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NEW EXPERIMENTAL ANALYTICAL APPROACH TO STUDY THE EFFECTS OF TEMPERATURE AND IRRADIANCE ON THE PHYSICAL PARAMETERS OF THE SOLAR PHOTOVOLTAIC MODULE IN SUNNY AND TEMPERATE ZONES

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Abstract

This paper illustrates an approach based on temperature and solar irradiance prediction for a realistic analysis of solar PV system performance. Unlike existing methods that often fix the module temperature or irradiance to make this study, in our study framework, simultaneous changes in temperature of solar irradiance are taken into account for realistic and accurate performance evaluation results under real environmental conditions. To contribute to the achievement of the above-mentioned works, our study is based on the need to understand the influence(s) of irradiation and temperature on the current, voltage

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and power of the photovoltaic module. This study is based on verifications of linear/non-linear, increase/decrease relationships between environmental insolation and/or module temperature and the electrical characteristics of the PV module such as current, voltage and power. This study also relies on the interpretation of the behavior of the linear regression coefficient (R^2), the slope of the linear fit, Pearson's *r*, the residual sum of R^2 to understand the behaviors of the current, voltage and power of the PV module under sunlight and variable temperature operation. The results of this analysis method showed that sunshine has a positive effect on current and power, but temperature has a negative impact on voltage.

1. Introduction

Today, the performance of photovoltaic modules is expressed in terms of power delivered under standard conditions. However, from an energetic and financial point of view, it is the quantity of energy delivered, depending on the location and implantation of the modules, that counts. This is why research on methods for predicting the behavior of modules, in real sunlight, and in terms of energy produced or average yield in real operating conditions, is particularly important. Numerous studies on the electrical behavior of photovoltaic modules highlight several factors that have a significant influence on the efficiency of the conversion of radiation into electricity: the level of illumination incident on the modules, the spectrum of this radiation and the operating temperature of the photovoltaic cells within the modules. Some authors such as Zaraket et al. [1] conducted a study on the effect of electrical stresses under varying temperature and light conditions on the performance of solar PV modules. They performed measurements of normal current-voltage and reverse current-voltage characteristics on a crystalline silicon solar module. The results from their studies showed that different levels of reverse current stress under temperature are confirmed as a major degradation factor and affect the performance, efficiency and power of a solar cell and module.

Several simulation models are often used to perform theoretical studies of the impact of environmental conditions on the performance of solar photovoltaic modules. Among them, there is the study on the influence of the variation of the electrical parameters of a solar photovoltaic module ND 240 QCJ SHARP whose authors are Derdar et al. [2]. The objective of their study was based on the modeling and simulation of the electrical operation of a solar PV module under standard conditions and the variations they present under environmental conditions such as temperature and irradiation. Their results showed that the current and power at the maximum point underwent a decrease significantly with the decrease in irradiation but the voltage decreased slightly with the decrease in irradiation. As for the increase of the module temperature, the current underwent a slight increase but the power and voltage decreased. A mathematical and iterative approach to analyze the appropriate parameters of the solar PV module has been designed by Raj and Kumar [3]. The objective of this approach is to have a reinvigorated strategy that will allow them to analyze the optimal parameters for modeling solar PV modules under varying environmental conditions. The authors of this study were able to design algorithms that are demonstrated on three distinct types of PV modules, namely thin film, monocrystalline and polycrystalline. Their results indicate that with increasing solar radiation, the short circuit current (I_{SC}), power at maximum point (P_{mpp}) and current at maximum point (I_{mpp}) have undergone an increase. But the voltages in open circuit (V_{OC}) and at the maximum point (V_{mpp}) underwent a slight increase. This allowed them to conclude that P_{mpp} and I_{mpp} are very sensitive but V_{OC} and V_{mpp} are less sensitive to solar radiation by holding all other parameters constant. However, for temperature variation and holding all other parameters constant, V_{OC}, P_{mpp} and V_{mpp} decrease with temperature increment. But the short-circuit current underwent a small increase. They were able to show that the max current is not affected by the temperature increase. The conclusion they drew from this, on the one hand, is that the V_{OC}, P_{mpp} and V_{mpp} of the module are much more sensitive to temperature, compared to the short circuit current of the module. On the other hand, the I_{mpp} has almost no sensitivity to temperature. Other recent work based on modeling and simulation of the impact of environmental variations such as irradiation and temperature on the output characteristics of grid-connected and off-grid solar PV modules has already emerged. Among many others, we can mention the works of: Bhavani et al. [4], Medeiros et al. [5], Syahputra et al. [6], Achouby et al. [7], Swarupa et al. [8], Li et al. [9], Ginidi et al. [10], ... All these works have indeed shown that these environmental parameters tend, for some of them, to increase, and/or for others, to decrease, the electrical characteristics of solar PV modules.

