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Modeling and Experimental Investigation of Monocrystalline Photovoltaic Module Performance under Derna Climate Conditions

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ABSTRACT The aim of this paper is to examine the major impact of cell temperature on the performance of mono-crystalline module under Derna City climate conditions. A mathematical model was developed to estimate cell temperature where the method of energy balance is applied using meteorological parameters such as ambient temperature, slope radiation and wind speed. The experimental measurements were conducted for a particular day of October 2019. The validation of the calculated results was performed by comparing the attained results against measured cell temperature of the module. It was observed that the cell temperature, slope irradiance and electrical power output from the PV module reach the highest at 11:30, with values of 64.7 °C, 968 W/m^2 and 47.73 W, respectively, whilst the ambient temperature found to be 36 °C. The energy balance method that presently deployed was highly successful in identifying the cell temperature, hence promising results of fitted parameters were of significance as the coefficient of determination (R^2) = 0.9996, and the root mean square error (RMSE) = 0.582.

Keywords: Photovoltaic, Cell Temperature, Derna, Performance, Modeling.

النمذجة والتحقيق التجريبي لأداء الوحدة الكهروضوئية أحادي البلورية في ظل الظروف المناخية في درنة

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الملخص الهدف من هذه الورقة هو فحص التأثير الرئيسي لدرجة حرارة الخلية على أداء الوحدة أحادية البلورية في ظل الظروف المناخية لمدينة درنة. تم تطوير نموذج رياضي لتقدير درجة حرارة الخلية حيث يتم تطبيق طريقة توازن الطاقة باستخدام معلمات الأرصاد الجوية مثل درجة الحرارة المحيطة وإشعاع المنحدر وسرعة الرياح. تم إجراء القياسات التجريبية في يوم معين من شهر أكتوبر 2019. تم إجراء التحقق من صحة النتائج المحسوبة من خلال مقارنة النتائج المحققة مع درجة حرارة الخلية المقاسة للوحدة. لوحظ أن درجة حرارة الخلية وإشعاع المنحدر وخرج الطاقة الكهربائية من الوحدة الكهروضوئية تصل إلى أعلى مستوى عند الساعة 11:30، بقيم 64.7 C° ، 968 W/m^2، 47.73 W، على التوالي، في حين أن درجة الحرارة المحيطة كانت 36 C°. كانت طريقة توازن الطاقة التي تم نشرها حالياً ناجحة للغاية في تحديد درجة حرارة الخلية، وبالتالي كانت النتائج الواعدة للمعلمات المجهزة ذات أهمية مثل معامل التحديد (R^2) = 0.9996، وجذر متوسط الخطأ التربيعي (RMSE) = 0.582.

الكلمات المفتاحية: الكهروضوئية، درجة حرارة الخلية، درنة، الأداء، النمذجة.

1. INTRODUCTION

There are several factors that affect the performance of the PV module. Some of these include meteorological variables like incident solar irradiance on the module, ambient temperature, module temperature, and wind speed. In the last few years, with the increasing use of PV systems, many studies have been conducted to clarify the effect of meteorological variables including temperature, radiation, wind, etc.[1]. Rehman and El-Amin studied the influence of the temperature module on the performance of polycrystalline modules and mathematically demonstrated that electrical efficiency relies on the temperature module [2]. Malik et al. [3], concluded that cold temperature would ensure more efficient photoconversion for single-crystalline PV cells as the efficiency of monocrystalline solar cells decreases as the operating temperature of the cells increases. At the same level of irradiance, output power and therefore efficiency decreases with an increase in cell temperature. A cost-effective solution is required owing to subsequently reduce the cell temperature then to get closer to the rated value of maximum efficiency. Ubertini and Desideri investigated the impact of the temperature module on the performance of the 15-kW polycrystalline system set up on the roof [4]. The study found that efficiency reduced by approximately 0.025% for every increase of 1 °C in the temperature of the module. Jones and Underwood [5] studied the variation on the temperature profile of PV modules under transient conditions. Furthermore, experiments were induced on a clear sky and cloudy day and the results showed that the temperature of the PV module ranged between 300 and 325 K (27-52°C) when the ambient temperature was 297.5 K (24.5 °C). Park et al. [6] investigated the electrical and thermal performance of quasi-transparent PV modules. The results revealed that the output power of the PV panel decreased by almost 0.48% under standard test conditions and by 0.52 % under actual outdoor weather circumstances of each 1°C increase in surface temperature of the PV module. Koehl et al. concluded that wind cooling between temperatures of 15 and 20°C for a wind speed of 10 m /s at a solar irradiance of about 1000 W / m² [7], would play a significant effect on the performance of the PV module.

