Performance Assessment of Three Different PV Modules as a Function of Solar Insolation in South Eastern Nigeria

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Abstract

Three silicon photovoltaic modules of Siemens product (55W_P monocrystalline, 50W_P polycrystalline and 10W_P amorphous silicon modules) were simultaneously deployed outdoor to evaluate their performances as a function of solar radiation. The research was carried out at University of Nigeria, Nsukka (Lat. 6^0 52' N, Long. 7^0 24' E and 397 metres above sea level). The performances of the modules were evaluated in terms of their response variables (V_{oc}, V_{max}, I_{sc}, I_{max}, P_{max}, and Eff) as a function of global and diffuse irradiance. These response variables were generally observed to be directly proportional to irradiance but significant decrease in efficiency Eff, maximum voltage V_{max}, open-circuit voltage V_{oc} and fill factor FF was noticed at irradiances above 600W/m^2. The correlation of Voc, Isc and Pmax with global and diffuse irradiance was performed using a second degree polynomials. Maximum efficiencies of 12.97%, 9.67% and 4.94% were achieved at irradiance of 600W/m^2 for the monocrystalline, polycrystalline and amorphous silicon modules respectively. However, at irradiance of 1000W/m^2, the efficiencies dropped to 9.61%, 7.65% and 3.62% for the monocrystalline, polycrystalline and amorphous silicon PV modules respectively. The maximum power outputs obtained at irradiance of 1000W/m2 are 37.52W, 28.84W and 6.94W for the monocrystalline, polycrystalline and amorphous silicon module.

Key Words: Solar Insolation, PV Modules, Tropical Region, Performance Assessment.

1. Introduction

Characterization and performance evaluation of photovoltaic modules under a natural insolation play a very important role in photovoltaic research and is essential in realizing the scope of new technologies on the horizon. Efforts and techniques should therefore be devoted to the identification of a set of meteorological parameters, which can be quantitatively correlated with actual photovoltaic module performance, using non-destructive and in-situ characterization techniques **[1].** The solar insolation is paramount and is considered in this regard. The specifications given by the manufacturers of different types of silicon PV modules are usually for standard test conditions (STC i.e. 1000 W/m^2 irradiance, 25^{0}C cell temperature and AM 1.5 global spectrum). As a result, the module performances vary with the locations of use and actual environmental conditions to which they are subjected. For instance, when the irradiance is 1000 W/m^2 in practice, the cell temperature will always simultaneously increase beyond 25^{0}C because of higher infrared radiation associated with increased solar irradiance. Also the irradiance and spectral distribution vary greatly from day to day and even during the hours of a day. Since a P-n junction solar cell only absorbs light photons with energy equal or greater than its band-gap, different band-gap materials will respond differently to the same spectral distribution. According to **Lasnier and Gan Ang [88],**

At low irradiance level,

a) The short-circuit current I_{SC} is proportional to the solar irradiance (neglecting the series resistance R_S)
b) The open-circuit voltage increases slightly with increasing irradiance. It does not depend on the surface area, being a function of the material only.
c) The maximum power of the module is proportional to the irradiance

At Mean Irradiance Level,

$$I_{SC} = I_{ph} - KE_e \quad \text{…(1)}$$

And

$$V_{OC} = \frac{KT}{q}\ln\left(\frac{KE_e}{I_0}\right) \quad \text{…(2)}$$

At High Irradiance Level

$$I_{SC} = I_0\left[\exp\left(\frac{qV_{oc}}{KT}\right)-1\right] \quad \text{… (3)}$$