In the same study contexts, research has been conducted, but this time through experimentation. This is the case study of Agyekum et al. [11], which was based on the effect of double surface cooling of a PV module on its efficiency. Their modus operandi is as follows: the back side of the PV module has been cooled with a cotton wick that absorbs water from a perforated pipe and uses capillary action to transfer the water to the surface of the back side of the module. Their experiment recorded a temperature drop of 23.55°C, which resulted in an approximate 30.3% improvement in the PV module's power output. The module also recorded an average efficiency of 14.36%, compared to 12.83% for the uncooled module. The efficiency improvement of a photovoltaic water pumping system by spraying water on the front side of the PV cells was performed by Abdolzadeh and Ameri [12]. Their main objective was to keep the temperature and reflection of the PV cells as low as possible, with the aim of improving the performance of a photovoltaic water pumping system. The experimental results, compared to those of traditional systems, showed that the cell power is increased by spraying water onto the PV cells. This is followed by an increase in pump flow rate as it operates under different lift heights.

A lot of work on the performance of outdoor organic solar cells has also been done. Bristow and Kettle [13] conducted an outdoor performance of the organic PV module (OPV) under the influence of temperature and irradiance. The performance of the latter was analyzed and compared to crystalline silicon (C-Si) technology. They observed that the OPV exhibits inferior performance under low light conditions such as cloudy days, due to the inflection behavior of the current-voltage curves. Different investigations on the power matrix of an OPV mini-module under stable temperature and irradiance conditions have been done by Bardizza et al. [14-17]. These studies are based on a large area and a small area solar simulator. A detailed analysis of the temperature and irradiance dependence of the electrical parameters allowed them to calculate temperature coefficients α between 0.26 and 0.31%/°C for the short circuit current and β between -0.11 and -0.16%/°C for the open circuit voltage. They also concluded from their work that the variation of maximum power with temperature is clearly not linear since P_{max} increases up to a certain temperature (about 35°C) and then tends to decrease or stabilize. In order to produce sufficient electrical energy from photovoltaic modules, it is imperative to understand the thermoelectric behavior of the module. In the same vein, it will also be necessary to question the discrepancies observed between the measurements provided by the manufacturer and those obtained under ambient conditions on the actual site.

Our study focuses on an analysis of the proportionality relationships between irradiation, temperature and electrical characteristics of mono-si PV modules under real operating conditions. In order to contribute to the above-mentioned work, our study is based on the need to understand the influence(s) of irradiation and temperature on the current, voltage and power of the photovoltaic module. To our knowledge, there is not yet a study on the relationship between irradiation and temperature on the characteristics of the PV module that takes into account the simultaneous variations of irradiation and temperature. So, our approach is based around the concomitant variation of the latter. To carry out this work, we will first focus on the operating site of our PV modules and the adapted methodology. Finally, we will present the results obtained in this work.

2. Description of the Data Collection Site and Methodology

2.1. Description of the data collection site

The experimental study was conducted at the Alioune Diop University in Bambey, Senegal. Senegal is located in the extreme west of Africa between 12.5° and 16.5° North latitude and 12° and 17° West longitude. It has a dry tropical climate characterized by two seasons: a dry season from November to June and a rainy season from July to October. Senegal has a large solar potential with an average annual irradiation time of about 3000h and an exposure rate of 5.7 kWh/m^2/day [18, 19]. The monocrystalline PV module used in this study is located at the Alioune Diop University in Bambey, Senegal. The geographical location of this site is 14°41’51.71” North and 16°28’44.5” West and is located on the south side and approximately on the national road N°3.

The photovoltaic system consists of 10 Wp monocrystalline silicon PV modules mounted on the 3.5m high roof of the building. The tilt angle of these PV modules is 15° and the orientation is due south for the optimal production standards of PV modules in Senegal. Table 1 shows the specifications of the PV modules.

