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Studying Effect of Temperature on the Efficiency of Solar Cells through the Interpolation Method

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Abstract

In this work, we employed the interpolation method to identify and determine the values of five parameters namely the parasitic series resistance R_S, the shunt resistance R_{Sh}, the photo-generated current density J_{ph}, the reverse saturation current density J_0, and the ideality factor n based on experimentally obtained results for our solar cell. The results obtained were compared with those of the least squares method (LMS). We then studied the effect of temperature on these parameters. The efficiency was also calculated, and this was found to decrease as the temperature increased. The open-circuit voltage and ideality factor were also found to decrease with increasing temperature. The J_{ph} value, meanwhile, decreases slightly as it approaches 30°C, but it becomes stable above this value.

Keywords: Solar cell; Function polynomial; Interpolation method, Open circuit voltage, Short circuit current, Temperature efficiency; Band gap.

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1. Introduction

In the quest for sustainable and renewable energy sources, solar cells have emerged as a promising technology for harnessing solar energy. As the demand for clean energy continues to rise, understanding the factors that influence the efficiency of solar cells becomes crucial for optimizing their performance. One such factor that significantly affects solar cell efficiency is temperature. Numerous studies have explored the complex relationship between temperature and the efficiency of solar cells, recognizing the need for a comprehensive understanding of this interaction to enhance the overall performance of solar energy systems. Temperature variations, inherent in real-world environmental conditions, can impact the electronic properties and performance of solar cells, influencing factors such as open-circuit voltage, short-circuit current, and fill factor [1-3]. This research aims to contribute to the existing body of knowledge by delving into the intricate interplay between temperature and solar cell efficiency. Our study employs the Interpolation Method, a sophisticated analytical technique widely recognized for its accuracy in modeling and predicting the behavior of complex systems. By utilizing this method, we seek to provide a nuanced analysis of how temperature fluctuations impact the efficiency of solar cells, offering insights that can inform the design and optimization of solar energy systems. As we embark on this investigation, we draw inspiration from seminal works in the field, such as the pioneering research by Shockley and Queisser [4] on the theoretical limits of solar cell efficiency. Additionally, recent advancements in materials science and solar cell technology serve as a foundation for our exploration into temperature-induced variations in solar cell performance [5-7]. Through our rigorous methodology and reliance on the Interpolation Method, we aspire to contribute valuable findings that will aid in the advancement of solar cell technology and its integration into sustainable energy solutions. Ultimately, unraveling the intricate relationship between temperature and solar cell efficiency is pivotal for achieving greater reliability and efficacy in harnessing solar power.

The experiment used in this study was performed using a solar cell simulator with the cell temperature varying between 25 and 60°C under constant light intensities of 215–515 W/m^2 [8]. The temperature dependence of the I-V characteristics of illuminated PV cells has been theoretically explained based on the band theory of solid-state physics [9]. The least squares method [10, 11] is based on the Lambert W function [12], while the experimental points {(Vi, Ji), i = 1, . . ., n} can be represented by a cloud of n points in the plane (V, J). The ordinary least squares method finds the straight line that minimizes the sum of the squares in the deviations between the observed values and those calculated by the Lambert function. More specifically in our case, the least squares method finds the values for the parameters (J_{ph}, J_0, R_S, R_{Sh}, n) that minimize the sum of the squares of the deviations, which is expressed as follows: $\sum_{i=1}^{n}\left(J_i - \hat{J}_i\right)^2$.

Nevertheless, this method requires initial values for the parameters, with these being chosen in a random manner at approximate intervals. Consequently, a good result is only likely when the estimated values are given such that they are believed to be close to the actual values of the unknown parameters. Thus, this method has two preconditions for extracting the parameters, making it less attractive.

The three-point [13], four-point [14], and five-point [15] methods are techniques that aim to make J–V characteristics more manageable, but they have some disadvantages compared to the least squares method. For example, the least squares method can be applied to problems with linear or nonlinear mathematical models, while these methods are limited to a fixed number of points and analytical methods with a series of simplifications and approximations.

The artificial neuron method [16-18] is a conditioned method where the available experimental data are used to train an artificial neural network based on a back-propagation algorithm. To predict the parameters of the equivalent circuit, this method needs to consider the variation of all parameters alongside varying operating conditions. Note that there are also other techniques for extracting the parameters of a solar cell [19-25].

The equation of J–V characteristic is written as follows:

$$J = J_L - J_0\ \left(exp\left(\frac{V+R_sJ}{nV_t}\right) - 1\ \right) - \frac{V+R_SJ}{R_{S\square}} \quad (1)$$

Where:

J is current density (mA/cm^2);

$J_{ph} \cong J_{SC}$ is the photo-generated current density $\cong$ short-circuit current (mA/cm^2);

J_0 is the reverse saturation current density (mA/cm^2);
R_S is the specific series resistor (Ω.cm^2);
R_{Sh} is the specific shunt resistance (Ω.cm^2);
n is the ideality factor; and $V_t = \frac{k_B T}{q}$ is the thermal voltage (V).

For this work, we applied the polynomial interpolation method to extract the five parameters $\left(J_{ph}, J_0, R_S, R_{Sh}, n\right)$ cited in the abstract based on Equation 1. This method has been validated for silicon PV cells using measurement data obtained at temperatures varying from 0 to 50°C. The estimated values were calculated using an optimized algorithm based on information extracted from the same measured data. MATLAB code was used for all aspects of the implementation. The proposed approach produces results that are more accurate than those produced by the least squares method under all operating conditions.

In addition, this study evaluated the effects of temperature on the five parameters for a single-junction solar cell under constant illumination. Sensitivity analysis was also conducted for performance parameters, namely the photo-generated current density J_{ph} and the open-circuit voltage V_{OC}. The fill factor FF, band gap energy E_g, maximum power P_{max}, and cell efficiency η were also established.

