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Research Article

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Method for Analyzing the Behavior of Irradiation and Temperature Variations on Variations in Photovoltaic Module Characteristics in the Semi-arid Climate of Senegal on the Basis of Real Data

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Abstract: In this study, we analyzed the daily behavior of the current and voltage of a photovoltaic solar module as a function of the daily variation in irradiation and module temperature. Unlike existing methods which often fix either temperature or irradiation, in this study we have considered simultaneous variations in module temperature and environmental irradiation. To contribute to the achievement of existing work, our study revolves around the need to understand the influence(s) of irradiation and temperature on photovoltaic module current, voltage and power. To carry out this work, we relied on the verification of a relationship of linearity or not, of an increase or decrease between irradiation and module temperature as a function of the PV module's electrical characteristics such as current and voltage. This verification is based on the interpretation of the behavior of certain parameters such as: the linear regression coefficient (R^2), the slope of the linear fit, Pearson's r and the residual sum of R^2. The results of this study show that irradiation has a positive effect on current, but temperature has a negative impact on voltage. The aim of this research is to provide a simple analysis method for PV module performance in a sunny, hot climate. Researchers, PV project developers and stakeholders can use the analysis results to assess project viability, optimize performance and maximize environmental and economic benefits.

Keywords: Solar PV system, Solar irradiance, Linear regression, Polynomial regression, fit

Introduction

Today, the performance of photovoltaic modules is expressed in terms of power delivered under standard conditions. However, from an energy and financial point of view, it's the quantity of energy delivered that counts, depending on the location and layout of the modules. Numerous studies on the electrical behavior of photovoltaic modules have highlighted several factors that have a significant influence on the efficiency of converting 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 and al. [1], have investigated the effect of electrical stresses under varying temperature and light conditions on the performance of solar PV modules. They measured the normal current-voltage and reverse current-voltage characteristics of a crystalline silicon solar module. The results of 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.

More simulation models are often used to carry out theoretical studies of the impact of environmental conditions on the performance of solar photovoltaic modules. Among them is the study on the influence of the variation of the electrical parameters of a solar photovoltaic module ND 240 QCJ SHARP authored by Abderrahim Derdar and al. [2]. The aim of their study was to model and simulate 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 current and power at the maximum point decreased significantly with decreasing irradiance, but voltage decreased slightly with decreasing irradiance. With increasing module temperature, current increased slightly, but power and voltage decreased. A mathematical and iterative approach to analyzing appropriate solar PV module parameters has been devised by Raj and al. [3]. The aim of this approach is to have a reinvigorated strategy that will enable them to analyze 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 show that with increasing solar radiation, short-circuit current (ISC), power at maximum point (Pmpp) and current at maximum point (Impp) increased. However, open-circuit voltage (VOC) and voltage at maximum point (Vmpp) increased slightly. This enabled them to conclude that Pmpp and Impp are highly sensitive, but Voc and Vmpp are less sensitive to solar radiation when all other parameters are held constant. However, for temperature variation and with other parameters held constant, VOC, Pmpp and Vmpp decrease with temperature increment. But the short-circuit current increased slightly. They were able to show that the max current was not affected by the temperature rise. The conclusion they drew was that the module's VOC, Pmpp and Vmpp are much more sensitive to temperature than the modules short-circuit current. Impp, on the other hand, has virtually no sensitivity to temperature. Other recent work has focused on modeling and simulating the impact of environmental variations such as irradiation and temperature on the output characteristics of grid-connected and off-grid solar PV modules. Among many others, we can cite the work of: Bhavani and al. [4], Medeiros and al. [5], Syahputra and al. [6], Achouby and al. [7], Swarupa and al. [8], Li and al. [9], Ginidi and al. [10], etc. All these studies have shown that some of these environmental parameters tend to increase the electrical characteristics of solar PV modules, while others tend to decrease them.

