

Estimation of energy efficiency in solar photovoltaic panels considering environmental variables

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Abstract. The present work has been made to find out the relationship between the efficiency of two types of photovoltaics panels, monocrystalline and polycrystalline, and the weather variation in the city of Bogota-Colombia. The power generated of two photovoltaic panels, one monocrystalline and one polycrystalline, were collected for one month, 24 hours in condition of variant weather. At the same time, it was implemented a weather station that registered the variations of climatic variables like wind speed, temperature, humidity, irradiance and rainfall, to relate them with the generated power of each photovoltaic panel. Once with this information collected it a study was made with all the correlated variables through of the statistic tool PCA (Principals Components Analysis) where it was seen the impact of each climatic variable over the generated power in both panels and therefore its impact over the efficiency.

1. Introduction

Due to the great growth that has had the use of solar energy in the world, the industry has evolved in materials and manufacturing technics of solar panels to lower production costs. However, the efficiency of the photovoltaic panels is still low, up to 17% in laboratory tests, being also affected by climatic factors of the region where the panels are installed [1].

For this reason, it is important to stablish the efficiency of the photovoltaic panels in real conditions of installation, since efficiency giving by manufacturers is established in laboratory conditions what can vary significantly in field by climatic factors such as temperature, wind, rainfall, humidity and solar radiation [2].

This document presents the implementation of a weather station that registered the climatic variables that affect the generation of solar energy in the city of Bogota and the generated power by two photovoltaic solar panels, one of monocrystalline type and other of polycrystalline type, to do an analysis through a statistical tool called PCA (principal component analysis) on how the climatic variables are correlated with the power obtained as well as the variation in the efficiency of solar panels with the climatic conditions registered.

2. Efficiency in photovoltaic solar panels



Solar energy can be transformed into electricity using the photovoltaic effect, which increase the electrical conductivity of a material under the action of light, due to the generation of charge carriers and holes [3].

2.1. Photovoltaic cell

A photovoltaic cell is a device that directly converts light into electric energy based on the photovoltaic effect [4]. Most photovoltaic cells are made of silicon. A photovoltaic cell consists of a PN junction, two electrodes and a conductive network anti reflection. A solar cell is basically made of two semiconductors, the first N-type and the second P-type. The N-type semiconductor is the component of the cell that will receive the light of the Sun, while P-type semiconductor will be on the back of the solar cell. The union of both kinds of semiconductors made up the junction PN [5].

2.2. Photovoltaic panels and Irradiance

The types of solar cells made from silicon are monocrystalline, polycrystalline and amorphous. Monocrystalline silicon cells are the most efficient, up to 17%, although the manufacturing process is expensive and has a deficient performance in conditions of poor lighting. The cells are cut from a silicon crystal, are rigid and must be mounted in a rigid framework to protect them. Polycrystalline silicon cells have an efficiency up to 13% and a low cost of production. These cells are cut from a silicon block consisting of many crystals.

Irradiance is the unit used to describe the incident solar radiation per unit area and is measured in W/m^2 . In a photovoltaic module, the incidence of solar radiation causes the appearance of generated current that is directly proportional to the irradiance. In short circuit operation, the resulting current varies in proportion to irradiance [6].

2.3. Efficiency panels solar

The efficiency of a solar cell is given by the ratio between the power output of the cell P_{out} and the incident power P_{in} , where P_{in} is the product of irradiance and the area of the cell. In (1) the efficiency of the cell parameters given by the manufacturer is related, as maximum power (P_{max}), maximum voltage power (V_{mp}), maximum current power (I_{mp}), open circuit voltage (V_{oc}), and short circuit current (I_{sc}).

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{max}}{P_{in}} = \frac{I_{mp}V_{mp}}{P_{in}} = \frac{I_{sc}V_{oc}FF}{P_{in}} \quad (1)$$

$$FF = \frac{P_{max}}{I_{sc}V_{oc}} \quad (2)$$

In (2) is related the fill factor (FF), which is the ratio of the maximum power and the product between short circuit current (I_{sc}) and open circuit voltage (V_{oc}) [6].

2.4. PCA principal components analysis

To analyze the impact that have the climatic variables have on the power of photovoltaic panels, it was used a multivariate statistical technique called Principal Components Analysis PCA. The PCA is a statistical technique that takes data and transforms it in such a way that new data have statistical properties. The statistical properties are chosen so that the transformation highlights the importance of the data elements. The data can also be reduced or compressed by removing or filtering elements less important [7]. The PCA is based on the search of linear combinations of elements of a vector X to find a combination with the largest variance. The principal components are derived from eigenvalues and eigenvectors of the matrix of covariance $VarX$ [8].

The PCA is also known as a technique for exploratory data analysis that basically projected data in a reduced hyperspace defined by orthogonal principal components. These components are linear combinations of original variables, where the first principal component has the largest variance, the second component has the second variance and thus the other components. Therefore, it is possible to select a considerable number of components in such a way that the dimension of the data is reduced while preserving the systematic variation in the data retained on the first principal components, while the noise is represented in the latest components [9].

3. Station weather and power measurement

To carry out the research on the correlation of climatic factors with the efficiency of solar photovoltaic panels, it was designed a weather station that allowed capture and record both climatic variables and power generated by the solar panels. This station is made up of a solar radiation sensor, a temperature sensor, an anemometer, a rain collector, a humidity sensor and a power interface (Figure 1).