The remainder of this article is organized as follows: Section 2 discusses the theory behind the proposed method, which uses a mathematical model to extract the five parameters. Section 3 then provides the experimental results, while Section 4 gives the calculated results. Section 5 focuses on comparing the results of the proposed approach with those of the least squares method (LMS). Section 6 then discusses the effect of temperature on the parameters and cell performance, before Section 7 concludes the article.

2. Theory for the Method

A limited polynomial expansion is a local approximation (i.e., in the neighborhood of some point), thus replacing a complicated curve with a simpler curve. The equation for the J–V characteristic is a function of class Cn+1 in the set IR, so it allows partial derivatives at any point P (V, J) of the J–V curve, particularly for low voltages in the vicinity of the short-circuit current P(0,JSC). Thus, its limited development to first order can be expressed as:

$$J = J(J,V) = J(J_1,V_1) + \left(\frac{\partial J(J_1,V_1)}{\partial J}\right)(J - J_1) + \left(\frac{\partial J(J_1,V_1)}{\partial V}\right)(V - V_1) + (|V - V_1| + |J - J_1|)\,\varepsilon(J,V) \qquad (2)$$

Where $\lim\limits_{(J,V)\to(J_1,V1)} \varepsilon(J,V) = 0$.

By carrying out the partial derivatives at the first measured point and denoting (V_1,J_1) these coordinates in the plane (V, J), we finally obtain:

$$J\left[1 + \frac{J_0\ R_S\ exp\,a}{nVt} + \frac{R_S}{R_{S\square}}\right] = J_1 + J_1\left[\frac{J_0\,R_S}{nVt}expa + \frac{R_S}{R_{S\square}}J_1 + V_1\left(\frac{J_0}{nVt}expa + \frac{1}{R_{S\square}}\right)\right]$$
$$- \left[\frac{J_0 R_S}{nVt}expa + \frac{R_S}{R_{S\square}}\right]V + (|V - V_1| + |J - J_1|)\varepsilon(J,V) \qquad (3)$$

where $a = \frac{V_1 + R_S J_1}{nV_t}$

We put:

$$\begin{cases} \alpha = \left[1 + \frac{J_0 \; R_S \, expa}{nVt} + \; \frac{R_S}{R_{S\square}}\right] \\ \beta = J_1 + J_1 \left[\frac{J_0 \, R_S}{nVt} expa + \frac{R_S}{R_{S\square}} J_1 + V_1 \left(\frac{J_0}{nVt} expa + \frac{1}{R_{S\square}}\right) \; \right] \\ \gamma = \left[\frac{J_0 R_S}{nVt} expa + \frac{R_S}{R_{S\square}}\right] \end{cases} \tag{4}$$

Equation (3) becomes:

$$J = \frac{\beta}{\alpha} - \frac{\gamma}{\alpha} V \tag{5}$$

For low voltages, the J-V characteristic curve shows that in this region, the curve is linear and almost horizontal. Therefore, we can perform a first-order polynomial interpolation in the vicinity of point P (J_1, V_1):

$$J = \; P_1 + P_2(V - V_1) \; \rightarrow \; J = \; P_1 - P_2 \, V_1 + P_2 \, V \tag{6}$$

Where P1 and P2 are the coefficients of the first-degree interpolation polynomial, which will be crucial for extracting all the parameters of our PV cell.

By comparing the two equations (5) and (6) we obtain:

$$\begin{cases} \frac{\beta}{\alpha} = P_1 - P_2 \, V_1 \\ \frac{-\gamma}{\alpha} \; = P_2 \\ \gamma = \alpha - 1 \end{cases} \Rightarrow \begin{cases} \alpha = \frac{1}{1 + P_2} \\ \beta \; = \frac{P_1 - P_2 \, V_1}{1 + P_2} \\ \gamma = -\alpha \, P_2 \end{cases} \tag{7}$$

Through linear interpolation in the low voltage range using a MATLAB code, we obtain (P1, P2). By utilizing equations (1) and (5) when the circuit is short-circuited (i.e., when the two terminals are directly connected to each other, and the voltage is zero), we obtain:

$$J_{SC} = J_{p\square} = P_1 - P_2 \, V_1 \tag{8}$$

From the system of equations (4) and (7), we obtain:

$$R_S = \frac{V_1 \, \gamma}{\beta - V_1 \, \alpha} \tag{9}$$

Since $R_S \ll R_{Sh}$ the equation of α becomes $\alpha = \left[1 + \frac{J_0 \; R_S \; exp \, a}{nVt}\right]$ and from this equation, we obtain J_0 :

$$J_0 = nV_t \left(\frac{\alpha - 1}{R_S}\right) exp\left(-\frac{V_1 + R_S J_1}{nV_t}\right) \tag{10}$$

By replacing J_0 in the V_{OC} equation of the open-circuit voltage, we obtain:

$$nLn\left(\frac{J_{p\square} R_S}{(\alpha - 1) nV_t}\right) + \; \frac{V_1 + \, R_S J_1}{V_t} - \frac{V_{OC}}{V_t} \; = 0 \tag{11}$$

The open circuit voltage V_{OC} is obtained from the J-V characteristic when the current density J is zero. By knowing $J_{ph}, J_1, V_1, V_{OC}, V_t, R_S$ and α, we can use the function fzero in Matlab code to find the value of n.. Substituting the found value of n into equation (10) we obtain J_0. Finally, to determine the value of the shunt resistance R_{Sh}, we use equation (5) and obtain:

$$R_{S\square} = \; \frac{R_S}{(\alpha - 1) - \frac{J_0 R_S expa}{nV_t}} \tag{12}$$

The power supplied by the PV cell per unit area is the product of the photocurrent generated by the cell and the voltage across the cell. In other words, it is the electrical power output produced by the cell, and it is given by the equation:

$$P = JV \tag{13}$$

3. Experimental Results

The current–voltage characteristics of a mono-crystalline PV cell as a function of temperature were measured in the condensed matter laboratory of the Polytechnic Institute of Kharkov in Ukraine in summer 2015. The results of this are presented in Figure 1. The performance of the cell was evaluated under a standard illumination of 1000W/m2 with temperatures ranging from 0 to 50°C.