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

A great deal of research into the operation of outdoor organic solar cells has not been overlooked either. Bristol and al. [13] conducted an outdoor performance of the organic PV module (OPV) under the influence of temperature and irradiance. Its performance was analyzed and compared with crystalline silicon (C-Si) technology. They observed that OPV performs less well in low-light conditions such as cloudy days, due to the inflection behavior of the current-voltage curves. Various investigations into the power matrix of an OPV mini-module under stable temperature and irradiance conditions have been carried out by Bardizza and al. [14], [15], [16], [17]. These studies are based on a large- and small-area solar simulator. A detailed analysis of the dependence of electrical parameters on temperature and irradiance enabled 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 all their work that the variation of maximum power with temperature is clearly not linear, since Pmax increases up to a certain temperature (around 35°C) and then tends to decrease or stabilize.

To generate sufficient electrical energy from photovoltaic modules, it's essential to understand the module's thermoelectric behavior. In the same vein, we also need to investigate the discrepancies observed between the measurements supplied by the manufacturer and those obtained under ambient conditions on the real site. This information will then enable us to carry out reliable technical dimensioning in the Sudano-Sahelian zone, taking into account climatic realities. In addition, monitoring photovoltaic production through the various parameters that influence the operation of any photovoltaic system will enable us to make a practical assessment of the opportunity and advantage over conventional sources of electricity production.

Our study focuses on an analysis of the proportional relationships between irradiation, temperature and the electrical characteristics of mono-si PV modules under real operating conditions. In order to contribute to the work mentioned above, our study is based on the need to understand the influence(s) of irradiation and temperature on the current and voltage of photovoltaic modules.

To our knowledge, there has never been a study of the relationship between irradiance and temperature on PV module characteristics that takes into account simultaneous variations in irradiance and temperature. The special feature of this study is that it was carried out on half-days (morning and afternoon), to better appreciate the variations. In fact, in the morning we have growth and in the afternoon we have decay with different slopes.

In order to carry out this work, we will first look at the operating site of our PV modules and the adapted methodology. Finally, we will present the results obtained in this work.

Description of the data collection site

The experimental data used in this study were obtained from our experimental platform at the Université Alioune Diop in Bambey, Senegal. The geographical location of this site is 14º41'51.71" North and 16°28'44.5" West, on the south side. Senegal has significant solar potential, with an average annual irradiation time of around 3,000 h and an exposure rate of 5.7 kWh/m^2 /day [18] [19]. The tilt angle of our PV modules is 15º and the orientation is due south. These values are used to meet the optimal standards for PV module production in Senegal. Table 1 shows PV module specifications.

Table 1: Electrical characteristics of the PV module

Parameters	Values
Maximum power	10W
Short circuit current	0.51A
Open circuit voltage	26V
Current at maximum	0.47A
Voltage at maximum	21.2V

Adapted work methodology

The main parameters measured were the overall irradiance of the environment, the module temperature, and the current and voltage generated by the module. Irradiance on the plane was measured with a reference pyranometer calibrated and adapted to permanent outdoor mounting. Module temperature was measured by a Pt1000 temperature sensor mounted on the back of the module. PV module current and voltage values are measured directly with high-precision multimeters. All environmental and electrical data were measured simultaneously daily from 09:00 UTC to 17:00 UTC. All the data obtained over 11 weeks of exposure, with regular cleaning, of the PV module were transformed into daily average data.

The linear regression required by IEC 60904-10, based on Bardizza and al. [17], is used to assess the linear dependence of open-circuit voltage and short-circuit current on PV module temperature and irradiance.

Definition of parameters used

• The slope of the linear fit extracted from the model is used to define the linear relationship between two variables under study, and to estimate an average rate of variation.

• The coefficient of determination (R^2), which takes values between 0 and 1, is a statistical measure that determines the quality of the model obtained.

• 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.

