THERMAL AND ELECTRICAL ENERGY YIELD ANALYSIS OF A DIRECTLY WATER COOLED PHOTOVOLTAIC MODULE

by

Busiso MTUNZI *, ***Edson L. MEYER, and Simon MICHAEL***

Fort Hare Institute of Technology, University of Fort Hare, Alice, South Africa

Original scientific paper
DOI: 10.2298/TSCI130118144M

Electrical energy of photovoltaic modules drops by 0.5% for each degree increase in temperature. Direct water cooling of photovoltaic modules was found to give improved electrical and thermal yield. A prototype was put in place to analyse the field data for a period of a year. The results showed an initial high performance ratio and electrical power output. The monthly energy saving efficiency of the directly water cooled module was found to be approximately 6[illegible]%. The solar utilisation of the naturally cooled photovoltaic module was found to be 8.79% and for the directly water cooled module its solar utilisation was 47.93%. Implementation of such systems on households may reduce the load from the utility company, bring about huge savings on electricity bills and help in reducing carbon emissions.

Key words: *solar energy utilisation, performance ratio, thermal response*

Introduction

In South Africa 95% of its primary energy mix consists of 77% coal, 13% oil, and 5% natural gas. The remainder 5% is contributed from biomass and renewable energy [1]. When burnt, the fossil fuels produce carbon dioxide, nitrogen dioxide, and sulphur dioxide. These gases contribute negatively towards the environment by causing global warming. Fossil and nuclear fuels are unsustainable and it is imperative that the daily reliance on them should be reduced. In place of these fuel sources, sustainable sources need to be used. Renewable energy resources are sustainable and can be used continuously without any notable negative impact [2].

Photovoltaic (PV) systems are cleaner means of electricity production, no emissions during electricity production, no noise from the PV generators and are very environmentally friendly. The PV systems have been used mainly in outlying areas not connected to the electricity utility grid. The silicon PV modules only convert around 15% of incoming solar radiation and the rest is lost through reflection and mainly as heat. It is therefore worth investigating on how the lost heat can be utilised. Real data need to be used to determine the performance of the PV modules with respect to electricity and warm water production. In this paper the performance analysis of the system was carried out for all seasons from the month of September 2011 to August 2012.

* Corresponding author: e-mail: bmtunzi@ufh.ac.za

Theoretical background

Efficiency of a cell

The efficiency of a cell is defined as the ratio of energy output from the solar cell to input energy from the Sun. This has been found to depend on the spectrum and intensity of the incident sunlight as well as the temperature of the solar cell [3]. The electric conversion efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_{\text{peak}} I_{\text{peak}}}{G A_{\text{cell}}} \tag{1}$$

where V_{peak} [V] is the maximum voltage, I_{peak} [A] – the peak current, G [Wm^{-2}] – the plane of cell/module irradiance, and A_{cell} [m^2] – the area of the cell or module.

The power from a PV module is determined using the relationship:

$$P_{\max} = V_m I_m \tag{2}$$

where $P_{\max}$ is the maximum power, V_{m} – the maximum voltage, and I_{m} – the maximum current.

The energy produced E, is generally given by the relationship:

$$E = \text{Power} \times \text{Time} \tag{3}$$

The time can be the day's length, month or year. The day's length in terms of hours is given according to eq. (4), [4]:

$$t_{\text{d}} = \frac{2}{15} \cos^{-1}[\tan(-\phi) \tan \delta] \tag{4}$$

where ϕ is the angle of latitude, δ – the declination angle and can be calculated from:

$$\delta = 23.43° \sin\left[\frac{360}{365}(n + 284)\right] \tag{5}$$

where n is the number of the day in the year.

The total energy produced per 1 m^2 of the solar module for one day can be estimated from the relationship:

$$E_{\text{d}} = \frac{E}{\text{Area of module}} \tag{6}$$

The PV Modules electrical performance characterisation

To characterise the performance of the PV system the International Standard IEC 61724 in [5] was used to calculate the performance ratio (PR) of the two modules, M1 the naturally cooled module and M2 the photovoltaic thermal system (PV/T). The relationships used:

$$Y_{\text{f}} = \frac{E}{P_{\text{o}}}, \quad Y_{\text{r}} = \frac{H}{G}, \quad PR = \frac{Y_{\text{f}}}{Y_{\text{r}}} \tag{7}$$

where Y_{f} [h] is the final yield, E [kWh] – the energy produced by the PV system, P_{o} [kW] – the installed/rated peak power, Y_{r} [h] – the reference yield, H [kWhm^{-2}] – the plane of array irradiance, and G [1 kWm^{-2}] – the irradiance at standard test conditions (STC) equal.

