Journal of Energy in Southern Africa 22(3): 16–22
DOI: http://dx.doi.org/10.17159/2413-3051/2011/v22i3a3218

Outdoor testing of amorphous and crystalline silicon solar panels at Thohoyandou

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Abstract
The use of solar panels is becoming one of the options for some of the rural communities in Limpopo Province, South Africa, to get electrical energy for their radio and television sets as the national grid may not reach them in the near future. Hence, dissemination of knowledge of how to use the solar devices and their maintenance is crucial for these communities. This will be possible only if there is appropriate information available for the potential end-users, installers and extension workers. With this in mind, an attempt has been made to evaluate the performance of an amorphous and a crystalline solar panel at our experimental site. Outdoor tests were conducted to measure solar radiation, open-circuit voltage, short circuit current, current-voltage (I-V) curve, fill-factor and conversion efficiency and hence to compare the performance of the two types of panels. It was found that both types give a satisfactory performance for the climate of this region.

Keywords: Amorphous and crystalline silicon solar panels, solar radiation, peak power, I-V curve, conversion efficiency, standard testing condition

1. Introduction

In the north-eastern Limpopo, a large number of villages are yet to be connected to the national electricity grid. People living in these villages opt for solar panels to get power for their television and radio sets, which form a major source for accessing information from the regional communication stations about the events taking place in the country and the world at large. The University of Venda is a tertiary institution situated in the rural area of the far north of the Limpopo Province in South Africa and the community members generally resort to seeking advice from us about the use and the installation of solar panels to generate electricity. It has become necessary to assist the rural community regarding the optimal use and the maintenance of the photovoltaic (PV) system that are usually available on the market. To provide a meaningful suggestion to the community, it is important to carry out field tests on the suitability of the panels. Effecting a successful comparison between two different types of PV modules, would require the determination of their outdoor performance at known irradiance and temperature. For this purpose, we need to measure the open circuit voltage (Voc) and short circuit current (Isc), which will in turn, lead to the measurement of the output power of the modules. We will also require the current-voltage (I-V) characteristics of these modules to make a useful comparison of their efficiency.

The choice of a suitable PV module for a given location is generally guided by the actual energy output under outdoor conditions, the validity of the data supplied by the manufacturer and the implications on cost of installations. Though the power output and the efficiency rating of the panel given by the manufacture can be taken as the starting point, it is important to test these panels under outdoor conditions to access the validity of the data in a given location.

2. Experimental considerations

The present study was carried out at Solar Research Site situated at the University of Venda, Thohoyandou, Limpopo Province, South Africa, latitude 22.95°S and longitude 30.48°E. The site has a Delta-T Weather Station Mast, which was used to obtain the solar radiation and the temperature data during the performance of the study.

In the present investigation an amorphous (a-Si) and a crystalline (c-Si) PV module are considered for evaluation and comparison. The module de-

Table 1: Specifications of the solar panels

Specification	*Crystalline solar module*	*Amorphous solar module*
Manufacturer	Astropower (AP-7105)	Unisolar (US-42-001416)
Peak power (P_{max})	75W	45W
Maximum power current (I_{mp})	4.4A	2.54A
Maximum power voltage (V_{mp})	17.0V	16.5V
Short-circuit current (I_{sc})	4.8A	3.17A
Open-circuit voltage (V_{oc})	21.0V	23.8V

scriptions and the manufacturer data are given in Table 1.

The area of cross-section of each of the module is 0.63m^2, so that the radiation (energy) falling on the panels at any given time of the day is almost the same. The modules were purchased in South Africa.

In order to evaluate the performance of the two panels under consideration, the solar radiation data as well as the I-V curves are essential. Data Logger (Delta-T 2000) was used to measure the radiation falling on the experimental location and to measure the temperature (daily and ambient temperature), while the DS tracer (DS Tracer 1996) was used to record an I-V curve by varying the electrical impedance connected across the PV arrays terminals. Varying the impedance from zero to infinity causes the array operating point to change from I_{sc} to V_{oc}. When the module is connected, the DS-Tracer accomplishes the impedance change through its operating range and presents a set of current and voltage values that form the I-V curves.