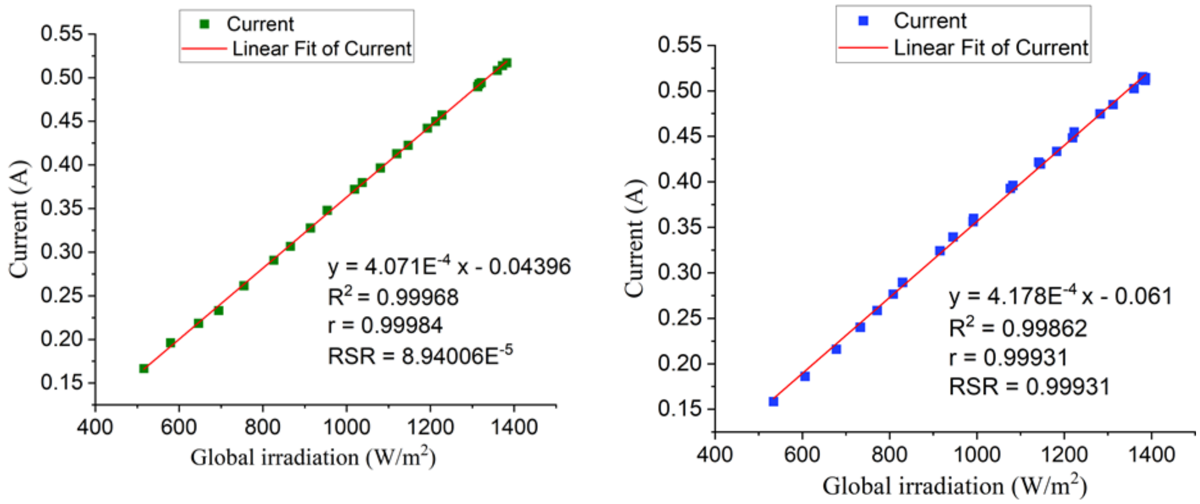
• The residual sum of R^2, abbreviated as RSR, represents the sum of the squared vertical differences between the data and the fitted regression line.

Results and Discussion

The results obtained in this study are presented graphically, and some are shown in the following subsections.

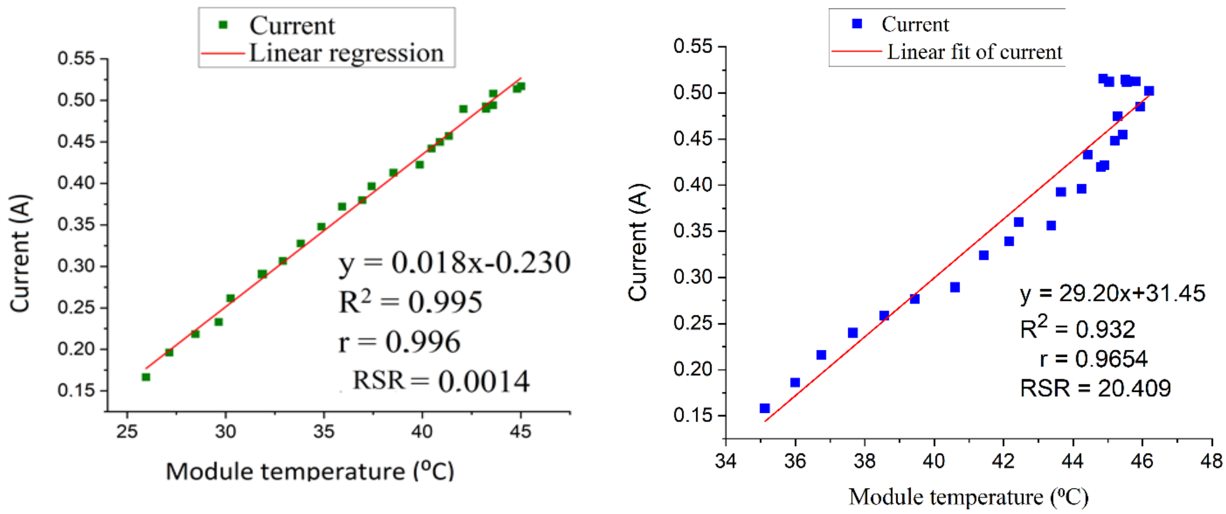
Current variation as a function of irradiance and temperature

Variations of the short-circuit current over the measured irradiation and temperature range, per half-day, are shown in Figures 1 and 2, respectively.



