Behavior of Four Solar PV Modules with Temperature Variation

AkramAbdulameerAbbood Al-Khazzar

Energy Engineering Department, College of Engineering, University of Baghdad

(akramabdulameer@gmail.com)

Received: 28.04.2016-Accepted:23.07.2016

Abstract-This paper presents a behavior and performance comparison of four different photovoltaic PV modules: mono-crystalline Silicon, poly-crystalline Silicon, amorphous Silicon and Cupper Indium Gallium diselenide (CIGS) under Iraqi climate conditions of Baghdad city. Temperature influence on the solar modules electric output parameters was investigated experimentally. the temperature coefficients of open circuit voltage, short circuit current and maximum power output for the four modules was calculated. These temperature coefficients are important for all systems design and sizing. Two mathematical models were implemented to extract the governing parameters of the PV modules. A detailed explanation for the temperature influence on the PV module parameters is presented. The results showed that the amorphous silicon and CIGS modules perform better than the crystalline modules in high operating temperature.

KeywordsSolar cell parameters, PV module, Temperature effect, PV module modelling.

1. Introduction

The dependence on fossil fuels for power generation is one of the most discussed issues in the past few decades. About 88.16% of the world's total energy consumption was supplied by burning oil, natural gas and coal. Harnessing solar energy is an efficient way in producing thermal and electrical energy, reducing the greenhouse gases emission, decreasing the importing rates of fossil fuels, in addition to the development in the industrial and the economic sectors which leads for new job opportunities [1].

Solar radiation can be converted directly to electricity by the photo-voltaic (PV) effect. Covering only 1 % of the Earth land area with 10% efficient solar photovoltaic PV modules would produce twice the current need of energy worldwide [2]. PV power generation systems has many features and some disadvantages, they are summarized in Table 1.

PV module temperature is one of the important factors that affects how much electricity your module/array will produce. It's ironic, but the more sunshine you get, the hotter the modules get and this in turns counteracts the benefit of the sun. Practically, the most efficient solar PV modules convert only 20% of the incident solar radiation to direct electrical current while the remaining is either reflected and the great part heats up the solar module material.

Table 1. Main advantages and disadvantages of relying on PV systems

Advantages	Disadvantages
Fuel source (sunlight) is free and infinite	Fuel source is variable and zero at night (need storage systems)
Zero emissions, no combustion or radioactive reactions (environmentally friendly) and silent	_ _ _
Very low operation and maintenance cost	High installation cost
No moving parts and low operation temperature (excellent safety record)	_ _ _
High reliability for the PV module (>20 years)	Poorer reliability of auxiliaries (power converters, storage system elements, etc.)
Quick installation and can be installed on any surface (land, new or existing building, etc.)	Need large space to meet the required power (low efficiency)
Daily output peak matches local demand (relative to the solar radiation) specially cooling load in summer and afternoon period.	_ _ _

There are some cases and applications where the PV cell temperature may reach high levels, as follows:

- High average ambient temperature (climate characteristics)
- Hybrid photovoltaic/thermal applications (PV/T)
- Building integrated PV systems (BIPV)
- Concentrated photovoltaic systems (CPV)

As known, PV technologies continue in the field of research and development (R&D). Many types of PV modules have been developed other than the most familiar classic crystalline silicon modules which are available since decades. The new types of PV modules characterized by low conversion efficiency but with low manufacturing cost in comparison with crystalline PV modules.

Nowadays, Solar cells are mainly based on crystalline silicon wafers and typically have noticeable high efficiencies about 15-20 %. Crystalline silicon technologies are the most commercially produced with about 89.6% of 2007 production (Fig. 1) [3]. Then, thin film solar cells materials have been developed such that copper indium gallium di-selenide (CIGS), cadmium telluride (CdTe), amorphous silicon (a-Si) and micro-amorphous silicon [3]. There is another new currently developing generation of solar cell technologies,such that dye sensitized, Nano-crystal, Polymer based solar cells and concentrated solar cell. These are novel technologies which are promising performance but not commercially proven yet.

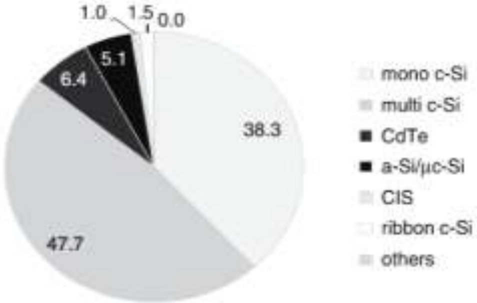


Fig1. PV technology market share in 2009 [4].

Choosing the suitable PV module is crucial and important step before installing a PV power generation system. the designer is limited by the PV module efficiency, overall cost of the PV system and the climate conditions. So, it is very helpful to identify how do different types of commercial PV modules behave with climate changes (in this study ambient temperature changes).

In this paper, outdoor experimental tests for four different types of solar modules for five months were done.Presenting physical explanations for how the ambient temperature affect the PV module performance. the PV module parameters were calculated and extracted for the PV modules using two mathematical models implemented in Matlab.

2. Mathematical Modelling

The solar cell is usually represented by an electrical circuit which is equivalent to asingle-diode model. This equivalent circuit can be used for one single cell, a module consisting of a number of cells, or an array consisting of many modules. When the diode is exposed to light, photocurrent I_{ph} is generated and flows from the n-side to the external load and return to the p-side. This arrangement can be readily represented using a simple equivalent circuit from an ideal current source I_{ph} and a diode as shown in Fig.2. For actual case, two resistances added to the circuit on series and on parallel.