The PV/T performance characterisation

Thermosyphon systems have been noted to be affected by random variations of solar radiation, ambient temperatures, wind conditions, connecting pipe sizes, and design parameters [6]. The daily thermal efficiency of the system can be found using the relationship [6]:

$$\eta_{\mathrm{th}} = \frac{mC_p(T_{\mathrm{f}} - T_{\mathrm{i}})}{A_{\mathrm{c}}H} \tag{8}$$

where m, C_p, T_{f}, T_{i}, A_{c}, and H are the fluid total mass in the thermosyphon system, heat capacity, final and input temperatures in the storage tank, collecting area of the PV module, and the daily total incoming solar-radiation on the collector surface from 06:00 to 16:00 hours, respectively.

The overall performance of the PV/T can be determined by finding the total efficiency η_{th} given by eq. (8) and energy saving efficiency η_{s} given by eq.(9), [6].

Here η_{e} and η_{th}, are electrical efficiency and thermal efficiency of the PV/T. The energy saving efficiency η_{s} of PV/T is given by eq. (9):

$$\eta_{\mathrm{s}} = \frac{\eta_{\mathrm{e}}}{0.38} + \eta_{\mathrm{th}} \tag{9}$$

where 0.38 is the electric efficiency of a thermal power station used to give the energy saving of the PV/T, [7].

Experimental method

The system used for the study consisted of two SW80 PV modules each with an area of 0.719 m^2 and 36 cells in series connection. One module, M1 was naturally cooled by air and used as a control and the other module, M2 was cooled by water in direct contact with the back of the module. It consisted of channels meant to allow the free flow of water in direct contact with the back of the module, [8]. Table 1 shows the two modules' rated performance under STC: 1000 W/m^2, 25 °C, AM 1.5, [9]. The modules have the same ratings.

Table 1. The SW80 Poly/RIA corresponding rated STC values

Quantity	STC value
Short circuit currency, I_{sc} [A]	4.42
Open circuit voltage, V_{sc} [V]	21.50
Peak current, $I_{\max}$ [A]	4.48
Peak voltage, $V_{\max}$ [V]	17.90
$P_{\max}$, [W]	80.19
Efficiency, η [%]	11.14

The experiment was carried out on a north facing test rig at a tilt angle of 32.75° which is the angle of latitude of Alice city, South Africa. The storage tank was placed at a height of 30 cm above the modules to enable thermosyphon effect. The set-up was as shown in fig. 1.

The modules were then connected to the I/V low cost system developed at the Fort Hare Institute of Technology [10], and to the Sunsaver maximum power point tracking (MPPT) charge controller as shown in fig. 2.

The charge controllers were connected through a Morningstar PC Meterbus to a personal computer for I/V data logging. Data logged from the controllers were module current and voltage output as well as load current, voltage, and battery voltage. All these were measured by the Sunsaver MPPT. Two 25 W DC loads were each connected to a battery through a charge controller. The lamps only got disconnected and connected from the battery bank through the control of charge controllers.

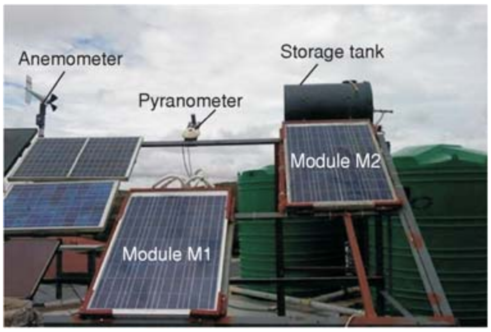

Figure 1. Naturally cooled (M1) and directly water cooled (M2) PV modules on a test rig