For designing and predicting the potential of any solar appliances at a location, we need monthly average daily solar radiation data on a horizontal surface. The operation and performance of PV modules mainly depend on system configuration and weather conditions. Furthermore, the module temperature and solar irradiance determine the module's operational curve and the coupling of the PV modules. In addition, the system components determine where a system will operate on the PV operational curve (Hecktheuer *et al*. 2004). It is desirable to operate a system near the maximum power producing point on the module's operational curve either at all times (during the sunshine hours) or during worst-case operation condition (Fitzpatrick, 2004).

The outdoor conditions under which a PV module is exposed are likely to be varying from the conditions stipulated by the manufacturer. Hence, the module may not perform at the desired points on the I-V curve in order to harness the maximum expected output. Commercially available PV module rating and operating parameters are provided with respect to the standards of American Society for Testing Materials (ASTM) at Standard Reporting Condition (SRC) or Standard Testing Conditions (STC) (Treble, 1991).

Module or array open-circuit voltage and module cell temperature should be read concurrently, since open-circuit voltage is a function of cell temperature. The module must be left in an open-circuit condition for a minimum of 15 minutes prior to the taking of the open-circuit voltage reading to ensure representative cell temperature reading (Markvart, 1994). Modules or arrays can contain cells, which vary significantly in temperature throughout the module due to hot spot heating, caused by cracked cells, mismatched cell or cell shading. Short-circuit currents should be measured immediately after the measurement of open-circuit voltage so that the test conditions are nearly identical (Markvart, 1994). Readings of the short-circuit current and irradiance must be made concurrently to minimize errors. The input signal (current-voltage to the DS Tracer) can also be used to calibrate the DS Tracer for radiation and temperature. The input signals provide necessary details and after calibration they will be displayed along with the I-V curve (DS Tracer 1996). The calibration of the temperature can be carried out by recording the ambient temperature of the panel using a thermometer and the details provided could be utilized to get the temperature data on the curve. Apart from those methods, the temperature of the solar cell can be determined by the equilibrium between the sun's radiation, the energy converted to electrical energy and the energy re-radiated to cold space (Krishna *et al.,* 2009)

3. Results and discussion

It is a generally accepted fact that the performance of crystalline silicon solar cells varies from location to location (Lund *et al.,* 2001). This variation is caused by the difference in irradiation at different locations, together with spectral response of the solar cell, temperature effects, etc. For solar cells with a wide band gap (amorphous silicon solar cell) it was observed that no long-term light induced degradation exists in the recent modules (Gottschalg *et al*., 2004). Lund et al., have studied the stability of the amorphous silicon modules under outdoor conditions and reported that the efficiency of the amorphous solar cell is stabilized after the initial degradation. It was also deduced that under the actual working conditions the amorphous solar cell could generate electrical power more steadily compared with the crystalline solar cell (Lund *et al.* 2001).

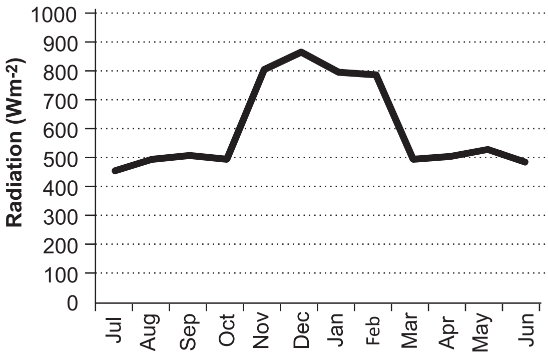

Figure 1: Solar radiation at 12H00 for a period of one year

3.1 Solar radiation characteristics and peak power

For the evaluation and assessment of the performance of a photovoltaic module at a given location, it is necessary to get an overview of the solar radiation characteristics. Measurements of solar radiation at different times of the day during a period of one year were made. Figure 1 represents the radiation at 12H00 for different months under study at the experimental site. It can be seen that an average maximum per month of 870 W/m^2 was measured on a horizontal plane.

