Temperature Effect on Power Drop of Different Photovoltaic Modules

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ABSTRACT

Solar module operating temperature is the second major factor affects the performance of solar photovoltaic panels after the amount of solar radiation. This paper presents a performance comparison of mono-crystalline Silicon (mc-Si), poly-crystalline Silicon (pc-Si), amorphous Silicon (a-Si) and Cupper Indium Gallium di-selenide (CIGS) photovoltaic technologies under Climate Conditions of Baghdad city. Temperature influence on the solar modules electric output parameters was investigated experimentally and their temperature coefficients was calculated. These temperature coefficients are important for all systems design and sizing. The experimental results revealed that the pc-Si module showed a decrease in open circuit voltage by -0.0912V/ºC while mc-Si and a-Si had nearly -0.07V/ºC and the CIGS has -0.0123V/ºC. The results showed a slightly increase in short circuit current with temperature increasing about 0.3mA/ºC ,4.4mA/ºC and 0.9mA/ºC for mc-Si , pc-Si and both a-Si and CIGS. The mc-Si had the largest drop in output power about -0.1353W/ºC while -0.0915, -0.0114 and -0.0276 W/ºC for pc-Si, a-Si and CIGS respectively. The amorphous silicon is the more suitable module for high operation temperature but it has the lowest conversion efficiency between the tested modules.

Key words: photovoltaic system, solar module, temperature effect, temperature coefficient

تأثير درجة الحرارة على انخفاض القدرة لأنواع مختلفة من الالواح الفوتوفولتائية

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الخلاصة

تمثل درجة حرارة الوح الشمسي العامل الثاني الاكثر تاثيراً في أداء المنظومات الشمسية الفوتوفولتائية بعد مقدار الاشعاع الشمسي. يقدم هذا البحث مقارنة اداء لاربع انواع مختلفة من الالواح الفوتوفولتائية : سيليكون احادي التبلور، سيليكون متعدد التبلور، سيليكون غيرمنتظم التبلور ونحاس انديوم (غاليوم) ثنائي السلينايد تحت الظروف المناخية لمدينة بغداد. تم التحقق عمليا من تأثير درجة الحرارة على مخرجات الالواح الشمسية وتم حساب معاملات درجة الحرارة والتي لها التاثير المباشر على تصميم وتقدير سعة المنظومات الفوتوفولتية. بينت النتائج العملية ان لوح السيليكون متعدد التبلور أظهر هبوط في مقدار فولتية الدائرة المفتوحة بمقدار 0.0912- فولت/درجة مئوية، بينما للوحي السيليكون احادي التبلور والسيليكون غير منتظم التبلور 0.07- فولت/درجة مئوية وللوح النحاس كان مقدار الهبوط حوالي 0.0123-

فولت/درجة مئوية. كما أظهرت النتائج زيادة طفيفة في تيار دائرة القصر مع زيادة درجة الحرارة بمقدار 0.3 ملي أمبير/درجة مئوية ، 4.4 ملي أمبير/درجة مئوية للوح السيليكون احادي التبلور،السيليكون متعدد التبلور على التوالي و 0.9 ملي أمبير/درجة مئوية لكل من لوحي السيليكون غير منتظم التبلور والنحاس. بالنسبة للقدرة العظمى الخارجة من اللوح الشمسي، لوح السيليكون احادي التبلور اظهر الانخفاض الاكبر من بين الالواح المدروسة بمعامل حرارة حوالي 0.1353- واط/درجة مئوية بينما كان الانخفاض 0.0915-،0.0114- و 0.0276- واط/درجة مئوية للوح السيليكون متعدد التبلور، السيليكون غير منتظم التبلور ولوح النحاس على التوالي.

كلمات رئيسية: النظام الفوتوفولتائي، اللوح الشمسي، تأثير درجة الحرارة، عامل درجة الحرارة.

1. INTRUDUCTION

Nowadays we get about 80% of the supplied energy is from depleted pollutant energy sources, e.g. fossil fuels. The environment damaged by the emissions currently generated by the use of fossil fuels such as serious environmental problems e.g., greenhouse effect, acid rain and ozone layer depletion, which are irreversible, **Dincar, 2003**. Recently, the enormous consumption of fossil fuel resulted in great interest to develop renewable energy sources such as solar energy. Photovoltaic power is a well-known technology and has lately experienced rapid growth over the last twenty years.

The solar cell is a p-n semiconductor junction exposed to sunlight, and generate electrical direct current. PVs have several advantages such as: no environmental pollution, high reliability, no noise and low maintenance cost. PV systems represents one of the most promising means of maintaining our energy intensive need. Like any other solar energy technology, PV system depends mainly on the amount of the incident solar radiation. In the other hand, the operating temperature of the PV cell has a noticeable influence on the performance of the PV system.

Solar photovoltaic cells like to be kept cool – they perform very well in strong winter sunshine. But Solar cells convert around 80% of absorbed sunlight into heat which gets trapped in the module and increases its operating temperature by as much as 20-30ºC above ambient **Mattei et al., 2006.** Thus it can reach 70°C or more in hot climates, Building integrated photovoltaic (BIPV), Concentrated photovoltaic (CPV) systems. Solar power Systems designers make sure to permit an effective ventilation and cooling to remove the heat as much as possible.

The problems of PV in Iraq were various natural parameters such as solar irradiance, ambient temperature, wind speed, and relative humidity. Iraq has a dry hot climate dominated in summer from March to November. Iraq is located near the equator where day length in summer lasts for 12-14 hours with a bright sunshine of 6-8 hours and monthly mean temperature is 40-50^{o}C. In such a climate, the working temperature of photovoltaic (PV) modules was measured as high as 75^{o}C.