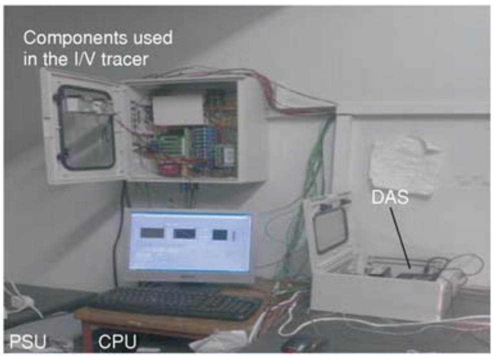

Figure 2. The I/V tracer and data acquisition system

The charge controllers were set to disconnect the load when the battery voltage reached 11.00 V and to reconnect the load when the battery voltage reached 12.10 V. The lamps only got disconnected at night when the batteries were discharged to 11.00 V and only got reconnected in the morning after sunrise when the voltage rose to 12.10 V. The load energy consumption pattern will however not be discussed in this paper. It is only the thermal efficiency and the PV modules' electrical efficiencies that were considered in this paper together with their performance ratios.

The I/V tracer was programmed to record the module I/V data automatically every 30 minute interval from 06 hour to 19 hour. The irradiance, wind speed, and temperatures were all recorded on the data-taker data logger every 10 minutes for 24 hours over the 12 months period and averaged over 30 minutes intervals. This was done to ensure that these measurements correspond to I/V measurements.

Results

The results detailed below were for the twelve months starting from September 2011 to August 2012.

Electrical

The mean daily values for each month of ambient temperature, module temperatures, irradiance, and energy received on plane of array were as shown on tab. 2.

Table 2. Mean daily values of ambient temperature, module temperatures, irradiance, and energy received each month

Month	T_{amb} [°C]	$T_{backmod}$ M1 [°C]	Efficiency M1 [%]	$T_{backmod}$ M2 [°C]	Efficiency M2 [%]	Irradiance [Wm^{-2}]	Energy [kWhm^{-2}]
September	[illegible]	30.19	9.47	22.70	9.80	548.60	6.51
October	[illegible]	30.44	7.34	23.82	9.83	441.13	5.69
November	19.97	28.61	9.42	24.08	9.33	418.83	5.75
December	22.54	24.16	8.29	27.17	8.23	380.30	5.37
January	26.48	31.84	8.91	32.00	8.00	456.41	6.34
February	24.13	33.67	9.15	29.35	8.03	434.97	5.72
March	22.92	31.28	7.98	27.50	7.33	360.16	4.38
April	19.63	28.49	8.64	24.55	7.51	409.67	4.57
May	18.43	26.52	8.63	22.61	7.55	383.99	3.95
June	18.38	21.65	9.12	18.80	7.91	320.81	3.17
July	14.90	22.55	9.46	18.74	7.62	387.49	3.91
August	15.13	21.31	9.12	18.21	7.46	333.86	3.63

The graphs illustrating the differences on the back of module temperature for the period September 2011 to August 2012 are shown in fig. 3.

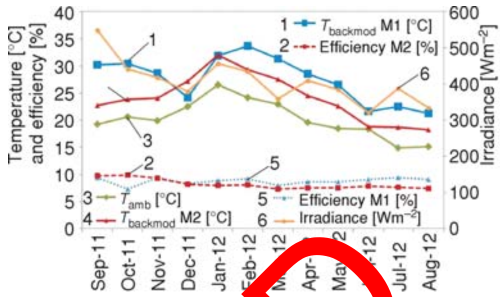

Figure 3. Monthly variations of temperature, efficiency and irradiance

The irradiance in the month of September was 30.7% more when compared to that received in the month of December. This was attributed to rains and cloud overcast which were noted in the months of November-December. The measured irradiances shown in tab. 2, confirm the differences in the average monthly irradiances. In the months of September and October though the irradiance was high, the back of module temperatures for the directly water cooled module (M2) was cooler when compared to M1. This was found to be due to the higher rate of water cooling effects on module M2 when compared to the naturally air cooled module M1. However in the month of December the reverse was true and this was likely due to the heat absorbed and contained in module M2. From the month of February to August 2012, both modules' back of module temperature appeared to be falling. However, module M1 had a higher electrical efficiency as compared to M2, though the opposite was expected. This discrepancy was attributed to water ingress on module M2. Water ingress contributes to increase in series resistance through oxidation of the conductors connecting the cells. Also water ingress may contribute towards cell circuitry introducing shunt paths and therefore reducing the shunt resistance of the module, hence lower efficience.

The PR of the modules was determined using eq. (7). The PR represented includes PR calculated using the rated efficiency for the SW80 module and the PR calculated using the determined efficiency for each module every month see fig. 4. The graph shows the PR determined for the whole year from the month of September 2011 to August 2012.