And

$$V_{OC} = \frac{KT}{q}\left[\ln\left(\frac{KE_e}{I_0}\right)+\ln X\right] \quad \text{… (4)}$$

$$= \frac{KT}{q}\ln\left(\frac{I_L}{I_0}+1\right) \quad \text{… (5)}$$

Where I_0

$$= A_0T^3\exp\left(-\frac{E_g}{KT}\right) \quad \text{… (6)}$$

2. *Research Methodology*

i. Monitoring Stage

The performance response of the silicon PV modules to environmental parameters, such as global and diffuse solar irradiance was monitored in our local environment, using a CR10X software-based data logging system with computer interface. The PV modules under test and meteorological sensors were installed on a support structure at the same test plane, elevated at a height of 406 metres (Alt. + 9 metres) above sea level **[2]**. The reason for this elevation is to ensure adequate exposure to insolation. The modules were tilted at approximately 22^0 (i.e. Lat. + 15^0)**[3]** to the horizontal and south-facing to ensure maximum insolation. The data considered were from 8.00am to 6.00pm each day continuously for a period of one year, spanning from November 2004 to October 2005 at the grounds of the National Centre for Energy Research and Development, University of Nigeria, Nsukka (Latitude 6^0 52' N, Longitude 7^0 24' E and Altitude 397 metres)**[4, 5]**. Table 1**[6]** lists the three silicon PV modules used for this experiment and their specifications at STC (Standard Test Conditions: 1000 W/m^2 irradiance, 25^0C cell operating temperature and air mass 1.5 global spectrum). Instantaneous data collection was performed by the data logger at intervals of 5 minutes and averaged over 10 minutes. Data download at the data acquisition site was performed every 10 days to ensure effective and accurate monitoring of the data acquisition system (DAS). The monthly hourly averages of each of the above parameters were obtained. The global solar radiation was monitored using a solar radiation sensor called SENSOL-MONOKRISTALLIN, manufactured by IKS PHOTOVOLTAIK Company in Western Germany, with calibration of 60.6 mV/1000 Wm^{-2}. The diffuse radiation was monitored using a shadow-band Eppley Radiometer with calibration 9.6 x 10^{-6} V/Wm^{-2}.

ii. Analysis Stage

Performance responses of the modules to these ambient parameters were investigated in terms of open-circuit voltage V_{OC}, short-circuit current I_{SC}, voltage at maximum power V_{max}, current at maximum power I_{max}, maximum power P_{max}, efficiency Eff and fill factor FF.

3. *Experimental Results and Discussion*

In order to further determine the rate of variation of module response variables with these meteorological parameters, a linear statistical model **[7]**

$Y = a + bH_g + cH_d$ **…………………………………………… (7)**

was fitted to the observed data for each of the modules using NLREG data analysis software, version 6.3, developed by Philip H. Sherrod **[8],** to predict module performances at various irradiance conditions **[9]**. The coefficients b and c are the rates of variation of output variables with respect to global and diffuse irradiance respectively and the following empirical equations of the output variables (equations 8 to 16) were subsequently developed.

For the monocrystalline module

V_{oc} = 0.01603Hd – 0.0007996Hg + 18.8596 …………………… (8)

Isc = 0.0028Hg + 0.00037Hd + 0.2272 ………………………….. (9)

Pmax = 0.03109Hg + 0.48903Hd – 16.9359 ……………………..(10)

For the polycrystalline module

Voc = 19.3086 – 0.000645Hg – 0.00128Hd ………………………. (11)

Isc = 0.0026Hg + 0.0028Hd + 0.09914 …………………………….(12)

Pmax = 0.0244Hg + 0.2024Hd – 4.8241 ………………………… (13)

For the amorphous silicon module

Voc = 0.00726Hd – 0.000962Hg + 21.377 ……………………… (14)

Isc = 0.00072Hg – 0.00395Hd + 0.2571 ………………………... (15)

Pmax = 0.00581Hg + 0.07645Hd – 2.3058 ………………………(16)

These correlations of Voc, Isc and Pmax of each of the modules with these ambient parameters were also evaluated and reported in table 1.

Monocrystalline PV Module		
	Hg	***Hd***
Voc	- 0.723	- 0.1031
Isc	0.9883	0.5163
P**max**	0.9505	0.6850
Polycrystalline PV Module		
Voc	-0.9307	-0.8338
Isc	0.9799	0.8509
Pmax	0.9729	0.8910
Amorphous Silicon PV Module		
Voc	-0.8525	-0.6863
Isc	0.9835	0.4268
Pmax	0.9437	0.8870

Table 1 Correlation of Output variables with the ambient parameters for the three modules

Here it was clearly observed that Isc and Pmax of each of the modules were highly and positively influenced by global and diffuse radiation whereas their Vocs were also highly influenced but negatively. Figs. 1 to 3 show the output characteristics of the monocrystalline, polycrystalline and amorphous silicon PV modules as a function of global irradiance.