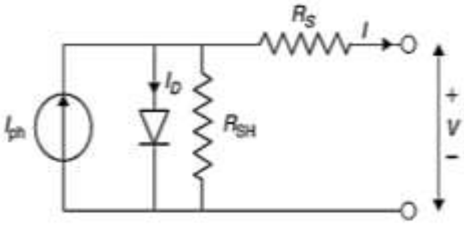


Fig 2. Equivalent electrical circuit of cell with internal resistances

The previous electrical representation in Fig.2 is the basic for any solar cell/module/array modelling and it is the most common in many handbooks or in academic articles. The output current (I) from the PV module consisting of (N_s) number of solar cells connected in series is given by the following equation:

$$I = I_{ph} - I_o\left[exp\left(\frac{q(V+IR_s)}{N_sAk_BT}\right) - 1\right] - \frac{V+IR_s}{R_{Sh}} \qquad (1)$$

Where, q is the electron charge (1.6x10-19 C), k_B is Boltzmann’s constant (1.38x10-23 J/K), T is the temperature of the modules (K).
Five unknown parameters in equation (1) must be calculated:

1- Photo-generated current, I_{ph}which basically has a linear relationship with the incident solar radiation.
2- Diode reverse (dark) saturation current, I_o is an indicator to the amount of recombination rate (or leakage) of charge carriers through the PN junction in reverse bias. I_o for a PN junction solar cell is noticeably increases with cell temperature [5].
3- Diode ideality factor,A indicates how good the cell is manufactured and how much deformations, impurities within the cell. A value is between 1 to 2.
4- Series resistance, R_s reduces the output voltage while the current flow through the bulk material of the cell and the conducting wire, ideally equals to zero.
5- Shunt resistance, R_{sh} reduces the output current of the module because of the leakage current through “the parallel branch”, so ideally it equals to infinity.

Equation (1) is a transcendental equation and has no direct solution because of I = f (V, I) and V = f (I,V), thus it can only be solved numerically. In Matlab, a numeric solver function (vpasolve) used to solve the unknown output current from a voltage values vector.
In this study, two mathematical models were applied for to modelling the PV module using Matlab:

1- Four-parameters model (4par-m): Simplified explicit method.
2- Five parameters model (5-par-m): Iterative method.

The models are used to extract the unknown parameters at reference condition STC. Then it is possible to find how these parameters react and behave with temperature based on experimental data. The simplified explicit method was presented by Khezzar et al. [6] with some approximations and assumptions. To evaluate the five parameters with less approximations, an iteration process needs to be done. An iteration method and modelling approach for a PV array was presented by Villalva et al. [7].

Any solar cell depends on a very important factor which evaluates its ability to convert solar radiation to a flow of electrons, that factor is the band gap energy. Band gap energy (E_g) is the minimum energy carried by a photon to liberate an electron from the valence band to the conduction band. Green [8], Nell and Barnett [9], Muzathik [10] and a lot others presented an equation for the reverse saturation current which can be used to determine the band gap energy:

$$I_o = CT^3 \exp(-\frac{qE_g}{Ak_BT}) \quad (2)$$

$$E_g = \frac{-Ak_BT}{q}\ln(\frac{I_o}{CT^3}) \quad (3)$$

Where C is a constant which depends on the semiconductor material physical properties (diffusion coefficients, charge carrier mobility, etc.) and the junction area. C is assumed to be independent on temperature [9].

3. Experimental Work

behavior of four PV modules was examined 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 (mc-Si), poly-crystalline silicon (pc-Si), amorphous silicon (a-Si) and copper indium gallium diselenide (CIGS)as shown in Fig.3. The tests were done under the outdoor exposure in Baghdad city, at department of energy Engineering / Baghdad University. The electrical specifications of the modules at standard test conditions STC (1000W/m^2 solar radiation, 1.5 AM, 25°C cell temperature) are tabulated in Table 2.

Table 2. Solar module specifications (available from the manufacturer datasheet)

	mc-Si	**pc-Si**	**a-Si**	**CIGS**
Area [m^2]	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

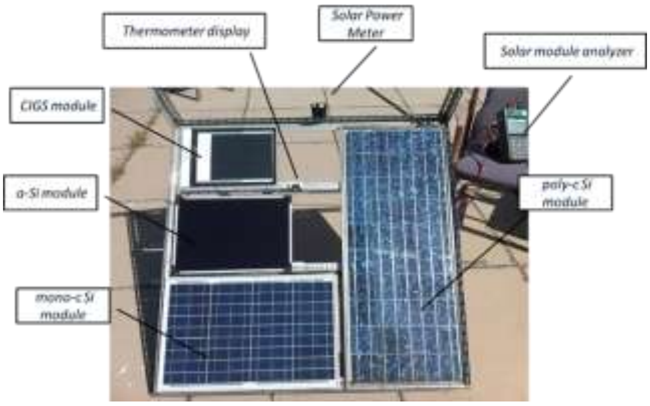


Fig 3. Experimental setup

Solar module analyzer PROVA 200A (see Fig.4) is used to test the PV module characteristics (V_{oc}, I_{sc}, P_m, V_m and I_m), conversion efficiency, also provides the current-voltage (IV) and power-voltage (PV) curves. Total incident solar radiation was measured by Solar Power Meter TES1333R. It is preferred to measure the actual internal p-n junction of the solar cell but that is practically impossible. Instead, for simplicity the temperature of the back side of the module which is greater by 1-2°C than the cell temperature. This assumption is widely used by many authors in previous studies. The temperature of the modules was measured using digital thermometer (TPM-10) (see Fig.4) attached firmly to the back of the module. The four modules were placed on a mobile steel stand moved manually to follow the sun and keep the incident solar radiation at the required value (1000 W/m^2) as shown in Fig.4.