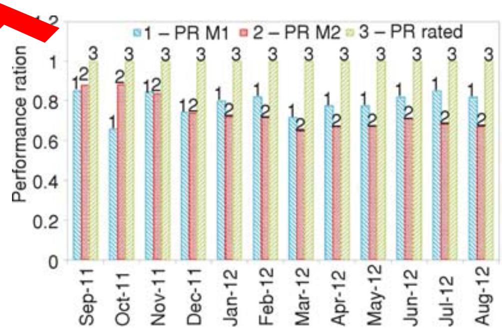

Figure 4. Performance ratio of modules

The difference between the PR rated (PRR) of value equal to 1 and the respective PR of the respective module for each month give all imaginable energy losses that was due to mismatches or wiring.

To explain the trends in fig. 4, the percentage differences between the PR for modules M1 and M2 and that between the modules and rated values were as shown in fig. 5.

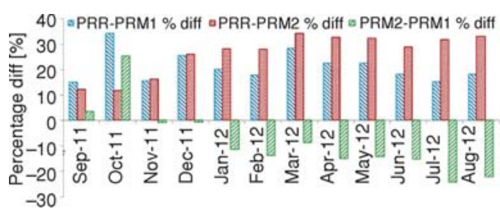

Figure 5. Percentage difference between PRR and modules M1 and M2 and between M1 and M2

From fig. 5 it can be noted that M2 outperformed M1 in the months of September and October 2011. In these months percentage differences of 3.4% and 25.3% were noted, respectively. However, in the months of November and December 2011 M1 outperformed by 0.96% and 0.73%, respectively. Worst perfor-

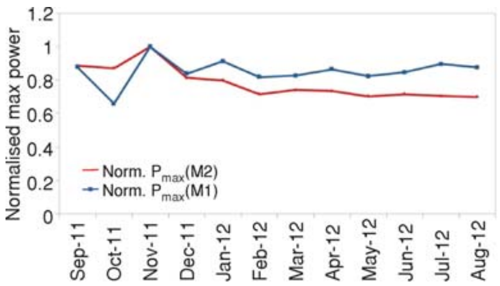

Figure 6. Normalised maximum power of the two modules

mance of M2 was noted in July, with M1 outperforming M2 by 24.2%. This bad performance of M2 was much pronounced from the month of January and continued to the end of the twelve months study period. In January the average back of module temperature of M2 was 32 °C while that of M1was 31.84 °C. The two modules with this set-up were expected to operate in a similar manner, unfortunately the output was different. The difference in performance could not have been due to temperature differences but attributed to something else, the water ingress was the likely agent.

To further confirm the observations, the monthly maximum power output and conversion electrical efficiency of the modules were determined around solar noon and were as shown in fig. 6.

In the month of October, a sharp drop in power output by M1 was noted when compared to module M2 and this response was also confirmed in fig. 5. This response was found to be due to higher back of module temperatures that were found to rise from mid-morning to afternoon when compared to those for M2. The power output from M2, however, was found to decrease in the following months when compared to M1. This was suspected to be due to an increase in series resistance and a decrease in shunt resistance noted on measurements made from the two modules. The change in series and shunt resistances was probably due to the water absorption which then affected the module circuitry.

Figure 7. Fill factor and conversion efficiencies of the modules

The monthly variations of the efficiency and fill factor (FF) from the modules were determined around solar noon. Generally, around solar noon, lowest efficiency levels are obtained [11]. The results were as shown in fig. 7.

Just as indicated above in fig. 7, M2 outperformed M1 in terms of efficiency and FF for the first two months September and October and from the month of December onwards M1 outperformed M2 in all respects. The higher FF and higher efficiency values noted in the first three months were due to cooler back of module temperatures and low water adsorption. The rise in temperature has been found to produce thermal agitation which not only increases the dark current but also enhances the losses of free carriers in a polycrystalline module [12].

Thermal response

The average monthly thermal efficiency values of the PV/T are shown on tab. 3.

From tab. 3 it can be noted that the PV/T had a higher thermal efficiency in September and October 2011 and July 2012 as compared to rest of other months. The total in plane irradiation *H*, shown in tab. 3 was determined from the product of irradiance and the length of the day using eq. (4).