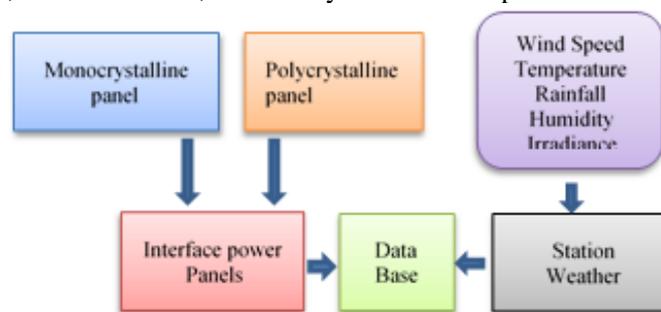


Figure 1. Design of weather station

3.1. Solar radiation Sensor

A Pyranometer that measures both the direct and diffuse components of solar irradiance and converts the incident radiation into proportional voltage was used for the measurement of the irradiance. The transducer is a photodiode hermetically sealed that includes an amplifier that converts the transducer current at 0 to 2.5 volts. The analog output is of 1.67 mV per W/m^2 , and its conversion is made at the station through an ADC channel (Figure2).

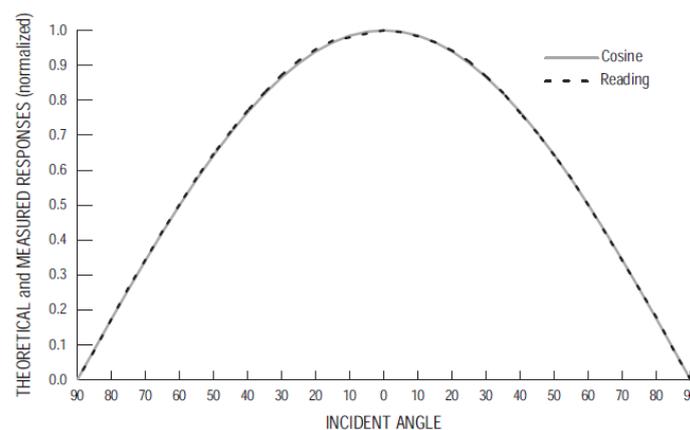


Figure 2. Response solar radiation sensor

3.2. Power measurement interface

To measure the power generated it was designed an interface connected to two solar panels with similar characteristics (50W@12V) but different technology (monocrystalline and polycrystalline), where it was measured as the voltage as the current in the output of each panel (Figure 3).

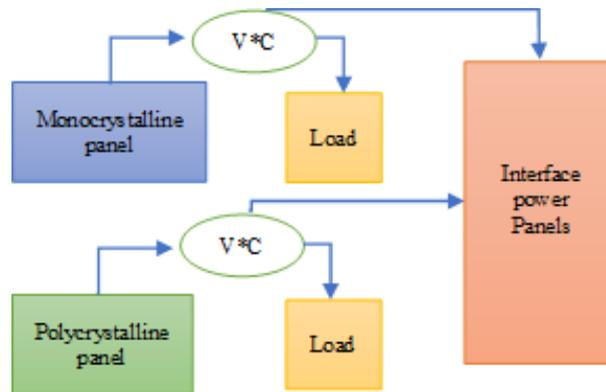


Figure 3. Interface of Power measurement

3.3. Solar panels

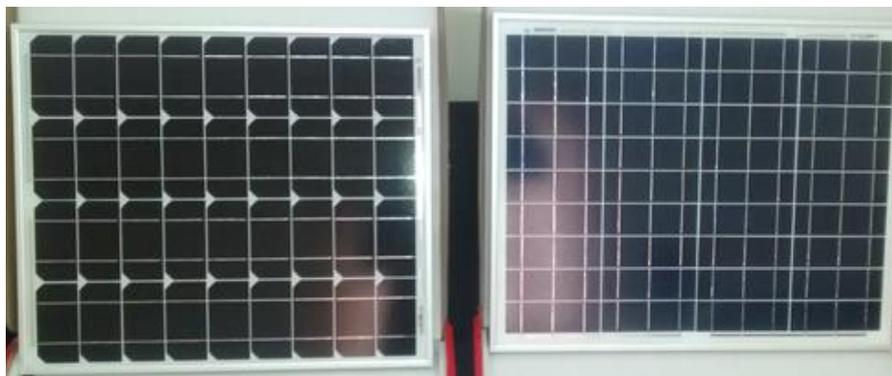


Figure 4. Monocrystalline (left) and polycrystalline (right) panels

The monocrystalline panel has a maximum power (P_{max}) of 50 watts, maximum voltage power (V_{mp}) 18.5V, maximum current power (I_{mp}) 2.70A, open circuit voltage (V_{oc}) 22.7 V, short circuit current (I_{sc}) 2.84A and an efficiency of 14.67%. The polycrystalline panel has a maximum power (P_{max}) of 50 watts, maximum voltage power (V_{mp}) 17.8V, maximum current power (I_{mp}) 2.80A, open circuit voltage (V_{oc}) 22.4V, short circuit current (I_{sc}) 2.95A and an efficiency of 13.37%. All specifications in these panels are determined under STC (Standard Test Conditions) with an irradiance of 1000W/m^2 , a temperature of $25\text{ }^\circ\text{C}$ and air mass 1.5 (Figure 4).

