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The Influence of the Cell Temperature on the Performance of Mono and Poly-Crystalline Silicon Solar Modules

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ABSTRACT

In this research paper, it has been studied the influence of the temperature of the cell on the performance and behavior of two types of modules, which are mono-crystalline silicon (mc-Si) and poly-crystalline silicon (pc-Si) solar modules. The experimental work has been achieved under the outdoor conditions, where the range of cell temperature is between 20 and 60 °C. It was applied three different values of solar radiation [500, 750, and 1000W/m^2 (standard condition, where cell temperature of 25 °C, solar irradiance of 1000 W/m², and air mass AM 1.5)]. All tests are achieved under the Iraqi weather conditions in the city of Baghdad. It was computed the temperature coefficients for each module and during any time during the experiment. It was found that the open circuit voltage decreased with -0.0912 V/ºC and -0.07 V/ºC when using the pc-Si module and mc-Si, respectively. While, the short circuit current increased slightly with 4.4 mA/ºC and 0.3 mA/ºC corresponding to the pc-Si and mc-Si, respectively. Finally, the lowest drop in output power was found when using the pc-Si module (-0.0915 W/ ºC), and the highest drop when using the mc-Si module (-0.1353 W/ ºC).

1. Introduction

Solar energy is considered one of the most important types of renewable energy due to its availability most days of the year. Currently, most of the energy companies work intensively using different approaches in order to meet the requirements of the global energy market, in addition to overcoming the challenges in this field. The main challenges are represented by increasing the efficiency and reducing the cost of solar cells. The main target of the solar cell is to convert the absorbed solar radiation into electrical energy based on the photoelectric effect.

It can be classified the solar cells into different types or families, one of them is the silicon solar cell. The silicon solar cell family contains many kinds, such as Monocrystalline silicon (mc-Si). Where, this type was developed in the early stage of production. The mc-Si was used widely in the world due to its advantages, such as low cost for maintenance, very low noise, reliability, and no negative effect on the environment (Cuce et al., 2013; Cai et al., 2012; Solanki, 2013; Sharma et al., 2014).

The industrial sector has directed to use solar photovoltaic (PV) energy to produce energy in large quantities due to its low cost and appropriate efficiency. There are also other advantages of using solar photovoltaic (PV) energy, which are low emission values and a relatively long-life span between 20 to 25 years. Currently, some countries, such as Colombia, have been adopted as the main source for providing the necessary energy in various fields (UPME, 2015).

The working principle of solar cells is to convert photons into DC electric current based on thin films using silicon. Where the voltage difference is generated with small ranges (0.5 to 0.8 volts). The efficiency of solar cells depends on the quality of the materials and the manufacturing processes. It can be considered that the Monocrystalline and Polycrystalline silicon are the common types of Solar Modules. The range of efficiencies for these types is between 13 % and 17 % under the standard test conditions (STC). Most of the time، it is difficult to provide the standard conditions for solar cells, because the actual conditions are different from (STC), and they vary greatly due to the geographical location and climatic conditions of the location of installed solar cells (Fuentes et al., 2007).

In order to reduce emissions as a result of the use of traditional energies, there has been a major move to take advantage of solar energy because of its available for free (El-Shaer,2014).

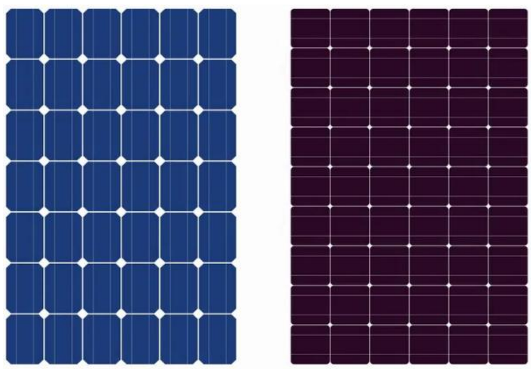
In order to utilize solar energy, it should be converted to usable form in the different applications. Where, it was used the solar modules to convert the solar energy into electrical energy. The main parts of the Solar module are the solar cells (PV), cells of Photovoltaic. Where it can be used to convert sunlight into DC current (electrical energy) according to the phenomenon of photovoltaics.

The process of ionization the atoms that existing in the silicon as a result of the Light that contains different wavelengths. Where the internal field is generated by the junction between positive charges (holes) and negative charges (electrons). The positive charges are attracted to the P-layer, and the negative charges are attracted to the N-layer. Most of the opposite attracted charges are only able to combine through outer circular through an external circuit due to the presence of the potential energy partition present. It can be classified the main types of PV, into three kinds which are Amorphous Silicon, Thin Film technology, and Crystalline Silicon (Mono and Poly-Crystalline), (Cuce E, *et. al.*, 2013). Recent studies report that the performance and efficiency of monocrystalline and polycrystalline PV modules are strongly affected by real operating conditions, particularly temperature variations and partial shading (Kumari et al., 2024; Lesmana & Dewantara, 2024; Lakhan & Mathur, 2024; Ouédraogo et al., 2021 and Ali et al., 2024).