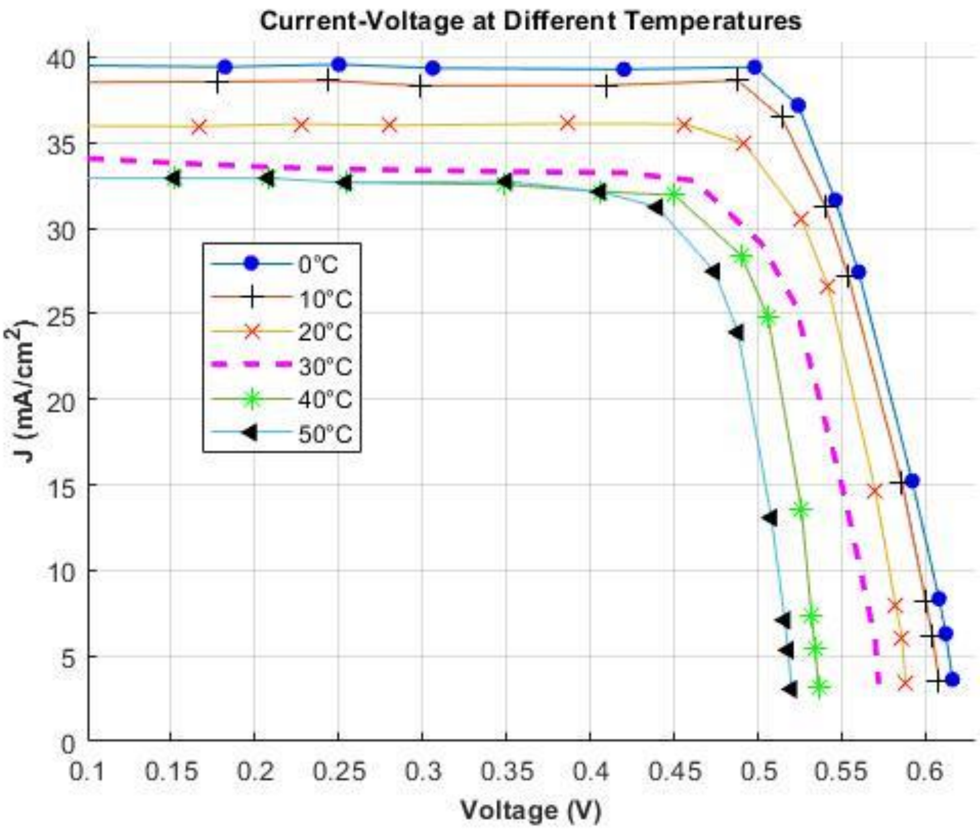

Fig. 1: The J-V characteristics of a solar PV cell under different temperatures

Figure 1 plots the J-V characteristics of a PV cell under constant light intensity with temperature as a varying parameter. It shows that the open-circuit voltage decreases considerably with increasing temperature, while the short-circuit current density J_L decreases with temperature and reaches a minimum value of 33.30 mA/cm^2 at a temperature of 50°C. The temperature change also affected the power output of the PV cell, as shown in Figure 2.

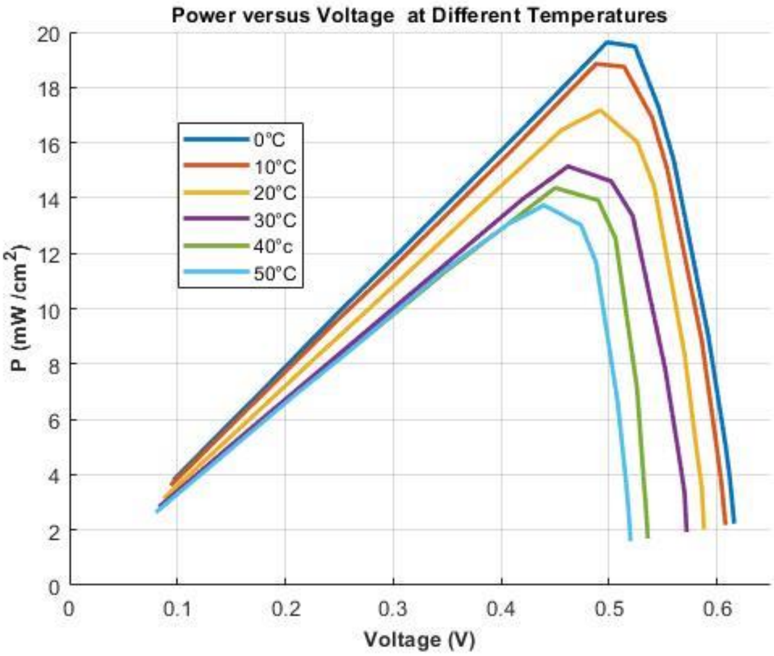

Fig. 2: P-V characteristics of the solar PV cell at different temperatures

As can be seen in Figure 2, the maximum power output of the solar cell decreased as its temperature increased.

4. Calculation Results

Of all the various types of functions, we are most familiar with polynomial functions. Indeed, polynomial functions are certainly very tidy and easy to manipulate, so it was logical to see if one could work in our case. Take for example the J-V characteristic at temperature θ°C. The goal here would be to find a polynomial interpolating function that approximates the experimental curve. We can surmise that a suitable polynomial function exists because the function J= f (V, J) is continuous and differentiable. Nevertheless, a question then arises as to how to find a harmonious, smooth curve that passes through the most interpolating points. To address this, we considered two techniques.

In the first technique; we will plot the J-V curve using the values measured at the temperature θ°C, then we will interpolate it with interpolating polynomials of degree varying from 1 to 5. Moreover, by wondering which is the interpolating polynomial whose representative curve could pass through the appropriate points in order to identify the appropriate interpolating polynomial. The results of the interpolation with different degrees are shown in figure 3.