The main objective of this work is to study theoretically and experimentally the performance of a PV module under Derna Climate Conditions. To achieve this, a MATLAB code is developed to identify the following:

- the cell temperature hence to be validated with measured data based.
- Examine the influence of cell temperature on the performance of PV module.

2. Methodology

2.1 Experimental investigation

The experimental work has been conducted at University of Omar Al-Mukhtar in Derna city of the location ($32.75^\circ N$; $22.63^\circ E$), on the eastern coast of Libya. The module positioned with a tilted angle equal to the (32.7°) of the location and facing south. The experimental setup that has been configured to have the experimental results of this study consists of the monocrystalline (m-Si) PV module as shown (Figure 1). This module comprises of 3×13 cells with short circuit current and Open circuit voltage of 4.78A and 21.6V, respectively under the standard test condition of 1000 W/m² irradiation, 25°C cell temperature and 1.5 air mass (AM). The specifications of the PV module are further detailed in Table 1.

Table 1: Specifications of the PV module.

Electrical Specification	
Model	H750
Peak power (P_m)	75 W
Short circuit current (I_{sc})	4.78 A
Open circuit voltage (V_{oc})	21.6 V
Max. power current (I_m)	4.33 A
Max. Power voltage (V_m)	17.3 V
Cell efficiency	15%
Module area	$0.592\ m^2$

For the purpose of investigating the PV module performance, the measurements were taken during a clear day from 8:00 a.m. to 4:30 p.m. in October 2019 and experimental data was recorded every half an hour. The measured data including slope irradiance, ambient temperature, cell temperature, voltage, current, and wind speed were of importance during the testing time and to be thoroughly considered. Solar radiation intensity has been measured by a pyranometer (RK200-03) at the same tilt angle of the PV module. Current and voltage readings for the module were monitored by two multimeters to provide detailed information about the PV module's power output. Anemometer was used to measure wind speed. To measure cell temperature, a thermocouple was installed by thermal tape on the front surface of the PV module. Another thermocouple was used to measure the ambient temperature. All the data were acquired by using the data logger and signals converter device. The layout of the experimental set-up with different instrumentations is shown in Figure 2.

2.2. Mathematical Modelling

2.2.1 Thermal model

It is acknowledged that the efficiency of a photovoltaic decreases with an increase in solar cell temperature, which plays a dominant role in the PV cell performance. In this study, the following assumptions are applied to compute the cell temperature [8].

- The radiation loss from the back-side of the PV module to the ground is ignored.
- Heat losses by conduction are also neglected.
- The temperature on the PV surface is considered to be uniform.

Thermal losses from the PV module to its environment are significant, restricting the thermal performance of the photovoltaic thermal system. Such losses may be correlated with all modes of heat transfer (i.e. conduction, convection, and radiation). In the current research, thermal losses are proposed and illustrated through the so-called thermal network diagram for a photovoltaic system as depicted in Figure 3.