Peak power is the maximum power, which is generated by a solar panel in full sunshine. Commercially available panels are rated with a peak power, but it should be noted that generally this peak power (observed maximum powers) will not be harnessed since the factory testing condition and the outdoor conditions are not similar. The observed maximum powers for the crystalline and amorphous modules for different months are given in Table 2. Though the sunshine duration is about 10 hours on a sunny day at the experimental site, readings are only presented from 10H00 to 15H00.

From Table 2, it can be noted that the observed maximum power increases until it reaches a maximum at mid-day and drops as it moves to the evening. It is observed that a maximum of 60W is obtained for crystalline against the rated value of 75W and 33W for amorphous against the rated value of 45W (Maluta & Sankaran. 2007). The variation in the observed maximum power is more in crystalline module.

It may also be seen that the observed maximum power variation from the average value does not vary significantly in the case of amorphous. In this work, we have compared the variation by looking at the difference between the hourly observed maximum powers for each month. It can be observed from the data that the variations of the crystalline and amorphous for the whole year are almost similar in magnitude. These results are consistent with earlier results observed for amorphous PV (Gottschlag *et al.,* 2004).

3.2 I-V characteristics

The other important electrical characteristics of a

Table 2: Observed maximum power for crystalline and amorphous PV modules

	Observed maximum power for crystalline module (in W)[1]						*Observed maximum power for amorphous module (in W)[2]*					
	Time of the day(in –H00)						*Time of the day(in –H00)*					
	10	11	12	13	14	15	10	11	12	13	14	15
Jul	39	46	48	42	38	36	19	26	26	25	24	20
Aug	46	47	52	48	47	45	21	27	29	27	24	23
Sep	49	54	55	55	52	48	23	29	30	29	26	25
Oct	50	55	57	54	51	50	25	29	31	28	27	26
Nov	52	55	59	53	52	50	28	30	32	29	28	26
Dec	52	58	60	56	53	50	28	31	33	29	28	25
Jan	54	55	58	53	52	50	27	29	32	28	27	25
Feb	48	50	55	51	45	43	27	28	30	28	26	24
Mar	48	50	54	47	46	44	25	26	29	27	26	21
Apr	44	49	53	51	50	46	24	26	28	27	26	25
May	44	48	51	50	46	45	23	27	28	26	25	23
Jun	43	46	49	44	42	41	20	28	27	25	25	23

Notes:

1. The maximum rated output power for crystalline (c-Si) module is 75W.
2. The maximum rated output power for amorphous (a-Si) module is 45W (the data was taken from July 2003 until June 2004)

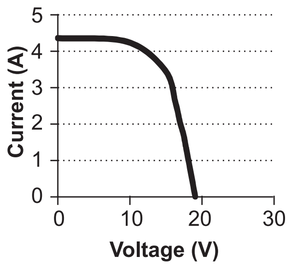

Figure 2A1: for c-Si module (Oct)

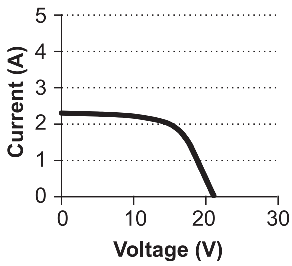

Figure 2A1: for a-Si module (Oct)

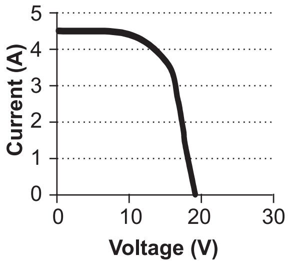

Figure 2A1: for c-Si module (Nov)