In this research paper, the main aims are to investigate deeply the effect of cell temperature on the behavior and performance of the Poly-Crystalline Silicon and Mono-Crystalline Silicon Solar Modules with Cell Temperature. It was used the experimental work to achieve these tasks during 5 months (from 1st of January until 30th of May). Where the daily period started from 9 Am to 16 PM.

2. Materials and Methods

In this research paper, it was selected the experimental approach to examine two different solar PV modules in the surrounding environment in Baghdad city, Iraq (latitude of 33.33°N and longitude of 44.43°E). All measurements were done at the Energy Engineering Department / University of Baghdad. Where, the period of experimental work started from 1st of January to 30th of May 2024. Two different solar modules have been examined, which are from the crystalline silicon family (poly-crystalline silicon and mono-crystalline silicon). Figure 1 shows the two PV modules that were used in the experimental work. Table 1 lists the modules specifications as provided by the manufacturers at reference conditions STC (Standard Testing Condition; solar radiation 1000w/m^2 and environment temperature 25 ºC).



(a) mc-Si solar module. (b) pc-Si solar module

Figure 1. The selected photovoltaic solar modules.

Table 1. Specification of (mc-Si) and (pc-Si) under STC.

	mc-Si	Pc-Si
Area, m^2	0.26	0.46
V_{oc}, V	22	23
I_{sc}, A	1.9	1.7
V_m	17	17.45
I_m	1.76	1.375
P_m	30	26
N_s	36	40

The instruments used in this work are:

- Digital thermometer TPM-10 is used to measure the temperature.
- Data logging solar power meter (TES1333R) is used to measure the entire solar radiation.
- Solar module analyzer (PROVA 200A) to examine the characteristics of (V_{oc}, I_{sc} , V_m , I_m and P_m), the efficiency and Fill Factor for the solar panel.
- PROVA 200A to generate the I-V curve by changing an internal resistive load with time from zero to infinity. Therefore, for each value of load, there is a value for voltage and current from (0, I_{sc}) to (V_{oc},0). When finding the vector of module output power by multiplying the I-V vectors. Then, it can be tracing the maximum point of the power vector to find the value of maximum power. The respective values of voltage and current specify the point of maximum power. The device has an option to set up the values for both solar radiation and the area of the solar module.
- Schematic representation of the measuring devices (Figure 2):
- Temperature sensor (TPM-10),
- Solar power meter (TES-1333R),
- Solar Module Analyzer (PROVA 200A).

(a)Temperature sensor -TPM-10.

(b) solar power meter TES-1333R.

(c) PROVA 200A Solar Module Analyzer

Figure 2. The Measuring devices that used in the experimental work.

It was placed both of mono-crystalline and poly-crystalline solar modules side by side on a specially designed stand of 2m height to support the PV modules and tilted at 33° (local latitude of Baghdad city) above the ground horizon. A Multimeter was connected in series with each of the solar panels to measure the required data.

A laptop computer was connected to the PROVA 200A to transfer the data directly as an Excel spreadsheet. The experiment time during all five months was started from 9:00 AM to 16:00. The experimental work focused on studying the temperature and effect of the solar radiation, which should be kept constant at a certain level, but sticking to one level restricts and limits the experimental data because of the time issue or weather instability. In order to cover as much as possible of the temperature range, and ensure high accuracy. The measurements were done for two solar radiation levels (500, 750W/m^2) added to 1000W/m^2.

3. Result and Discussions

3.1 Temperature Measurements

Figure 3 illustrates the average (monthly) values of temperature for (mc-Si), (pc-Si) solar modules and the ambient temperature. Where, the daily experiment period started from 9 AM to 1 PM, and from the 1st of January until the 30th of May, 2024.

Based on the results of tests, it was found that the heating behavior for the selected modules are approximately similar during the period of tests. The temperature for the poly-crystalline module (large area) was above the surrounding temperature by 20ºC. In spite of that, the mono-crystalline silicon module has less area than the poly-crystalline silicon module, but there is a small difference in temperature between them.

Also, there is another difference (factor) between the selected modules, which is the module encapsulation and lamination. In this work, the poly-crystalline silicon modules are made of two glass layers for front and back surfaces with aluminum framing, and a mono-crystalline silicon module made with a front glass thin layer and a back polymer (Tedlar film) material. Where it can be improved thermal stability and durability, in addition to enhancing the rigidity and heat dissipation for the aluminum frame when using the dual glass structure.