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

4. Results and Discussions

Experimental data were collected from 1st January to 1st June, 2015. The module temperature and the module output parameters (open circuit voltage, short circuit current and maximum power output) were recorded at a constant solar radiation and a range of ambient temperature between 13 to 47°C. the temperature of the back of the module was found to be between 22 to 60°C.

To analyze the data, a scatter plot was used between each of V_{oc}, I_{sc} and P_m and temperature. It had been seen that there is a linear relationship, so a linear regression was used to find a relation between them and the temperature. a linear equation was extracted by Microsoft Office / Excel as most of the previous works in literature. The amount of how much

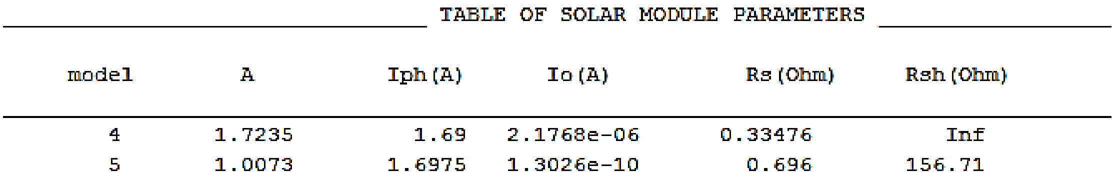
V_{oc}, $I_{sc}$and P_m influenced by the cell temperature call the temperature coefficient (TCO). TCOs equal to the slope of the straight line which is generated by the curve fitting.TCO has units of X/ºC, where X can be either V, A or W.

Table 3. Temperature coefficients summary

TCO	mc-Si	pc-Si	a-Si	CIGS
$\boldsymbol{V_{oc}}$ [V/ºC]	-0.0734	-0.0912	-0.0727	-0.0123
$\boldsymbol{I_{sc}}$ [A/ºC]	0.0003	0.0044	0.0009	0.0009
$\boldsymbol{P_m}$ [W/ºC]	-0.1353	-0.0915	-0.0114	-0.0276

A Matlab code is programmed based on the details of the two mathematical models as given by Khezzar et al. [6] and Villalva et al. [7]. The Matlab code calculates the solar module parameters at STC and evaluate modeled output current for each module separately. Fig. 5 shows a screenshot of the Matlab command window.

The parameters those determine the performance of any solar module and determine the shape of the IV curve are evaluated by the two models are tabulated in Table 4. As shown in the results, there is a quite noticeable difference between the values of the ideality factor (A) that results from the set of approximations in the 4par-m. The photo-generated current (I_{ph}) has nearly the same valuein the models.



```
______________________________ TABLE OF SOLAR MODULE PARAMETERS _______________

     model          A          Iph(A)       Io(A)         Rs(Ohm)      Rsh(Ohm)

_______________________________________________________________________________

       4         1.7235         1.69    2.1768e-06       0.33476          Inf
       5         1.0073       1.6975    1.3026e-10         0.696       156.71
```

Fig 5. Sample of the parameters of mc-Si module extracted by the two models

Table 4. Solar module parameters at STC based on the module datasheet

		mc-Si	pc-Si	a-Si	CIGS
A	4par–m	1.723	1.337	1.704	1.613
	5par–m	1.0073	0.844	1.437	0.995
$\boldsymbol{I_{ph}}$ [A]	4par–m	1.69	1.46	0.33	2.43
	5par–m	1.6975	1.4682	0.354	2.4972
$\boldsymbol{I_o}$ [A]	4par–m	2.17E-06	1.73E-07	8.34E-13	3.77E-07
	5par–m	1.30E-10	1.50E-11	5.05E-16	6.59E-10
$\boldsymbol{R_s}$ [Ω]	4par–m	0.334	0.983	12.642	0.551
	5par–m	0.696	1.474	16.794	0.286
$\boldsymbol{R_{sh}}$ [Ω]	4par–m	∞	∞	∞	∞
	5par–m	156.71	261.78	223.63	6.396

The two models evaluate the reverse saturation current (I_o) from same equation but the difference in the results from the models is due to the dependence of (I_o) on (A). Both models calculate R_s, but the iteration process in the 5par-m show better accuracy than 4par-m that explains why the 5par-m nearly coincides with the experimental curve as illustrated in Fig.6, while 4par-m showed a deviation at the current region in the I-V curve from the experimental curve.

The 4par-m neglects the shunt resistance (R_{sh}=∞) which apparently is a very good assumption because of the high value of R_{sh} extracted by 5par-m. This assumption matches with the works of a lot of authors in the literature except for the CIGS which has a small R_{sh}.