Table 1. Electrical features

Settings	Values
Maximum power (W)	10
Short circuit current (A)	0.51
Open circuit voltage (V)	26
Current at max power point (A)	0.47
Voltage at max power point (V)	21.2

2.2. Appropriate methodology

The main parameters measured were the global solar irradiance of the environment, the temperature of the module, the current, the voltage and the power that are generated by the module. The sunshine on the plane was measured with a reference pyranometer calibrated and adapted to a permanent outdoor mounting. The temperature of the module was measured by the Pt1000 temperature sensor attached to the back of the module. The current and voltage values of both modules are measured directly with our multimeters. All environmental and electrical data were measured simultaneously on a daily basis from 09h00 (UTC) to 17h00 (UTC). All the data obtained over 11 weeks of exposure, with regular cleaning, of the PV module were transformed into daily average data. The electrical parameters including open circuit voltage, short circuit current and power have been extracted and analyzed as a function of solar irradiance and temperature. The focus is on the study of these electrical parameters at different combinations of temperature and irradiance: Isc = f(Irra), Isc = f(Tm), Voc = f(Irra), Voc = f(Tm), P = f(Irra), P = f(Tm). The linear regression required by IEC 60904-10, after Bardizza et al. [17], is used to evaluate the linear dependence of open-circuit voltage, short-circuit current, and power on PV module temperature and solar irradiance from the slope of the linear fit, coefficient of determination (R^2), Pearson coefficient (r), and residual sum of R^2.

3. Definition of the Parameters Used

The slope of the linear fit that is extracted from the model is used to define the linear relationship between two variables of interest and to estimate an average rate of change. A positive slope indicates a direct proportional relationship between the two variables and a negative slope indicates the opposite.

The coefficient of determination (R^2), which takes values between 0 and 1, is a statistical measure that allows us to determine the quality of the model obtained. An R^2 close to the value of 0 indicates that the fit line does not explain any of the variability of the response data around its mean. An R^2 close to 1 indicates that the fit line explains all the variabilities of the response data around its mean.

The Pearson coefficient (r), which is a coefficient between -1 and $+1$, is used to determine whether or not there is a strong relationship between the data studied. A positive Pearson's *r* indicates that there is a linearly positive relationship between the predictor variable and the response variable, a negative Pearson's *r* indicates the opposite, and a zero Pearson's *r* indicates that there is no relationship.

The residual sum of R^2, abbreviated as RSR, represents the sum of the squares of the vertical differences that connect the data and the fitted regression line. If the RSR value is close to zero, then the data match perfectly. On the other hand, the smaller this sum, the better the fit of the model used to the data.

After presenting the methodology of the analysis used in this work, we now provide the results.

4. Results and Discussions

The results obtained in this study are presented in graphical form and some are shown in the following subsections.

4.1. Variation of the current as a function of irradiation and temperature

4.1.1. Determination of the fitting parameters

The variations of the short-circuit current over the measured range of temperature and solar irradiance are shown in Figures 1 and 2.

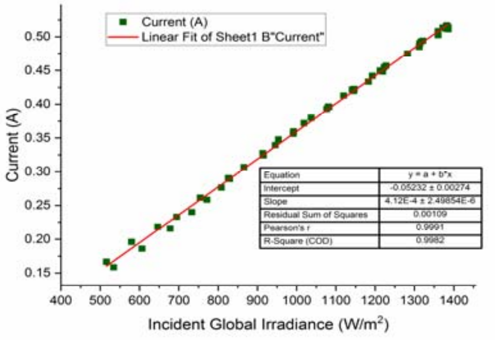


Figure 1. Current variation as function of irradiation.

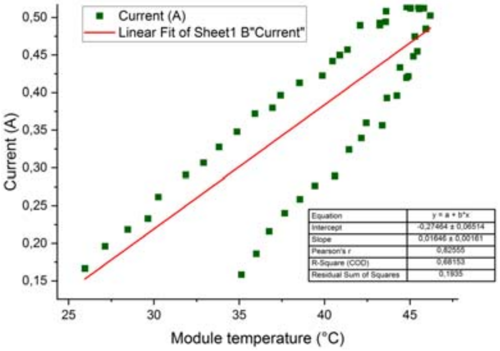


Figure 2. Current variation as function of temperature.

