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Effects of Environmental Conditions on Photovoltaic Generation System Performance with Polycrystalline Panels

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***Abstract*— Photovoltaic solar energy is the third most widely used renewable source worldwide, after hydroelectric and wind energy, and this energy source requires experimental and theoretical development in specific topics such as the effect of environmental conditions on energy performance. Thus, this study's main objective was to determine the influence that meteorological conditions have on the performance of solar photovoltaic systems, based on measurements from a measurement station installed in the city of Barranquilla-Colombia, to determine the factors that significantly affect the system's energy efficiency deviation. The experimental results show a dependence of the solar panel energy performance on some weather conditions, which is an uncontrolled phenomenon such as the ambient temperature and the atmosphere's humidity. Also, solar panel temperature and irradiance were the parameters with greater importance in the systems power generation. Also, the panel temperature must be controlled to obtain the desired response, because the panel temperature is inversely proportional to the voltage and directly proportional to the current. However, the negative effect of increased panel temperature in sunny climates is compensated by increased solar hours, so the summer system has less instantaneous efficiency, but it has higher solar output throughout the day. Therefore, solar energy production study should be related to total daily production.**

***Keywords*— Photovoltaic solar energy; weather conditions; solar systems performance; solar panel temperature.**

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I. INTRODUCTION

Renewable energies are considered as potential energy sources for the immediate future because of the low environmental impact and high availability in some geographical areas. The growing need to preserve the environment, the high energy demand, and the advancement in research have meant that renewable generation systems' costs decrease every time [1].

There are already several power generation plants using fossil fuel as an energy source in Colombia that have opted for the implementation of photovoltaic generation systems. On the other hand, the entry into force of international standards has helped many companies from different economic sectors to bet on this generation system. In Barranquilla, Colombia, there are already several photovoltaic generation plants installed in the covers of commercial centers and companies in the productive sector. These systems have received a great reception at the international level so that several authors show valuable results of the implementation of solar photovoltaic devices. Therefore, a study was developed on the inclusion of photovoltaic solar energy in low voltage networks, developing five types of these networks, evaluating different load segments obtaining satisfactory results from photovoltaic solar energy devices [2]. While an optimization technique was applied for sizing of autonomous photovoltaic hybrid systems, developing through optimization methods to maximize these systems' performance, obtaining the comparative methods [3]. Furthermore, some researchers studied the effects of photovoltaic panels' operating temperature utilizing computational tools, evaluating the temperature-dependent energy conversion performance, concluding that the increase in temperature in a photovoltaic panel negatively affects the power conversion performance of the panel [4]–[8]. Although, the analysis using cogeneration methods to waste heat recovery was conducted [9], which allows considering as a strategy to implement heat extraction methods in solar panel systems through cogeneration cycles, and thus through this avoid an excessive temperature increase in the panels while taking advantage of other types of renewable energies.

This research analyzes the behavior of environmental and meteorological conditions and their impact on power generation in one of the photovoltaic generation plants located in the city of Barranquilla. The research focuses on reviewing and analyzing climatic parameters collected during one year and obtained from a meteorological station located in the same place as the project site. The meteorological variables are analyzed in a particular way and evaluated according to the electric generation parameters to visualize their impact.

The continuous variations and effect of climatic parameters in Barranquilla, such as wind speed, ambient temperature, humidity, irradiance, and panel temperature, on solar panel performance are studied experimentally. The parameters considered in the 45kWp photovoltaic solar were the electricity generation, mainly the current, voltage, and DC power obtained, which make this research attractive.

II. MATERIAL AND METHOD

Regarding the strict sense of its use, in practice, it is essential to identify the availability of solar radiation in each environment as a prior point of feasibility analysis of the installation of a photovoltaic system. This task supposes a complicated process since the analysis of diverse factors is required. Thus, for the study of solar radiation availability, these analysis components can be classified into geographical, astronomical, geometric, physical, and meteorological [10].

A. Geographical Factors

As the latitude increases or decreases, towards the north or the south, the intensity of the solar radiation decreases. Thus, the earth surface near the equator line receives the highest radiation throughout the year, which makes up this location with the highest sunlight incidence.

The farther the Sun is from the surface, the more intense the radiation. Therefore, the intensity of this varies according to the time of day and the year. In essence, outside the tropics, the highest intensity of solar energy occurs when the Sun reaches its maximum height around midday during the summer season.