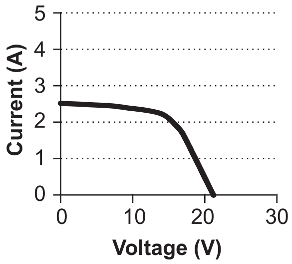

Figure 2A1: for a-Si module (Nov)

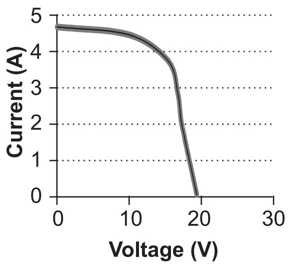

Figure 2A1: for c-Si module (Dec)

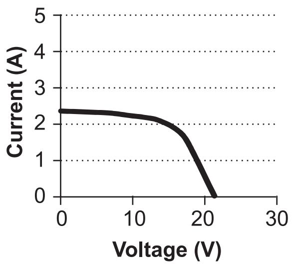

Figure 2A1: for a-Si module (Dec)

Figure 2: Sample I-V curves for c-Si (crystalline) and a-Si (amorphous) modules for the months of October, November and December, 2003

module are, short-circuit current (I_{sc}), open-circuit voltage (V_{oc}) and maximum power point (P_{max}). A few sample curves obtained in the present study are given in Figure 2. Maximum power is generated at only one point on the I-V curve, at about the 'knee' of the curve, which represents the maximum efficiency of the solar device in converting sunlight into electricity.

The maximum V_{oc} obtained for amorphous solar panel is about 21.78V, whereas for the crystalline solar panel the maximum V_{oc} obtained is 19.83V both in the month of December, when we get the maximum radiation. The open-circuit voltage increases with an increase in the incident radiation and time of the day. It can be noted from Table 3 that the values of V_{oc} during mid-day for the entire period of study for both modules do not vary significantly.

Though variations in the values of the open-circuit voltage of an amorphous module and crystalline module are very small, it is noted that the V_{oc} is nearly the same for the amorphous module from September to June. The maximum value for I_{sc}, obtained for amorphous solar panel is 2.736A, while the maximum value for I_{sc} obtained for the crystalline panel is 4.566A. It is interesting to note that these maximum values are recorded in December 2003.

A sample curve of the variation of I_{sc} with the irradiation data collected for the month of May in the present study is given in Figure 5. It may be observed from this figure that as the irradiation increases the short circuit current also increases. This observation is concurrent with the observation that the current generated by the solar energy is proportional to the flux of photon with above-band-gap energy. This is because the irradiance increases in the same proportion of the photon flux, which, in turn, generates a proportionately higher current

Table 3: Open-circuit voltage and short circuit voltage for both crystalline and amorphous solar cells at 12H00

Radiation (Wm^{-2})		*Crystalline*		*Amorphous*	
		V_{oc} (V)	*I_{sc} (A)*	*V_{oc} (V)*	*I_{sc} (A)*
Jul 2003	460	19.00	3.552	20.50	2.136
Aug 2003	500	19.30	4.268	21.78	2.220
Sep 2003	513	19.37	4.180	21.25	2.443
Oct 2003	500	19.42	4.468	21.59	2.642
Nov 2003	810	19.78	4.542	21.50	2.549
Dec 2003	870	19.83	4.566	21.10	2.736
Jan 2004	801	19.58	4.540	21.08	2.478
Feb 2004	792	19.32	4.455	21.70	2.378
Mar 2004	500	19.75	4.345	21.57	2.565
Apr 2004	510	19.54	4.435	21.56	2.363
May 2004	533	19.20	4.260	21.50	2.400
Jun 2004	490	19.30	3.752	21.70	2.236

(Markvart, 1994). It must be noted that in this work, only the solar radiation on a horizontal surface have been considered. Other factors such as the difference in the spectral responses to irradiance at varying incidence angle, and to irradiance of varying spectral composition are not considered.