The analysis of the results obtained (see in Figures 1 and 2) clearly shows that an increase in irradiation and temperature leads to an increase in the current I_{CC}. And the following remarks are drawn.

A linear increase of the short-circuit current (with a positive slope) as a function of temperature and irradiation shows a positive proportionality relationship between I_{CC} and these parameters. This is in perfect agreement with the results found in the literature.

Pearson's *r* values of 0.991 for irradiation and 0.8256 for temperature show that there is a strong positive linear correlation between I_{CC} and these parameters.

The fit with the linear regression lines that we obtained allowed us to extract an R^2 value equal to 0.998 for irradiation and an R^2 value equal to 0.682 for temperature. We can therefore affirm that the fitting of the data with a linear regression line is able to determine to 99.8% the distribution of the current as a function of the irradiation. Concerning the evolution of the current as a function of temperature, the adjustment by a line determines 68.2% of the current distribution. This is due to the fact that the photo-current (Iph) of a solar cell increases weekly with the increase of the temperature and significantly with the increase of the irradiation.

Also, with fairly low residual sums of squares (close to zero), we can conclude that our analysis method used is in good agreement.

4.1.2. Quality study of linear regression curves

To assess the regression quality of the linear regression study method, we used residual plots. These are the normal probability plot of the residuals (also called the *normality* of the distribution) and the plot of the residual variables against the independent variables. The normal probability plot of the residuals allows us to check whether the variance is normally distributed. If the plot of the resulting residual data is approximately linear, then we can assume in this case that the error terms are normally distributed. The plot of the residuals against the independent variables provides an indication of whether or not a model requires improvement. It not only helps to verify the validity of the regression model, but it can also provide clues on how to improve it.

Equation (1) gives the formula for estimating the percentiles of the probability diagram,

$$\text{Percentiles} = \frac{i - \frac{3}{8}}{n + \frac{1}{4}}. \tag{1}$$

The normal probability plot of the residuals and the plot of the residual variables against the independent variables are given in Figures 3 and 4.

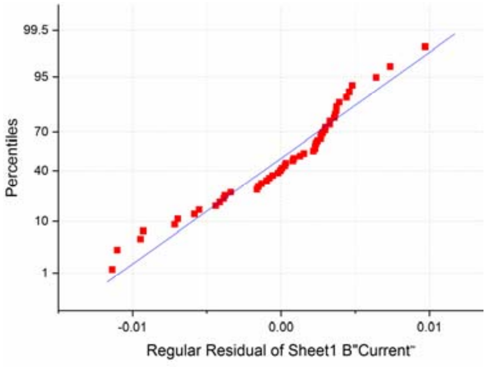


Figure 3. Normal probability of residuals for $I_{SC} = f(\text{Irra})$.

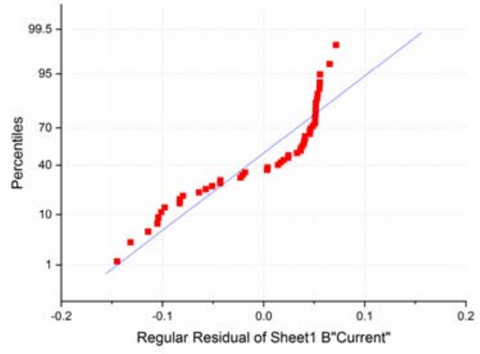


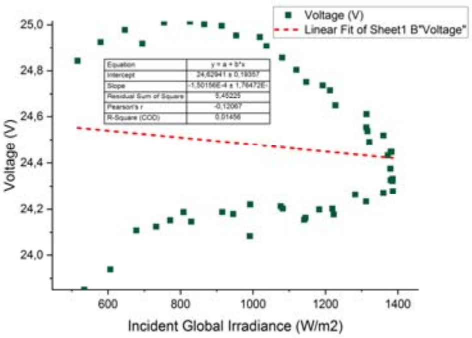
Figure 4. Normal probability of residuals for $I_{SC} = f(\text{Tm})$.

From these figures, we notice that the residuals follow a linear curve and they are randomly distributed around zero (Figure 3) in the case of the variation of the current with sunshine. For the variation of the current with temperature, we observe more deviation on the residuals, when we fit the data with a linear profile. In this study, we have limited ourselves to a linear profile. But for a better distribution of the residuals around zero, it will be necessary to have profiles with higher order terms.