The extension of the atmosphere that the Sun's radiation has to travel is lower at higher altitudes. Thus, the atmospheric components will be smaller, and the fraction absorbed, reflected, and ultimately diminished will be lower. With each 1000 m increase in altitude, the intensity is 10 to 12% higher. Consequently, the higher the altitude of the place where the photovoltaic generation plant will be installed, the lower the attenuation of the Sun's rays, and therefore, a more outstanding production of electricity can be generated.

B. Astronomical Factors

The Solar Constant is the amount of energy per unit area and time that affects the upper layers of the Earth's atmosphere. When the Sun is closer to Earth, the Solar Constant reaches 1,412 W/m2; This happens at the end of December and is commonly called perihelion. When the Sun is farthest from Earth, the Solar Constant decreases to 1321 W/m^2, occurs at the beginning of July and is called aphelion [11]. On the other hand, an essential aspect of analyzing is that the Earth presents a rotation movement on its axis, which forms an angle of 23.5° to the normal plane of the ecliptic. Together with the translation, this movement gives rise to the seasons and favors the presence of climatic zones bounded by latitude intervals.

C. Geometric Factors

The position of the Sun on a point on the Earth's surface presents an angle of incidence to the horizontal plane of the place, called the angle of solar altitude (A). Its value can be estimated using a trigonometric function that requires the solar declination, the latitude of the analysis area and the solar time. The expression allows finding the value of the solar altitude angle (A) [12]. Additionally, the same solar position presents an azimuthal angle (Z), also called the Sun's azimuth, which is formed by its projection in the horizontal plane and its orientation towards the south [13].

D. Physical Factors

When a solar ray passes through the atmosphere, three phenomena occur: absorption, scattering, and reflection of photons because the atmosphere contains gases and a series of particles that interact with solar radiation [14]. Other elements contained in the atmosphere whose interaction with solar radiation is essential are aerosols [15].

The aerosol contained in the atmospheric shows that this is constituted by a set of particles in suspension and specifically the tropospheric influence directly on the decrease of solar radiation (with significant effect in the UV spectrum) in polluted regions. The stratospheric aerosol can reduce the surface irradiance for long wavelengths. However, it can also change the photon's optical path through the stratospheric ozone, increasing the surface irradiance, especially for short wavelengths (UVC with long wavelengths between 200 nm and 290 nm) [16], and large solar zenith angles. The spectral measurements analysis shows a marked increase in the ratio of diffuse/direct solar radiation, but no significant variations are found on the global irradiance.

E. Meteorological Factors

The meteorological factors are closely related to the region's temperature, rainfall, wind speed, thunderstorms, and humidity, among others. These factors have a close relationship with physical factors since their presence modifies the atmospheric and climatic characteristics of a given environment, so they have an apparent influence on the processes of absorption, dispersion, and reflection of solar radiation [17].

By specifying the cloudiness, it has a flat effect on the solar radiation so that it attenuates the spectrum to the same extent for the entire range of wavelengths. Different types of clouds attenuate the solar radiation to be considered, such as the cumulonimbus, the cumulus, and the nimbostratus. Generally speaking, denser and darker clouds are more efficiently block the Sun's rays, while white, less developed clouds, including fog, will have less effect.

F. Experimental Description

This research is based on real data which were collected through measurements recorded in specialized instrumentation for this purpose, during the period between May 9, 2017, and May 9, 2018. This study is based on the review and analysis of 187133 samples of meteorological parameters, distributed in 11 variables, which were taken in 15-minute cycles. The operational or electrical parameters were reviewed and analyzed through 7 variables of three investors, in cycles of 6 minutes and in a data population that exceeds 200000 samples.

Additionally, the temperature value of the solar panels' surface is calculated through the model described in Mattei's work [18] and purchased by Schwingshackla [19], which will be classified within the meteorological parameters. In the same way, the voltage per panel, current per panel, the individual DC power, and the total DC power are calculated.

The plant has 150 photovoltaic modules PV 315 Wp polycrystalline cell, with an inclination (11°), south orientation with a slight deviation to the west (5°) located on a building roof in Barranquilla city, Colombia, as shown in Fig. 1b.