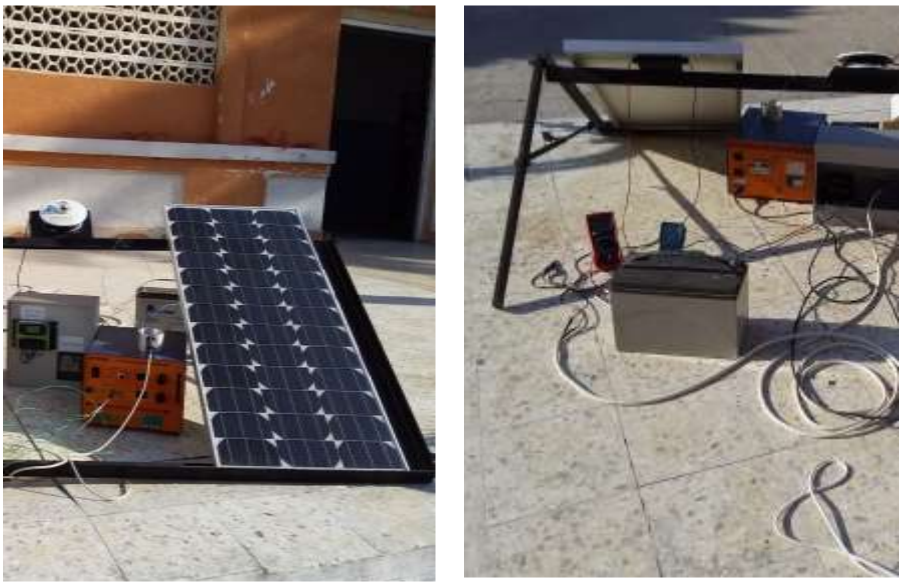

Figure 1: Photograph of the experimental setup.

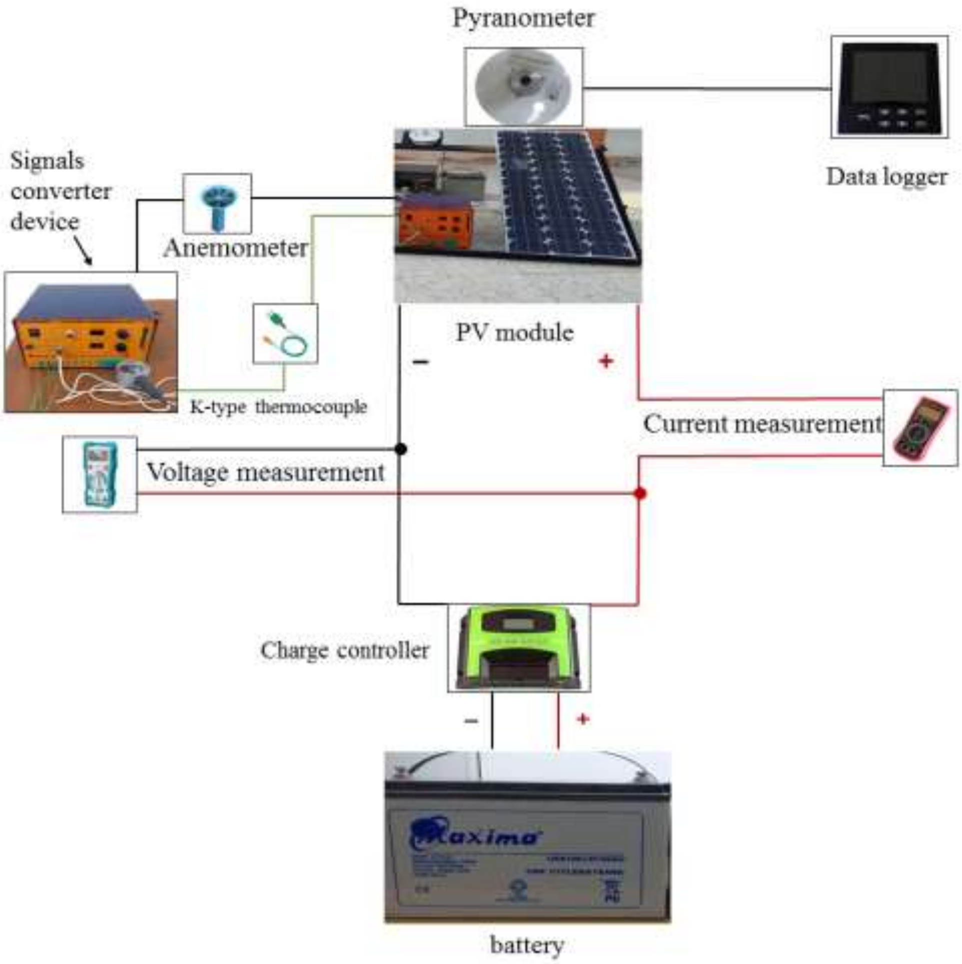

Figure 2: Layout of the experimental setup.