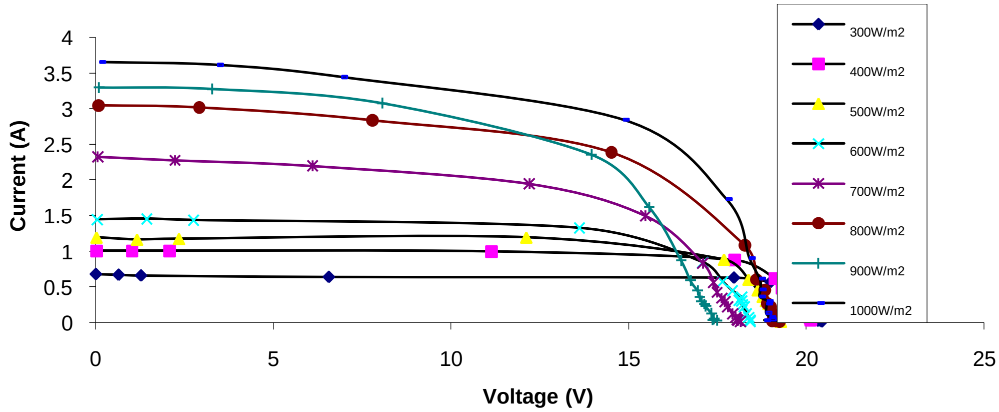

Fig 1. I - V Characteristics for the monocrystalline silicon Module as a function of global irradiance

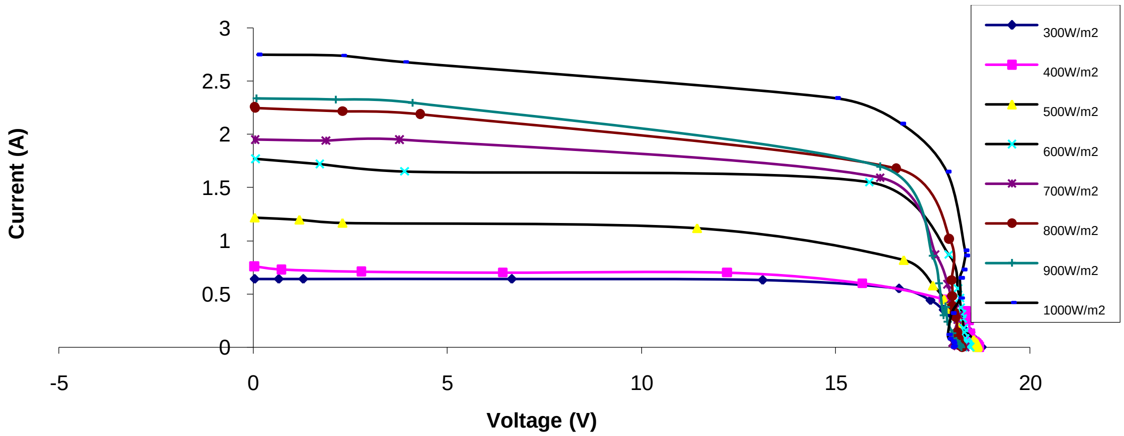

Fig. 2. I - V characteristics at varying irradiance levels for the Polycrystalline silicon PV module