Fig. 1 Experimental setup, a) Meteorological station, b) Solar generation plant

TABLE I
METEOROLOGICAL AND ELECTRICAL VARIABLES

Meteorological variables	Electrical variables
Ambient temperature (° C)	The voltage between the panel and the inverter (Vpv)
The temperature on the surface of the solar panel (° C) - calculated.	The current between the panel and the inverter (Ipv)
Dew point temperature (° C)	The voltage between inverter and meter (Vac)
Atmospheric pressure (hPa)	The current between inverter and meter (Iac)
Relative humidity (%)	Power generated (Pac)
Precipitation (mm)	Inverter temperature
Accumulated precipitation (mm)	Generated energy (kWh)
Wind speed (km / h) Wind direction (North 0 ° - South 180 ° - East 90 ° - West 270 °)	
Irradiance (W/m^2)	
UV index (dimensionless)	

III. RESULTS AND DISCUSSION

Next, the trend graphs of solar radiation, ambient temperature, panel surface temperature, wind speed, precipitation, and relative humidity are presented. The direct variables will be related by graphs with the independent variables such as voltage, electrical current, electrical power, and electric power generation. Finally, the panel efficiency is correlated with the irradiance and surface panel temperature. To analyze the monthly behavior, the verification and evaluation of data will be carried out during the periods 2017 - 2018 from May 9, 2017, to May 9, 2018.

For the analysis of the data and the large number of them, the variables are categorized according to the measurement range. The range are morning (06:00 - 10:00), noon (10:00 - 14:00), and afternoon (14: 00 - 18:00), for which the average of the values included in the established range was taken. Fig. 2 shows the variable irradiance curves throughout all the months of the year, plotted from the average value of the set of data contained in each measurement range.

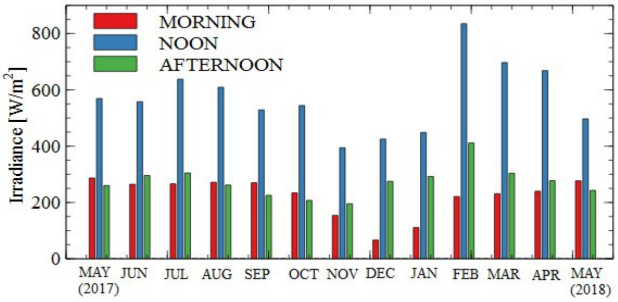

Fig. 2 Behavior of solar radiation per measurement range during all months of the year

The month of February describes a characteristic pyramidal curve of this variable since, in the morning and afternoon sessions, the values are usually lower than those of the midday workday. It is February (Fig. 2 and 3) the month that showed higher average values than the other months in the midday, even in the afternoon is only exceeded by July, while in the morning shows lower values to the other months, it only exceeds the month of December in solar energy production during the measurement range in question.

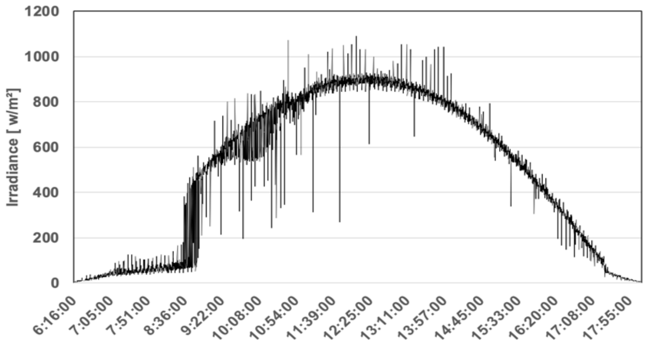

Fig. 3 Behavior of solar radiation during February 2018

Analyzing Fig. 4 shows that August and July presented average values of temperature in the panel higher than all the other months, and its shape is pyramidal. Likewise, in Fig. 2 it is observed that the same months presented the second and third largest average solar production, which also indicates that a large part of this incident energy was used to transfer thermal energy to the solar cell. The opposite happens with December; on this date, the average solar production was low, and in the same way, the temperature of the panel describes the same pyramidal behavior.