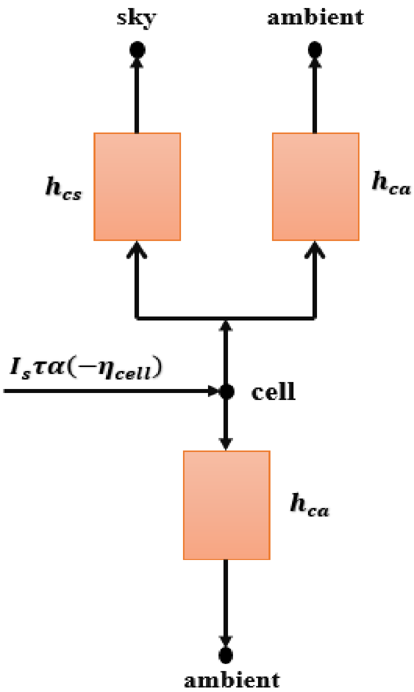

Figure 3: Thermal losses represented by the thermal network diagram for a photovoltaic system.

The model of the PV module was developed using a MATLAB program, which was mainly originated according to an energy balance technique given by

$$G_S\tau\alpha\,(1-\eta_{cell}) = \left(h_{cs}\times T_c - h_{cs}\times T_{sky}\right) + (h_{ca}\times T_c - h_{ca}\times T_a) \qquad (1)$$

where $\boldsymbol{T_c}$ is the cell temperature, $\boldsymbol{T_{sky}}$ the sky temperature, $\boldsymbol{T_a}$ the ambient temperature, $\boldsymbol{h_{cs}}$ the heat transfer coefficient from the solar cell to the sky and $\boldsymbol{h_{ca}}$ is the surface heat transfer coefficient for the front and back surfaces of the PV module, $\boldsymbol{G_S}$ is slope irradiance, $\boldsymbol{\tau}$ is the transmittivity, $\boldsymbol{\alpha}$ is the absorptivity.

The equivalent temperature of the sky is determined by a relationship being reported in [9]:

$$T_{sky} = 0.0552\times T_a^{1.5} \qquad (2)$$

The coefficient of convective heat due to the wind is calculated in the following relationship[8]:

$$h_{ca} = 5.67 + 3.8v \qquad (3)$$

According to Cole et al [10] , $2\times\boldsymbol{h_{ca}}$ is the heat exchange coefficient corresponding to the total surface area of the module i.e. two times the surface area corresponding to $\boldsymbol{h_{ca}}$ because the heat is lost by the two faces of the PV module.

The radiative heat transfer coefficient $\boldsymbol{h_{cs}}$ is calculated by the equation following:

$$h_{cs} = \frac{\sigma \varepsilon_c (T_C^4 - T_{sky}^4)}{T_c - T_{sky}} \quad (4)$$

where σ is the Stefan Boltzmann constant and ε_c is the emissivity of the PV module cover.

The $\boldsymbol{T_c}$ temperature was initialized by using the following proposed formula:

$$T_{co} = T_a + 10$$

$$T_c = \left\{ \frac{G_S\, \tau\alpha\, (1 - \eta_{cell}) + (h_{cs} \times T_{sky} + 2 \times h_{ca} \times T_a)}{(h_{cs} + 2 \times h_{ca})} \right\} \quad (5)$$

To solve the above equations, an iterative scheme is applied using an initial value of Tc = 10°C -above the dry-bulb temperature- is assumed. During the iterative process, the new value of Tc (i.e. T_{co}) is calculated by Eqns. (4), (5) at each new iteration. This newly determined value is then compared with the Tc value of the previous iteration step hence to examine the convergence. If the absolute difference between Tc and T_{co} is met within an acceptable threshold of (<0.01), the iterative process will be stopped. Otherwise, the Tc value will be computationally updated with a new T_{co} value and the iterative process is repeated until convergence is met. The computer program is outlined through a flowchart presented in Figure 4.