(a) Morning *(b) Afternoon*

Figure 1: Current variation as function of irradiation



(a) Morning *(b) Afternoon*

Figure 2: Current variation as function of module temperature

Analysis of the results obtained in Figures 1 and 2 clearly shows that increasing irradiation and temperature increases the short-circuit current. Now the parameters obtained from the linear fitting curve allow us to say that:

• The positive values of the slopes in each statistical model show a linear increase in short-circuit current during the first half of the day (Fig. 1.(a) and 2.(a)) and a linear decrease in short-circuit current during the second half of the day (Fig. 1.(b) and 2.(b)) as a function of temperature and irradiance. This shows a positive proportional relationship between ISC and these two parameters;

Pearson r values equal to 0.999 for irradiation and equal to 0.996 (Fig. 2.(a)) and 0.965 (Fig. 2.(b)) for module temperature show that there is a strong positive linear correlation between short-circuit current and these parameters;

R^2 values equal to 0.999 for irradiation and temperature mean that fitting the data with a linear regression line is able to determine 99.9% of the current distribution as a function of irradiation and module temperature;

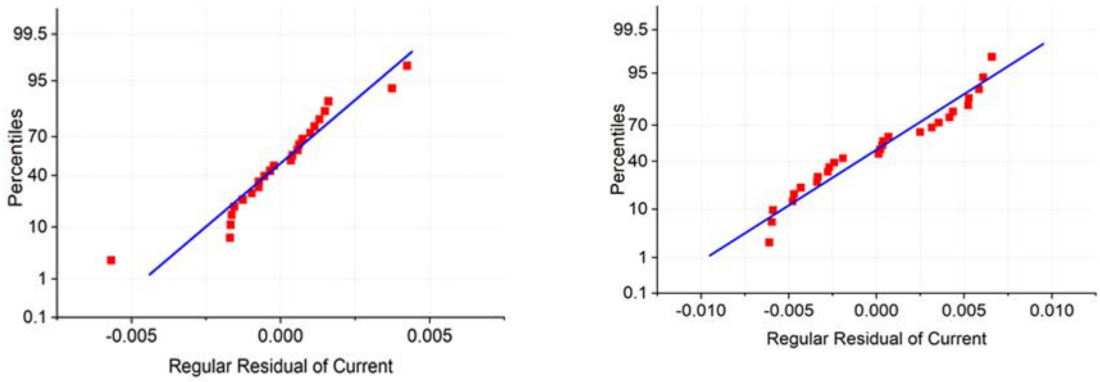
Similarly, with fairly low residual sums of squares (close to zero), except for Figure 2.(b), we can conclude that our analysis method is, for the most part, a good fit.

Quality study of linear regression curves

To assess the quality of our regressions, we used residual plots. This is the normal probability plot of the residuals (also known as the normality of the distribution). The normal probability plot of residuals is used to check whether the variance is normally distributed. If the plot of the resulting residual data is approximately linear, we can assume that the error terms are normally distributed. Equation 1 gives the formula for estimating the percentiles of the probability diagram.

