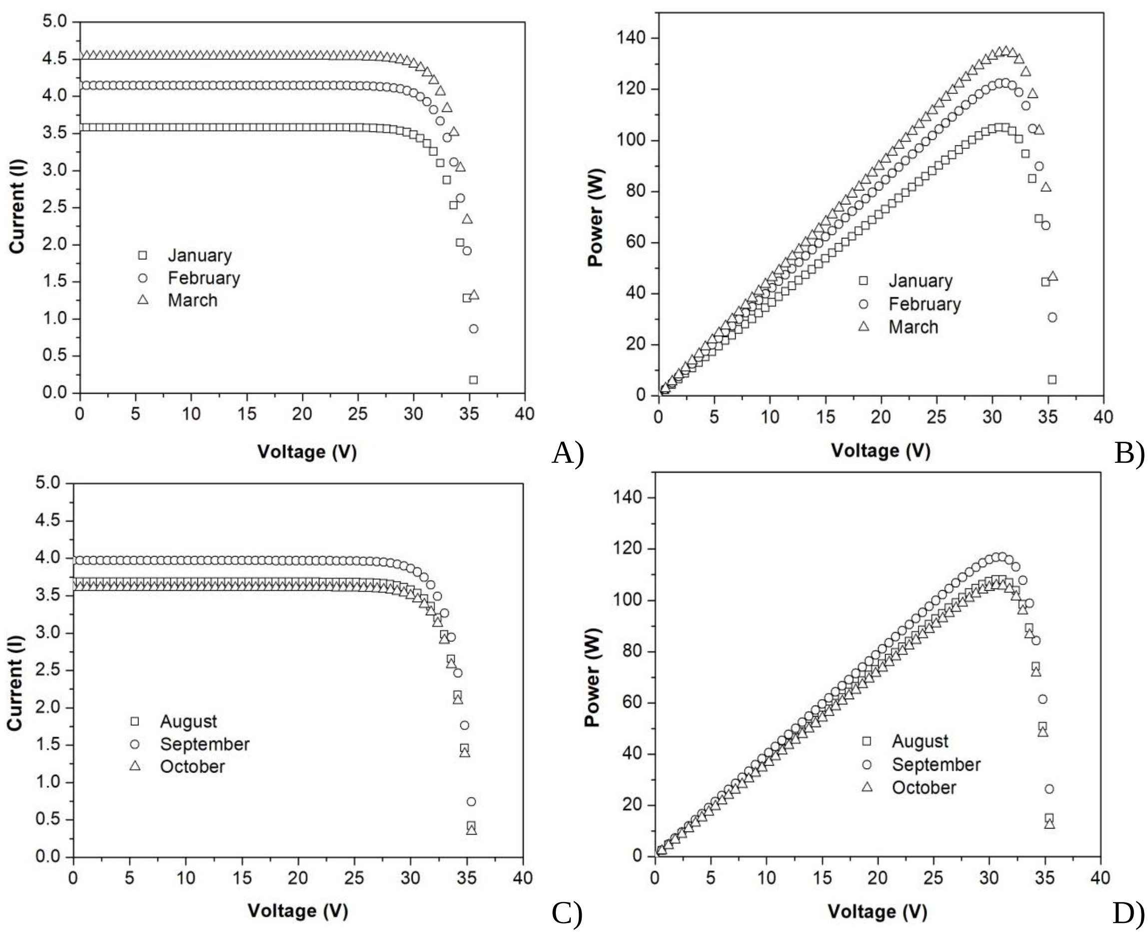


Figure. 5 I-V and Power – V curve considering average temperature and global radiation
Bibliographic source: Own elaboration

The power of solar panels depends mainly of solar radiation; this climatic variable determines the month with the highest and lowest energy gain. March and January are the best and worst performing months respectively, the analysis of the latter values proves too the slightly correlation in PV system in two climatic variables; global radiation and temperature, March combine the highest temperature with the highest global radiation. Although in the second period there were several rainy days, the energy gain does not decrease significantly.

In Figure 6 were plotted the energy gain vs time for both periods. The energy gain data generated by the solar panels were taken from the photovoltaic inverter. Considering the first value, reported in January 1st until the day 100, 2403 kWh were collected, compared with the second period, started in the day 213 until the day 304, 1944 kWh were collected. This confirms that the rate change according to the energy gain in function of the time was better in the first period than in the second period. The pluvial precipitation had a considerable influence on solar radiation and module temperature as reduction in the power due to absorption, scattering and reflection, because of the continuous change in light intensity incident on the solar panels due to water vapor, fog, and clouds.

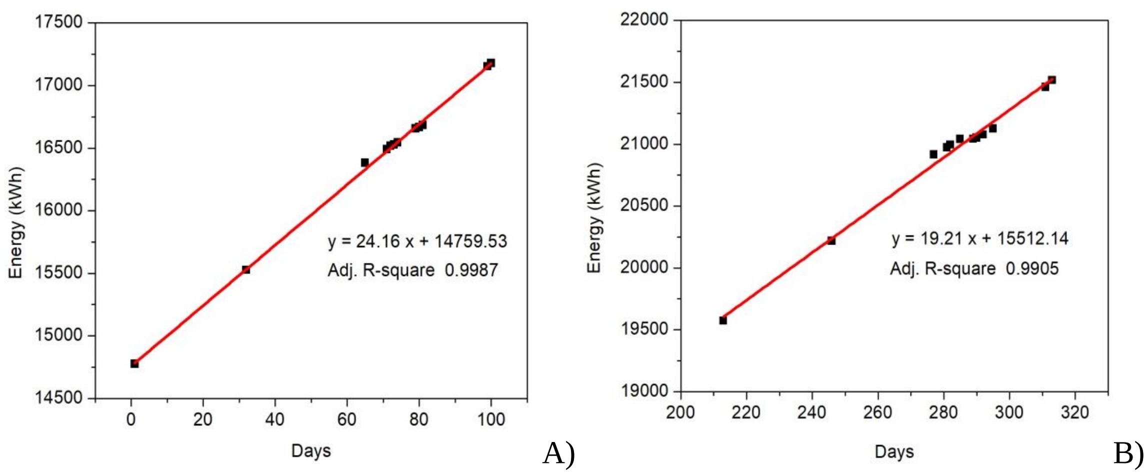


Figure. 6 Photovoltaic inverter results A) first period, B) second period
Bibliographic source: Own elaboration

4. Conclusions

In this study several mathematical models were fitted with measured data and later used and compared with measurements of energetic gain done in the PV power plant located in the UTP (Puebla City) in order to assess the validity of the models and know the effects of the climatic conditions. These models were applied on the meteorological data base of the INIFAP and Conagua. PV solar cells have huge potential to contribute to covering energy demand in Puebla; however the energy conversion efficiency is usually lower than that of the ideal solar cell owing to various additional mechanisms. PV module temperature increases as the solar irradiance increase according to local time, however, is not the only parameter that we need to take in account, the wind velocity and pluvial precipitation are important too. In this comparison of two periods the PV panels had more energetic gain in March and less energetic gain in January; the mathematical models used for the estimation of the monthly average power of the panels gave acceptable estimates in function of climatic conditions.

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