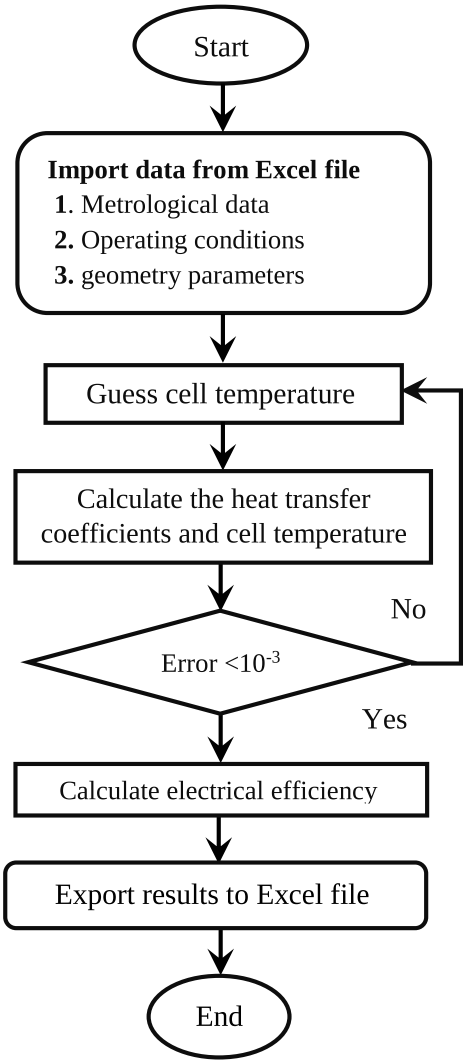

Figure 4: Flowchart of the used computer program for analysis of PV module

2.2.2. Electrical model

- The simple relationship of power for a photovoltaic module is

$$P = I \times V \quad (6)$$

- The electrical efficiency is calculated as follows:

$$\eta = \eta_{ref}\left[1 - \beta_{ref}(T_c - T_{ref})\right] \quad (7)$$

where η_{ref} is the reference efficiency at standard conditions, β_{ref} is the thermal coefficient of cell efficiency which is dependent on materials of PV module, here the value is taken 0.00045/K for silicon cell [11].

3. Results and discussion

3.1. Experimental results

The experimental work has been conducted from 8:00 a.m. to 4:30 p.m. for a particular day of October 2019. The experimental results obtained for the PV module are shown in Figs. 5 and 6. The hourly variation of ambient temperature, cell temperature, solar irradiance, and power output obtained from the experimental work during the test day for the PV module are shown in Figures 5.and 6. It can be observed from figures that both the cell temperature, slope irradiance and electrical power output from the PV module reach highest at 11:30, with values of 64.7 °C, 968 W/m² and 47.73 W, respectively, whilst the ambient temperature is about 36 °C.

3.2. Validation

The calculated value from the present developed model of cell temperature has been validated by their corresponding experimental value. In order to compare the calculated result with those measured, accuracy was assessed using well-known statistical indicators [12]: the coefficient of determination (R^2) and the root mean square error (RMSE). They are defined as

$$R^2 = \frac{\sum_{i=1}^{n}(c_i - c_a)\,.\,(m_i - m_a)}{\sqrt{[\sum_{i=1}^{n}(c_i - c_a)^2].[\sum_{i}^{n}(m_i - m_a)^2]}} \quad (8)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(c_i - m_i)^2} \quad (9)$$

where c_i, m_i, c_a and m_a are the ith calculated value, the ith measured value, the average of the calculated value and the average of the measured value, respectively.