In literature, it is well documented that the electrical efficiency decrease with an increase in the working temperature of PV module. Many researchers have investigated that influence in a controlled environment using a sun simulator and/or environmental chamber. Other authors made their experiments under outdoor exposure for more realistic behavior and actual operation environment. In such experiments, all other variables for example, irradiance, wind speed, etc. are kept constant.

Many researchers have been examined the effect of temperature on different PV technologies. **Vokas et al., 2006,** showed the electrical efficiency of the PV panel reduces with temperature increases. **Makrides et al., 2009** evaluated the temperature influence of 13 PV modules of different types, which exposed to actual conditions in Stuttgart, Germany and Nicosia, Cyprus. The temperature coefficient for mono crystalline varied -0.353 to -0.456 %/ºC, for multi crystalline and amorphous silicon was -0.403 to - 0.502 %/ºC and -0.039 to - 0.461%/ºC respectively. **Makrides et al., 2012** analyzed the temperature effect on different PV technologies in Cyprus. The results showed that the highest average losses in annual energy yield were for mono crystalline silicon about 8% and 9% for poly crystalline silicon modules. For thin film technologies, the average losses were 5%. **Buday (2011)** studied the effect of solar radiation, module temperature and the incidence angle on PV module performance in United Solar Ovonic (USO), Michigan, USA. The PV modules were mc-Si, a-Si also CIGS. Mc-Si module had a power drop of -0.5%/°C, while -0.24%/°C and -0.0021%/°C for CIGS and a-Si respectively.

If the Cell temperature increased, this will increase the reverse saturation current of the PV cell which significantly decreases the open circuit voltage. Also, the band gap of the PV material decreases which leads to a small increase in photo generated current **Nelson, 2003.**

This paper presents a comparison study of experimental testing results for the performance of four different solar modules (mono-crystalline silicon, poly-crystalline silicon, amorphous silicon and copper indium gallium di-selenide) under natural sun and outdoor exposure in Baghdad for five consecutive months. The data collected were, the open circuit voltage, short circuit current and maximum power output with a wide range of ambient temperatures and keeping the incident solar radiation constant. Also, to investigate how the operating module temperature affect the performance of the used solar modules by presenting accurate temperature coefficients. The importance of these coefficients serves as a guide for the design and sizing of any PV systems in similar climates around the globe.

2. PHOTOVOLTAIC MODULE OUTPUT PARAMETERS

- The short-circuit current I_{sc}, is the current that flows through the external circuit when the electrodes of the solar cell are short circuited. The short-circuit current of a solar cell depends on the photon flux density incident on the solar cell, that is determined by the spectrum of the incident light. The I_{sc} depends on the area of the solar cell.
- The open-circuit voltage V_{oc}, is the voltage at which no current flows through the external circuit. It is the maximum voltage that a solar cell can deliver. The V_{oc} corresponds to the forward bias voltage, at which the reverse saturation current compensates the photo-current.
- The maximum power output,P_m is a key parameter since solar cells are used to produce electrical energy. When a solar cell is in an open-circuit or short-circuit state, it produces no power. At a defined point known as the maximum power point (MPP), a solar cell reaches its maximum power and thus $P = P_m$, $I = I_m$ and $V = V_m$ and this is clear in **Fig.1**. The power of a solar cell can produce at the MPP is always lower than the hypothetical value obtained by multiplying open-circuit voltage V_{oc} by short-circuit current I_{sc}. The ratio of P_m

to the product of V_{oc} and I_{sc} is a key measurement value of a solar cell, along with efficiency. This ratio is known as the Fill Factor, FF as shown in Eq.(1):

$$FF = \frac{P_m}{V_{oc} \quad I_{sc}} \quad (1)$$

- The fill factor is a measure of the squareness of the current-voltage (I−V) curve and it is an indicator for how the total internal electrical resistances effect the output current. A squarer curve indicates a greater maximum power and ideality. The closer this number is to 1 the more square the curve is but that is in an ideal non-exist case. Commercially available solar cells' fill factor ranges from around 60% to 80%, while this factor for lab cells can go as high as about 85%.

3. EXPERIMENTAL SETUP

Performance of four different (PV) solar modules are tested for five months from 1st January to 1st June 2015 under solar radiation of 1000 W/m^2. The four tested solar modules were mono-crystalline silicon, poly-crystalline silicon, amorphous silicon and copper indium gallium diselenide (see **Fig.2)**. The tests were done under the outdoor exposure in Baghdad city, at the energy laboratory / department of energy Engineering / Baghdad University. The electrical specifications of the modules at standard test conditions STC (solar radiation of 1000W/m^2, air mass AM 1.5, cell temperature 25°C) are presented in **Table 1**.

The four modules were placed on a steel holding stand which is not fixed to the ground but movable to follow the sun and keep the incident irradiance at the required value (1000 W/m^2) as shown in **Fig.3**. Solar module analyzer PROVA 200A is used to test the characteristics (V_{oc},I_{sc}, P_m, I_m and V_m), efficiency and Fill Factor of solar panel, also provides the IV and PV curves. Solar radiation was kept constant as possible, Solar Power Meter TES1333R is used to measure the total incident solar radiation (see **Fig.4**). The temperature of the modules was measured using digital thermometer (TPM-10) attached firmly to the back of the module. **Table 2** provides some of the technical specifications of the apparatus used in this study.

4. RESULTS AND DISCUSSION

The monthly average temperature of the four modules and the ambient are shown in **Fig.5** only for the time of doing the tests which was mostly between 9 AM to 1 PM for the months 1st January until 1st June, 2015. The pattern of how much the modules were heated does not change noticeably. The poly-crystalline module which has large area had nearly 20ºC above the ambient temperature while the temperature of the CIGS module with much smaller area was 15ºC. In June or July, it is expected that the tendency of the solar module still to heat up in the same and may be more because of the solar radiation and the shortage in wind speed. Usually in summer, in the afternoon time where the solar radiation reaches its maximum values, the recorded ambient temperature in those months may reach 50ºC, which means the solar modules may has operation temperature over 75ºC.