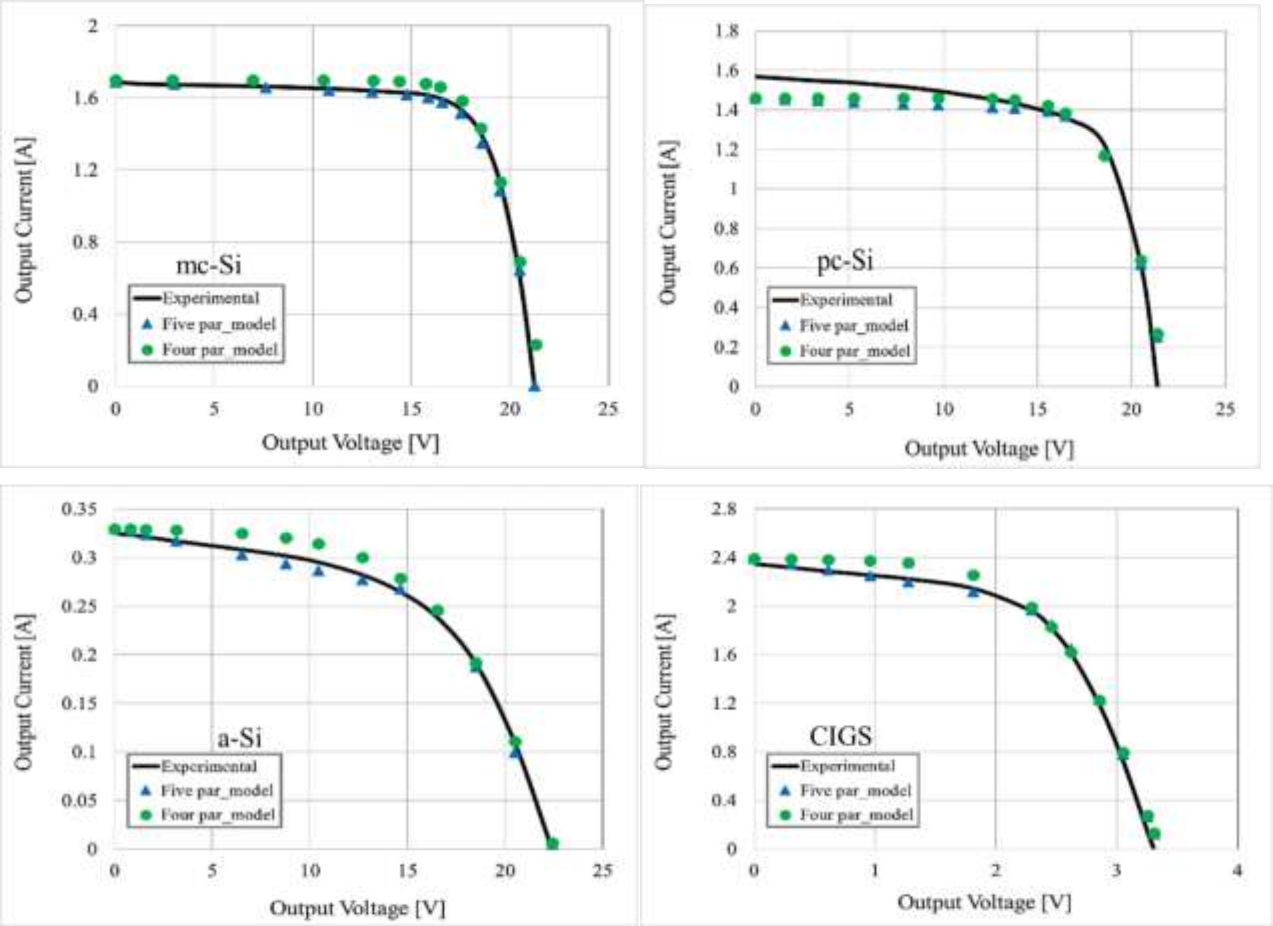


Fig 6. Experimental and modeled I-V curve at STC for the four modules.

Semiconductor physicians tried since decades to reduce the effect and the value of the reverse saturation current of the diode. Large I_o means that more electrons thermally diffused and find their way in the reverse bias from the n-layer to the p-layer. In case of the solar cells electrons must be forced to leave the n-layer to the external circuit. The experimental results of I_o plotted versus module temperature as illustrated in Fig.7.

In the results, amorphous silicon solar module has the largest value of I_o because of the randomness in its atomic structure due to many dangling bonds which represent traps for the free electrons while they are thermally diffused and hence increase the recombination while mc-Si which is the most orderly arranged and the purest PV cell used has a lowI_o.

The defects and impurities in a poly-crystalline silicon cell represent a trap for more recombination of Electron-Hole Pairs (EHPs), this recombination increases with temperature as a result of increasing the thermal diffusion of the charge carriers which rises the reverse saturation current and hence decrease the open circuit voltage of the pc-Si module more than mc-Si module.

Increasing the temperature decreases the amount of energy required to liberate the electrons from the outer shell of the atom (i.e., the band gap energy). This step is important to understand why does the short circuit current increase if the temperature increased. After determining the reverse saturation current at reference STC and the value of E_g is already known at 25ºC, then the constant C will be known. C is considered to be independent of temperature, then E_g easily be calculated from equation (3).

Fig. 8 shows the experimentally calculated E_g versus the module temperature. mc-Si module showed a vague vision of a linear relationship, despite of that the values distributed in a range of 0.016eV and E_g can be considered constant with temperature. $E_g$of pc-Si decreased about 0.04eV through the temperature range. Amorphous silicon has the clearest linear relationship with noticeable decrease about 0.08eV. CIGS has the smallest temperature influence on E_g with nearly 0.006eV.

It is known that the electrical resistance of a conductive material increases with temperature, this is because of the mobility of charge carriers has an inverse relationship with the temperature. As temperature increases, the carrier scattering is increased on lattice vibrations and impurities. This reduction in mobility decreases the conductivity and hence increases the series resistance.