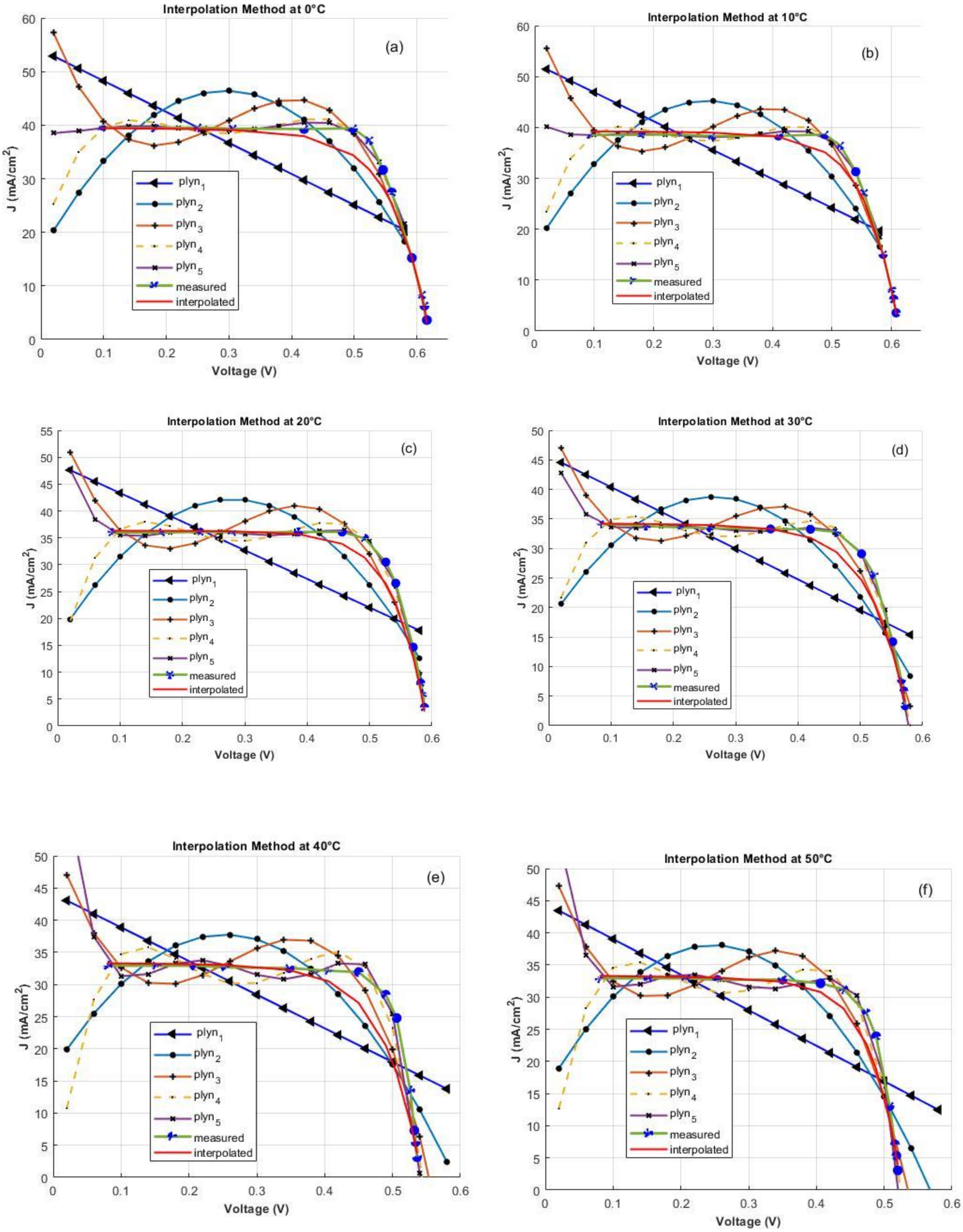

Fig. 3: J-V characteristics of a PV solar cell obtained through polynomial interpolations with optimal parameters and varying temperatures from 0 to 50°C.

Figure 3 clearly shows that polynomials of low degrees (1, 2, 3) do not give good results for the considered temperatures, because none of their interpolations adequately fit the experimental data. Indeed, none of these polynomials passes through the two points at the ends of the segment. The higher degree interpolating polynomials (4, 5) yield good results up to a temperature of 40°C, with them reproducing the experimental curve quite faithfully within the interpolation interval but very rarely outside this interval, because a polynomial interpolation is not an extrapolation. As shown in Figure 3 (a and b), from a temperature of 40°C, the interpolating polynomial of order four starts to oscillate excessively between the data points, and its curve quickly deviates from the experimental curve. This polynomial is therefore not suitable for interpolation at high temperatures. The only suitable polynomial for the full temperature range of 0 to 50°C is the one of order five because it intersects all the points. Therefore, to construct a polynomial approximation of the function $J = f(V, J)$ to order five, we need to make a limited expansion of the function J=f (V, J) to order six. Unfortunately, this function is nonlinear and implicit, so this limited expansion is problematic due to the large number of elementary operations that it involves.

For the second approach, we propose a method that we believe has proven to be effective. It starts with observing the J-V characteristic. As can be seen in Figure 3, at low voltages, the points are aligned and almost horizontal. Thus, for this region, we interpolate the function J= f (V, J) with a polynomial of order 1. The model $J = f(V, J)$ is nonlinear in $(J_L, J_0, R_S, R_{Sh}, n)$, but it can be linearized using an expand transformation limited to order 1 (see Equation 2). On performing this linear interpolation in MATLAB code, we obtain the P_1 and P_2 coefficients of the interpolating polynomial. This knowledge, combined with the successive application of Equations 5 to 11, allows us to calculate the values for all the PV cell's parameters.