In general, current-voltage curve is the most informative curve for testing the performance of any PV module or array. **Fig.6** illustrates the effect of temperature on the I-V curve for the four modules. Two arbitrary selected temperatures showed great influence on the output voltage especially on open circuit voltage while small increase in the output current has been noticed. Another important characteristic curve is the P-V curve which is shown in **Fig.7**.

A scatter plot is used to analyze the data of the maximum power output, open circuit voltage and short circuit current against the operating module temperatures. The scatter plot shows that there is a linear relationship between them and the operating module temperature. The temperature coefficient (TCO) is defined as the amount of change in V_{oc}, I_{sc} or P_m with temperature. TCO considered to be equal to the slope of the linear equation as given in Eq.(2), the value of the slope of each straight line equation is provided by Microsoft Office/Excel using linear regression fitting option. the TCOs of P_m, I_{sc} or V_{oc} are symbolized as the following:

$$\mu_{V_{oc}} = \frac{\Delta V_{oc}}{\Delta T} \quad , \quad \mu_{I_{sc}} = \frac{\Delta I_{sc}}{\Delta T} \quad , \quad \mu_{P_m} = \frac{\Delta P_m}{\Delta T} \tag{2}$$

Temperature variation effects greatly on the output voltage as the open circuit voltage have a logarithmic relationship with the inverse of the reverse saturation current which is greatly influenced by temperature. In **Fig.8**, pc-Si module showed a decrease by -0.0912V/ºC while both mc-Si and a-Si had nearly the same $\mu_{V_{oc}}$ with nearly -0.07V/ºC and the CIGS has -0.0123V/ºC. The voltage ratio which is the measured open circuit voltage to the value at STC decreased from 98% to 85% when the temperature increased from 22ºC to 63ºC for mc-Si as presented in **Fig.9** on the other hand the pc-Si, a-Si and CIGS lost 17%, 11.5% and 14% respectively. The difference in $\mu_{V_{oc}}$ between the four modules is due to the value of the band gap energy characterized for each semiconductor and the recombination rates which greatly increased with temperature level. Another factor influence the decrease in open circuit voltage is the impurities and the deformation in the semiconductors crystals which represents a source of recombination. That explains why the pc-Si has the largest $\mu_{V_{oc}}$.

A scatter plot illustrates the linear relationship represented by a linear regression equation with the positive slope which shows slightly increase in $I_{sc}$with temperature increasing and this effect can be neglected as shown in **Fig.10**. Both ploy-crystalline silicon and amorphous silicon modules have larger $\mu_{I_{sc}}$ than the other two modules. This increasing of the output current is a result of the decrease in the band gap energy because the electrons gain thermal energy added to the electromagnetic radiation energy required to liberate the electrons from the valence band in the semiconductor material to the conduction band where the electrons are free to move and the current is generated. This increase is still relatively small and compensate slightly the drop in voltage which is clear in mc-Si module where the temperature effect I_{sc} on can be neglected.

In **Fig.11** the maximum power plotted against the module temperature. mc-Si showed a degradation of 0.1353W for each degree centigrade. pc-Si, a-Si and CIGS have μ_{P_m} of -0.0915, -0.0114 and -0.0276W/^{o}C respectively.

For better representation of how much does the module temperature decreases the output power, change the temperature coefficient in the form of the performance ratio (PR) which is defined as the output power produced at any condition to the power produced at STC:

$$PR = \frac{P_m \; at \; any \; operation \; conditions}{P_m \; at \; STC} \tag{3}$$

Fig.12 shows the monthly average performance ratio (PR). In May, the mono-crystalline silicon module lost about 15% of its power in January and it's expected to reach more than 20% in June or July. While the Amorphous silicon lost only about 5.5% in May.

The relation of the fill factor with module temperature is important to understand the effect of temperature on the combination of series and shunt resistances. The results is shown in **Fig.13**.The results showed that the fill factor decrease with about 0.1-0.17%/^{o}C for the different module. Which, means that the temperature does not have the great influence on the resistances.

Table 3 summarize the temperature coefficients of the aforementioned output parameters of the four PV module used in this work. **Table 4** introduces a comparison between the temperatures coefficients of maximum power obtained in this work with the a sample of other previous work such as **Radziemska, 2003, Virtuani et al., 2010, El-Shaer et al., 2014, Spataru et al., 2014, Dash** and **Gupta, 2015, Shaari et al., 2009, Makrides et al., 2009** and **Buday, 2011.** Those works studied the temperature effect on the performance of different types of PV modules.

5. CONCLUSION

From the previous results, the following points can be concluded:

- Regardless the wind speed effect on the module temperature, the module temperature on the most is greater by 10-15ºC than the ambient temperature.
- It is found from the analysis that a-Si and CIGS photovoltaic modules seem to be better option in hot climates considering the temperature loss to be minimum due to low temperature coefficient. However the choice still depend on the module efficiency, installation area and the capital cost.
- With temperature increasing, the reverse saturation current increases rapidly causes major drop in voltage rate. Also the photon generation slightly increases as a result of the reduction in band gap. Hence this leads to marginal changes in current.
- Fill Factor seemed to be has little dependence on the module temperature for tested modules. Therefore the temperature effect on the parasitic internal resistances can be neglected.

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NOMENCLATURE

A = diode ideality factor, dimensionless.

A_m= surface area of the solar module, m^2.