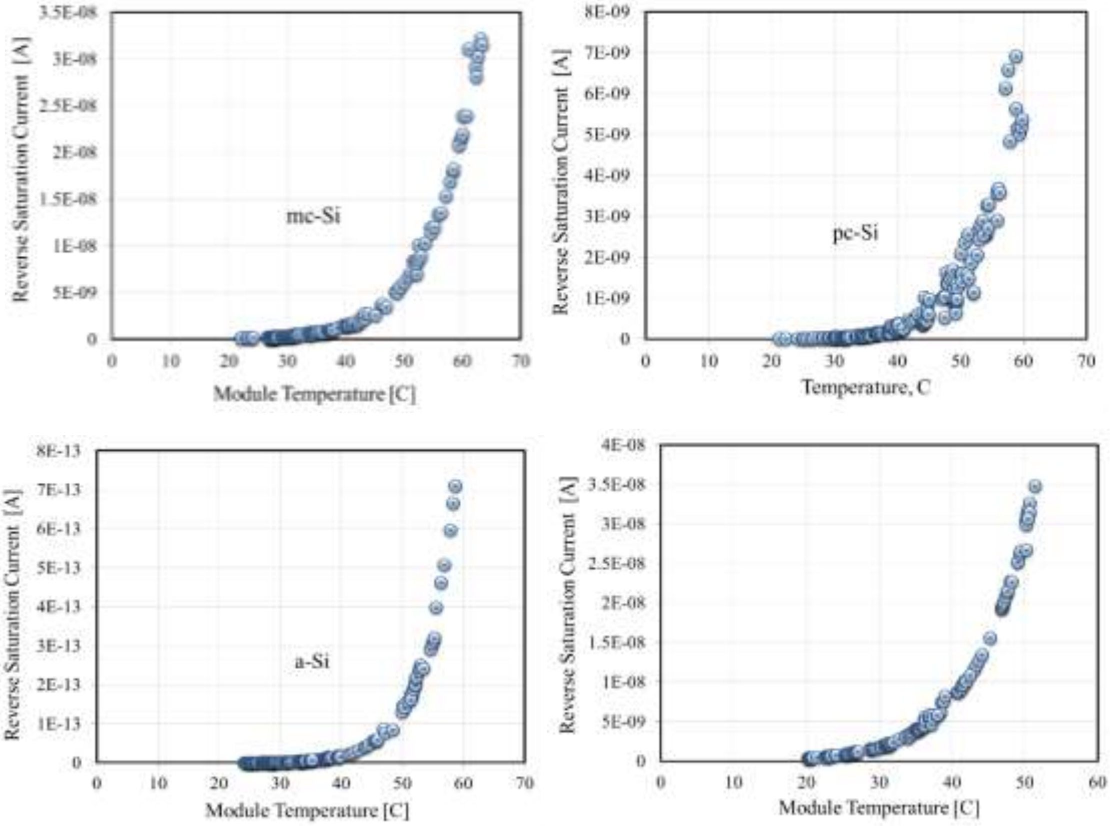


Fig 7. Reverse saturation current behavior with temperature change

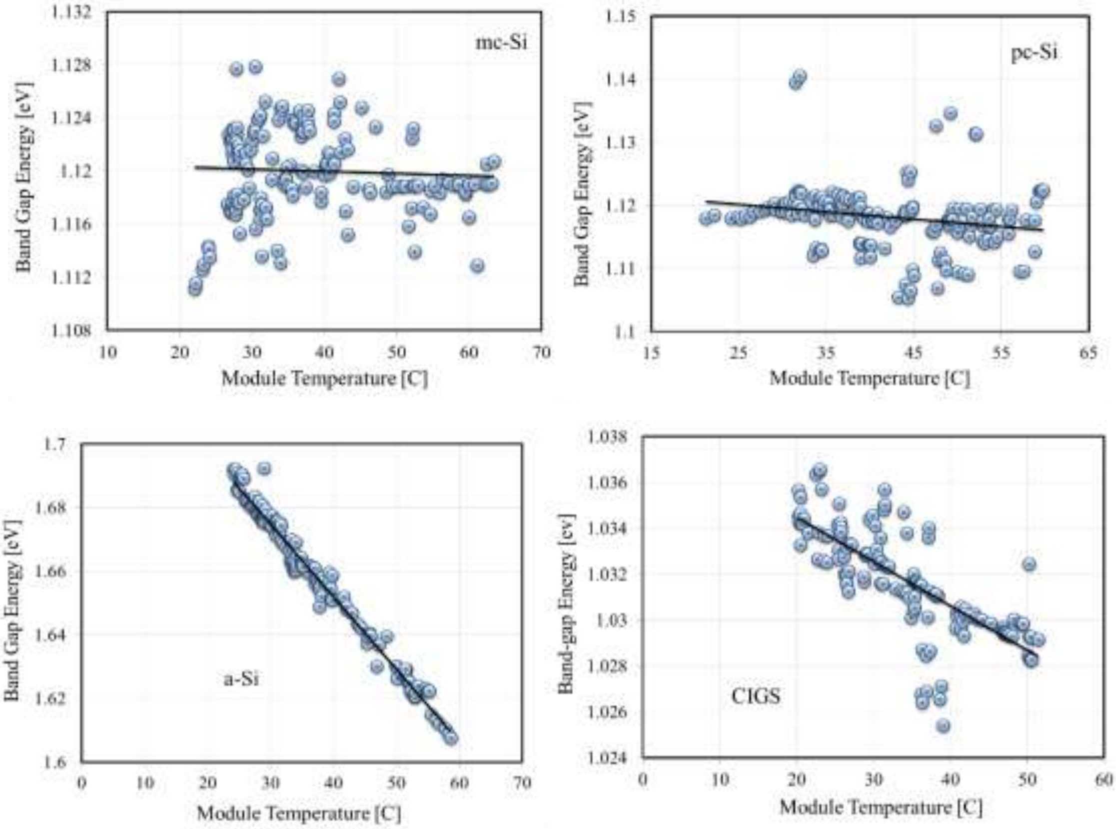


Fig 8. Band gap energy variation pattern with temperature

The series resistance was calculated based on the experimental data and plotted versus module temperature as shown in Fig.9. It is expected from fundamental physics, R_s increases with temperature but in this study that effect clearly occurred only in the case of mc-Si module while the pc-Si and a-Si module show a slightly drop in R_s. For the CIGS, R_s remains constant. This unexpected behavior happened because, of in solar cells many factors affect the internal resistance unlike pure conductive materials.

This result for comparison sake matches with the work of Radziemska [11] where a drop was found in R_s with temperature increasing. Also, Kandil et al. [12] Found a very slow rate decreases in R_s (1.3 and 1.2 Ω) at two temperatures (20 and 40˚C). Kandil [12] clearly stated that this low decrease has small influence on the overall PV module performance compared with the other module parameters. On the other hand, Kishor et al. [13] showed that R_s of a mc-Si module increases from 0.23Ω at 25ºC to 0.63 Ω at 75ºC. Bensalem and Chegaar [14] found that for pc-Si module, the series resistance increased from 0.1825Ω/cm2 to 0.3663Ω/cm2 when the temperature rises 15ºC to 50ºC. It can be concluded that the temperature has no noticeable effect on R_s and the results agrees with many authors such as De Soto et al. [15], Duffie and Beckman [16] and others where they neglected the change of R_s with temperature in their PV systems modeling.