3.4. Implementation

The implementation of weather station and the power interface was carried out in the city of Bogotá at an altitude of 2592 meters above the sea level. Both panels were installed under the same conditions. Rainfall, humidity, irradiance and wind speed sensors were installed on a post parallel to the location of the panels, while the temperature sensor was located near the panels surface.

4. Testing and results

Once the weather station and the power interface were implemented and validated, all the variables were registered every two minutes since October 20 to November 20, 2016. The records were stored in a log file that included the timestamp, wind speed(m/s), rainfall (mm), irradiance (W/m^2), relative humidity (%), temperature ($^\circ\text{C}$), voltage (V) and current (mA) of each panel. The first analysis began with some graphics showing the relationship between climatic variables and the irradiance to observe the impact

that may have on the power generated by the panels. For this analysis were selected different days where some climatic conditions were more relevant than others.

4.1. Irradiance and temperature

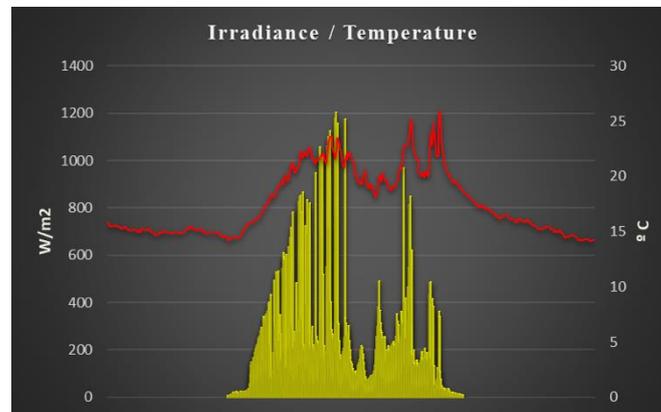


Figure 5. Irradiance and temperature

The figure 5 corresponds to records of October 20, where there were conditions of dry weather for good levels of irradiance and a warm temperature. The graphic shows that irradiance levels behave according to the temperature levels. The left side of the graphic shows the irradiance scale in W/m^2 , where is seen that this variable reaches the $1200W/m^2$. The the right side shows the temperature scale in $^{\circ}C$, where is seen that this variable reaches a peak of $25^{\circ}C$ when the irradiance levels are the highest. The highest levels of irradiance occurred around 11:00 am.

4.2. Irradiance and rainfall

The figure 6 corresponds to records on October 26, where there was intense rainfall producing low levels of irradiance.

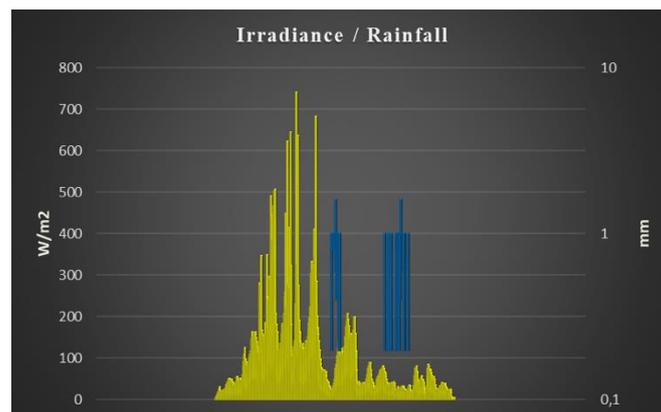


Figure 6. Irradiance and rainfall

The graphic shows that irradiance levels fall dramatically with the rainfall. The left side of the graphic shows the irradiance scale in W/m^2 which reaches $750 W/m^2$. On the right the rainfall is showed achieving levels of 1.6 mm in just 2 minutes. On this day, the weather station records a total of 13.8 mm of rainfall.

4.3. Irradiance and relative humidity

The figure 7 corresponds to records on October 27 where the weather conditions were cloudy producing low levels of irradiance and elevated levels of humidity. The graphic shows that irradiance levels rise when the humidity levels fall. The left side of the graphic is the irradiance scale in W/m^2 , which reaches $1000 W/m^2$. The right side is the humidity, which achieves maximum levels of 90% and minimum of 41.2%.

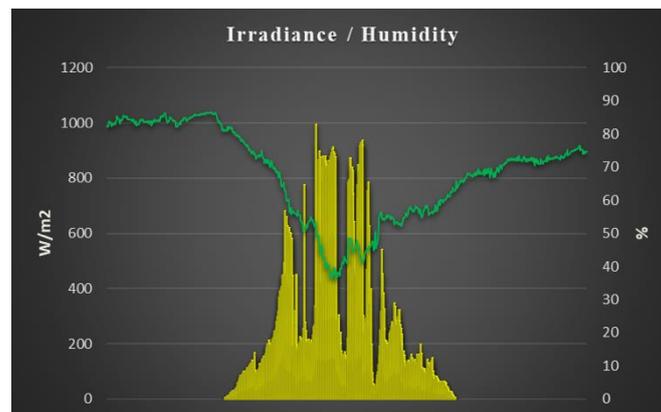


Figure 7. Irradiance and humidity

4.4. Irradiance and wind speed

The figure 8 corresponds to records on October 22, where there were conditions of cloudy weather with intense winds.