AM = air mass, dimensionless.

I = output current of the solar module, A.

I_m= current at maximum power point, A.

I_{sc}= short circuit current, A.

N_s= number of solar cells connected in series.

P_m= power at maximum power point, W.

PR = performance ratio, dimensionless.

T = temperature, ºC.

TCO = temperature coefficient, X/ºC where X=V, A or W.

V = output voltage of the solar module, V.

V_m= voltage at maximum power point, V.

V_{oc}= open circuit voltage, V.

μ_X = temperature coefficient of X where X is P_m , V_{oc} or I_{sc}.

Table 1. Solar module specifications (available from the manufacturer datasheet).

	mc-Si	pc-Si	a-Si	CIGS
Area [m²]	0.26	0.46	0.147	0.055
V_{oc} **[V]**	22	23	27	3.5
I_{sc} **[A]**	1.9	1.7	0.35	2.7
V_m **[V]**	17	17.45	18	2.8
I_m **[A]**	1.76	1.375	0.227	2.5
P_m **[W]**	30	26	5	7
Ns	36	40	18	6

Table 2. Measurement apparatus range, resolution and accuracy.

	Measuring range	Resolution	Accuracy
Solar module analyzer PROVA 200A			
DC voltage measurements	0-60 V	0.001-0.01 V	±1% ±(1% of Voc±0.09 V)
DC current measurements	0-6 A	0.1-1 A	±1% ±(1% of Isc±0.9 mA)
Solar power meter TES1333R			
Solar Radiation measurements	0-2000 W/m^2	0.1 W/m^2	±10 W/m^2 or ±5%. higher temperature induced error of ±0.38 W/m2/°C from 25°C
Digital thermometer TPM-10			
Temperature measurement	-50~70 °C	0.1 °C	±1 °C

Table 3. Temperature coefficients summary.

		mc-Si	pc-Si	a-Si	CIGS
$\mu_{V_{oc}}$	**V/ºC**	-0.0734	-0.0912	-0.0727	-0.0123
	%/ºC	-0.3336	-0.3965	-0.2693	-0.3514
$\mu_{I_{sc}}$	**A/ºC**	0.0003	0.0044	0.0009	0.0009
	%/ºC	1.58E-4	0.00251	0.00257	0.0003
μ_{P_m}	**W/ºC**	-0.1353	-0.0915	-0.0114	-0.0276
	%/ºC	-0.45	-0.352	-0.228	-0.39

Table 4. Maximum power degradation comparison with some previous studies.

	mc-Si		pc-Si		a-Si		CIGS	
	W/ºC	**%/ºC**	**W/ºC**	**%/ºC**	**W/ºC**	**%/ºC**	**W/ºC**	**%/ºC**
Our Results	**0.1353**	**0.45**	**0.0915**	**0.352**	**0.0114**	**0.228**	**0.0276**	**0.39**
Radziemska, 2003	-	0.65	-	-	-	-	-	-
Shaari et al., 2009	0.1742	-	0.2525	-	0.1036	-	-	-
Makrides et al., 2009	-	0.456	-	0.502	-	0.0461	-	-
Virtuani et al., 2010	-	-	-	-	-	0.13	-	0.36
Buday, 2011	-	0.5	-	-	-	0.0021	-	0.24
El-Shaer et al., 2014	-	0.25	-	0.14	-	-	-	-
Spataru et al., 2014	-	0.4546	-	-	-	0.04	-	-
Dash and Gupta, 2015	-	0.446	-	0.387	-	0.234	-	-

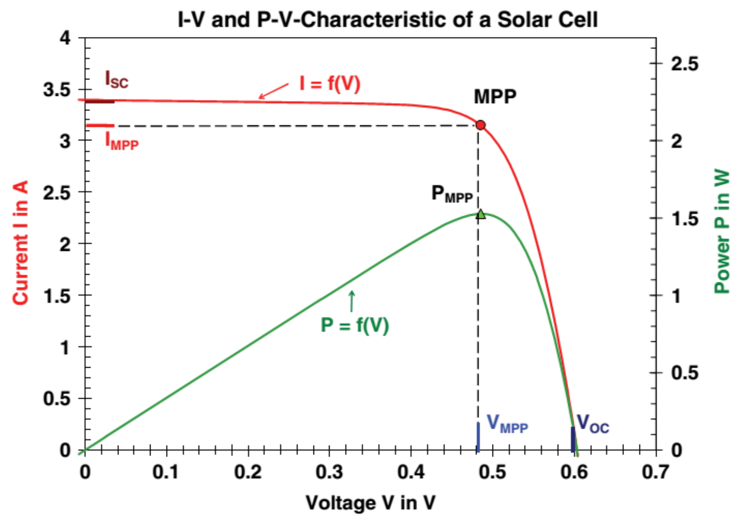

Figure 1. Characteristic curves I-V and P-V of a mono-crystalline silicon solar cell with a cell area of 102 cm^2.