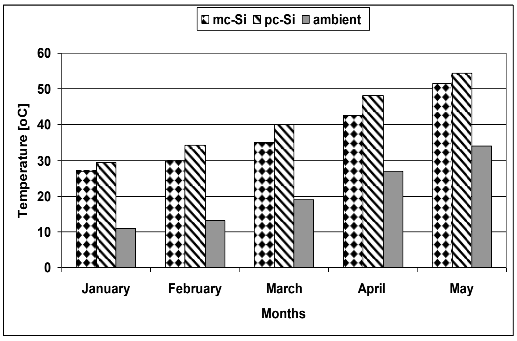


Figure 3. The average temperature using different modules.

3.2. Temperature Coefficients of the Solar Modules

As mentioned in section 2, three different solar radiations were selected to study the collected data about the effect of increasing the temperature. Also, because it was hard to get low temperature degrees at 1000 W/m^2, it was applied the following equations to lift up the data from any level to another at a specific temperature. Where these equations are used by many researchers [Khezzar et al. (2009), Villalva et al. (2009), Duffie and Beckman (2013), Hansen (2013)]:

$$I_2 = I_1 \frac{G_2}{G_1}; \; V_2 = V_1 + a\, ln\left(\frac{G_2}{G_1}\right) \quad (1)$$

Where I can be either I_{sc} or I_m, and V is either V_{oc} or V_m, are the modified ideality factor and the subscripts 1 and 2 refer to the radiation levels.

In order to analyze the data of the scatter plot that was used to represent the relation of V_{oc}, I_{sc} and P_m against the module temperature. It will be seen that there is a linear relation between them. Therefore, it was used the linear regression to find the linear equations of the current and voltage with temperature. The linear equations were found based on the fitting process by Microsoft Office / Excel 2019. Where, TCO is the temperature coefficient, which is equal to the slope of the straight line found by the linear fitting.

3.3 Temperature Coefficient of Open-Circuit Voltage

In order to present the full details of the performance of Photovoltaic Modules, it was measured the open circuit voltage of the solar module at the end of the IV curve using PROVA 200A. Where the resistant load was infinity. It was found at high radiation levels; there is a very small change in the magnitude of the open circuit voltage. wherever the relation between the open circuit voltage and the solar radiation is logarithmic. It can be written the variation of voltage (V_{oc}) with temperature according to the following form (Khezzar et al., 2009),

$$V_{oc} = a\, ln\left(\frac{I_{sc}}{I_o} + 1\right) = \frac{A\ N_s\ k_B\ T_c}{q}\, ln\left(\frac{I_{sc}}{I_o} + 1\right) \quad (2)$$

Based on the achieved analysis, it was found that the relationship between the open circuit voltage and the inverse saturation current can be represented as a logarithmic relationship. The results showed the values of voltage ratio decreased with12% and 17% when the temperature changed from 22 ºC to 63 ºC for mc-Si and pc-Si. Where the voltage ratio is equal to the open circuit voltage (measured) divided by the voltage magnitude under the STC. The main reasons behind the differences in the results of the voltage ratio are the heat transfer, module construction, and thermal losses.

3.4. Temperature Coefficient of Short-Circuit Current

It was used PROVA 200A to measure the short circuit current of the solar module at the initial period for the I-V curve, where the resistance load is zero. Where the short circuit current is linearly proportional with the solar radiation, and occasionally it is considered to be equal to the photo-generated current.

The results showed that there are more fluctuations around the linear regression fitting line than in the results of the open circuit voltage (Figure 4). These fluctuations occurred as a result of the instability and the variation of the incident solar radiation around 1000W/m^2 with $\pm$5W/m^2. Also, this was the main reason for take large number of data to increase the resolution of the plot.

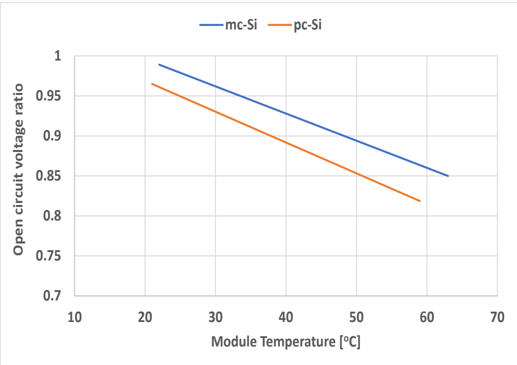


Figure 4. The variation of open circuit voltage ratio with module temperature.

The results were presented using a scatter plot to prove that the relationship is a linear regression equation. Where the slope represented by the TCO of I_{sc} ($\mu_{I_{sc}}$). In general, it was found that there is little increment in the magnitude of short circuit current when with the temperature increased around 0.3m A/ºC for mc-Si and 4.4 mA/ºC for pc-Si. It was found that Ploy-crystalline silicon has a positive coefficient higher than monocrystalline silicon, as shown in Figures 5 and 6.