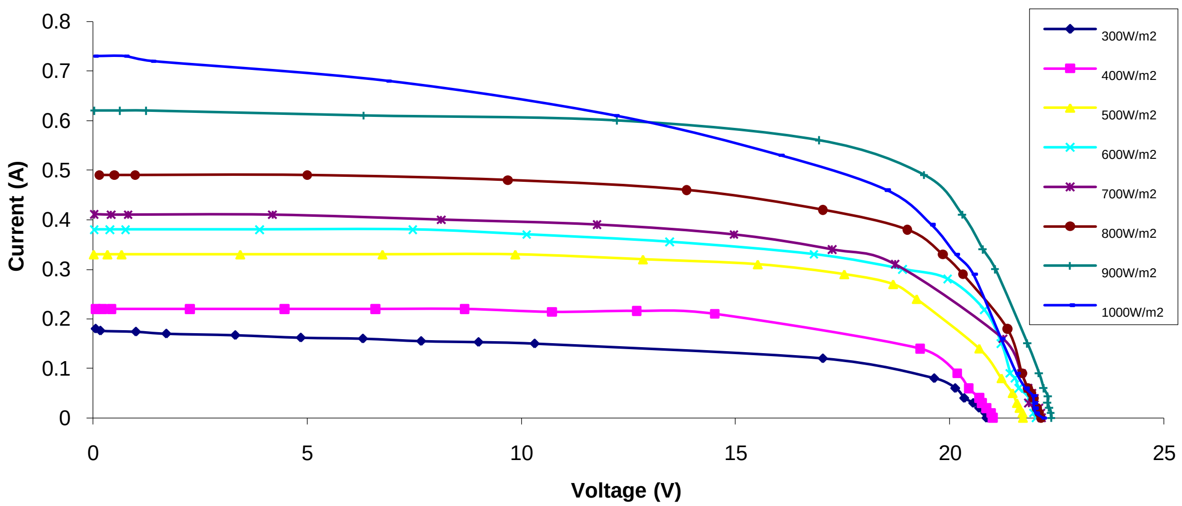

Fig. 3. I - V characteristics at different irradiance levels for the Amorphous silicon module

The short-circuit current was observed to be proportional to insolation. We also observed that increase in module temperature causes a rise in short-circuit current and a decline in both the open-circuit voltage and peak power as shown in the figures. This increase in module temperature arises due to high insolation heating, low wind speed with the consequent low heat transfer from the module to the ambient, and a high ambient temperature. The rise in short-circuit current during this increase in temperature could be attributed to the fact that the band-gap of silicon material decreases as the temperature increases and the saturation current I_0 of the silicon material also increases with temperature according to equation (6) thereby leading to an increase in short-circuit current according to equation (3) and a decrease in open-circuit voltage according to equation (4). Further dependence of module output parameters, like efficiency and maximum power, on global and diffuse irradiance were investigated and shown in figures 4 – 6 for the three photovoltaic modules.

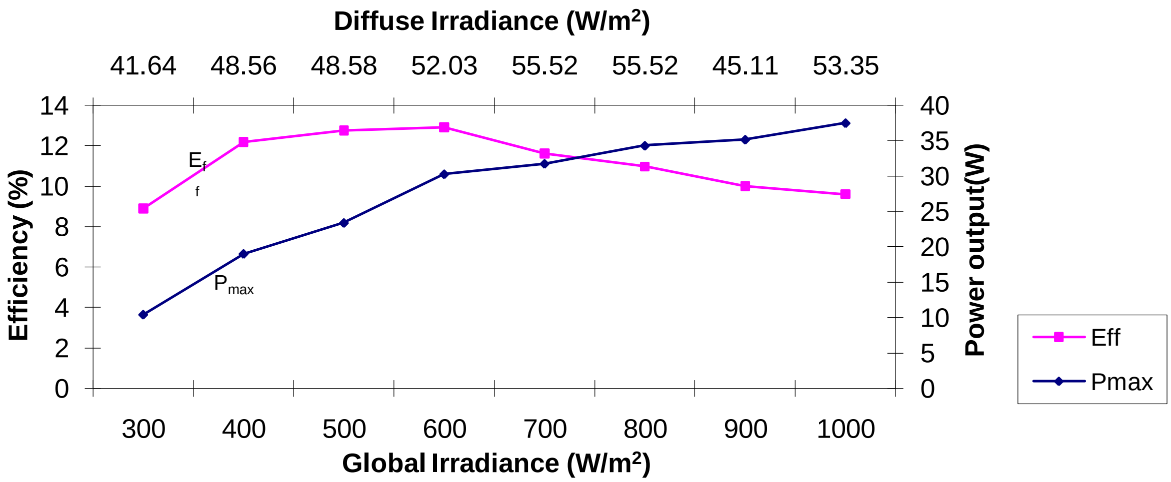

Fig. 4 Variation of Efficiency and Power output as a function of gobal and Diffuse irradiance for the monocrystalline module.