Finally, to find a synthetic (analytical) representation of the experimental data, errors must be taken into account. The word "error" is not used here in the sense of a fault, such as false reasoning in the method or a faulty instruction in the program. It refers more to unavoidable errors that can be classified under four categories: data errors, rounding errors, number of points errors, and coefficient errors. To overcome the drawbacks associated with these, we present an approach for correcting these errors. This consists of completing the interpolation with an additional adjustment method that involves replacing the parameters $(J_L, J_0, R_S, R_{Sh}, n)$ with their values in function (1) and adjusting them one by one. This results in a curve that best fits the experimental data points, which in turn allows us to increase the precision of our created model. The obtained results for the five parameters using the second technique are presented together in Table 1.

From Table 1, we can see that the short-circuit current J_L, the ideality factor n, the saturation current J_0, the series resistance R_S, the shunt resistance R_{Sh}, and the open-circuit voltage V_{OC} decrease gradually with increasing temperature until $\theta(^\circ C) = 40°C$. Above this, they vary only slightly.

Table 1: Parameters extracted and obtained from the method proposed for the PV cell, in the temperature range from 0 to 50°C

$\boldsymbol{\theta(^{\circ}C)}$	0	10	20	30	40	50
$\boldsymbol{J_{ph}(mA)}$	39.50	39.35	36.35	34.30	33.35	33.40
$\boldsymbol{J_0(mA)}$	5.87 10^{-7}	3.926 10^{-6}	2.47 10^{-7}	9 .219 10^{-7}	1.4 10^{-7}	1.4$10^{-7}$
$\boldsymbol{n}$	2 .2	2,04	1 .93	2.1	1.60	1.54
$\boldsymbol{R_s}(\Omega)$	0.170	0.124	0.02	0.24	0.024	0.0241
$\boldsymbol{R_{sh}}(\Omega)$	2553	6459	6050	2117	1813	1813.77
$\boldsymbol{V_{OC}(V)}$	0.62	0.617	0.593	0.576	0.536	0.524

5. Comparing the Proposed Method with the Least Squares Method

To validate the proposed method, we compared its results with those of another well-known method that is already used by several researchers [10, 11], namely the least squares method [26].

The least squares method is used to determine the best line of fit for a series of data points. There are two varieties for this method:

- Ordinary or linear least squares, which uses simple calculus and linear algebra;
- Nonlinear least squares, which specializes in estimating a nonlinear model with n parameters from m observations, where $m > n$.

Now, which form of least squares should we use to model the J-V Function (1) is a nonlinear function, so the second type is more appropriate. In addition, this function is implicit and contains an exponential term, so we use the function W Lambert [27] to make it explicit, so it can be expressed in the form $J = f(v)$.

$$J = \frac{-V}{R_s} + \frac{V_t}{R_s}\left(-LambertW\left(\frac{R_s J_0 R_{s\square}\, exp\left(\frac{R_{S\square}(R_S J_{L+})+R_S J_0+V}{nV_t(R_S+R_{S\square})}\right)}{nV_t(R_S+R_{S\square})}\right)\right) + \frac{R_{S\square}(R_S J_{L+})+R_S J_0+V}{nV_t(R_S+R_{S\square})} \quad (15)$$

Let: $J = f(V, J_0, J_L, n, R_S, R_{Sh})$, i.e. the function to be fitted to the n data points (V_i, J_i), i= 1, 2, . . . , n. The notation implies that we have a function of V which contains the parameters J_0, J_L, n, R_S and R_{Sh}.

To find the parameters of J_0, J_L, n, R_S and R_{Sh}, we have used the least squares method (LMS). The error ε thus is defined as:

$$\varepsilon = \sum_{i=1}^{N}\left(J_i - J(V_i, p)\right)^2 \quad (16)$$

Where p is the variable used to minimize the error.

The curve fitting comprises two steps: The first step involves choosing the variation interval of each parameter and initializing it to begin the adjustment process. The second step is to calculate the values for the parameters that lead to the best fit with the data and minimize the error ε as much as possible.

The results of the above process are illustrated in Figure 4.

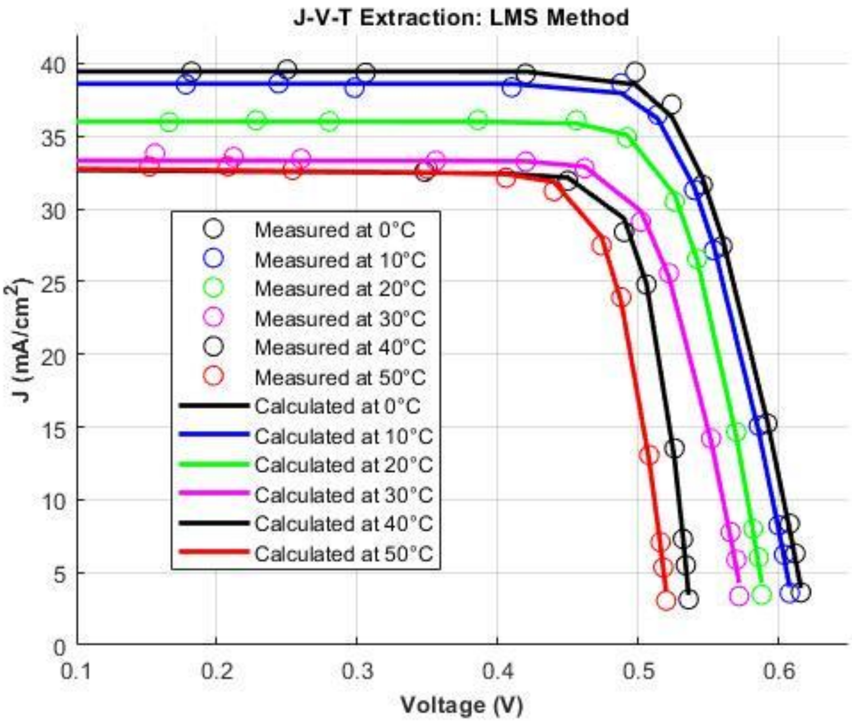

Fig. 4: The J-V characteristics of the PV solar cell as obtained by the least squares method for temperatures from 0 to 50°C.