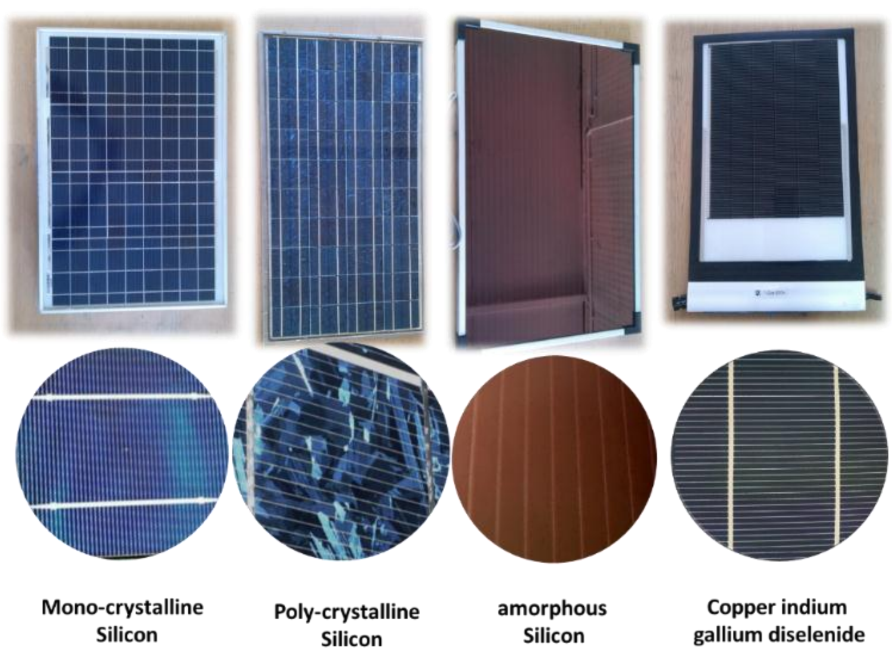

Figure 2. The four PV modules used in the test and close up views.

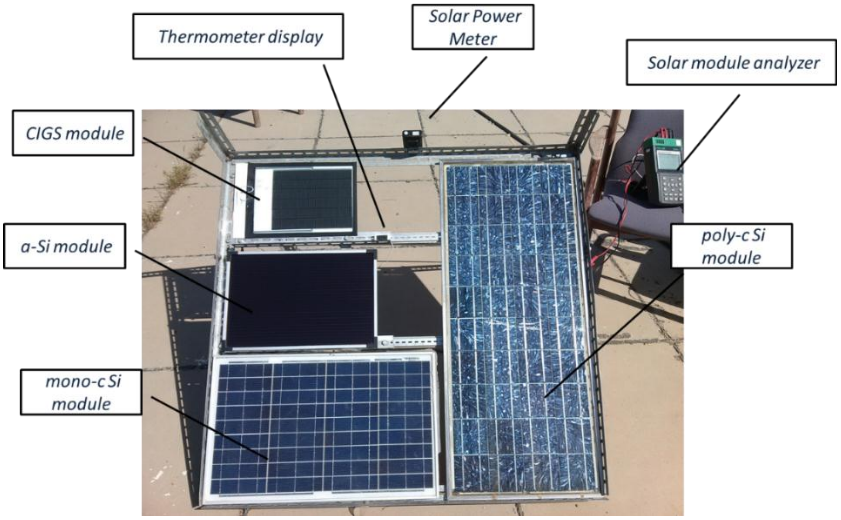

Figure 3. Experimental setup.

Figure 4. Measuring apparatus from left to right: solar module analyzer, Solar Power meter and digital thermometer.

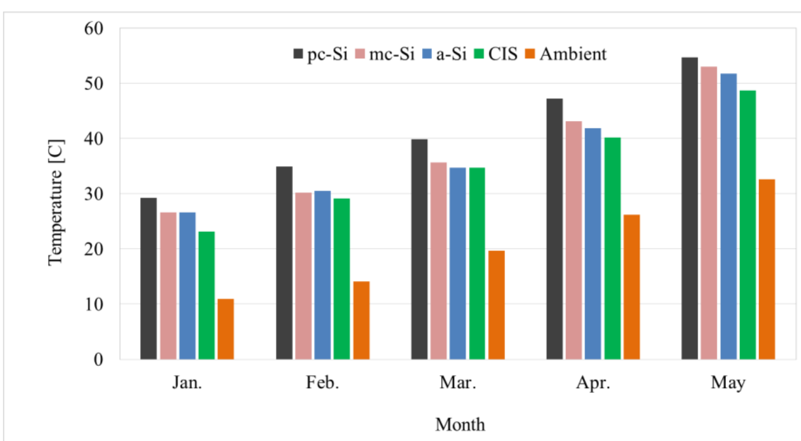

Figure 5. The monthly average temperature of the four modules and the ambient.