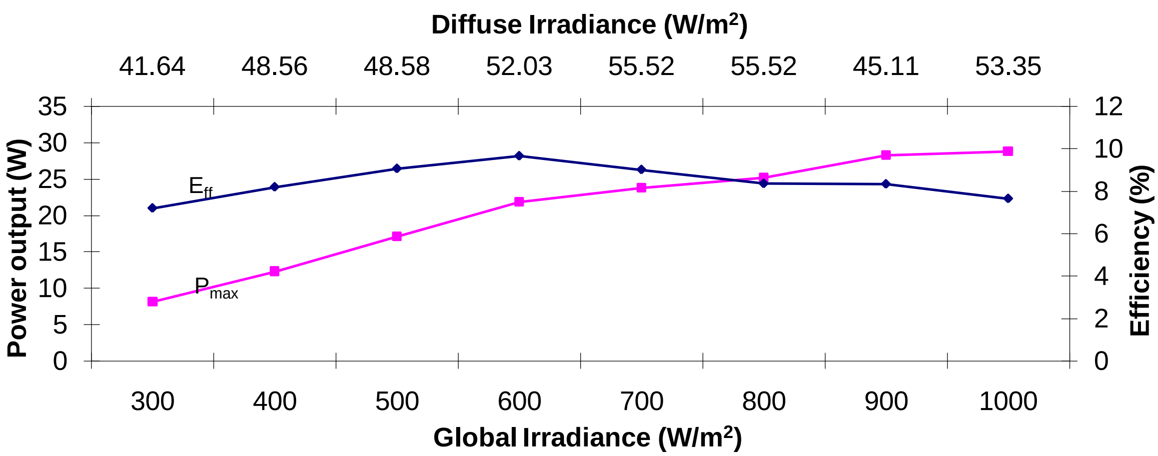

Fig. 5. Variation of efficiency and power output as a function of global and Diffuse irradiance for the Polycrystalline module

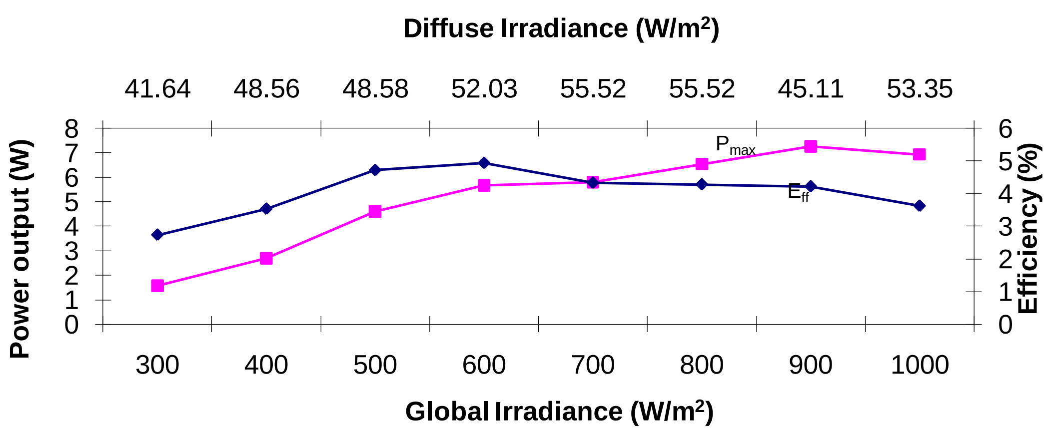

Fig. 6. Variation of Efficiency and Power output as a function of global and Diffuse irradiance for the Amorphous silicon module

It was observed here that the maximum power P_{max} showed slightly linear relationship with the two parameters (global irradiance and diffuse irradiance), while the efficiency showed approximately symmetrical structure at global irradiance of 600 W/m^2. This is because of temperature rise **[10].** The variation of open-circuit voltage and short-circuit current simultaneously with global and diffuse irradiance for the three modules were plotted in figs. 7 – 9.