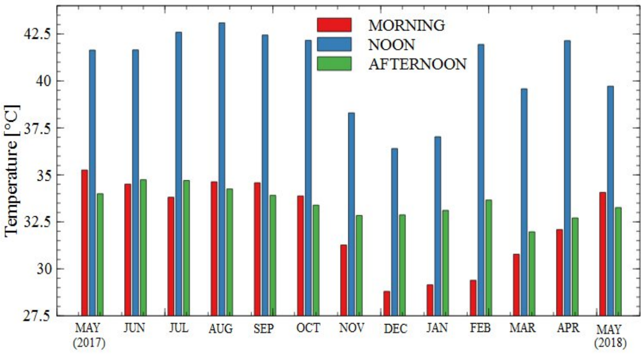

Fig. 4 Behavior of the temperature in the panel per measurement range during all the months of the year

The behavior of the temperature in the panel per measurement range is very similar in shape to the irradiance curves throughout the year, even those that describe flat or slightly flat. However, it is observed that the only atypical month in this analogy is September. This month has a pyramidal behavior in temperature but slightly flat in irradiance. On the other hand, Fig. 5 shows that March was the month that experienced the highest average wind speeds, barely reached by December during the afternoon, this had as a consequence that March was one of the months with lower average temperatures and of non-pyramidal behavior, that is, slightly flat behavior.

Likewise, it can be seen in Fig. 5 that September was the period with the lowest wind speeds during the year, which indicates that it would have effects on the temperature of the panel, as is observed in Fig. 4, where it can be seen that this month has a pyramid behavior in its average values and also in noon reaches the second-highest average value compared to the other months.

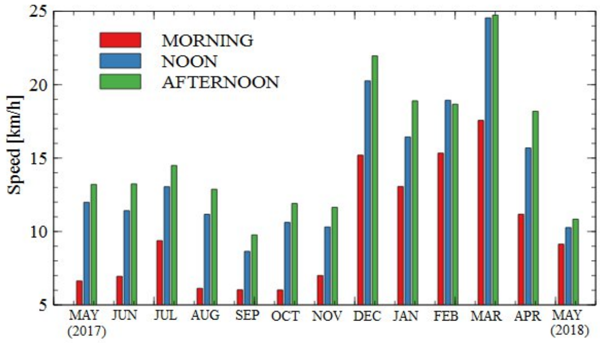

Fig. 5 Behavior of wind speed per measurement range during all months of the year

Fig. 6 shows the humidity behavior during the year of study, and by measurement range, it is clear that most months describe a reverse pyramidal curve, unlike the irradiance and temperature of the panel that in noon reach their maximum values. The humidity seen in this figure decreases its percentage in the midday interval, except in January, March, and April, which trend is linear, and June shows a slightly flat curve since in the afternoon hours it increases the percentages. These months with linear behavior coincide precisely with the linear months in Figure 4 of the panel's temperature. Likewise, when in June the humidity increases, the temperature of the panel is reduced (Fig. 4 and 6).

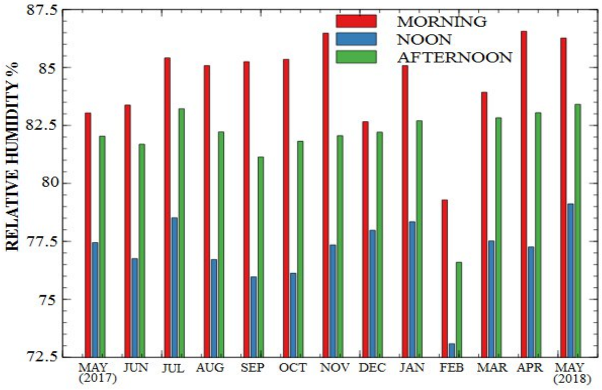

Fig. 6 Behavior relative humidity per measurement range during all months of the year

The study year observed in Fig. 7 that the month with outstanding rainfall was May 2017, followed by significant rainfall in June, July, August, September, and a little late in October.

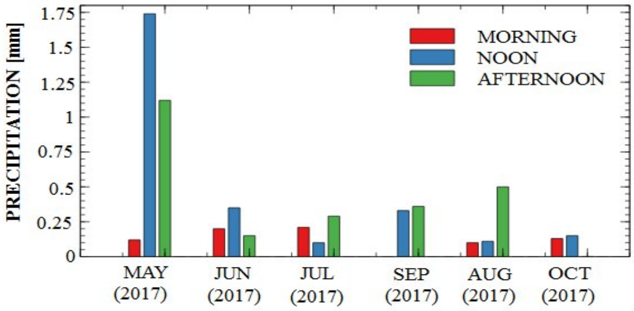

Fig. 7 Behavior of rainfall per measurement range during all months of the year

In May of 2017, June, August and October, the highest rainfall occurred during the noon, measurement range in which the irradiance potential is higher, which could affect the generation of normal electrical power in those months. In July, the highest rainfall occurred in the morning and afternoon; the lowest averages of irradiance during the day are presented at these time intervals. During September, rainfall was significantly elevated in the afternoon hours. Clearly, it is observed that September was the month of those months where there were rain phenomena, in which the precipitation conditions affected the photovoltaic generation potential to a lesser extent since rainfall was only potentiated in the afternoon.