Table 3. Average daily monthly results

Month	T_i [°C]	T_f [°C]	ΔT [°C]	T_a [°C]	H [kWhm^{-2}]	η_{th} [%]	η_e [%]	η_s [%]
September	10.89	28.64	17.75	19.22	6.51	46	9.80	71.79
October	12.66	25.39	12.73	20.63	5.69	41	9.83	66.92
November	16.62	27.80	11.18	19.97	5.75	31	9.33	55.55
December	19.70	30.07	10.37	22.54	5.37	33	[illegible]	54.66
January	26.92	39.08	12.16	26.48	6.34	35	8.00	56.05
February	25.06	39.32	14.26	27.91	5.72	39	8.03	60.13
March	21.10	32.37	11.27	22.94	4.38	44	[illegible]	63.29
April	18.50	32.27	13.77	19.91	4.57	46	7.51	65.76
May	16.15	27.53	11.38	18.43	[illegible]	38	7.55	57.87
June	10.26	16.60	06.3	15.63	3.17	33	7.91	53.82
July	13.01	27.43	14.42	21.75	3.91	50	7.62	70.05
August	13.75	24.82	11.06	[illegible]	3.63	39	7.46	58.63
Average	17.05	29.28	12.79	22.79	6.51	39.58	8.22	61.21

Figure 8 further illustrates the efficiency variations graphically.

From fig. 8, it can be seen that the energy saving efficiency of the system was largely dependent on thermal efficiency.

The total thermal and electrical energy collected from the PV/T for each month and for the whole year were as shown in tab. 4.

The monthly thermal and electrical energy values of the system were determined using thermal and electrical efficiency values. The month of September gave the highest output as compared to the other months. An equivalent thermal energy of 80.4 kWh and electrical energy of 17.05 kWh was obtained during this month. The initial highest electrical energy value was most likely due to the fact that the module M2 had not yet absorbed water.

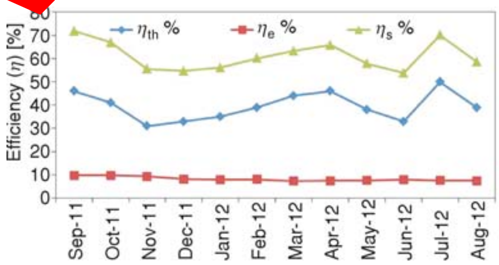

Figure 8. Monthly variations of energy saving efficiency η_s, ambient, inlet and final storage tank temperatures

The total amount of energy falling onto the module was found to be 1727.65 kWh for the year in question. The overall energy utilized by PV/T was 828.12 kWh, implying a 47.93% of solar energy utilisation. The naturally cooled module's solar utilisation was found to average 152 kWh, giving a utilisation percentage of 8.79%. The PV/T system, M2, was as a result found to have a better solar utilisation as compared to M1. The thermal and electrical efficiencies of the two modules from the month of September 2011 to the month of August 2012 are shown in fig. 9. They detail the response of the modules for each, respective, month.

The major drop in electrical energy production was noted as from the third month the project was set-up, to the end of the year. This was attributed to water absorption which in turn oxidised cells as shown in fig. 10.

Table 4. Monthly and yearly energy collected from the directly cooled PV module

Month	η_{th} [%]	η_e [%] M2	η_e [%] M1	H [kWhm^{-2}]/month	E_{therm} (M2) [kWhm^{-2}]/month	E_{elect} (M2) [kWhm^{-2}]/month	E_{elect} (M1) [kWhm^{-2}]/month
Sep-11	46.00	9.80	9.47	174.00	80.04	17.05	16.48
Oct-11	41.00	9.83	7.34	159.74	65.49	15.70	11.72
Nov-11	31.00	9.33	9.42	157.00	48.67	14.65	14.79
Dec-11	33.00	8.23	8.29	143.12	47.23	11.78	11.86
Jan-12	35.00	8.00	8.91	162.66	56.93	13.01	14.49
Feb-12	39.00	8.03	9.15	152.76	59.58	[illegible]	13.98
Mar-12	44.00	7.33	7.98	123.91	54.52	9.08	9.89
Apr-12	46.00	7.51	8.64	142.75	65.66	[illegible]	12.33
May-12	38.00	7.55	8.63	140.28	53.31	[illegible]	12.11
Jun-12	33.00	7.91	9.12	115.08	37.98	9.10	10.50
Jul-12	50.00	7.62	9.46	140.28	70.14	10.69	13.27
Aug-12	39.00	7.46	9.12	116.08	45.27	8.66	10.59
Sum				**1727.65**	**684.81**	**143.31**	**152.01**