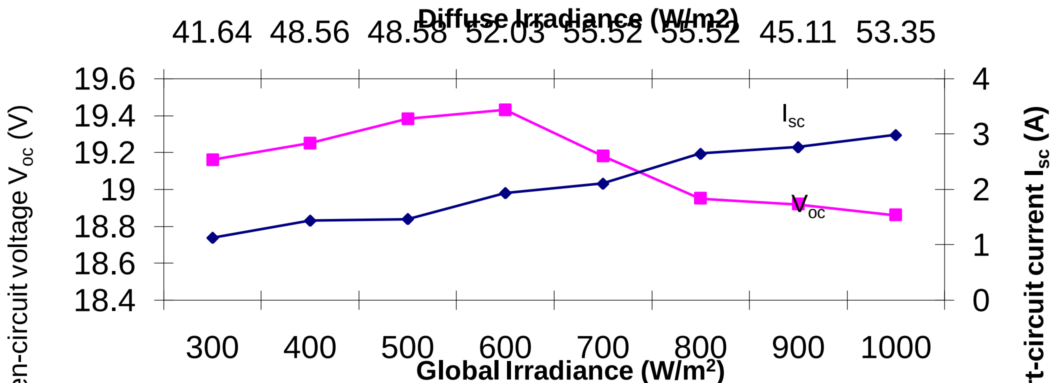

Fig. 7 Variation of V_{oc} and I_{sc} with global and diffuse irradiance for the monocrystalline module

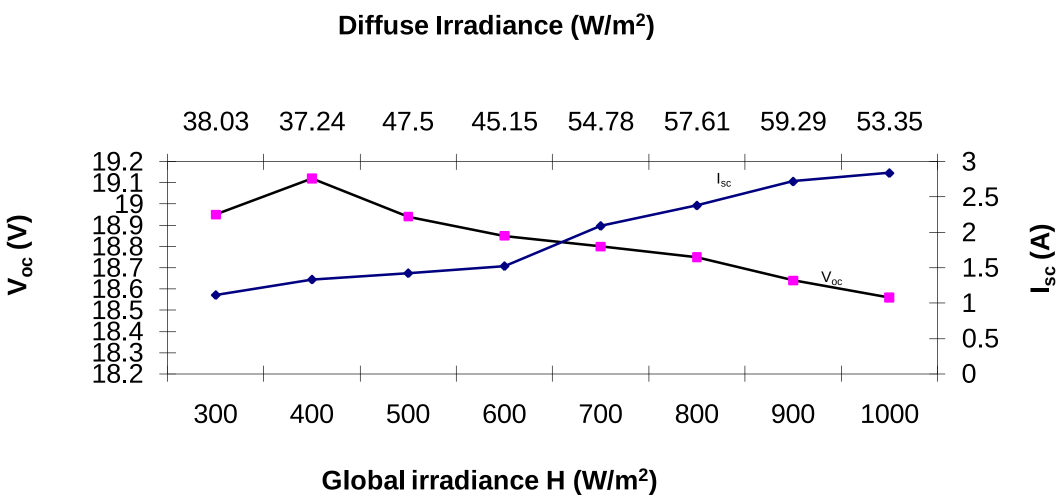

Fig. 8. Variation of V_{oc} and I_{sc} with global and diffuse irradiance for the polycrystalline module