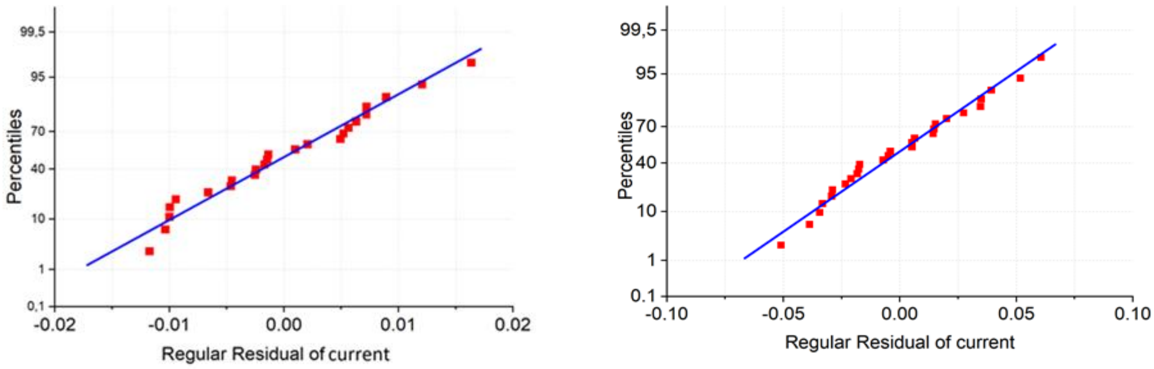
Pencentille= (i-3/8)/(n+1/4) (1)

Where n is the total number of data and i is the i-th data



(a) Morning *(b) Afternoon*

Figure 3: Normal probability of residuals for ISC as function of irradiation



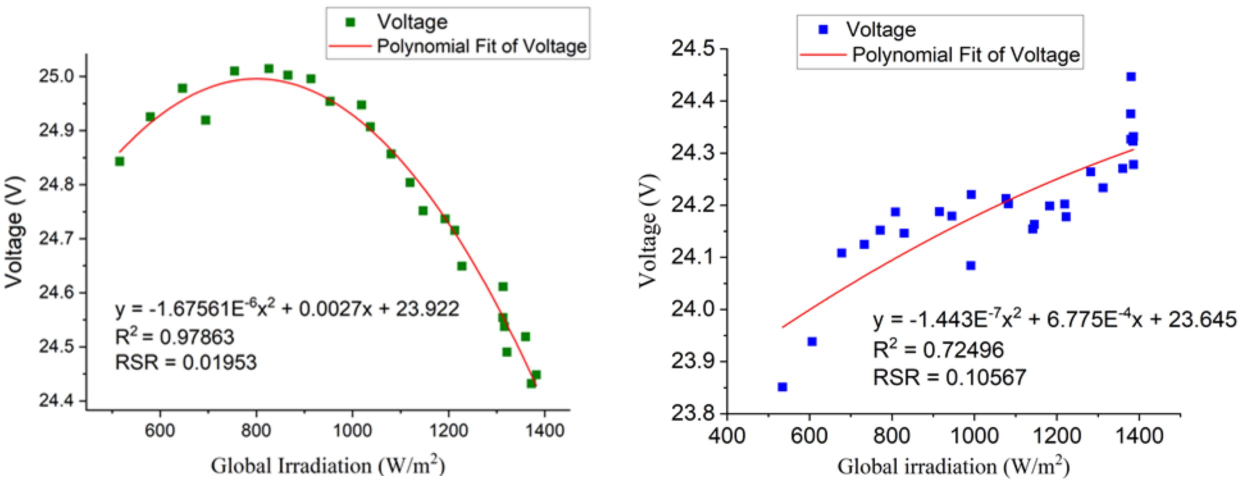
(a) Morning *(b) Afternoon*

Figure 4: Normal probability of residuals for ISC as function of temperature

From these figures, we can see that the residuals follow a linear curve and are randomly distributed around zero in all cases of current variation as a function of irradiance and temperature. So we can say that the variances of our regression models are normally distributed, which allows us to say that our analysis method used is a good match.