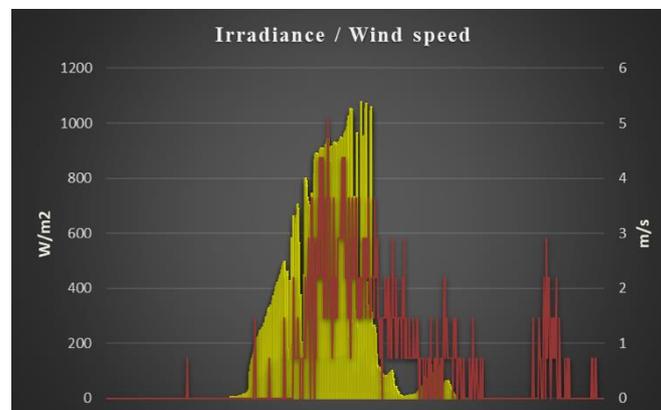


Figure 8. Irradiance and wind speed

The graphic shows that the irradiance levels rise when the wind speed increases, however is not clear a direct correlation between these variables. The left side of the graphic shows the scale of irradiance in W/m^2 , which achieves $1075 W/m^2$. The right is the wind speed scale which achieves maximum levels of 5.1 m/s.

4.5. Power generated by the panels according to the irradiance

The figure 9 corresponds to records on October 29, where there was cloudy weather with persistent rainfall.

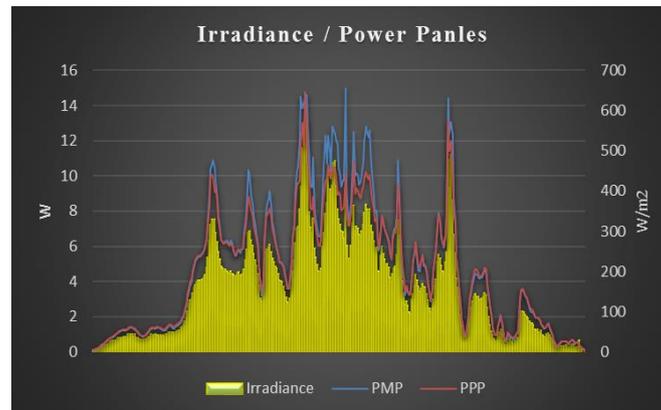


Figure 9. Power panels and irradiance

The graphic compares the power generated by the photovoltaic panels (Power of Polycrystalline Panel PPP and Power of Monocrystalline Panel PMP) with incident irradiance. The graphic shows that the levels of power of the two panels follow the same pattern of irradiance. It is seen that monocrystalline panel delivers more power at the maximum values of irradiance than the polycrystalline panel. On the right, the graphic shows the irradiance scale, which reaches maximum 600 W/m². On the left is the power panels scale, where it is seen that the panels achieve a 15 watts of output power.

4.6. Monocrystalline Panel Power and temperature

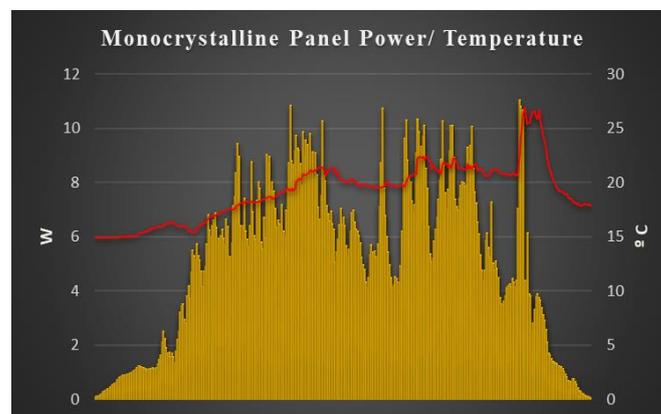


Figure 10. Monocrystalline Panel Power and temperature

The figure 10 corresponds to records on October 30, where there was dry weather with a maximum temperature of 25° C. In the graphic is seen the relationship between the temperature and the generated power of the monocrystalline panel, where the maximum temperature levels correspond with the panel power. The left side of the graphic shows the power scale, which achieves the 11W. On the right, there is the temperature scale which achieves a maximum level of 25 °C.

4.7. Monocrystalline Panel Power and wind speed

The figure 11 corresponds to records on October 30, where there were weather conditions with recurrent winds. In the graphic a direct relationship between the wind speed and the panel power is not seen. The left side of the graphic shows the panel power scale, which reaches until 11W. On the right, is seen that the wind speed scale gets a speed of 3.64 m/s.