4.2. Variation of the voltage as a function of sunshine and temperature

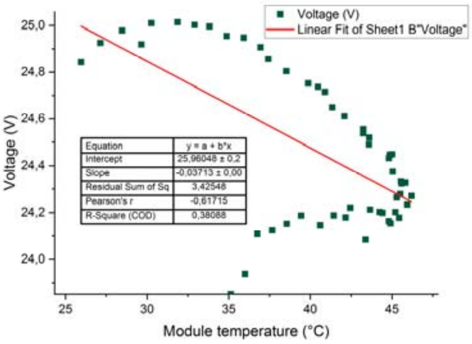
4.2.1. Determination of the fitting parameters

The variations of V_{OC} in the measured range of temperature and irradiance are shown in Figures 5 and 6.



Equation	y = a + b*x
Intercept	24,62941 ± 0,19357
Slope	-1,50156E-4 ± 1,764726
Residual Sum of Square	5,45225
Pearson's r	-0,12067
R-Square (COD)	0,01456

Figure 5. Voltage variation as function of irradiation.



Equation	y = a + b*x
Intercept	25,96048 ± 0,2
Slope	-0,03713 ± 0,00
Residual Sum of Sq	3,42548
Pearson's r	-0,61715
R-Square (COD)	0,38088

Figure 6. Voltage variation as function of temperature.

The analysis of the curves shows two trends: a trend above the linear regression curve corresponding to the first half of the day and a trend below the linear regression curve corresponding to the second half-day.

The voltage increases slightly over a short period of time and decreases randomly with increasing temperature and sunshine. This decrease is synonymous with slopes of negative values at each curve. We can then deduce that V_{OC} has a negative proportional relationship with temperature and sunshine. This is in perfect agreement with the results found in the literature.

The negative Pearson's *r* of which -0.12067 for irradiation and -0.61715 for temperature allows us to conclude that V_{OC} has a negative correlation with these parameters. This correlation is quite strong in temperature and very weak in irradiation. Thus, we conclude that from this value, that the sunshine does not have too much impact on the voltage V_{OC}, which is in agreement with the literature.

The R^2 values close to 0 and quite low for irradiance and temperature, respectively confirm the insufficient linear variability of the V_{OC} data. And the vertical deviations that exist between the regression curve and the data distribution can confirm this. The influence of these parameters on the voltage is therefore not linearly constant because of the variability of environmental factors during the day.

The values of the residual sums of squares that deviate slightly from the zero-value show that higher order terms must be introduced in the fitting model.

4.2.2. Quality study of linear regression curves

To study the quality of our fit, we can also refer to the normal probability diagram. These diagrams are given in Figures 7 and 8.

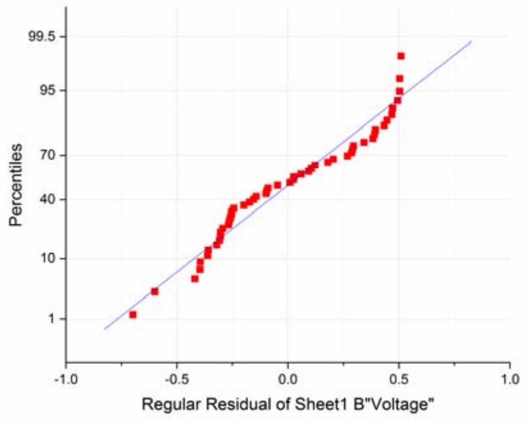


Figure 7. Normal probability of residuals for $V_{OC} = f(Irra)$.

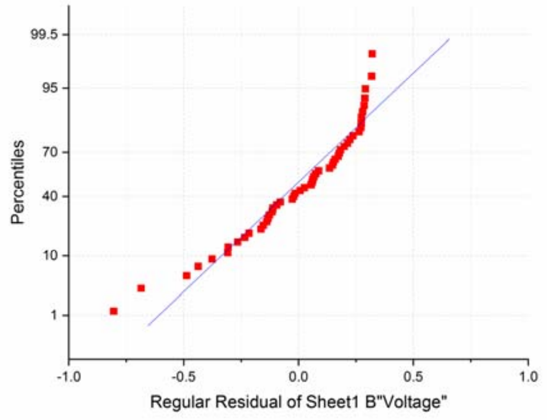


Figure 8. Normal probability of residuals for $V_{OC} = f(Tm)$.