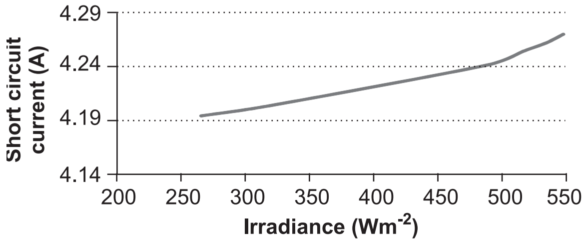

Figure 3A: Variation of ISC versus irradiation for May 2004 for c-Si module

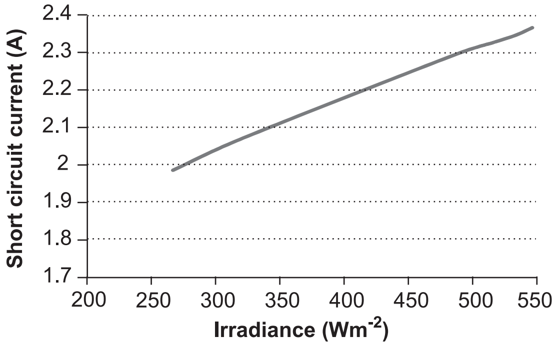

Figure 3B: Variation of ISC versus irradiation for May 2004 for a-Si module

3.3 Conversion efficiency

The conversion efficiency of a solar cell is the percentage of the solar energy shining on a PV device that is converted into electrical energy. The efficiency of energy conversion is still low, thus requiring large areas for sufficient insulation and raising concern about unfavourable ratios of energies required for cell production versus energy collected (Dinçer *et al.,* 20101). Thus, not all energy from sunlight reaching a PV cell is converted into electricity. This may be due to the reflection and scattering of solar radiation in the afternoon and also the increase in the cell temperature (Dinçer *et al.,* 20101). Hence, there is an increase in the amount of light reflected away from the cell surface. Therefore, minimizing the amount of light reflected away from the cell's surface can increase the module's conversion efficiency.

The conversion efficiency can be computed using the following relation (Markvart, 1994):

$$\eta = \frac{(V_{oc})(I_{sc})(FF)}{(Incident\ solar\ radiation)\ (Area\ of\ the\ panel)} \quad (1)$$

The fill factor (FF), short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) increase as the irradiation increases. It can be seen from equation (1), that as the irradiation increases the parameters in the numerator also increase and we generally expect an increase in the conversion efficiency. As stated by Dinçer *et al.,* the effect of increase in the cell temperature also play a role on the conversion efficiency as Voc will decrease at high cell temperature (Dinçer *et al.,* 20101). However, the increase in the open-circuit voltage and hence the peak power, is not remarkable while the irradiation increases. Hence, it is generally expected that the conversion efficiency decreases as the irradiation increases (Gottschalg *et al*., 2004; Markvart, 1994 & Stone, 1993).

As evident from Figures 4 and 5, a similar trend is observed in our calculation. The average conversion efficiency of the crystalline module during our present study is 15.3 whereas the amorphous module conversion efficiency is 8. These values compare favourably with the generally expected values which are approximately 15-17 for crystalline modules and approximately 5-7 for amorphous modules (Valizadeh 2001; Graham & Ficher 1994).

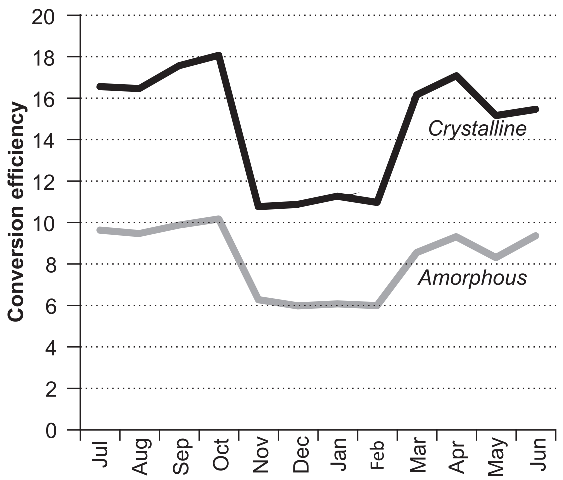

Figure 4: Conversion efficiency of the crystalline and amorphous module at different times of the day (July 2003–June 2004)