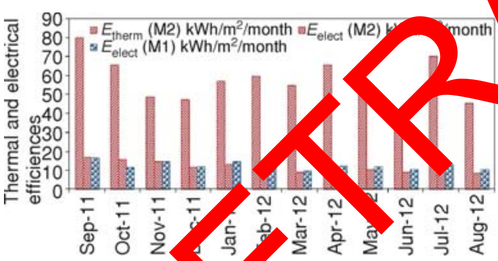

Figure 9. The thermal and electrical efficiencies of the two modules

Figure 10. Oxidised cells on M2

RETRACTED

Once silicon cells get oxidised, their series resistances increase, causing lower power generation from the respective cell. This in turn contributes to less power from the module.

The thermal efficiency of the module M2 averaged 39.58% throughout the year, while its electrical efficiency averaged 8.22%. Module M1's electrical efficiency averaged 8.79%, indicating a 0.57% higher electrical efficiency when compared to M2. This difference was attributed to water ingress in M2.

The monthly energy saving efficiency of the PV/T system was found to be approximately 61% while its yearly average electrical efficiency was found to be 8.22%.

Conclusions

Higher electrical efficiency values were obtained from the PV/T for the months of September and October 2011 as compared to the other months. A highest PR of 0.88 was achieved with module M2, while with M1 a maximum PR of 0.85 was attained. However, more electrical energy losses were noted in M2 when compared to M1. This was indicated by the difference between the PRR when compared to the corresponding module's PR. The monthly energy saving efficiency of the PV/T was found to be approximately 61%.

References

[1] Moodley, S., *et al.*, Analysing Scenarios for Energy Emissions Reduction in South Africa, *Journal of Energy in Southern Africa, 16* (2005), 4, pp. 34-40
[2] Carl von Carlowitz, H., *Sustainability and Energy*, http://www.efcf.com/reports/E23.pdf
[3] Eikelboom, J. A., Jansen, M. A., *Characterisation of PV Modules of New Generations*, *Results of Tests and Simulations*, ECNC-00-067, Petten, The Netherlands, 2000
[4] Duffie, J. A., Beckman, W. A., *Solar Engineering of Thermal Processes,* 4th Gen Team, John Wiley and Sons, Hoboken, N. J., USA, 2006
[5] Colli, A., *et al*., Performance Mornitoring of Different PV Technologies and PV Yield in Northern Italy, *Proceedings*, 25th EU PVSEC, Valencia, Spain, 2010, Session 4AV.3.11. pp. 4344-4349
[6] He, W., *et al.*, Hybridphotovoltaic and Thermal Solar-Collector Designed for Natural Circulation of Water, *Applied Energy, 83* (2006), 3, pp. 199-210
[7] Huang, B. J., *et al.*, Performance Evaluation of Solar Photovoltaic/ Thermal Systems, S*olar Energy 70* (2006), 5, pp. 443-448
[8] Mtunzi, B., Meyer, E. L., Benchmarking of the SW80 Polycrystalline Modules Using the Sun as Source of Light, *Thermal Science, 18* (2014), Suppl. 2, pp. S317-S322
[9] ***, SW80 Performance under Standard Conditions, http://www.solarworld-usa.com/system designers/~/media/Global/PDFs/Sunmodule-SW-80-90-poly-RIA.pdf.
[10] Simon, M., On the Evaluation of Spectral Effects on Photovoltaic Modules Performance Parameters and Hotspots in Solar Cells, Ph. D. thesis, University of Fort Hare, Alice, South Africa, 2009
[11] Meyer, E. L., Mtunzi, B., Comparative Study of a Directly-Cooled PV Water Heating System to a Naturally-Cooled Module in South Africa, *Proceedings*, 38th Photovoltaic Specialist Conference, Austin, Tex., USA, 2012, pp. 1296-1299
[12] Malik, A. Q., *et al.*, Influence of Temperature on the Performance of Photovoltaic Polycrystalline Silicon Module in the Bruneian Climate, *AJSTD, 26* (2010), 2, pp. 61-72

Paper submitted: January 18, 2013
Paper revised: September 17, 2013
Paper accepted: October 27, 2013