Fig. 8 shows that in August, September, and October, the inverter 2 was not as efficient in the day at noon as it was in December, January, and February.

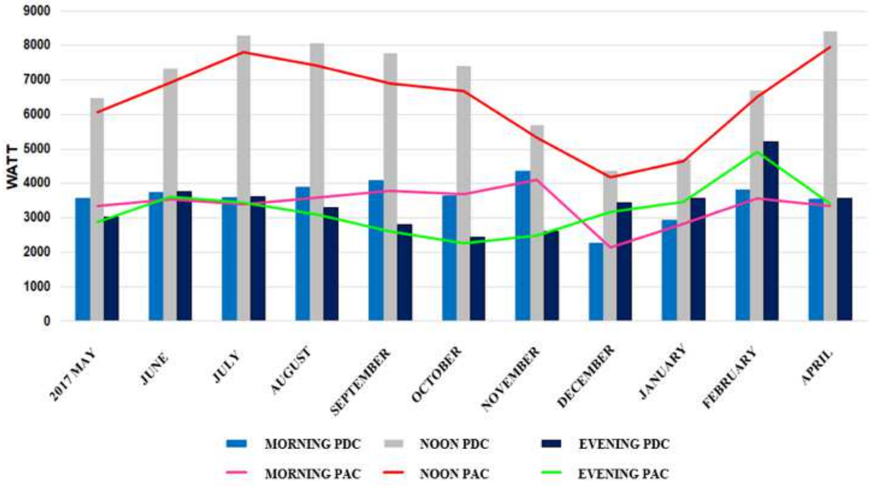

Fig. 8 Behavior of the AC and DC power in the three measurement ranges

In the morning session, the most efficient months of investor 2 were October, December and April, while August, September, November and February were the months with the highest losses. In the afternoon, May 2017, November and January were the months with the highest efficiencies in investor 2, while August, September and February were the most inefficient months.

In addition to the above, it can be observed that the DC power is higher or slightly higher in the morning compared to the afternoon in May 2017 to November, while from December to February, the afternoon session presents higher average values of the DC power compared with the morning shift. The month of April is characterized by having symmetric DC power values in the morning and afternoon hours. It should be noted that the average DC power is higher at noon during the entire period of information registration.

Fig. 9 corroborates what was found by Schwingshackla, especially in the temperature and voltage trend in the mid-day, whereas the panel temperature increases the voltage decreases, in the same way in the months when the panel temperature decreases, the voltage increases. Between June and November, where it is observed that the variation of average temperature in the panel is irrelevant, the voltage remains constant. In the afternoon hours is also observed the behavior of both variables as described in the previous paragraph.

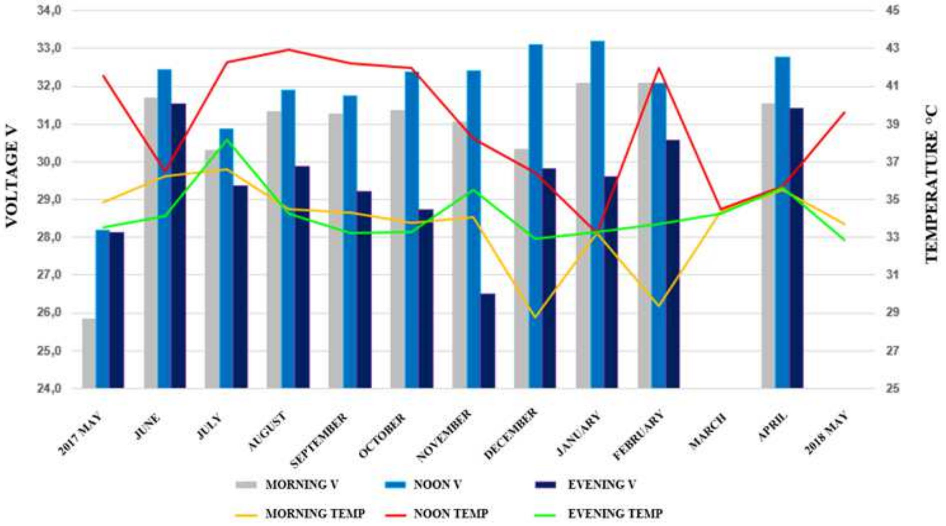

Fig. 9 Behavior of DC voltage compared to panel temperature in three measurement ranges