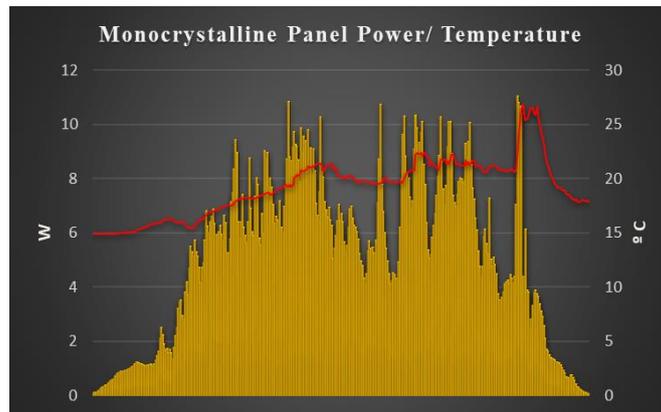


Figure 11. Monocrystalline Panel Power and Wind Speed

4.8. Monocrystalline Panel Power and rainfall

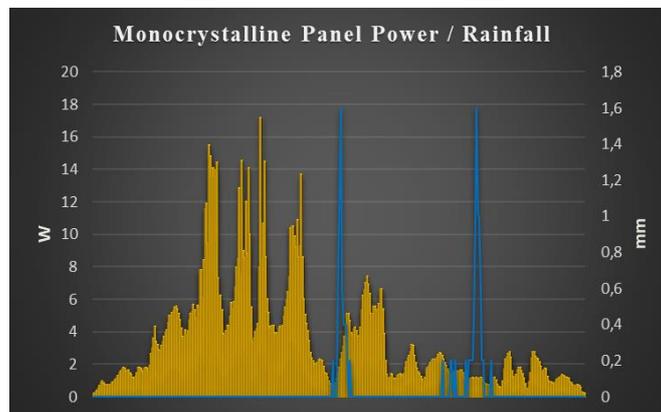


Figure 12. Monocrystalline Panel Power and rainfall

The figure 12 corresponds to records on October 26 where there was cloudy weather with intense rainfall. In the figure 12 is seen the relationship between rainfall and the generated power of the monocrystalline panel, where maximum levels of rainfall correspond to low levels of the panel power. The left side of the graphic shows th panel power scale, which achieves the 17 W. On the right, it is showed the rainfall scale that achieves maximum levels of 1.6 mm.

4.9. Monocrystalline Panel Power and humidity

The figure 13 corresponds to records on November 2, where there was a cloudy weather. In the graphic is seen the relationship between the humidity and the power generated for the monocrystalline panel, where the maximum humidity levels coincide with the lowest levels of the power panel. The left side of the graphic shows the panel power scale, which achieves the 19W. On the right, the humidity scale is showed achieving the minimum level of 58%.

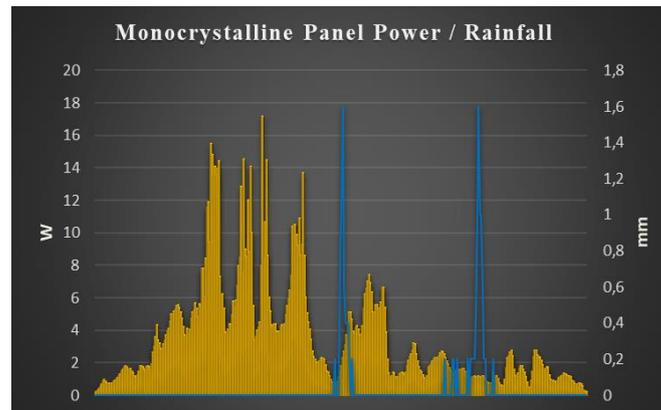


Figure 13. Monocrystalline Panel Power and relative humidity

5. Analysis of results

Once seen the relationship among the different climatic variables (temperature, humidity, rainfall and wind speed) and the irradiance through the graphics and after a preliminary analysis of the impact that have these variables have on the panels power, it was made a deeper analysis based on the information collected by the weather station. From the information obtained of the irradiance and the power output of the solar panels, a polynomial regression determines a function that relates both variables. In (3) is shown the function obtained from the polynomial regression according to the irradiance and the power panel.

$$y = -10^{-5}x^2 + 0,0339x - 0,2681 \quad (3)$$

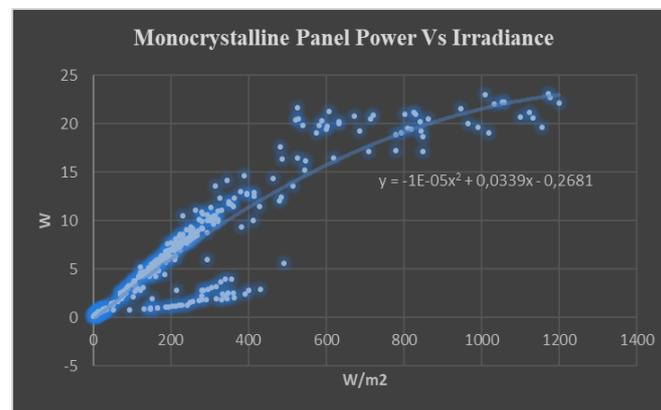


Figure 14. Scatter plot Panel Power Vs irradiance

In the coefficient matrix shown in the figure 15, the variables that have a positive correlation are presented in blue color, while those that have negative correlation are presented in red colour. More tenuous colours indicate that the variables are not correlated. For example, the irradiance has a negative correlation with the humidity, while it has a positive correlation with the current.

Additionally, it was obtained an array of scatter plots (figure 16) between every variable to appreciate how they relate each other, however as the correlation coefficients matrix as the scatter plot matrix only allows to see the relationship between pairs of variables. For this reason, it was used a multivariate statistical tool called PCA (principal component analysis) to be able to determine how every variable is correlated with the power obtained from the photovoltaics panels.