3.4 Transposing to standard testing condition

Commercially available solar panels generally list the data for short-circuit current, open-circuit voltage at standard test condition (STC). When these modules are exposed to the outdoor conditions at an experimental site, it is generally not possible to get the same values for the module parameters. Obviously the irradiation and temperature of the modules will not remain constant. Hence, an attempt was made to transpose the values of V_{oc} and I_{sc} obtained in the present investigation to the STC. For this purpose, the following two equations (Hammond Backsus, 1994) were used.

i. $V_{oc}(\mathrm{STC}) = V_{oc} : measured + \left(2.2mV / {}^0C\right)$ (2)

$$(ns)\left(T_c - 25\right)\ln\left(\frac{1000}{G}\right)\left[0.025V(ns)\right]$$

ii. $I_{sc}(\mathrm{STC}) = I_{sc} measured \left(\frac{1000}{G}\right)$ (3)

where ns is number of series cells, T_c is measured Temperature in ^{0}C, V_{oc} is the open circuit voltage, I_{sc} is the short circuit current and G is the measured irradiance.

The difference between transposed values and the manufacturer values are presented as ΔV_{oc} and ΔI_{sc} for both amorphous and crystalline panels for different radiation in Table 4. It can be seen that the difference is minimum when the radiation is high. The difference between the manufacturer's value and the transposed values of I_{sc} are significant for the values of irradiance less than 600 W/m^2.

From the results of the present investigation, it is noted that the equations (2) and (3) need some modification for the type of modules under study and also for the present location as these equations are developed for the northern hemisphere. We hope that due to the irradiation level and ambient temperature, latitude and climate, there will be a difference between the Northern and Southern hemisphere.

4. Conclusions

A close perusal of the measured values of open-circuit voltage and short-circuit current for crystalline and amorphous modules reveals that these values are very close to the values given by the manufacturer under STC. However, in the crystalline module the variation is more prominent in comparison with an amorphous module. The fill factor and the sharpness of the I-V curves are almost similar for the crystalline and amorphous modules. The results obtained using the conversion equations to transpose the measured values of open-circuit voltage and short-circuit current to STC did not compare well with the manufacturers' value at low irradiation levels. The results of the peak power and conversion efficiency measurements suggest that, with proper installation and maintenance, both these modules can be used by rural communities for climate in this region.

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Table 4: Difference between the transposed Voc and Isc from the manufacturer values

	Radiation (Wm^{-2})	*Amorphous solar cell*		*Crystalline solar cell*	
		ΔV_{oc} (V)	*ΔI_{sc} (A)*	*ΔV_{oc} (V)*	*ΔI_{sc} (A)*
Jul 2003	460	1.75	1.473	1.53	2.767
Aug 2003	500	1.47	1.270	1.23	3.736
Sep 2003	513	1.98	1.592	1.12	3.723
Oct 2003	590	1.65	1.308	1.09	4.136
Nov 2003	810	1.64	0.023	0.64	0.810
Dec 2003	870	1.64	0.025	0.56	0.450
Jan 2004	801	1.51	0.080	0.87	0.868
Feb 2004	792	1.48	0.167	1.15	0.825
Mar 2004	500	1.60	1.960	0.70	3.890
Apr 2004	510	1.64	1.463	0.94	3.896
May 2004	533	1.76	1.333	1.30	3.192
Jun 2004	490	1.79	1.393	1.24	2.920

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Received 16 July 2007; revised 4 February 2011