The current also has alterations as a function of the temperature on the surface of the panel. These percentages of increases and falls in these electrical parameters were already recorded in previous paragraphs. In Fig. 10, the midday range shows that as the panel temperature increases the current, it does in the same way, likewise in the months when the panel temperature decreases, the current decreases. Only atypical behavior is observed between May 2017 and June of the same year, where the panel temperature decreases and the current increases. Unlike what happens with voltage, which in the afternoon describes a behavior similar to that of noon, the measurement ranges that describe a characteristic behavior are a morning and noon in the electric current variable.

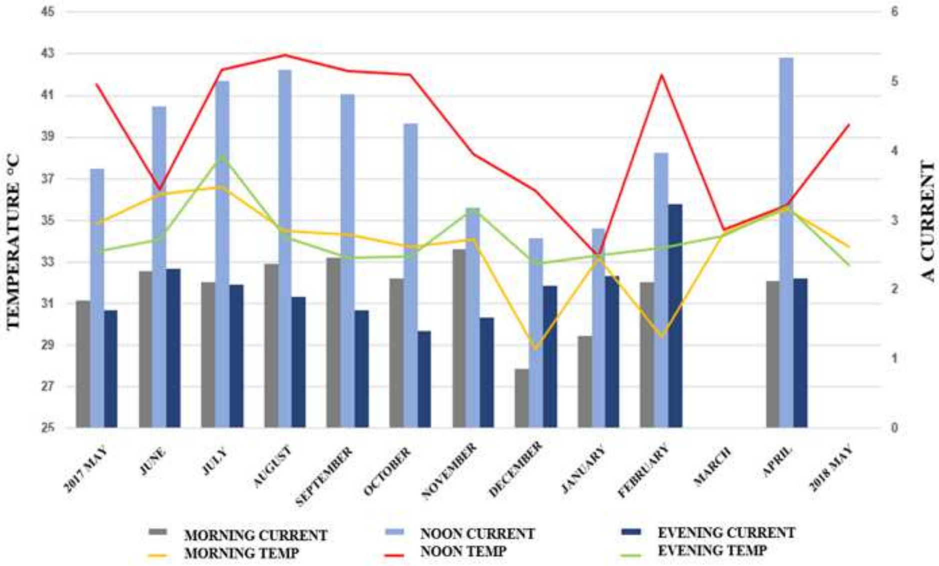

Fig. 10 Behavior of the DC current compared to the panel temperature in the three measurement ranges

The control and monitoring of DC voltage and current can provide information about the DC power parameter behavior; they are variables that are closely related by direct proportionality. It has already been seen in previous graphs that the DC current and DC power describe a curve with a very similar silhouette during the study period, which means that the analysis of any of these two variables with any other parameter, whether operational or meteorological, will serve to find the relationship that exists with any other variable to compare.

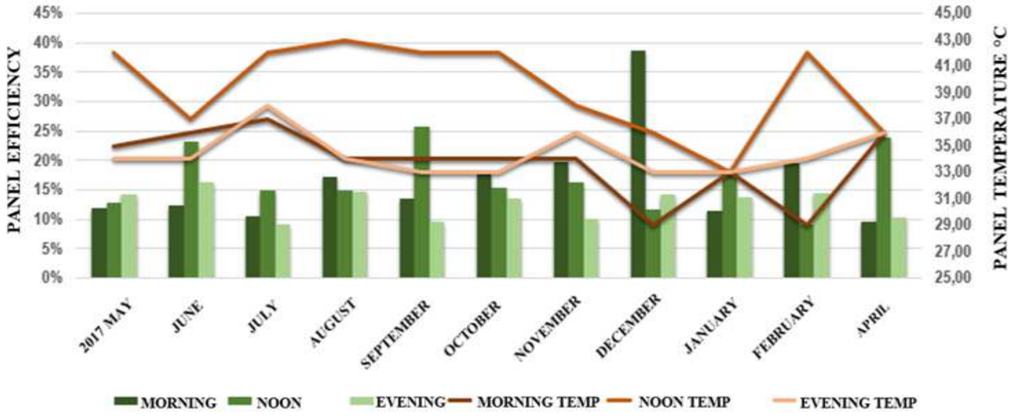

Fig. 11 Behavior of panel efficiency as a function of panel temperature

The panel efficiency values ranging from 10% to 15% is shown in Fig. 11, which is expected in polycrystalline panels. In noon September was the month with greater efficiency, reaching 25%, while February is below 10% efficiency in the same measurement range. Draws attention to December's case in the morning, where the values of efficiency exceed 35%, a value far from the normal range of performance of these devices. Both temperature and irradiance (at constant wind speeds) are inversely proportional to efficiency.