To extract the abovementioned parameters using the least squares method, the fitting can be done in MATLAB with a single line of code, polyfit, which returns the J_0, J_L, n, R_S and R_{Sh}.The results obtained with this are given in the table below:

Table 2: Parameters extracted, obtained from the least squares method for the PV cell, for temperatures from 0 to 50°C.

$\boldsymbol{\theta(^{\circ}C)}$	0	10	20	30	40	50
$\boldsymbol{J_{ph}(mA)}$	40.30	39.359	36.80	34.54	33.63	32.25
$\boldsymbol{J_0(mA)}$	1.727 10^{-6}	3.926 10^{-6}	4.75 10^{-7}	1 .08 10^{-7}	4.71 10^{-7}	2.70 10^{-7}
$\boldsymbol{n}$	2 .2	2.04	1.70	1.74	1.35	1.50
$\boldsymbol{R_s}(\Omega)$	0.170	0.124	0.0430	0.013	0.0130	0.065
$\boldsymbol{R_{sh}}(\Omega)$	858.37	6459	2173	2765	3638	2500

Comparing a new extraction technique with an established technique is usually a sufficient way to demonstrate if the new technique is worthy of replacing the old one. For this study, we compared our proposed method with the least squares method based on the comparison method proposed by Bland-Altman et al. [28]. When evaluating the level of agreement between two methods, it is useful to plot the difference between the methods' results against the mean of those results (a difference plot). To illustrate the agreement between the two methods, we took the J-V characteristic for a temperature of 50°C as an example, and this is presented in Figure 5.

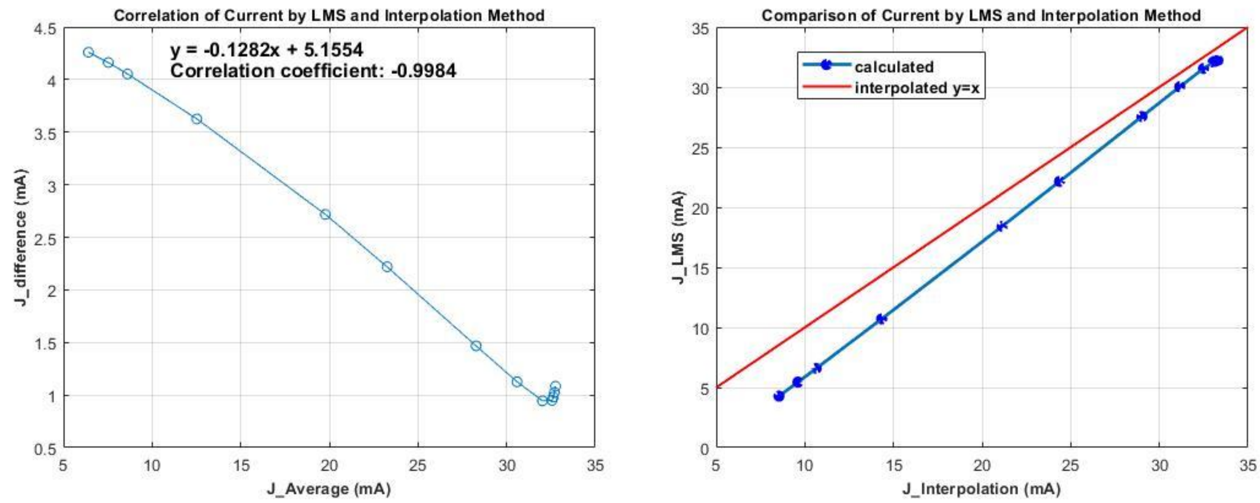

Fig. 5: Difference from the mean for the currents calculated by the two methods and the current calculated using the LMS method with respect to the current calculated by the interpolation method, together with the line of equality in red

A comparison is performed in two steps: The first step generally involves calculating the correlation coefficient R between the two methods. For the data in figure (5- correlation of current by LMS and Interpolation Method), R could be calculated by a single line of code in MATLAB, corrcoef, and this returned R = 0.99, which is very close to 1, indicating a strong correlation. Nevertheless, this does not imply that the two methods agree, because R measures the strength of the relationship between the two variables rather than the agreement between them.

Thus, the second step is to plot the currents calculated by the two methods and draw the line of equality, which is where all the points would lie if the two methods gave exactly the same value each time. This helps in assessing the level of agreement between the two methods. In Figure (5-Comparison of current by LMS an Interpolation Method), the points lie very close to the line of equality, meaning the methods are in almost perfect agreement. It could therefore be concluded the two methods have a strong correlation and good alignment along the line of equality, so the proposed method agrees well with the least squares method.

6. Effect of Temperature

We here try to answer a relevant and important question: How is the efficiency of a solar cell affected by temperature? For example, if the temperature of the cell increases, does its efficiency also increase? Or will it diminish or maybe not be affected at all? We therefore set out to investigate how the short-circuit current and the open-circuit voltage behave as a function of temperature.

The short-circuit current essentially depends upon the number of charge carriers that are collected above the forbidden band, so we would expect it to be mainly influenced by how the band gap changes with temperature. In general, the band gap can be expressed as a function of temperature through the following formula [29, 30]:

$$E_g(T) = E_g(0) - (\beta\, T^2)/(\gamma + T) \quad (17)$$

Where E_g is the band gap energy, which is indirect for Silicon, $E_g(0) = 1.1557$ eV is its value at absolute zero (0K), where $\beta = 7.021 \times 10^{-4}\ eV/K$ and γ = 1108 K.