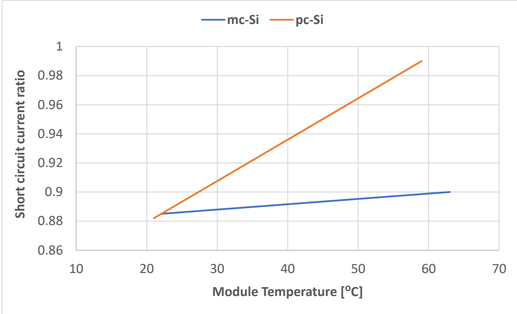


Figure 5. Short circuit current ratio vs. module temperature for the two modules.

3.5. Temperature Coefficient of Maximum Power Output

It was used PROVA 200A to measure the output power (maximum) for both solar modules. While it was tracked as the largest point on the PV curve.

Figure 6 shows the performance ratio PR (monthly average) during the five months (January, February, March, April, and May). Where this value is equal to the maximum power under any specific condition divide by the power under Standard Test Conditions. It can be noticed that the performance ratio PR of the (mc-Si) in the month of May decreased by about 15% of its value in the month of January. It can be expected that the percentage reduction in the performance ratio PR to reach higher than 20% in the summer months (July or August).

While the pc-Si produced 90% of its power at STC in the month of January, but in May it was decreased to be 70%. It can be noticed that the high agreement between the obtained results and the results of other researchers who used different approaches, which confirms the validity of the approach used to obtain the results.

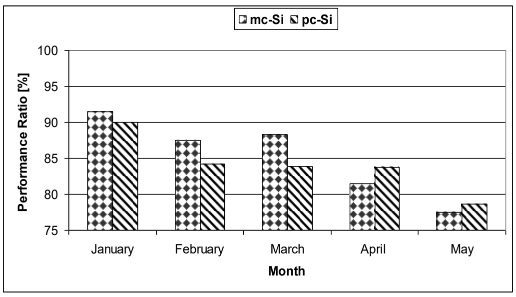


Figure 6. The monthly average performance ratio.

Table 2. The verification case study for the maximum power drop

	Current	Ref	Ref No.	Diff%
(mc-Si) W/ºC	0.164	0.1742	Shaari et al. (2009)	5.8
(mc-Si) % ºC	0.61	0.65	Makrides et al. (2009)	7.7
(pc-Si) W/ºC	0.225	0.2525	Shaari et al. (2009)	10.8
(pc-Si) % ºC	0.352	0.331	Shaari et al. (2009)	6.3

4. Conclusions and Remarks

It can be summarized the conclusions based on the present work as follows:

1. It was obtained that the wind speed has a slight influence on the temperature of the module. Based on the obtained results, the variation of the module's temperature with the ambient temperature during the test period. It was found during most of the experiment period that the temperature of the module is higher than the ambient temperature by (10-20 ºC). Where the module temperature reached about 60ºC in May.
2. It can be considered that the selection of the type of PV is the most essential factor to specify the amount of the energy obtained.
3. It was found that the values temperature coefficients are accepted and it located within the range of the existing data in the literature and the manufacturer's datasheets.
4. Both types of photovoltaic modules (mc-Si and pc-Si) are suitable to work under the conditions of low temperature, because their temperature coefficients are high relatively. But it should be taken into consideration the efficiency and cost.
5. It can be neglected the resistances of parasitic internal, because they are affected little by temperature, where this effect can be ignored.
6. Finally, it was found for the crystalline modules that there is no significant difference between the results of the 4-parameter model and the 5-parameter model. The reason behind this is the high magnitude of the shunt resistance. Therefore, it can be relied on the results of the 4-parameter model in order to reduce the complexity of the solution.

Abbreviations

V_{oc}	Open-circuit voltage of the PV module, V	
I_{sc}	Short-circuit current of the PV module, A	
V_m	Voltage at maximum power point, V	
I_m	Current at maximum power point, A	
P_m	Maximum output power of the PV module	W
Ns	Number of cells connected in series	–
ή	PV module efficiency	%
G	Solar irradiance	W/m²
Tc	Cell temperature	°C
FF	Fill factor	–

Conflict of interest

The authors declare no conflicts of interest concerning this research.

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Author Contribution

Emad T. Hashim: Conceptualization, Methodology, Investigation, Formal Analysis, Writing – Original Draft.

Narjes Sadeq Katee: Data Curation, Validation, Investigation, Visualization.

Deghoum Khalil: Methodology, Formal Analysis, Software, Visualization.

Oday I. Abdullah: Supervision, Writing – Review & Editing, Project Administration, Validation.

Zhanbolat Lyazat: Resources, Data Curation, Investigation.

Meruyert Beisembekova: Resources, Data Curation, Writing – Review & Editing.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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