The experimental versus calculated values of cell temperature during the test day for the PV module is shown in Figure 7. According to this figure, it is found that there is a good concordance between the experimental and the calculated results with a coefficient of determination (R^2) = 0.9996, and the Root mean square error (RMSE) = 0.582.

3.3 .Effect of cell temperature on PV cell electrical efficiency

The hourly variations of the electrical efficiency and cell temperature for the PV module during the test day are shown in Figure 8. It can be seen from this figure that electrical efficiency decreases with increasing cell temperature. The minimum electrical efficiency reaches 10%, corresponding to the highest cell temperature.

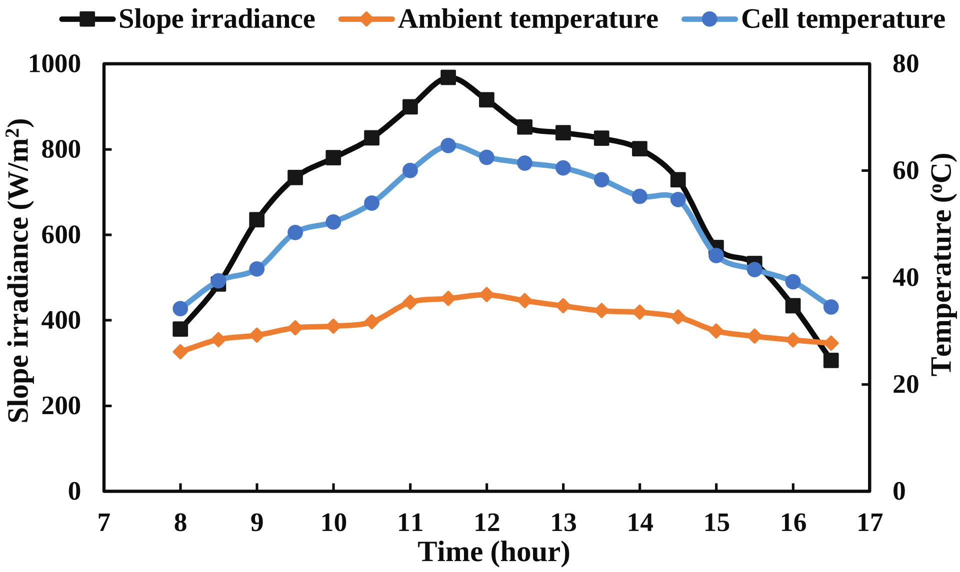

Figure 5: Variation of ambient temperature, cell temperature, and slope irradiance during the test day.

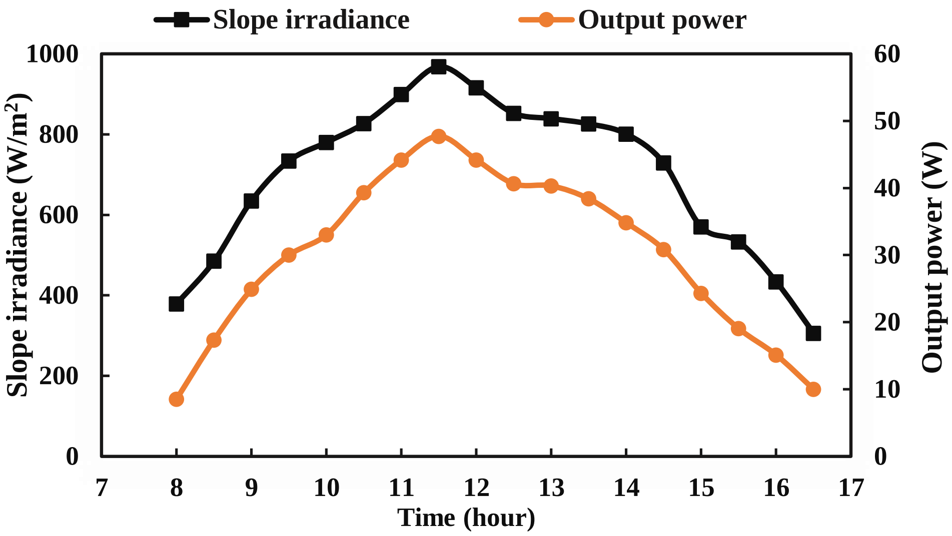

Figure 6: Variation of slope irradiance and power output during the test day.