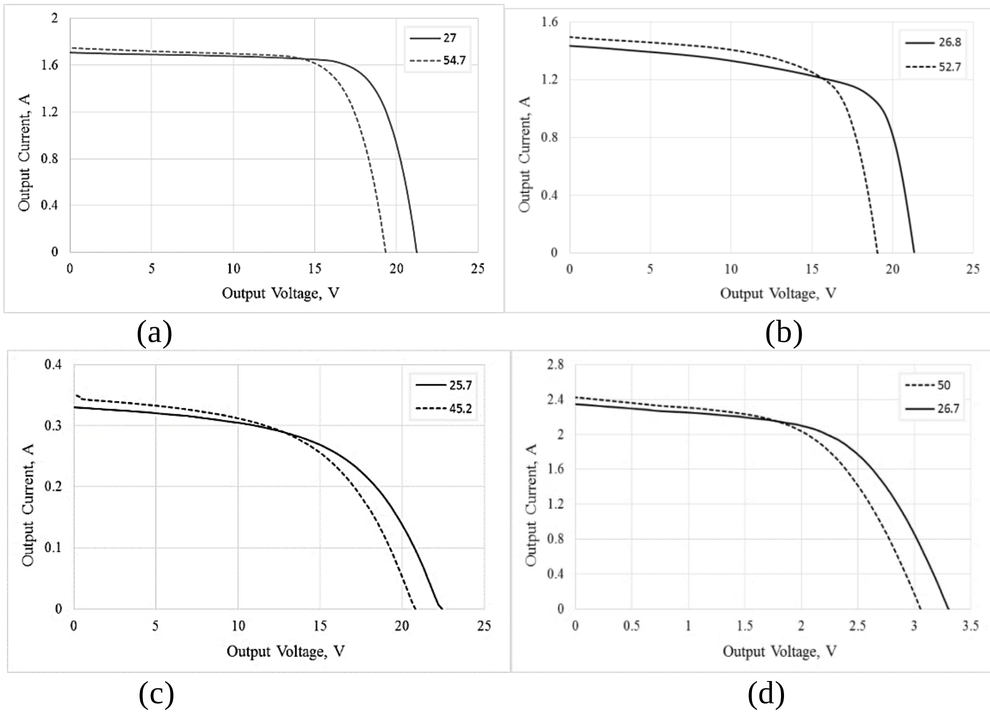

Figure 6. Current-Voltage curve at solar radiation of $1000 W/m^2$ and two different selected temperatures in °C, for (a) mc-Si (b) pc-Si (c) a-Si (d) CIGS modules.

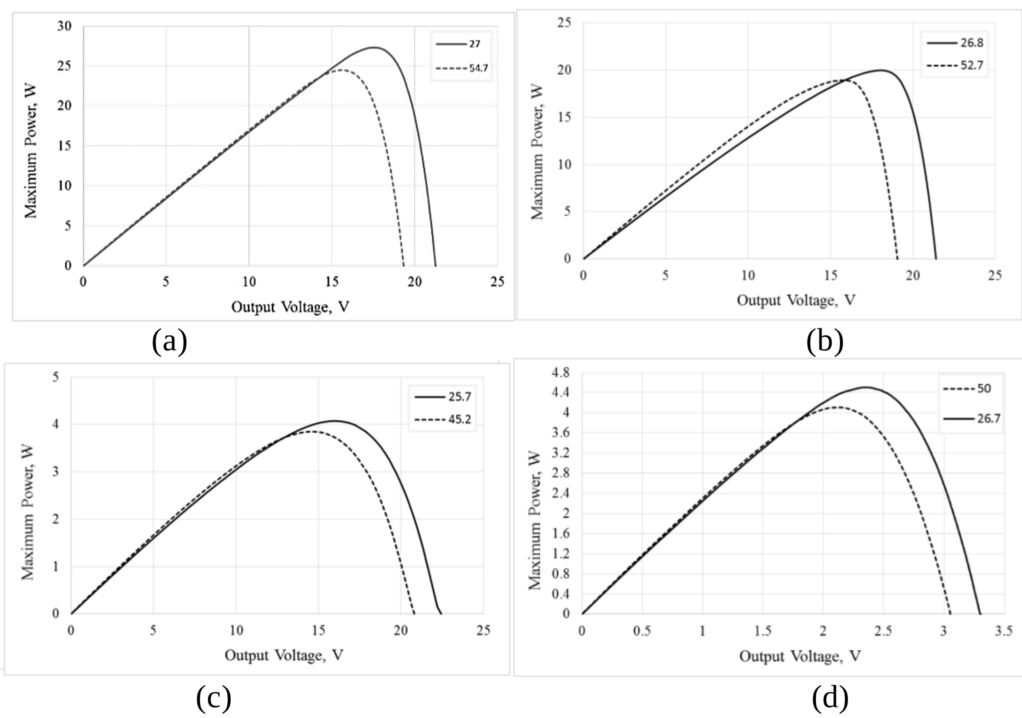

Figure 7. Power -Voltage curve at solar radiation of $1000 W/m^2$ and two different selected temperatures in °C, for (a) mc-Si (b) pc-Si (c) a-Si (d) CIGS modules.