Figure (6-Energy gap versus Temperature) shows that the effect is linear in the considered temperature region, with the gap energy decreasing from 1.1178 eV to 1.1045 eV. In other words, for a temperature increase of 1°C, the energy gap decreases by 2.663 x 10-4eV. Most of the energy gap's variation with temperature is attributed to a shift in the relative position of the conduction and valence bands due to lattice expansion in response to rising temperature. Thus, the band gap decreases as the temperature increases, and this in turn allows the solar cell to broaden its absorption spectrum due to more photons being above the band. The new band gap, which is a reduced band of our solar cell, decreases in value, so the short-circuit current must essentially increase as the temperature increases, as has been described in the literature [8, 9]. The behavior of the short-circuit current differs in our case, however. Figure 5-b shows that the current J_L decreases by about 15.57% mA/cm^2/°C between 0°C and 30°C. Above 30°C, the photo-current J_{ph} remains stable at 32.25 mA/cm^2 up to 40°C before rising to 33.40 mA/cm^2 at 50°C. The calculated intrinsic and extrinsic parameters of the cell are given in Table 3.

Table 3: The effect of temperature on the Silicon *PV* cell's parameters, namely the gap energy, open-circuit voltage, short-circuit current, fill factor, and efficiency.

$\boldsymbol{\theta(^\circ C)}$	0	10	20	30	40	50
$\boldsymbol{E_g}$ (eV)	1.1178	1.1153	1.1127	1.1100	1.1073	1.1045
$\boldsymbol{V_{OC}}$ (V)	0.62	0.617	0.593	0.576	0.536	0.524
$\boldsymbol{J_{ph}}$ (mA)	39.50	39.35	36.35	34.30	33.35	33.40
FF	0.8014	0.7762	0.7868	0.7665	0.8038	0.8091
$\boldsymbol{\eta}$ (%)	19.6267	18.8464	17.1749	15.1443	14.3678	13.7363

Table 3 shows that all the parameters vary with temperature: The current J_{ph} decreases gradually with temperature, but the voltage V_{OC} decreases more rapidly and linearly under rising temperature conditions. The efficiency also decreases steadily and in a linear fashion, while the fill factor exhibits oscillations in this temperature range.

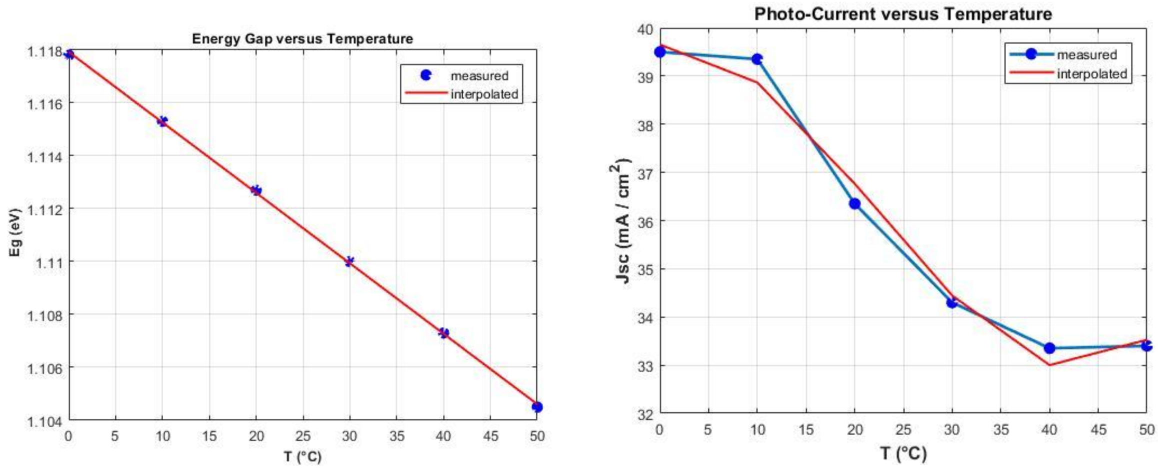

Fig. 6: Variations the gap with temperature, as calculated by Equation (17), and the photo-current measured over the *0–50°C* temperature range

The next thing we turned our attention to was how the open-circuit voltage behaves as the temperature varies. The open-circuit voltage V_{OC} depends on the current J_{ph} and the reverse saturation current J_0 , according to the following relationship:

$$V_{OC} = \frac{n\, k_B T}{q}\, ln\left(\frac{J_L}{J_0}\right) \tag{18}$$

Now, one may be inclined to expect the voltage V_{OC} to increase with temperature, because there is a temperature term (n k_BT/q) multiplying the ln (J_L/J_0) term. Nevertheless, the latter term contains J_{ph}, which, as we mentioned earlier, decreases as the temperature increases. The results obtained through the two methods also show that J_0 is slightly dependent on the temperature (see Tables 1 and 2). Overall, the voltage V_{OC} drops as the temperature increases. Figure (7-open circuit voltage versus Temperature) shows how the voltage V_{0C} decreases linearly by about 2.2 mV for each degree increase in temperature.

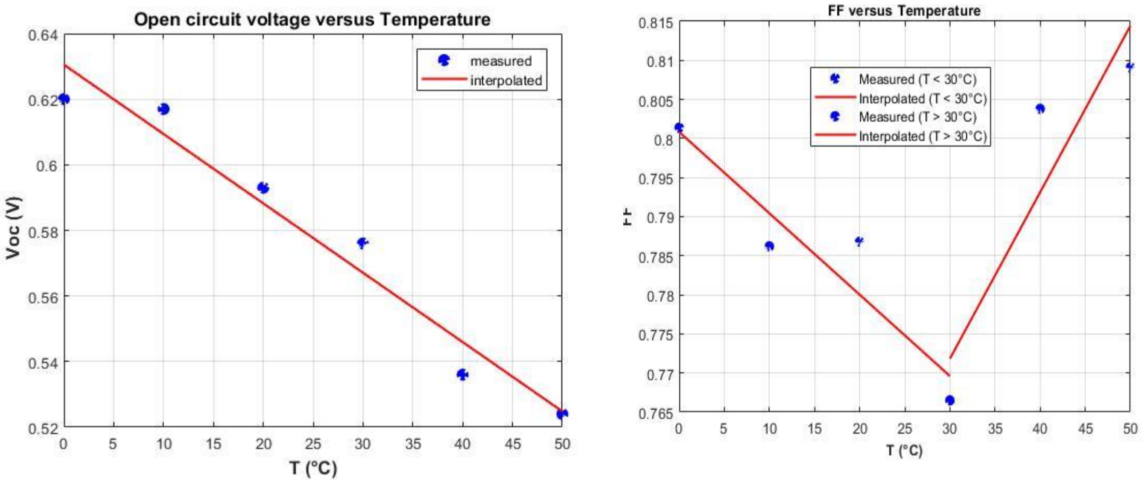

Fig.7: The Open-circuit voltage and Fill factor for the *0–50°C* temperature range