Fig. 10 shows the temperature effect on the shunt resistance. As module temperature increases, the results showed a decrease in R_{sh} which is agrees with Karatepe et al. [17]. Bensalem and Chegaar [14] found that for pc-Si module, the shunt resistance decreased from 2.47 kΩ/cm2 to 1.83 kΩ/cm2 when the temperature rises 15ºC to 50ºC.While other authors considered that R_{sh} is independent on temperature and have a linear relationship with solar radiation.

The maximum power of a solar cell is always less than the hypothetical value of power obtained by multiplying V_{oc} by I_{sc}. The ratio of P_m to $V_{oc}I_{sc}$ is a key measurement value of a solar cell, in addition to the efficiency, this ratio is called the Fill Factor [18] . The fill factor determines the squareness of the I−V curve, and it is an indicator for how the total internal electrical resistances affect the output current. A squarer curve indicates a greater maximum power and ideality. The closer this number to 1, the squarer the curve is but that is in an ideal non-exist case. Commercially, solar cells have FF ranges from about 60 to 80%, while for laboratory cells FF can has higher value about 85%.

Fig. 11 shows the temperature effect on Fill Factor which is the resultant of the effect on R_s and R_{sh}. Nearly all the modules have the same change of FF, -0.00125/ºC. this result agrees with the -0.002/ºC presented by Radziemska [19] for a mc-Si cell. Tobnaghi et al. [20] found a drop of -0.00428/ºC also for a mc-Si solar cell.