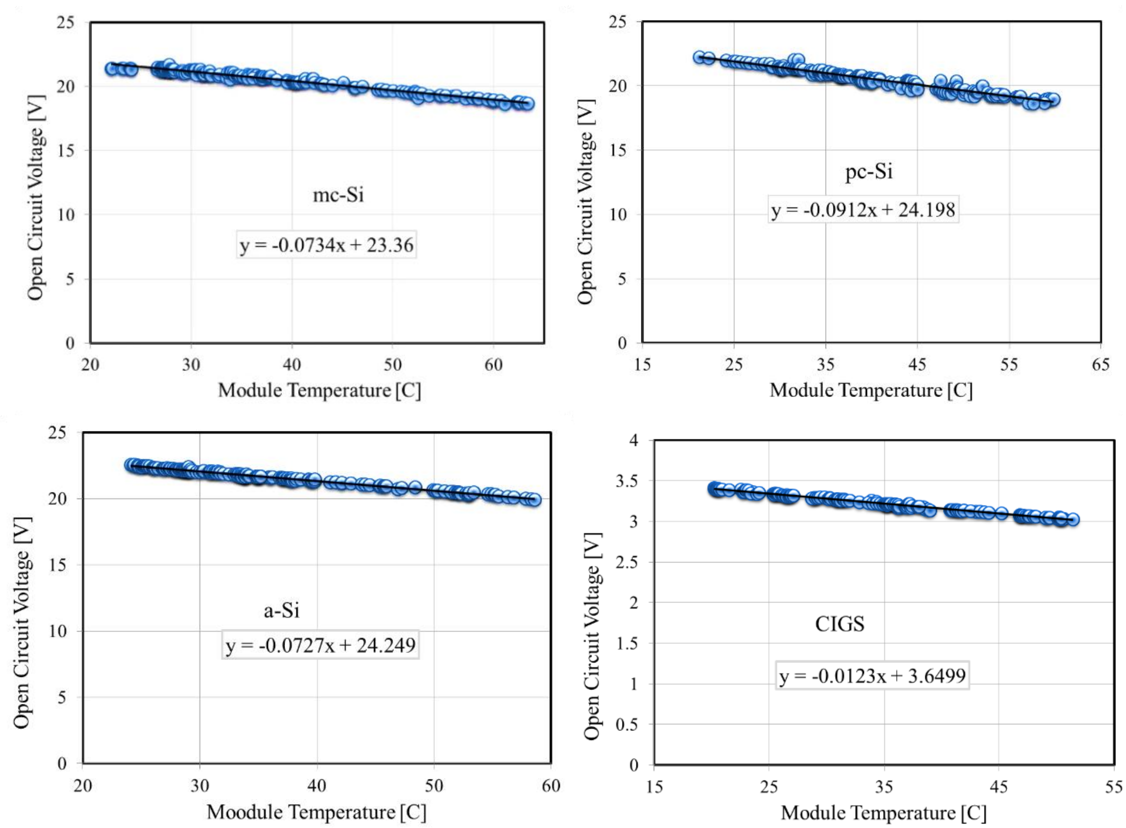

Figure 8. Experimental open ciruit voltage vs. module temperature for the four modules.

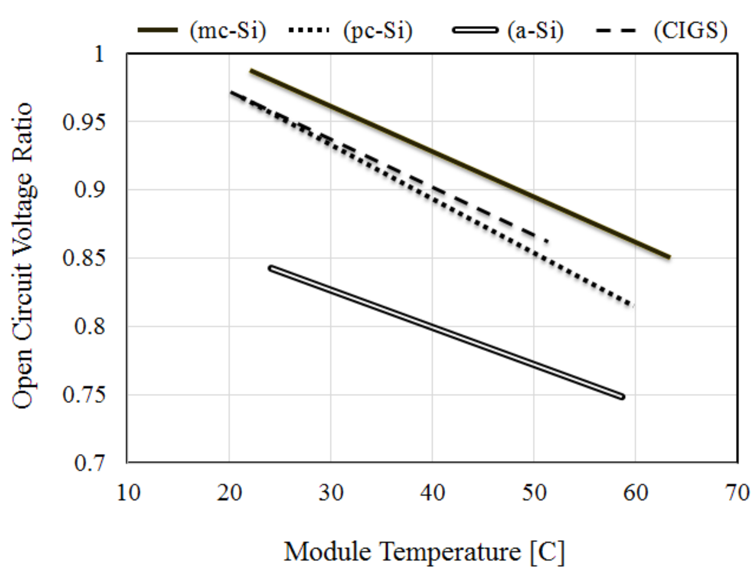

Figure 9. Open ciruit voltage ratio vs. module temperature for the four modules.

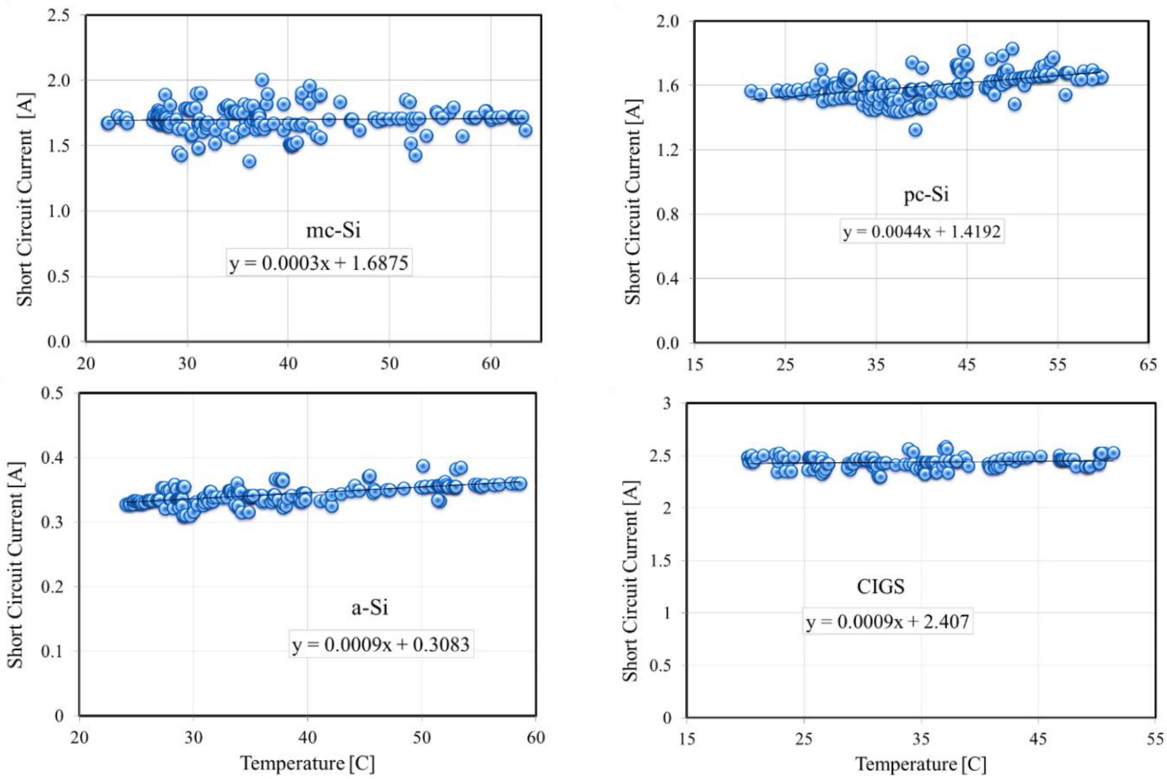

Figure 10. Experimental short ciruit current vs. module temperature for the four modules.