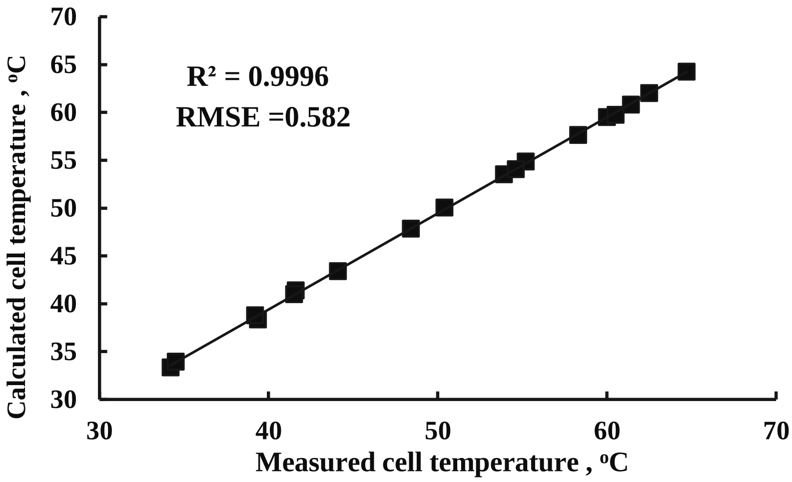

Figure 7: Experimental versus calculated values of cell temperature during the test day.

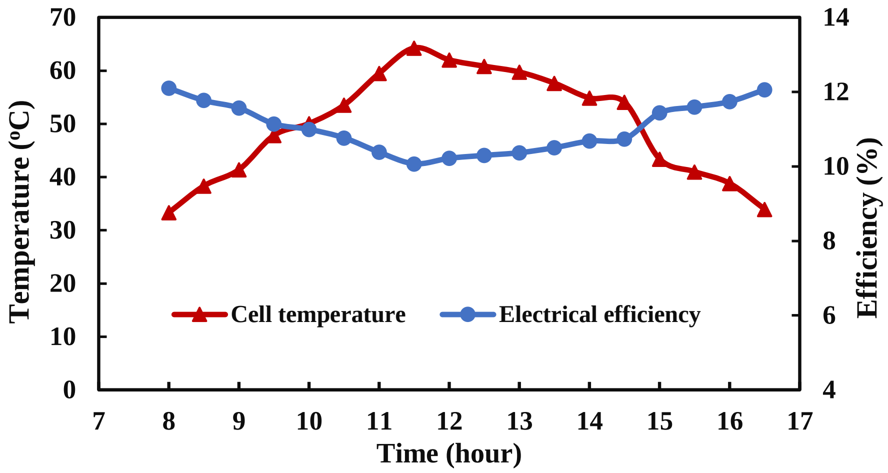

Figure 8: Variations of the electrical efficiency and cell temperature during the test day.

4. Conclusions

As the objective of the current research work was to evaluate the performance of a monocrystalline module mathematically and experimentally. Thus, concluding remarks were drawn from the present investigation as follows:

- A mathematical model based upon MATLAB software was developed limited to the scope of the current study.
- A set of experiments were carried out based in an in-house PV cell being established at the laboratory of energy based in the faculty of engineering – Derna.
- Cell temperature, slope irradiance, ambient temperature, wind speed as well as power output were all merely measured.
- The calculated cell temperature was validated against obtained experimental data. It is, subsequently, found to be in very good agreement with their experiments.
- The results prove that the electrical efficiency of the PV depends upon cell temperature, as the electrical efficiency decreases with the increase on cell temperature magnitude.

5. References

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