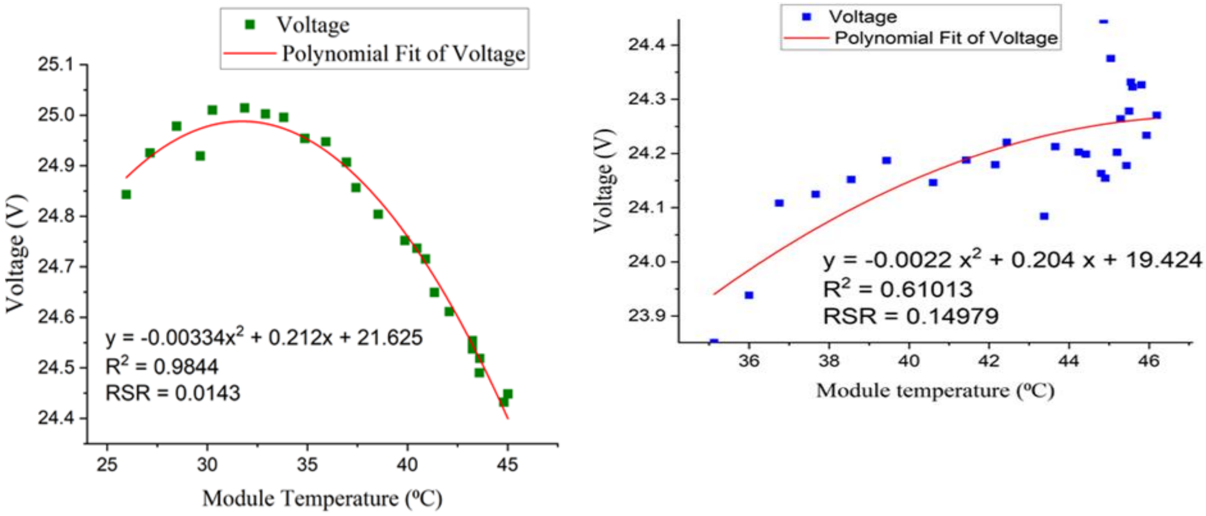
Voltage variation as a function of irradiance and temperature

Variations in Vco over the measured temperature and irradiation range are shown in Figures 5 and 6, respectively.



(a) Morning (b) Afternoon

Figure 5: Voltage variation as function of irradiation



(a) Morning *(b) Afternoon*

Figure 6: Voltage variation as function of temperature

Analysis of the figures shows that polynomial regression is more suitable for interpolating the daily evolution of module voltage as a function of the daily variation in irradiance. This is justified by the fact that polynomial regression gives R2 values close to 1. We also noticed that the way in which module voltage evolves from the first half-day (deterministic evolution) is totally different to that of the second half-day (random evolution).

From these two curves we can say that over the course of a day:

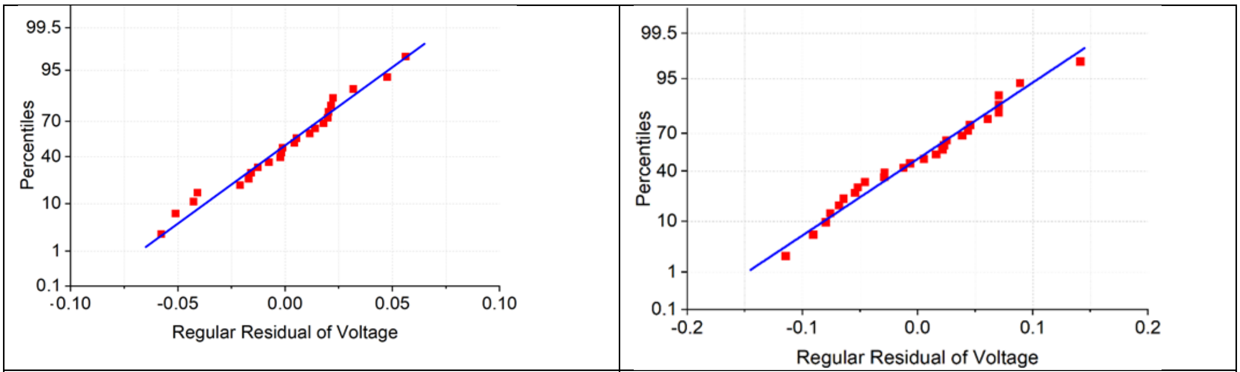
• The voltage increases slightly with increasing irradiance, reaching a maximum over a short period, and decreases with increasing irradiance and temperature (Fig. 4.(a) and 5.(a)). This decrease is synonymous with negative slopes on each curve. We can therefore deduce that Vco has a negative proportional relationship with temperature and irradiance. This is in perfect agreement with the results found in the literature;