We notice that on all the graphs, the residuals are not normally distributed and their random distributions deviate a little from zero. This is due, as we have just explained, by the fact that the variation of the voltage is not too sensitive to the variation of the irradiation and the temperature.

4.3. Variation of power as a function of sunshine and temperature

4.3.1. Determination of the adjustment parameters

The variation of power over the measured range of temperature and illumination is shown in Figures 9 and 10.

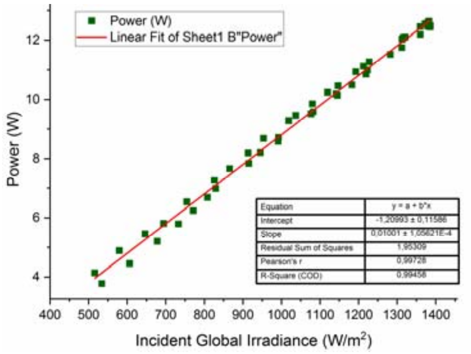


Figure 9. Power variation as function of irradiation.

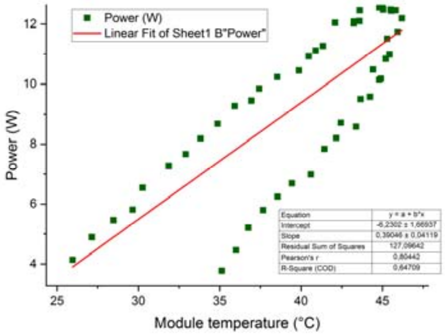


Figure 10. Power variation as function of temperature.

The analysis of these figures shows us that the dependence of power on irradiation describes a linearly positive function over the whole day. As for the dependence of the power on the temperature, we notice a quasi-linear variation during the first half-day. When the power reaches its maximum, there is a progressive decrease. This decrease is explained by the fact that we are in the second part of the day when the temperature decreases as well as the irradiance decreases.

Fitting the power data as a function of illuminance gives coefficients of determination R^2 equal to 0.99548 and Pearson's r equal to 0.99728. These extracted values are very close to 1. Now for the evolution of power as a function of temperature, these coefficients are equal to $R^2 = 0.64709$ and $r = 0.80442$, respectively. These values of R^2 and r very close to 1 testify that the linear model used to fit the data correctly reproduces the variations of power as a function of irradiance and temperature.

For the dependence of power on irradiance and on voltage, we have an RSR = 1.953 for irradiance and an RSR = 127.096 for temperature. The rather large value of the RSR for power as a function of temperature is explained by the fact that the evolution of power depends largely on the evolution of irradiation during the day. Now during the second half of the day when the irradiation decreases quite rapidly and the temperature decreases quite slowly, we note that the power varies linearly by deviating a little far from the linear regression curve. However, this does not impact too much on the validation of our model as we have an R^2 and an r that are close to 1.

4.3.2. Quality study of linear regression curves

The graphs of the normal probability of the residuals of the irradiation and the temperature are given in Figures 11 and 12, respectively.

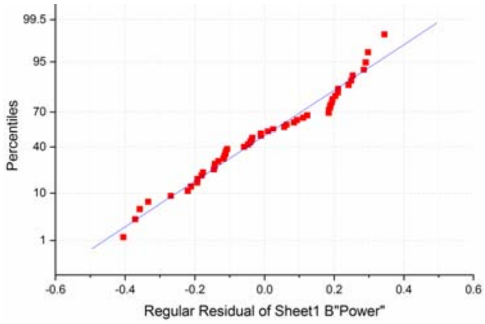


Figure 11. Normal probability of residuals for P = f(Irra).

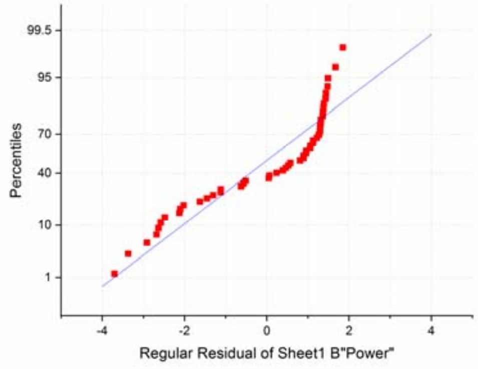


Figure 12. Normal probability of residuals for P = f(Tm).