Pearson's r	Wind	Rain	Irrad	humid	Temp	VP	CP
Wind	-	0,450	0,593	-0,155	0,589	0,780	0,644
Rain	0,450	-	-0,242	0,333	-0,048	-0,102	-0,197
Irrad	0,593	-0,242	-	-0,558	0,613	0,867	0,948
Humid	-0,155	0,333	-0,558	-	-0,805	-0,535	-0,522
Temp	0,589	-0,048	0,613	-0,805	-	0,817	0,639
VP	0,780	-0,102	0,867	-0,535	0,817	-	0,910
CP	0,644	-0,197	0,948	-0,522	0,639	0,910	-

Figure 15. Correlation coefficients Matrix

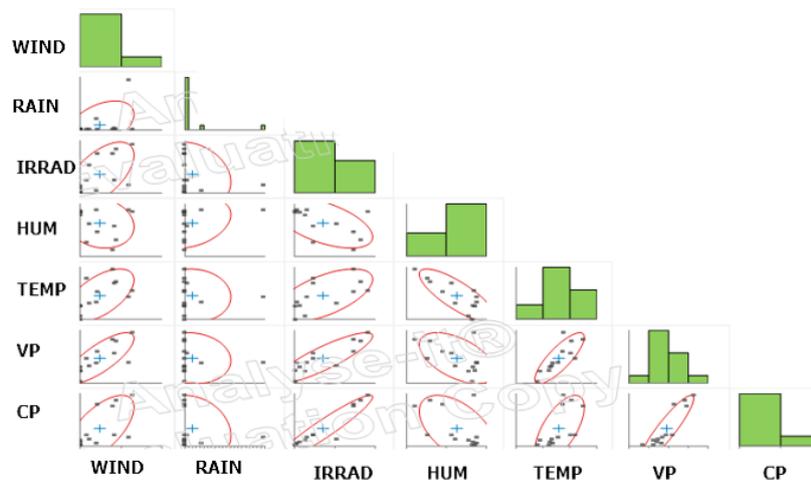


Figure 16. Scatter Plot Matrix

To make a PCA analysis, it is necessary to select the observers, in this case the records of time where the variables were correlated. Since the magnitudes of the variables are very different, the information contained was normalized in the matrix by dividing each column by its standard deviation, in this way the information contained in the matrix is made dimensionless and the significant differences between the variances of the variables decrease.

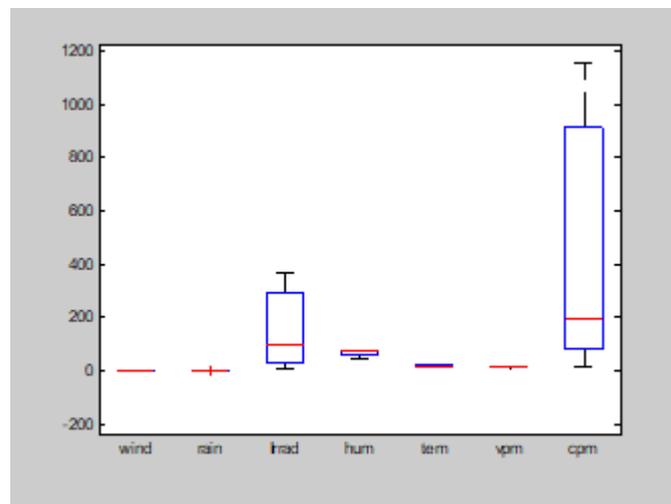


Figure 17. Magnitude of the climatic variables and power

5.1. PCA Monocrystalline Panel Power and irradiance

Table 1. PCA - Irradiance coefficients

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
WIND.	0,35	-0,41	0,793	0,223	-0,140	0,045	0
RAIN.	0	0	0	0	0	0	1
IRRAD.	0,38	0,566	-0,048	0,717	0,095	-0,08	0
HUME.	-0,41	0,404	0,372	0,003	0,101	0,717	0
TEMP.	0,429	-0,28	-0,447	0,084	-0,262	0,677	0
VOL.P.	0,464	0,038	0,052	-0,366	0,795	0,109	0
COR.P	0,398	0,508	0,159	-0,542	-0,508	-0,06	0

The first principal component analysis is done in dry weather with elevated levels of irradiance. In this first analysis PCA were taken as the environmental variables (wind speed, rainfall, irradiance, humidity and temperature) and the power panels variables (voltage panel VP and current Panel CP). To determine which are the most principal components a vector called latent is found, which indicates the amount of accumulated variance provided for each principal component.

Table 2. Variance components

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Latent	0.74	0.910	0.983	0.994	0.998	1.000	1.000

According to latent vector, it is seen that the components that are most important are the first two, which reached 91% of the variance. In the table of coefficients is seen that PC1 has the highest positive correlation with the variables of power panel (voltage and current), temperature and irradiance, while it has negative correlation with humidity. PC2 shows correlation positive between the variables of irradiance and current while negative correlation with the wind speed. Since there was not rainfall on this day its coefficient is zero.