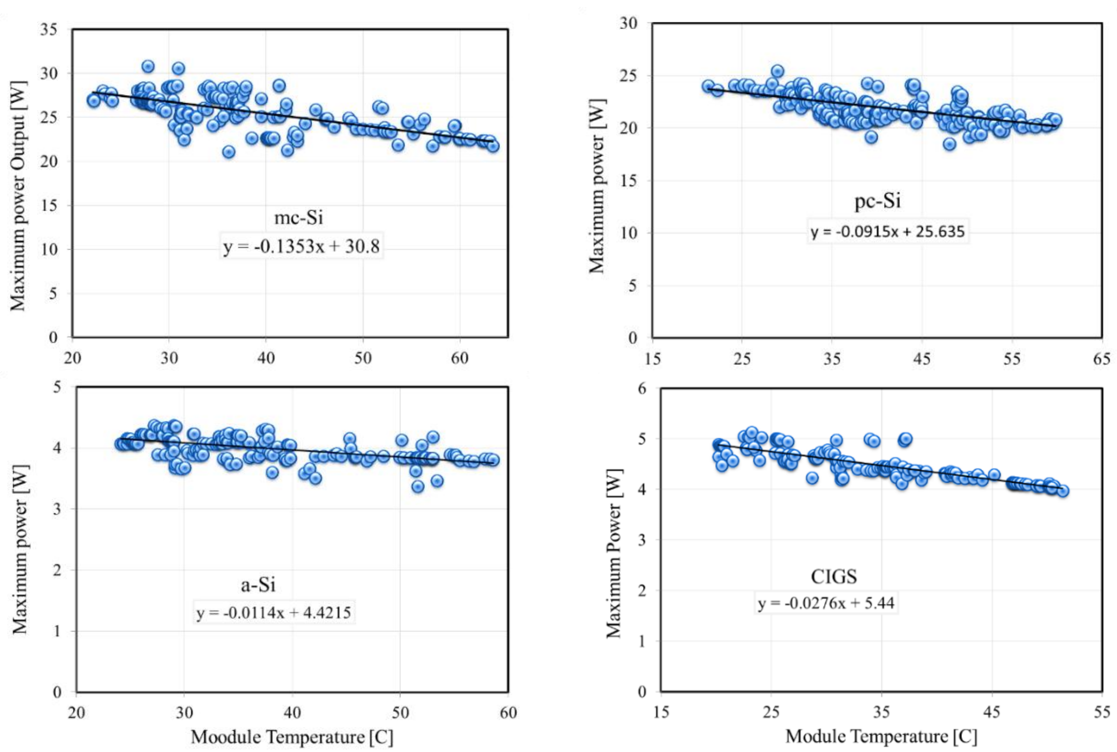

Figure 11. Maximum power output vs. module temperature for the four modules.

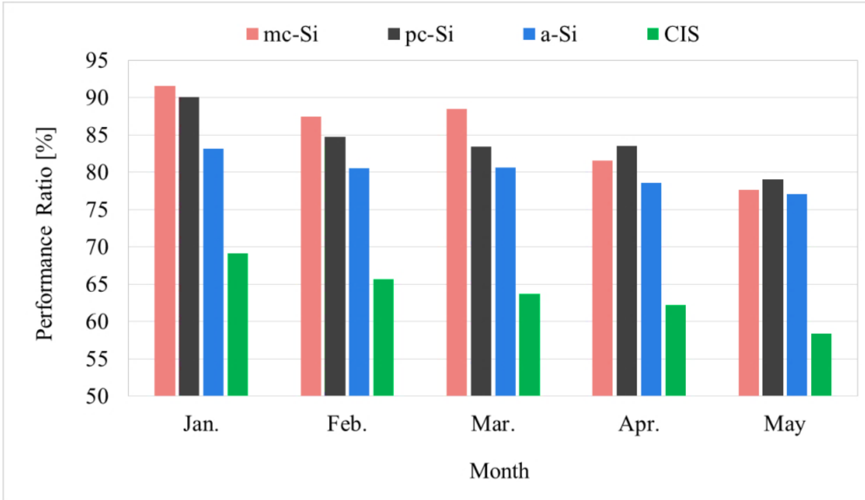

Figure 12. Monthly averaged perfromance ratio for the four modules.

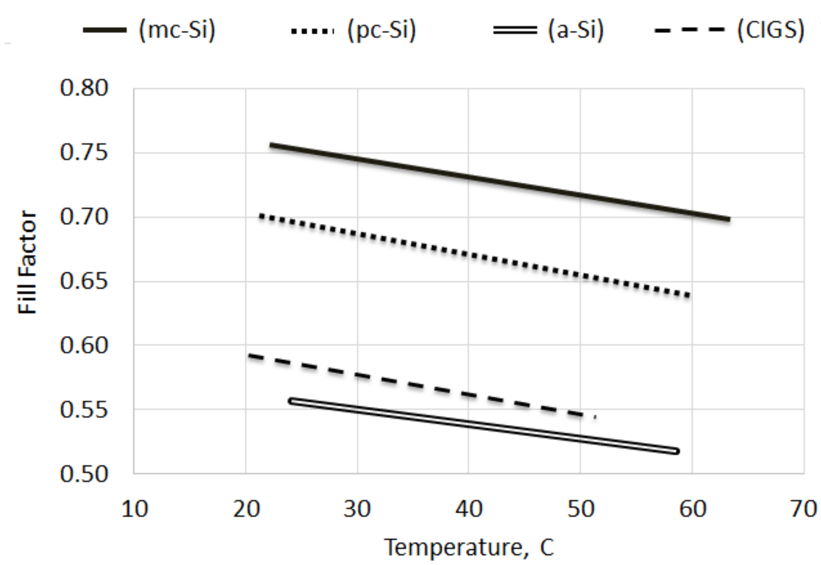

Figure 13. Temperature effect on the fill factor