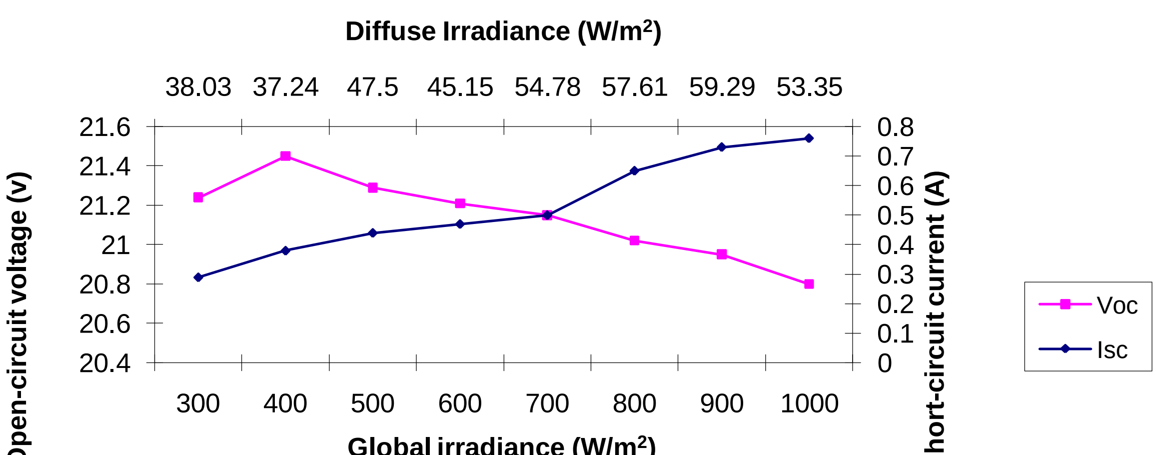

Fig. 9 Variation of V_{oc} and I_{sc} with global and diffuse irradiance for the amorphous silicon module

Here it was noticed that the open-circuit voltage increased linearly with global and diffuse irradiance up to 19.43 V at irradiance of 600 W/m^2 and then dropped consistently with increase in irradiance to 18.86V at irradiance of 1000 W/m^2 and module temperature of 45.07 ^{0}C for the moncrystalline module. The open-circuit voltages of the polycrystalline and amorphous silicon modules increased linearity with increase in irradiance up to 19.12V and 21.45V at 400W/m^2 respectively and also dropped consistently with increase in irradiance to 18.56V and 20.80V respectively at 1000 W/m^2. The performances of the three photovoltaic modules at different levels of these meteorological parameters were summarized in tables 2 – 4. Here the fill factor and the module performance ratios (MPR) of the modules at different levels of global and diffuse irradiance conditions were also computed and inserted. The maximum power output achieved for the modules at irradiance of 1000 W/m^2 were 37.52W, 28.84W and 6.94W representing 68.22%, 57.68% and 69.4% of the manufacturer's power specifications for the monocrystalline, polycrystalline and amorphous silicon PV modules respectively.

For each of the three module types, significant decrease in efficiency Eff, maximum voltage V_{max}, open-circuit voltage V_{OC} and fill factor FF was noticed with increase in irradiances above 600 W/m^2 while maximum current I_{max} and short-circuit current I_{SC} showed linearity with increase in irradiance. At irradiance of 600 W/m^2, the module efficiencies were 12.92%, 9.67% and 4.94%, representing 76%, 76.7% and 62% of the manufacturer's specifications for the monocrystalline, polycrystalline and amorphous silicon PV modules respectively. This shows that diffuse irradiance favors the performance of PV modules more significantly than global irradiance, which is usually associated with high temperature **[11]**. The annual average values, which represent the averages of these monthly values over a period of one year, were presented in table 5. The table shows the variation of open-circuit voltages, short-circuits current and module temperatures under different global and diffuse irradiance conditions at different times of the day for the monocrystalline, polycrystalline and amorphous silicon modules respectively. It is observed here that the short-circuit current peaks at between 1200 hours and 1400 hours when the average irradiance and module temperatures are maximum, while the open-circuit voltage peaks around 1000 hours when the average irradiance is relatively moderate with sufficient diffuse component and average module temperature is close to ambient. The module performance ratios (MPR), defined as the ratio of the measured efficiency to the efficiency at STC **[12]**, were plotted against the global irradiance as shown in figure 10. From the result, we noticed that MPR showed linearity with irradiance up to 600W/m^2 and then declined approximately linearly with increase in irradiance beyond 600 W/m^2 for each of the three modules.