The form factor, which is commonly abbreviated to FF, indicates not only the efficiency of a photovoltaic cell but more importantly its aging. It is defined as the ratio between the maximum power P_{max} and the value of the product $V_{OC} . J_{SC}$, where $J_{SC} \cong J_L$:

$$FF = \frac{J_{max} V_{max}}{J_L V_{OC}} \tag{19}$$

The measurement results are shown in Table 3, with the fill factor values ranging from 77.62 to 80.91%, depending on the cell temperature. Figure (7-FF versus temperature) shows that the form factor has two different slopes: First, there is a descending one for low temperatures between 0 and 30°C with a slope around 0.10%/°C. This means the form factor decreases by 0.0010 for each temperature increase of 1 degree centigrade, which is a very small variation. Next, there is an ascending slope for higher temperatures between 30 and 50°C of around 10.85%/°C. Thus, the fill factor increases by 0.1085 for each temperature increase of 1 degree centigrade.

Moving on to considering the efficiency of the PV cell, the yield equation is given by the following relationship:

$$\eta = \frac{P_{max}}{P_0} = FF\frac{V_{OC}\,J_L}{P_0} \tag{20}$$

Where P_0 is the power of the incident solar radiation. This equation also features the fill factor FF, the short-circuit current J_{ph}, and the open-circuit voltage V_{OC}. The FF decreases slightly as the temperature increases, the current J_{ph} decreases with the increase in temperature before stabilizing at 30°C and above, and the voltage V_{OC} decreases by 2.2 mV for each degree of temperature increase. Equation 20 shows that the efficiency η is proportional to V_{OC}, so the overall efficiency drops as the temperature increases.

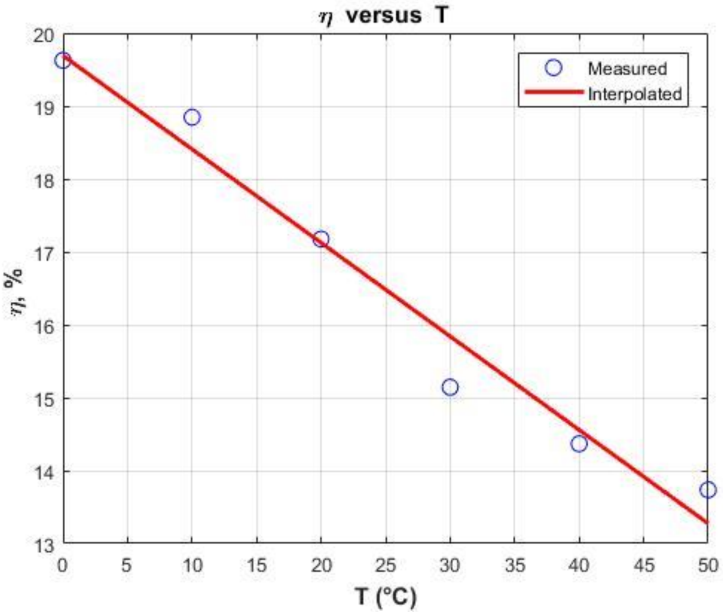

Fig.8: Photovoltaic cell efficiency versus temperature

Figure 8 shows how the efficiency varies with temperature at a solar radiation of 1000W/m^2. Note that there is a linear relationship between the ambient temperature and cell efficiency (η = -0.1283T + 54.72), so a decrease in temperature leads to an increase in efficiency. Thus, to attain the desired efficiency for a PV module, we can ascertain what ambient temperature is needed for the module. By then manipulating the temperature around the PV module, we can affect its efficiency.

7. Conclusion

The interpolation method was used to extract the five parameters (J_L, J_0, R_S, R_{Sh}, n) from the equivalent circuit of a single silicon diode PV cell. This method is based on applying the linear polynomial interpolation function to extract explicit analytical solutions for the J-V characteristics. It yields parameter values that closely resemble those produced by the least squares method for curve fitting, but it is faster and more convenient, and it does not require initial values for the PV cell's parameters. Additionally, this method avoids the need for determining the variation intervals of each parameter and eliminates the use of the Lambert function. Both methods indicate that the most significant effect of temperature is on the open-circuit voltage, which decreases as the PV cell temperature increases. This reduction in the open-circuit voltage means that the cell cannot attain its maximum power output, even though there is a corresponding increase in the output current. Moreover, the cell's efficiency decreases as its temperature increases. We therefore concluded that the considered solar cell works better at lower temperatures. This is important for improving cell efficiency and maintaining cell integrity against thermal damage.

Conflict of interest:

The authors have no conflicts of interest to declare.

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Highlights

- Utilizing the interpolation method for precise determination of five essential parameters in a solar cell, with a comparative analysis against results obtained using the least squares method (LMS).
- Examining the impact of temperature on these parameters, unveiling a reduction in solar cell efficiency with increasing temperature.
- Noteworthy decreases observed in both open-circuit voltage and ideality factor as temperature rises.
- Analysis of photo-generated current density (J_{ph}) indicates a slight decrease until reaching 30°C, followed by stabilization beyond this temperature.
- Establishing a clear correlation between temperature increase and declining solar cell efficiency.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: