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Performance of Single Crystal Silicon Photovoltaic Module in Bruneian Climate

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Abstract: This article deals with the electrical characteristics of a single crystal photovoltaic module in the Bruneian climate. Experiments have been conducted in the Department of Physics, University of Brunei Darussalam. This study includes the measurements of open circuit voltage, short circuit current, maximum output power and efficiency of the module. The dependence of these parameters on working temperature and irradiance has been computed and the coefficients of dependence are established. The correlations have been presented to evaluate the electrical parameters of photovoltaic devices at any working temperature with reference to the standard test conditions in any region of the globe having the similar climate to Brunei Darussalam.

Keywords: Photovoltaic module, Electrical characteristics, outdoor testing of PV modules, I-V characteristics of PV modules, PV modules in natural environment.

1. Introduction

The electrical performance of a photovoltaic (PV) device is represented by its current-voltage (I-V) and power-voltage (P-V) curves. The manufacturers of PV devices measure the performance of these devices at standard reporting conditions (SRC) or standard test conditions (STC). These measurements are taken under laboratory conditions using a sun simulator [1-2] which is controversial as such conditions can never be found in a natural environment [3-4]. The performance of PV devices depends upon climatic parameters, such as the insolation level and the ambient temperature which are locality dependent variables. It is desirable to measure the rating of these devices at the site of installation for the effective design of a photovoltaic system. This allows accurate predictions of output power to be made and it is then possible to simulate different climatic conditions and look into their influence on the system performance. The objective of the present investigation is to explore the influence of Bruneian climate on the electrical properties of PV devices.

2. The Experiment

A single crystal PV module (Solartech, Mesta 30030538) was placed on the roof of Physics laboratories at University of Brunei Darussalam. A thermopile pyranometer (Kipp and Zonen CM-11) was placed near to the module to measure the irradiance. The experiment was started in June 2006 and carried out for a period of eight months. The circuit diagram and methodology for this experiment has already been discussed earlier [5-6]. The

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experiment was conducted twice a week and each time performed at three different times of day corresponding to the solar noon, two hours before and two hours after solar noon. These three times provide the true variation in irradiance, the working temperature and their effect on the performance of the module. Solar noon is the time when the Sun is at a longitude of 115^{o} East in Brunei and this is the time that divides the day exactly into two equal parts. The influence of the Bruneian climate on the performance of this module is studied by comparing the electrical characteristics of the module with that reported at STC. The I-V characteristic of this module at STC is given in Table 1.

Table 1. I-V characteristics of PV module (Solartech, Mesta 30030538, 76 W) at standard temperature conditions (STC) supplied by the manufacturer.

V_{oc}	I_{sc}	V_{max}	I_{max}	P_{max}	*Irradiance*	η	T_W
21 V	5.4 A	16.5 V	4.6 A	4.6 A	1000 Wm^{-2}	12%	25 ^{o}C

3. Results and Discussion

A single crystal PV module consisting of 36 solar cells was mounted horizontally on a stand and placed under the sun on the rooftop of the Physics laboratories, University of Brunei Darussalam. The outdoor performance of this module was measured twice a week for a period of eight months starting form June 2006 to January 2007. Each test consists of three experiments conducted at the solar noon, and two hours before and after the solar noon. The aim of this exercise was to study the variation of insolation and working temperature on the performance of the PV module. Both these parameters are time as well as locality dependent and strongly influence the electrical properties of PV devices. These devices may not generate nominal electrical power in the outdoor operation with varying microclimatic conditions. Brunei Darussalam is located in the equatorial region of the globe where sun shines approximately for 12 hours a day that makes it the most suitable for PV applications. The experimental set up is shown in Figure 1.

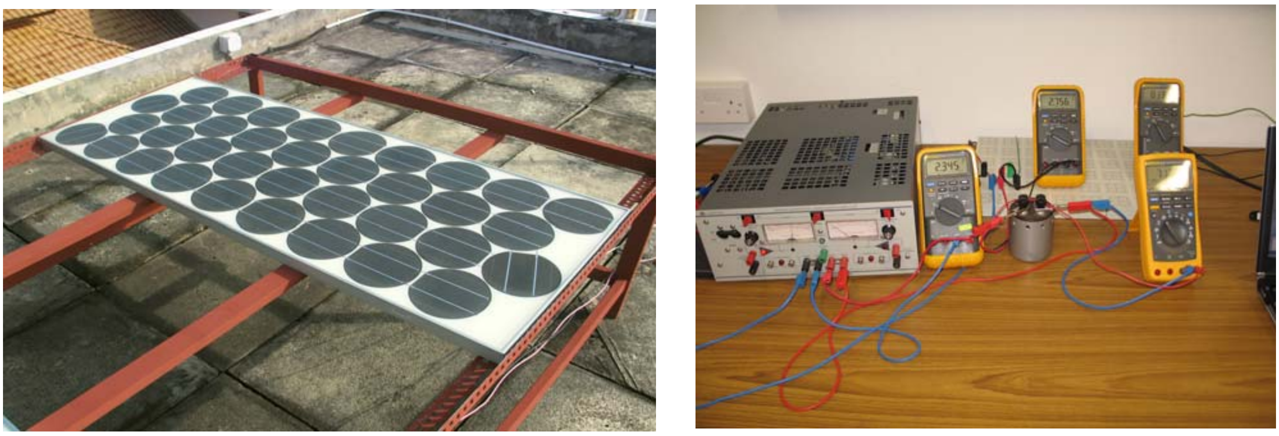

Figure 1. Experimental set up

The seven well known electrical parameters of a PV module are open-circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum voltage

(V_{max}), maximum current (I_{max}), maximum power output (P_{max}), conversion efficiency (η) and the working temperature of the module (T_W). The working temperature of the module (T_c) can be measured or calculated. In the present study this temperature has been calculated using the measured ambient temperature with a set of equations which have already been described elswhere [7-8].

Six tests were conducted at different days in the month of June, 2006, out of these six tests only one is depicted in Figure 2. The results obtained show the maximum values of V_{oc}, I_{sc}, V_{max}, I_{max}, P_{max}, efficiency (η) and working temperature as 19.93V, 8.21A, 15.41V, 7.28 A, 95.12W, 19.4% and 71 °C, respectively. The minimum values recorded for these parameters were 17.67V, 0.96 A, 3.69 V, 1.38 A, 21.21 W and 29 °C, respectively. Neither the maximum nor the minimum measured values of these parameters correspond to a single test reflecting the response of PV device to sudden variations in the microclimatic conditions of the region in which it has been installed. An insolation of 200 Wm^{-2} enables the module to produce a maximum voltage (V_{max}) of 15.41 V, with the lowest I_{max} and P_{max} of 1.38 A and 21.21 W and a moderate efficiency of 17%. The minimum irradiation of 200 Wm^{-2} was recorded on June 29, 2006 at 1415 hours local standard time corresponding to a working temperature of 34 °C and an efficiency of 17% which is 5% higher than that has been reported at STC. This test clearly indicates that a PV device can work in a cloudy climate with as low irradiance of 200 Wm^{-2} and therefore has a potential to be used for localities with cloudy and low insolation conditions.

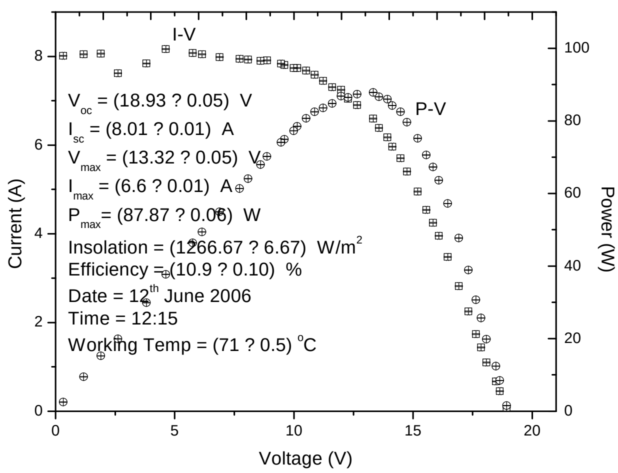

Figure 2. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of June 2006. The various working parameters are highlighted in graph.

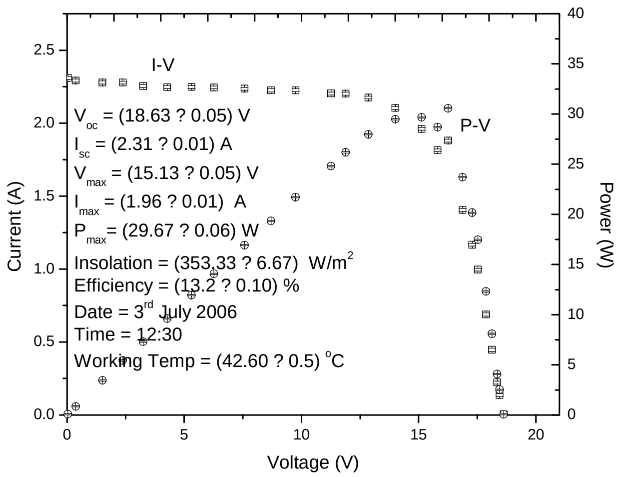

Figure 3. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of July 2006. The various working parameters are highlighted in graph.

Only one test was conducted in the month of July 2006 (see Figure 3). The day was clear at 1015 hours local standard time with an irradiance of 1150 Wm^{-2} that produced a working temperature of the module of 69 °C.

Under such outdoor conditions the module performed with an efficiency of 11%. Later at solar noon and then at two hours after solar noon the sky was cloudy and irradiance levels reduced to 624 Wm^{-2} with a working temperature of 52 °C that gives an efficiency of approximately 14%. An increase in the efficiency can be related with a decrease in the working temperature of the module.

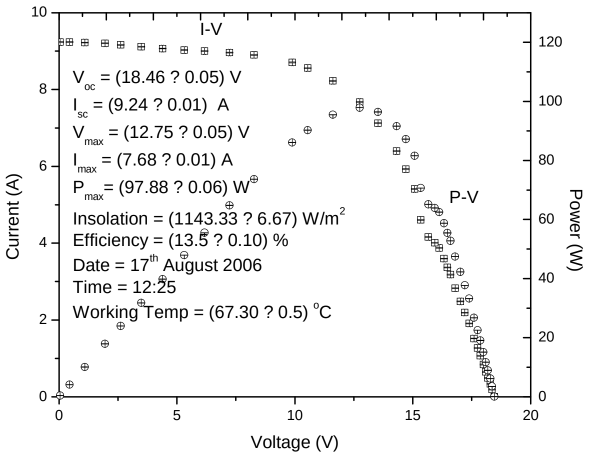

Figure 4. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of August 2006. The various working parameters are highlighted in graph.

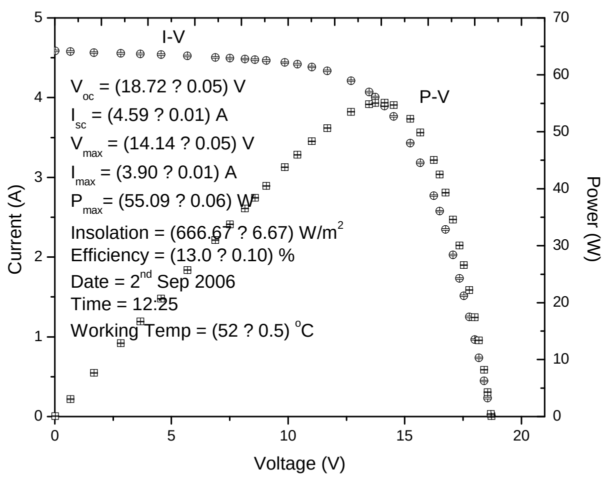

Figure 5. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of September 2006. The various working parameters are highlighted in graph.

Four tests were carried out in the month of August (10th , 17th , 24th and 31st) 2006 and one of these is shown in Figure 4. The amount of solar radiation reaching at the surface of module during this month lies in the range of 70 Wm^{-2} to 1140 Wm^{-2} and the variation in the efficiency was 8-20%. It is interesting to note that the irradiance on 17th at 1415 hours and 24th at 1415 hours were approximately the same with almost the same working temperature of the module (70 ^{o}C) but the efficiency for these two events was not the same clearly indicating that in the outdoor environment temperature in not the only the parameter to influence the working efficiency of a PV devices but other climatic parameters also play role. An overcast condition was observed on 10th August 2006 at 1415 hours with an insolation of 70 Wm^{-2} and the working temperature of 27 ^{o}C. Under such conditions the module did not stop functioning but produced an efficiency of 11%. Ideally this is not possible but the natural environment is entirely different. If these conditions occur in the morning then the module may not be able to function properly. As this spell was in the afternoon and before this the module was working at a temperature of 61 ^{o}C leading to thermal agitation in the module capable of producing free carriers. The thermal agitation rescues the module during the overcast period. The open circuit voltage, short circuit current and maximum power during this period were 17 V, 0.54 A and 5.13 W respectively. The most effective parameter was the short circuit current due to the obvious reason of insufficient incoming radiation to produce direct free carriers in the module and hence low power output.

There were three tests done in the month of September 2006. Out of these, there were two events when the working temperature of the model (67 ^{o}C) was the same but the irradiance were different (1150 and 1006 Wm^{-2}), a higher efficiency of 19% was measured for low insolation of 1006 Wm^{-2} rather than for higher irradiance. Therefore, the higher insolation in a natural environment does not necessarily lead to a higher efficiency. The maximum efficiency of 20% was recorded during this month corresponding to an insolation of 830 Wm^{-2} and a working temperature of 59 °C. On the other hand the output power of the module is sensitive to the irradiance level. It is worth noting that, there were four different occasions when the efficiency was 13% (2nd September, 2006 at 1015 hours and at 1225 hours, on 14th September, 2006 at 1215 hours and on 21st September, 2006 at 1215 hours). Corresponding to these events an insolation of 743 Wm^{-2}, 667 Wm^{-2}, 300 Wm^{-2} and 1273 Wm^{-2} and the working temperatures of 51°C, 52°C, 39°C and 71°C were recorded respectively. From the first principle of photovoltaic theory, higher insolation gives a higher efficiency but this effect was counter balanced by the effect of temperature which reduces the efficiency. The combination of high working temperature and high insolation resulting in an efficiency of only 13% that is slightly more than that measured at STC.

Three test were conducted in the month of October (5th, 15th and 19th) 2006 and one of these is depicted in Figure 6. There are two different occasions when the working temperature (59°C) and the insolation of 0.9 Sun (900 Wm^{-2}) were the same but efficiency was different that is 14% and 18% corresponding to 5th October, 2006 at 1215 hours and 19th October, 2006 at 1058 hours. This clearly indicates that the working temperature and insolation are not the only variables affecting the rating of PV devices in an outdoor environment. During this month, there were three different days and times for which the efficiency was 15%. This corresponds to the irradiance and working temperatures of 930 Wm^{-2} and 58 °C (12th October at 1040 hours), 973 Wm^{-2} and 61 °C (12th October at 1215 hours) and 1200 Wm^{-2} and 69 °C (19th October 2006 at 1215 hours). The irradiance and working temperature on 12 th October at 1040 hours and 1215 hours are comparable, therefore, the efficiency would be the same as expected. But on 19th October 2006 at 1215 hours, the insolation and the working temperature were higher compared with other two events as discussed above. It looks like high insolation and high working temperature counter balance each other's effect. The maximum working temperature of the module recorded for the month of October 2006 was 70 °C with an insolation of 1014 Wm^{-2}. The efficiency, V_{oc}, I_{sc} and P_{max} were 14%, 18.51 V, 8.13 A and 89 W respectively. The recorded values for these parameters clearly demonstrate the influence of natural environment on the rating of PV module.

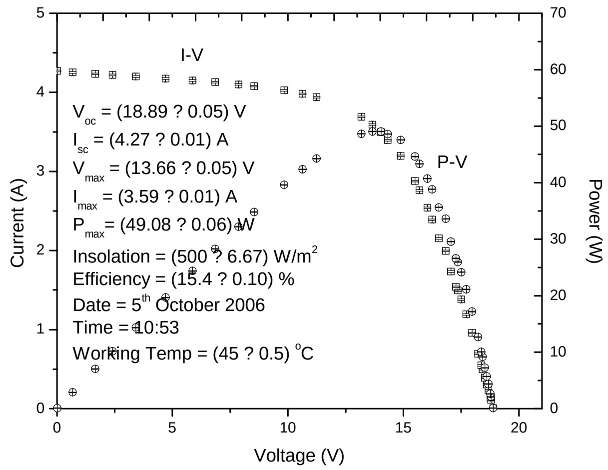

Figure 6. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of October 2006. The various working parameters are highlighted in graph.

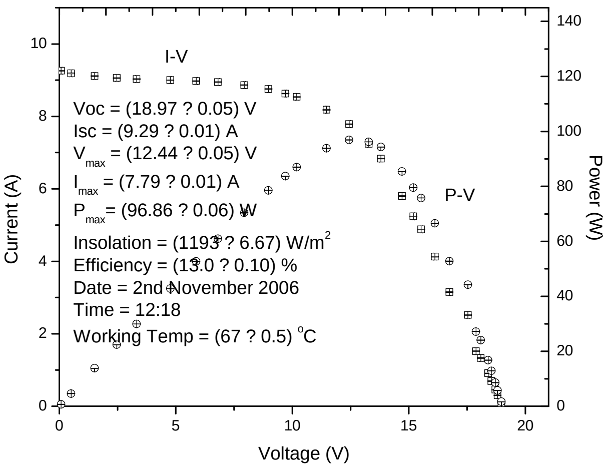

Figure 7. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of November 2006. The various working parameters are highlighted in graph.

One out of two tests conducted in the month of November 2006 is shown in Figure 7. The efficiency of 12%—16% was observed for the month of November 2006. The insolation and the working temperature were 580 Wm^{-2}—1200 Wm^{-2} and 49 ^oC—69 ^oC, respectively. The results obtained reveal that the combination of low insolation and low working temperature gives high efficiency, while high insolation and high working temperature gives a low efficiency. This may be due to the fact that high insolation generates more free carriers which move from valance band to conduction band whereas a high working temperature increases the short circuit current and decreases the open voltage. The product of high current and low voltage gives a lower power and hence lower efficiency.

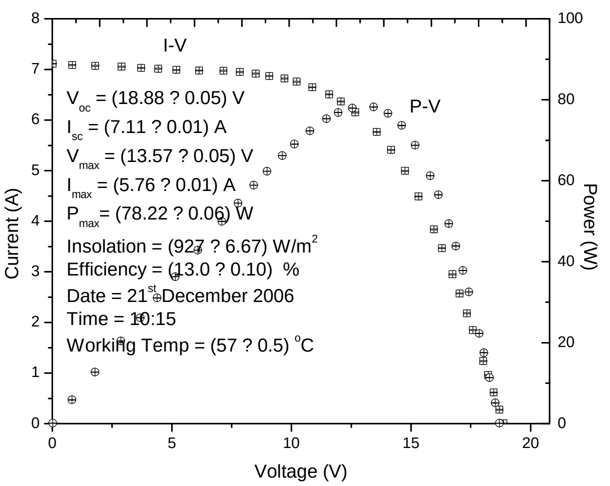

Figure 8. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of December 2006. The various working parameters are highlighted in graph.

Four tests were conducted in the month of December (9th, 14th, 21st and 28th), 2006 and one of these is shown in Figure 5(a). A maximum efficiency of 17% was measured corresponding to a working temperature of 56 ^oC and an insolation of 990 wm^{-2}. The recorded efficiency is 5% more than that at STC while the irradiance are approximately the same as that of STC. The combination of high insolation and low working temperature increases the efficiency of the module. It is notable that there were six different events when the efficiency of the module was 15% but the working temperature and irradiance were different for every event along with the other electrical parameters. The lowest irradiance of 187 Wm^{-2} was observed on 21st December 2006 at 1215 hours local standard time that corresponds to a working temperature, efficiency, P_{max}, I_{max} and V_{max} of 37 ^oC, 12%, 14 W, 1.03 A and 10.24 V, respectively. It is worth to note that all rating parameters are lower than those reported at STC due to very obvious reason that irradiance is only approximately of 0.2 sun but under such conditions the PV module works with a reasonable efficiency. It might be due to a very short and a sudden blockage of the Sun disk with to heavy clouds. However, this sudden blockage of the sun disk directly affects the current and voltage of the module but as the module was working at a temperature of 57 ^oC before this spell, the thermal agitation processes rescue the module.

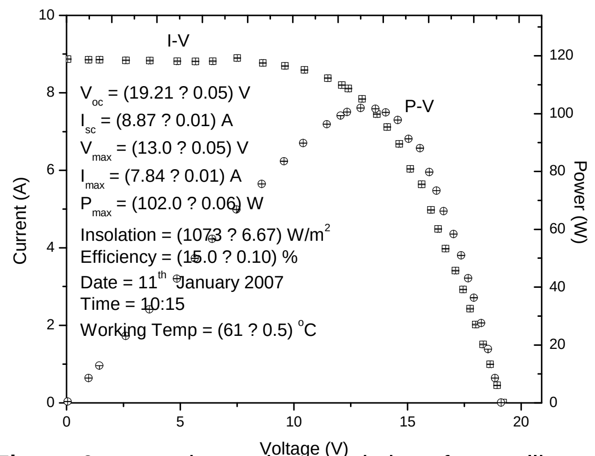

Figure 9. I-V and P-V characteristics of crystalline single crystal photovoltaic module of 76 W for the month of January 2007. The various working parameters are highlighted in graph.

Out of two tests carried out in the month of

January 2007 (4th and 11th) only one shown in Figure 9. The efficiency and the working temperature lie in the ranges of 12-17% and 42-61 °C, respectively. It is noted that a combination of low insolation and low temperature gives high efficiency and high insolation with high temperature gives low efficiency.

The results obtained for a period of eight months demonstrate that the working temperature of photovoltaic devices along with other climatic variables in a natural environment play a central role in the conversion efficiency and electrical power output of these devices. A number of researchers around the globe paid considerable attention to predict the working temperature and its influence on the performance of PV modules/cells [9-13] in natural as well as in a controlled environment. Eight months data have been used to develop temperature coefficients for the under investigation PV module. The temperature coefficients obtained for current, voltage, power and efficiency are shown in Figures 10-11.

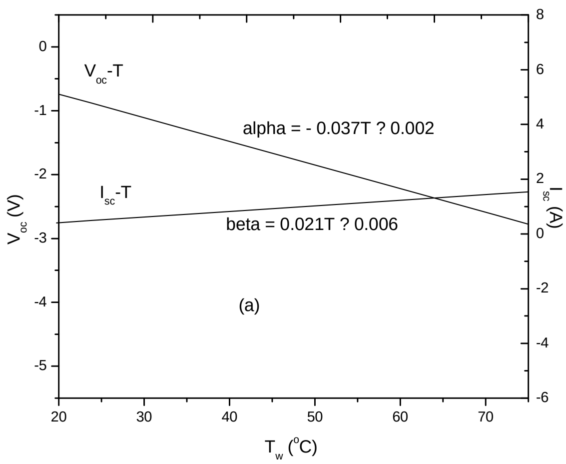

Figure 10. Variation of V_{oc} and I_{sc} with the working temperature of module with reference to standard temperature condition (STC).

In a natural environment a considerable fraction of the incident light is transformed into heat. Theoretically, as silicon is an indirect semiconductor therefore this heat is dissipated in the bulk of the device.

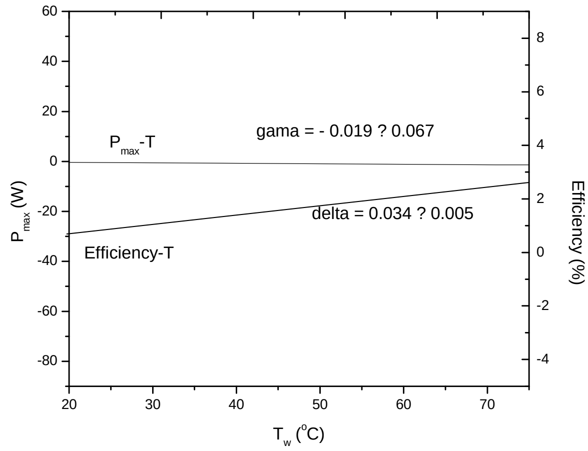

Figure 11. Variation of P_{max} and efficiency with the working temperature of module with reference to standard temperature condition (STC).

In a natural environment a considerable fraction of the incident light is transformed into heat. Theoretically, as silicon is an indirect semiconductor therefore this heat is dissipated in the bulk of the device. Consequently, the operating temperature of a device can vary over a wide range, especially when operating in a hot climate. In semiconductor materials the flow of free carries depends on the lifetime of minority carriers and the band gap energy which are temperature dependent. The band gap energy decreases with an increase in temperature and the minority carriers lifetime increases as temperature increases. Therefore, an increase in temperature will increase the light generated current and thus I_{sc} firstly due to the increased light absorption and secondly due to the increase in minority carrier diffusion length [14-15].

The open circuit voltage decreases more rapidly as temperature increases because of the exponential dependence of diode current on the temperature as expressed in Equation (3). Both current and voltage of PV devices are sensitive to temperature. Consequently, P_{max}, fill factor and efficiency of these devices are also affected when operating in a natural environment. The results presented in Figure 10 demonstrate that the open circuit voltage decreases substantially with temperature because at this stage the thermally excited electrons dominate the electrical properties of the module. The increase in temperature should theoretically increase the short circuit current but experimentally it is noted that the change in the short circuit current is not always positive. Sometimes the short-circuit current decreases as well with an increase in the temperature. The results obtained reveal that in the presence of diffused radiation an increase in the working temperature of the module decreases the short-circuit current as well as the maximum output power. Similarly our results also demonstrate that a combination of high working temperature and high irradiance also decrease the short-circuit current. A decrease in short-circuit current always leads to a decrease in the output power of the PV device. It is very difficult to explicitly relate the two variables in a natural environment where a number of climatic parameters are simultaneously affecting the module. It has been noted that the module performed under cloudy spells as well, where all irradiance reaching the surface of the module were diffused. This clearly indicates that PV devices also convert indirect or diffused radiation; however their performance is affected due to the overcast conditions. It would be a matter of interest to use the combination of the sun simulator and the environmental chamber to simulate the above mentioned climatic conditions and study their influences on the electrical properties of PV devices. This is because of the fact that in a controlled environment the variation of two variables can be studied by keeping all others as constant. The change in the maximum voltage and the maximum current due to change in the working temperature is very similar to the change in the open circuit voltage and short circuit current, respectively.

The graph between the working temperature and the efficiency shown in Figure 11 has a positive slope indicating that the efficiency of PV device increased as the temperature increases. This graph is a linear best fitting of eight months data which does not necessarily represent the individual events but rather an average effect. Every time the efficiency was not increased with an increasing temperature. The data obtained reveal that a combination of high temperature with high irradiance leads to a reduction in the efficiency. The presence of diffused radiation develops a moderate temperature and therefore the efficiency increased for such periods. Our results demonstrate that the single crystalline PV module working in a region with high irradiance declines in efficiency when compared to that at STC. The efficiency of single crystal silicon module will improve in those regions where climatic conditions support the availability of mixed types of diffused and direct components of solar radiation. This is because of the fact that the presence of such climatic conditions produces a moderate working temperature in the natural environment. Artificially such conditions can be achieved by reducing the working temperature of the module which can be achieved through the removal of heat produced by non-active absorption of photons, recombination of electron-hole pairs, photocurrent, parasitic current and lack of effective cooling of the module due to the additional tempered glass pane. Heat can be removed from the module either through air cooling or water cooling. A project has been under plan to use these options and look into the performance of the module. It is expected that the electrical rating of PV modules would be improved by cooling.

The temperature coefficient due to open circuit voltage, α, short circuit current, β, the maximum output power, γ, and the efficiency, δ, are tabulated in Table 2.

Table 2. Temperature coefficients for a single crystal PV module of 76 W with reference to the standard temperature conditions (STC).

Temperature coefficient	Value
$\frac{dV_{oc}}{dT}(\equiv \alpha)$	$-(36 \pm 2) \times 10^{-3}$ V °C^{-1}
$\frac{dI_{sc}}{dT}(\equiv \beta)$	$(23 \pm 7) \times 10^{-3}$ A °C^{-1}
$\frac{dP_{max}}{dT}(\equiv \gamma)$	$-(58 \pm 5) \times 10^{-3}$ W °C^{-1}
$\frac{d\eta}{dT}(\equiv \delta)$	$(38 \pm 5) \times 10^{-3}$ % °C^{-1}

These temperature coefficients are used to calculate out values of the open circuit voltage, the short circuit current, the maximum output power and the efficiency of the module as a function of the working temperature (T_W) with reference to their values at standard test conditions. The following correlations have been developed:

$$(V_{oc})_{Tw} = (V_{oc})_{STC} + \alpha(T_W - T_{STC})$$

$$(I_{sc})_{Tw} = (I_{sc})_{STC} + \beta(T_W - T_{STC})$$

$$(P_{max})_{T_w} = (P_{max})_{STC} + \gamma(T_W - T_{STC})$$

$$(\eta)_{Tw} = (\eta)_{STC} + \delta(T_W - T_{STC})$$

Where T_{STC} stands for the temperature at STC and $T_W > T_{STC}$.

The values of temperature coefficients reported in Table II are in agreement qualitatively with the earlier studies conducted by Dyk et. al. [16], Mayer and Mapuranga [17] and Malik and Fauzi [7] however there are quantitative difference. The quantitative differences are due to the different techniques used to measure the electrical characteristics of PV modules/cells, tests are conducted at different localities and modules/cells used for these tests have different ratings at standard test conditions. It has been observed that the electrical parameters of modules/cells in a natural sunlight can only be reproduced if the PV devices are taken from the same single crystal ingot, manufactured by the same manufacturer and are tested under the same climatic conditions.

4. Conclusions

The efficiency of PV devices in the outdoor environment is a complex function of micro-climatic parameters. Among these parameters the working temperature of the PV device plays a crucial role in determining the rating of these devices. A combination of high working temperature and high irradiance leads to a lower conversion efficiency compared with low temperature and low irradiance. Two PV devices manufactured by the same manufacturer having slightly different electrical performances at standard test conditions perform differently under the same operating conditions in the outdoor environment. In a natural environment dominated by diffused radiation an increase in the working temperature of the PV device decreases the short circuit current and the output power. A combination of high working temperature with high irradiance leads to a reduction in the efficiency of PV devices with compared to that at STC.

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