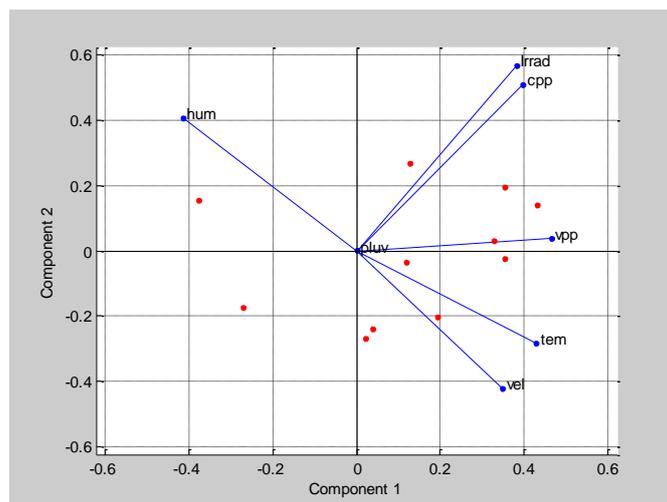


Figure 18. Monocrystalline Panel main components - irradiance

Since the two first principal components have the greater part of the variance, all variables are plotted according these components. In Figure 18 the correlation between all the variables with the power output of the panel is clearly seen, the vectors of variables that are found with a small angle with respect to irradiance have a positive correlation, while those that have approached 90 degrees angle have a negative

correlation, as it is the case of humidity also shows that the rainfall has not a vector since that was not present in the samples.

5.2. *PCA Monocrystalline Panel and rainfall*

The second principal component analysis is done with persistent rainfall and cloudy weather conditions. In this analysis PCA were taken as the environmental variables (wind speed, rainfall, irradiance, humidity and temperature) as the power panels variables (voltage panel VP and current Panel CP).

Table 3. PCA - Rainfall coefficients

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
WIND.	0,1962	0,6185	-0,328	0,2791	-0,533	0,32	0,04
RAIN	-0,086	0,6148	0,7559	-0,003	0,2074	-0,0	0,00
IRRAD.	0,4582	-0,165	0,2688	-0,247	-0,334	-0,1	0,70
HUME.	-0,455	-0,166	0,1346	-0,355	-0,152	0,75	0,14
TEMP.	0,3973	0,2932	-0,342	-0,543	0,5456	0,21	0,04
VOL.P.	0,4134	-0,267	0,1784	0,5949	0,351	0,49	0,06
COR.P	0,4557	-0,162	0,2854	-0,293	-0,341	0,11	-0,6

According to the latent vector, it is seen that the most important components are the first two, which reached 87% of the variance.

Table 4. Variance components

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Latent	0.602	0.877	0.936	0.979	0.994	0.999	1.000

In the table of coefficients is seen that PC1 has the highest positive correlation with the variables of power panel (voltage and current) and irradiance, while it has negative correlation with humidity. PC2 shows a positive correlation between the variables of wind speed and rainfall since it was a day where there was an intense rain.

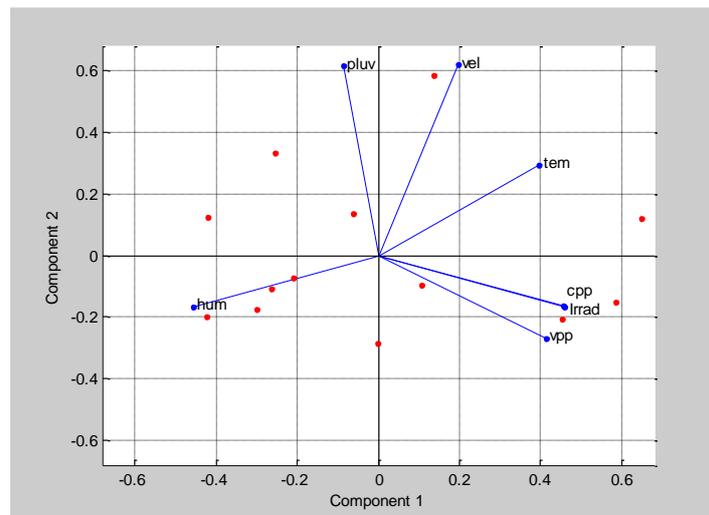


Figure 19. Monocrystalline Panel main components - rainfall

In Figure 19 is seen more clearly the correlation between all the variables with the power output of the panel, the vectors of variables that are found with a small angle with respect to irradiance have a

positive correlation, while those who have approached 90 degrees angle have a negative correlation, as it is the case of humidity and rainfall.

5.3. C. Analysis of the efficiency

Once made the principal components analysis between panels power and weather variables and after appreciating the relevance that they have, it was made an estimate of the efficiency of the panels according to incident irradiance. Since irradiance is given depending on the area of solar panels (W/m^2), the first thing that must be done to find the relationship of irradiance according to the area of panels used for this study.

The monocrystalline panel area is determined according its dimensions: $0,630\text{m} \times 0,541\text{m} = 0,34083 \text{ m}^2$. As the magnitude of the irradiance measured by the sensor is given for an area of 1 m^2 , it is found a relationship k in (4) with the area of the panel:

$$k = \frac{1\text{m}^2}{0,34083 \text{ m}^2} = 2,934 \quad (4)$$

According to the technical specifications of the Monocrystalline panel its efficiency is 14.67% and the maximum power output is of 50W at STC (standard test conditions). The 50W are given with an irradiance of $1000 \text{ W}/\text{m}^2$, therefore, we can check the value of the constant k finding the value of efficiency with maximum values given in (5).

$$\eta = \frac{P_{\text{out}}*100}{P_{\text{in}}} = \frac{P_{\text{max}}*k*100}{P_{\text{in}}} = \frac{50\text{W}*2,934*100}{\frac{1000\text{W}}{\text{m}^2}} = \frac{14670}{1000} = 14,67\% \quad (5)$$