As the variation of the power is, in large part, a function of the variation of the irradiation, we notice that the residuals follow a linear curve. This strengthens the fit of our model. Now, if the variation of the power is a function of the temperature, then we have residues which are distributed randomly by deviating from the linear curve (see in Figure 12).

Now, to solidify our hypotheses drawn so far and to have more precision to the distribution of the scatterplots observed on the variables of the dataset, we will apply a factorial analysis method.

4.4. Validation of the hypotheses of interdependence of the variables by a PCA

A factor analysis is a principal component analysis (PCA) using R software. This method of factor analysis allows the study of the typology or similarity between individuals (parameters in our case) by quantitative variables (numerical variables) and also allows the study of the relationship between the variables. We have used PCA in this section to study the interrelationships between the variables considered in this part of the study.

The interdependence of short circuit current, open circuit voltage and power as a function of irradiance and temperature is given in a circle called the *correlation circle* of variables. This circle makes it possible to identify the corollary variables between them.

By hypothesis, if a group of variables falls on the same side of the circle and if these variables are close to each other, then they are said to be *significantly* or *strongly* related in the positive direction. Now, if one or a group of variables is on the other side of another group of variables in the correlation circle, then that group of variables is said to be either strongly or weakly correlated with the group of variables. Thus, this correlation is negative. Figure 13 shows the correlation circle of variables such as current, voltage, power versus irradiation and temperature.

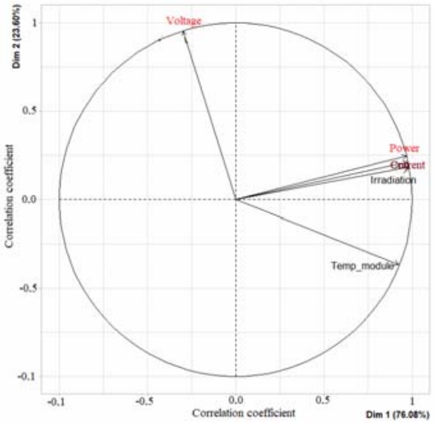


Figure 13. Principal components analysis plot of variables.

To give more confirmation on the interdependence (correlation) between the variables, we will also use the correlation matrix that determines the interdependence between the variables. This matrix uses the correlation coefficient (Pearson's *r*) to measure the weight of dependence between the variables studied. This coefficient measures the interdependence between two quantitative variables and varies between -1 and $+1$. Table 2 shows the correlation matrix between the variables studied.

Table 2. Correlation coefficients

Parameters	Current	Voltage	Power
Irradiation	1.00	-0.12	1.00
Tm	0.84	-0.62	0.80

From Figure 13 and the matrix given in Table 2, we derive the following confirmatory hypotheses.

The current and power of the PV module are strongly related with irradiance, with correlation coefficients that are $+1$. This strong relationship is also observed from the correlation circle where we see a condensed grouping of variables.

The current and the power of the PV module are quite strongly linked with the module temperature, with correlation coefficients worth $+0.84$ for the current and $+0.80$ for the power. This fairly strong link, in the positive direction, is also observed on the correlation circle.

The PV module voltage has a fairly strong negative correlation relationship with temperature (correlation coefficient equal to -0.62) and very weak with irradiation (correlation coefficient equal to -0.12). This can be justified also at the level of the correlation circle where the voltage and the groups of variables (irradiation and temperature) are located on both sides.

5. Conclusion

Measurements of the electrical characteristics of a 10 Wp solar PV module placed outdoors were performed and then the temperature and irradiation dependence of the electrical parameters were analyzed. The temperature and irradiation dependence of the electrical parameters were analyzed separately and our results are consistent and partially confirm the previously published literature. The results showed that a single linearly positive dependence is observed at the short circuit current and power as a function of irradiance and temperature. However, a linearly negative dependence is observed at the open circuit voltage at all measured temperatures and irradiances. The negative values of the slope and Pearson's r allow us to understand that as the temperature of the PV module increases, its voltage decreases. However, this decrease is not specifically caused by temperature, given the lower value of R^2 and a residual sum quite far from 0. The data measured so far suggest that for each level of illumination, there is a specific temperature at which the power reaches its maximum. Moreover, as the solar energy increases, this temperature tends to increase as well. The results of this work make a significant contribution to the evaluation of PV technology.

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