• R^2 values close to 0.978 for irradiance and 0.984 for temperature, corresponding to the first half-day, show that the polynomial model used to fit the data correctly reproduces voltage variations as a function of irradiance and temperature. However, R^2 values close to 0.724 for irradiance and 0.610 for temperature, corresponding to the second half of the day, confirm the insufficient variability of Vco data as a function of irradiance and temperature variation. This is confirmed by the random distribution around the regression curve. The influence of these parameters on blood pressure during the second half of the day is therefore not strong. This suggests that higher-order terms need to be introduced into the fitting model;

• The values of the residual sums of squares, which are close to zero, show that our data match perfectly and that the fit is linearly better.

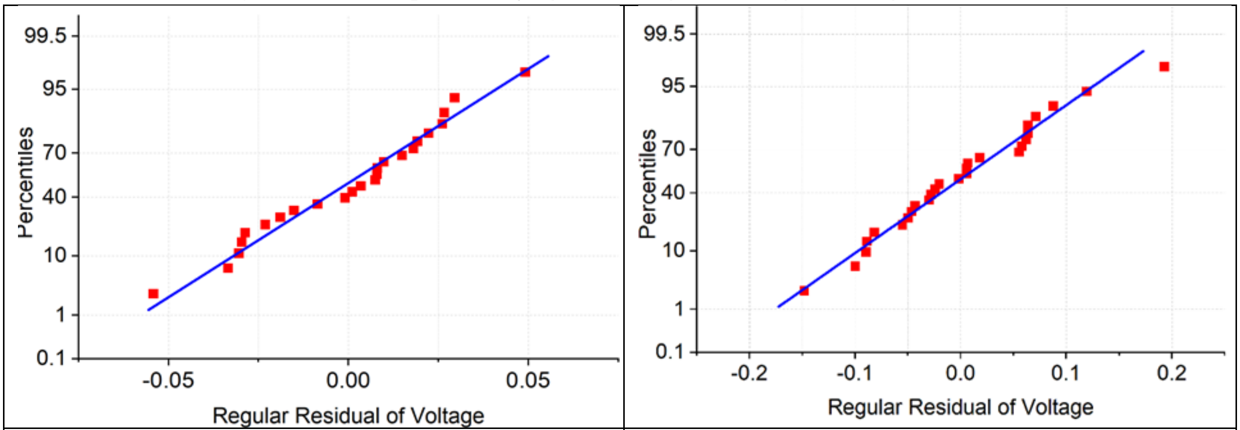
Quality study of linear regression curves

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



(a) Morning	*(b) Afternoon*

Figure 7: Normal probability of residuals for ISC as function of irradiation



(a) Morning	*(b) Afternoon*

Figure 8: Normal probability of residuals for ISC as function of temperature

We have noticed that on all the graphs, the residuals are normally distributed and their random distributions are close to zero. This strengthens the fit of our regression model. We can therefore confirm that our statistical models can be used in similar studies.

Conclusion

In this work, an analysis of the irradiation and temperature dependence of the PV module's short-circuit current and open-circuit voltage was carried out. The study was carried out on a half-day basis, and our results are consistent with and largely confirm the findings of previous work. The results of our study show that a positive linear dependence is observed at the short-circuit current level as a function of irradiation and temperature. However, a linearly negative dependence is observed at the open-circuit voltage as a function of measured temperature and irradiation. The negative values for the slopes of the models obtained show that as PV module temperature and irradiation increase, PV module voltage decreases. The very large Pearson's r and R2 values show that there is a strong relationship between these parameters and that our models are adaptive.

The data measured so far show that for every level of illuminance, there is a specific temperature at which PV module current and voltage reach their maximums. Moreover, as irradiance increases, this temperature also tends to rise.

The results of this work make a significant contribution to the evaluation of PV technology.

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