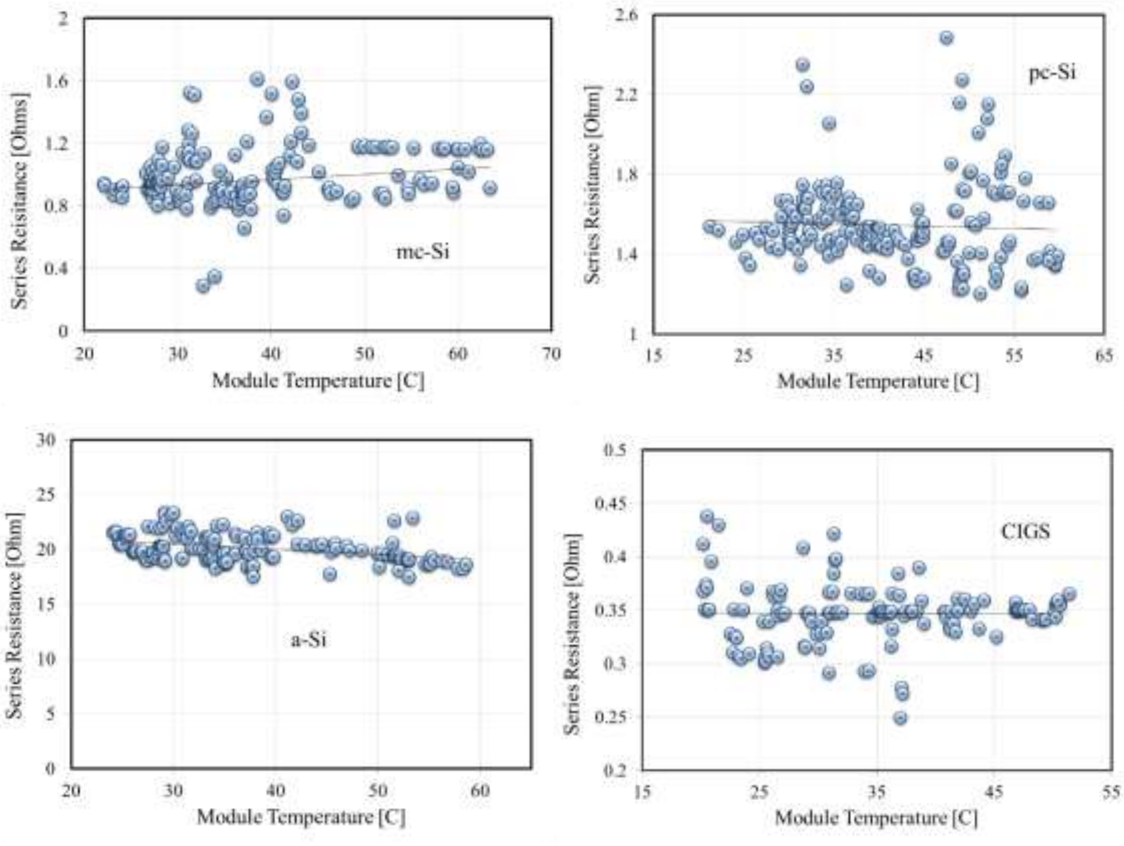


Fig 9. Temperature effect on the series resistance of the four modules.

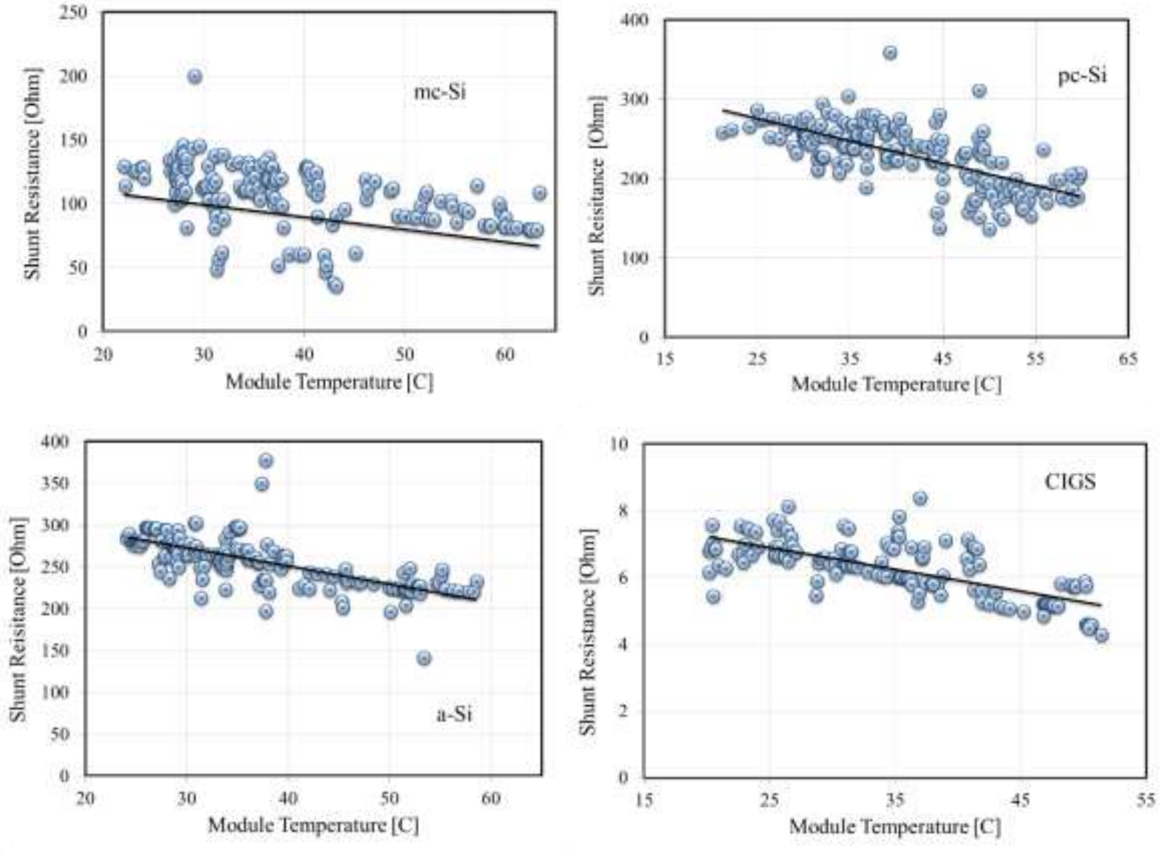


Fig 10. Temperature effect on the shunt resistance for the four modules.

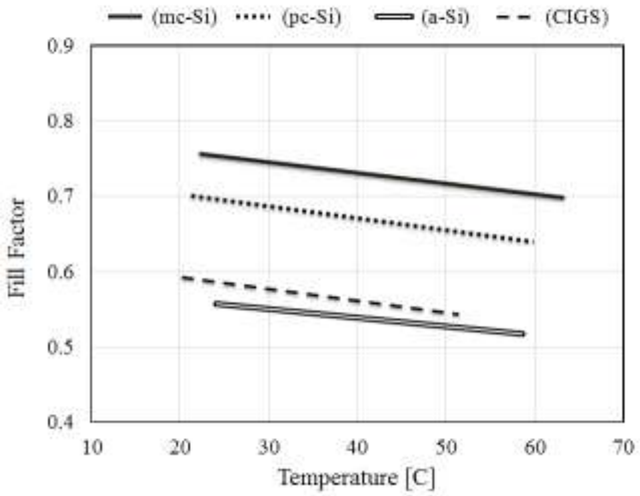


Fig 11. Temperature effect on Fill Factor.