In the same way the polycrystalline panel area is determined according to its dimensions: $0,550\text{m} \times 0,680\text{m} = 0,374 \text{ m}^2$. As the magnitude of the irradiance measured by the sensor is given for an area of 1 m^2 , it is found the relationship k with the area of the panel (6).

$$k2 = \frac{1\text{m}^2}{0,374 \text{ m}^2} = 2,673 \quad (6)$$

According to technical specifications of the Monocrystalline panel its efficiency is 13.37% and the maximum power output is of 50W at STC (standard test conditions). The 50W are given with an irradiance of $1000 \text{ W}/\text{m}^2$, therefore, we can check the value of the constant k finding the value of efficiency with maximum values given in (7).

$$\eta = \frac{P_{\text{out}}*100}{P_{\text{in}}} = \frac{P_{\text{max}}*k*100}{P_{\text{in}}} = \frac{50\text{W}*2,673*100}{\frac{1000\text{W}}{\text{m}^2}} = \frac{13365}{1000} = 13,365\% \quad (7)$$

Once factors are determined to find the efficiency in monocrystalline and polycrystalline panels, it was related with the irradiance received.

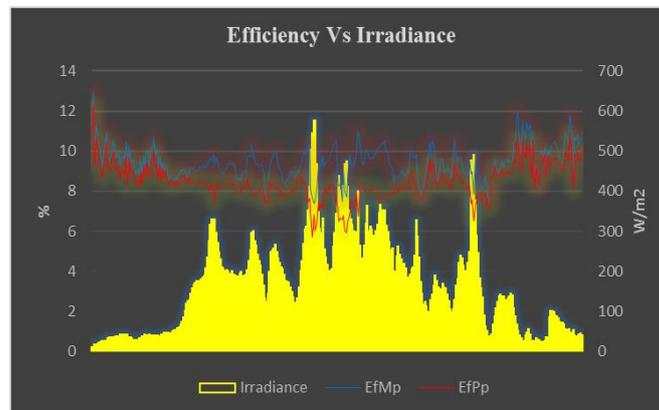


Figure 20. Efficiency Panel according to irradiance

The average efficiency for monocrystalline panel was 9.45% while in the polycrystalline panel was 8.48%. As expected the efficiency of polycrystalline panel it was lower, however, the average efficiency of the two panels was significantly lower than the given by the manufacturer. In the PCA is seen that the panel power has a high positive correlation with the irradiance, while it has a high negative correlation with the humidity and rainfall.

Also, the hours of the day where conditions are more favourable for panel power were determined. In Figure 21 are the vectors of variables and the hours where the irradiance is more predominant. For example, the hours where more power is generated is between 10 a.m. and 11 a.m., while the hours where the humidity was predominant are form 5 a.m. to 6 a.m. and from 4 p.m. to 5 p.m.

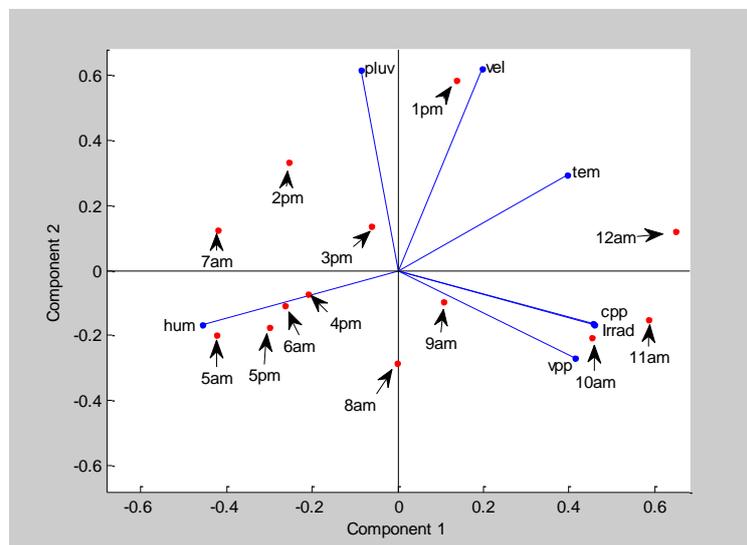


Figure 21. Principal component correlated with efficiency

6. Conclusions

As monocrystalline panel power as polycrystalline panel power, depends not only on their incident irradiance and manufacturing specifications, but is also affected by environmental conditions.

From the study carried out with principal components analysis it was seen the relevance of each climate variable on the generation of power in photovoltaic solar panels of monocrystalline type and polycrystalline type. The variables that had higher positive correlation with the power generated by the

photovoltaic panels were temperature and irradiance, while the variable that had greater negative correlation was the humidity.

Although the rainfall also gave a negative correlation with the generation of power, it was not so critical as the humidity since the rain was not constant. The other variables do not have a noticeable correlation in most of the cases.

Efficiency in actual installation conditions, which differ with the conditions that are defined the specifications of the panels, is significantly reduced with climatic variations such as those in the city of Bogotá. Although, type monocrystalline photovoltaic technology is more efficient, it can be seen that it is around 4% below manufacturer's specification. The same happens with the efficiency of polycrystalline type photovoltaic technology, which reduces in the same proportion.

References

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