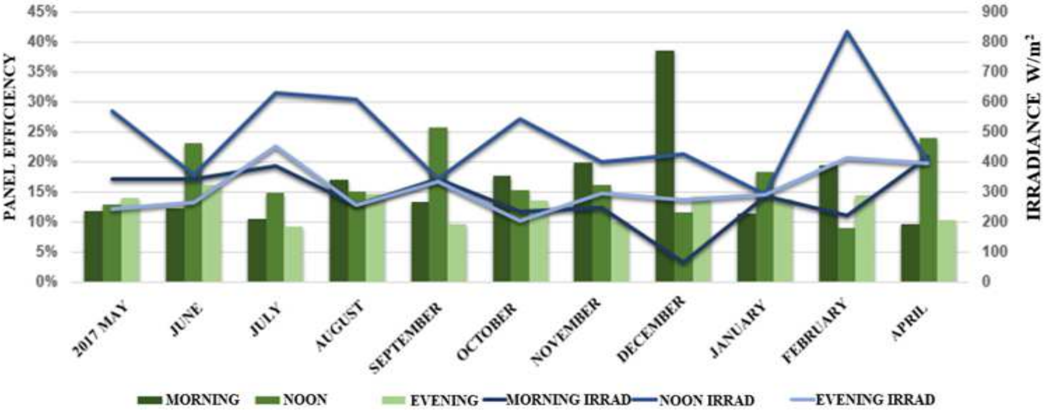

Fig. 12 Behavior of the efficiency of the panel as a function of irradiance

The specific cases are observed in Fig. 12 in June, September, and February at noon, where the values of irradiance and temperature of the panel decrease but the efficiency increases. In December, both the irradiance and the panel temperature drop markedly during the morning shift, and the efficiency reaches exceptionally high values.

IV. CONCLUSION

In this research, the approaches made in other studies were tested and deepened. Despite December and January being the months where the Earth receives higher irradiance indexes, reaching 1412 W/m^2 because it is closer to the Sun in what is commonly known as perihelion, these are the months with the lowest values of the average irradiance recorded, equivalent to 425 W/m^2 at noon. Although August is one of the months with the lowest wind speeds and the second month with the highest ambient temperature, which directly affects the month with the upper panel temperature, it was the third month under April and July with the highest DC power values. March was the month that recorded the highest wind speeds, with average values higher than 22 km/h, and the second month with the lowest ambient temperature. As a result of the above, this was one of the months with constant panel temperature values throughout the three measurement ranges and the second-lowest on the day at noon. The period between December 2017 and April 2018 was the one that recorded the highest wind speeds and, at the same time, the months with the lowest panel temperature. Effects of panel temperature on voltage and current were observed. In the case of voltage, the described behavior is inversely proportional to the panel's temperature while the current show slight increases as the panel temperature increases. Humidity is the only variable that describes a reverse pyramidal shape because the average values in the noon are lower than in the morning and afternoon. The above implies that there is less humidity in this region in the time interval where the environmental conditions for energy production are favorable.

The voltage shows a close relationship with rainfall. In May 2017, rainfall was significantly higher, and the voltage was significantly lower. Also, DC current, DC power, AC power, and inverter temperature describe symmetric and proportional curves with a similar shape.

December and January were the months in which the investor's most significant efficiencies were recorded, while September, October, August, and July respectively were the months with the lowest efficiencies in the investor. As the humidity decreases, the DC current and DC power increase.

The panel's efficiency is inversely proportional to the irradiance (at constant wind speeds) and the temperature in the panel. In the case of irradiance, it was found that the efficiency decreases by 0.047% for each W/m^2. While for each ° C that increases the generator's temperature, the yield decreases between 1.6% and 2%. These results are in a range of wind speed between 6 km/h and 23 km/h.

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