5. Conclusion

This paper presents an investigation and physical analysis of the behavior of different types of PV modules under a range of temperature nearly 20-60ºC along a period of five months from the 1st January to the 1st June, 2015 in the natural Iraqi environment of Baghdad. Added to that, the paper provides a comparison of two selected mathematical models to extract the PV module parameters.

The main conclusions can be drawn from the work done and presented are:

- For crystalline PV modules, there were no difference between the four parameter model and the five parameter model because of the high shunt resistance and the simplified four parameters model is sufficient.

- Selecting the type of the PV technology is crucial for the PV application, some types like silicon featured with high voltage and low current while CIGS has a large output current and lower voltage.
- It was found from the analysis that a-Si and CIGS photovoltaic modules seem to be better choice in high temperature conditions due to low temperature coefficients. However, the choice still depends on the module efficiency and the capital cost.
- With temperature increasing, the reverse saturation current increases rapidly causes major changes in voltage rate. Also the EHP generation slightly increases as a result of the decrease in band gap which leads to a slight increase in the output current. This conclusion was expected from the literature research of the project. Nevertheless, the temperature effect was presented and discussed in details.
- Fill Factor seemed to has little dependence on temperature for tested modules. Therefore, the temperature effect on the parasitic internal resistances can be neglected.

References

[1] Duran E., Galan J., Sidrach-de-Cardona M., Ferrera M.B. and Anduja J.M., "A New Application of Duty Cycle Sweep Based on Microcontrol1er to Obtain The I-V Characteristic Curve of Photovoltic Modules", pp1-6, print ISBN: 978-1-4224-1705-6, Apr. 2008.

[2] Smestad, G. P. “Optoelectronics of Solar Cells”, SPIE-The International Society of Optical Engineering, Washington, USA, 2002.

[3] Hirshman, W. P., G. Hering and M. Schmela, “Cell and Module Production 2007” Photon International, 152. 2008.

[4] Hirshman WP. “Market Survey on Worldwide Cell Production 2008”. Photon International, 170 – 206. March 2009.

[5] Hu, C. and White, R.M. “Solar Cells”, McGraw-Hill, New York, pp. 21. 1983.

[6] Khezzar, R., Zereg, M. and Khezzar, A., “Comparative Study of Mathematical Methods for Parameters Calculation of Current-Voltage Characteristic of Photovoltaic Module”, in 2009 International Conference on Electrical and Electronics Engineering, pp. 124–128. November 2009.

[7] Villalva, M.G., Gazoli, J.R. and Filho, E.R., “Comprehensive Approach to Modelling and Simulation of Photovoltaic Arrays”. IEEE Trans. Power Electron. 24, 1198-1208. 2009.

[8] Green, M. A. “Accuracy of Analytical Expressions for Solar Cell Fill Factors”. Solar Cells, 7(3), 337-340. 1982.

[9] Nell, M. E., and Barnett, A. M. “The Spectral P-N Junction Model for Tandem Solar-Cell Design”. Electron Devices, IEEE Transactions on, 34(2), 257-266. 1987.

[10] Muzathik, A. M. “Photovoltaic Modules Operating Temperature Estimation Using a Simple Correlation”. International Journal of Energy Engineering, 4(4), 151. 2014.

[11] Radziemska, E., “Effect of temperature on dark current characteristics of silicon solar cells and diodes”, International Journal of Energy Research, 30, (2) 127-134, 2005.

[12] Kandil, K. M., Altouq, M. S., Al-asaad, A. M., Alshamari, L. M., Kadad, I. M., and Ghoneim, A. A., “Investigation of the Performance of CIS Photovoltaic Modules under Different Environmental Conditions” Smart Grid and Renewable Energy, 2, 375-387, 2011.

[13] Kishor, N., Villalva, M. G., Mohanty, S. R., and Ruppert, E.,”Modeling of PV module with consideration of environmental factors”. In ISGT Europe (pp. 1-5). October, 2010.

[14] Bensalem, S., and Chegaar, M. “Thermal behavior of parasitic resistances of polycrystalline silicon solar cells”. Revue des Energies Renouvelables, 16(1), 171-176. 2013.

[15] De Soto, W., Klein, S.A., Beckman, W.A., “Improvement and validation of a model for photovoltaic array performance”. Sol. Energy 80, 78–88. 2006.

[16] Duffie, J. A., and Beckman, W. A., “Solar engineering of thermal processes”. (4th Ed.). New York etc.: Wiley. 2013.

[17] Karatepe, E., Boztepe, M. and Colak, M. “Neural Network Based Solar Cell Model”, Energy Conversion and Management, Vol. 47, 9-10, pp. 1159 - 1178, 2006.

[18] Häberlin, H. “Photovoltaics system design and practice”. John Wiley & Sons. 1st ed. 2012.

[19] Radziemska, E., “The effect of temperature on the power drop in crystalline silicon solar cells”, Renewable Energy, (28) 1–12, 2003.

[20] Tobnaghi, D. M., Madatov, R. and Naderi, D. “The Effect of Temperature on Electrical Parameters of Solar Cells”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering Vol. 2, Issue 12, December 2013.