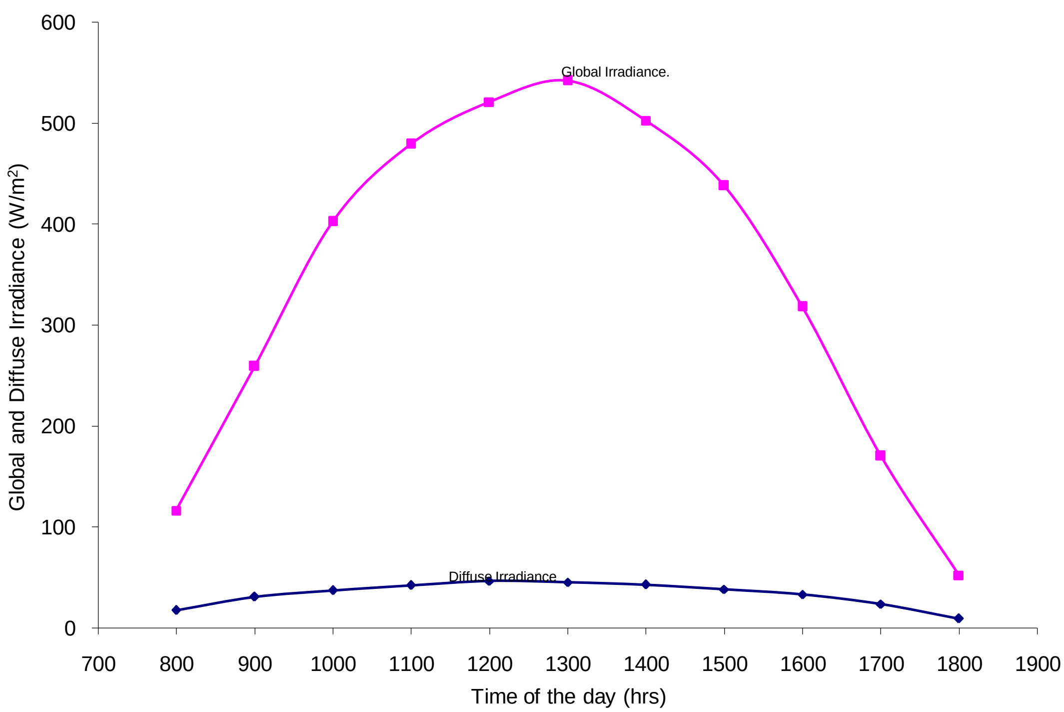

Fig. 10 Variation of Global irradiance (H) and Diffuse Irradiance (H_d) with the time of the day

4. Conclusion

From the characterization and performance evaluation of the PV modules under the influence of global and diffuse irradiance in our local environment, it was discovered that the maximum power output and efficiencies of the modules tested were significantly lower than their rated performances. At irradiance of 1000 W/m^2, the power output reduced by about 31.88%, 42.32% and 30.6% of the manufacturer's specifications for the monocrystalline, polycrystalline and amorphous silicon PV modules respectively. Maximum efficiencies of 12.97%, 9.67% and 4.94% were achieved at irradiance of 600W/m^2 for the monocrystalline, polycrystalline and amorphous silicon modules respectively.

However, at irradiance of 1000W/m^2, the efficiencies dropped to 9.61%, 7.65% and 3.62% for the monocrystalline, polycrystalline and amorphous silicon PV modules respectively. These results indicate that the design of photovoltaic systems for use in our local environment based on the rated performances would be very much in error.

Nomenclature

AM	Air Mass
DAS	Data Acquisition System
Eff	Efficiency
FF	Fill Factor
Isc	Short-circuit current
Voc	Open-circuit Voltage
MPR	Module performance Ratio
NLREG	Non-linear Regression
Pmax	Maximum power
STC	Standard Test Condition

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Glob. Irrad. H (W/m²)	**Diffuse Irrad. H_d (w/m²)**	**V_{oc} (V)**	**I_{sc} (A)**	**V_{max} (V)**	**I_{max} (A)**	**P_{max} (W)**	**η (%)**	**FF (%)**	**MPR**	**K_T**
300	38.03	19.16	1.12	16.30	0.64	10.43	8.90	48.60	52.35	0.22
400	37.24	19.25	1.43	16.98	1.12	19.02	12.18	69.09	71.65	0.30
500	47.50	19.38	1.46	16.48	1.42	23.40	11.98	82.70	70.47	0.37
600	45.15	19.43	1.93	15.07	2.01	30.29	12.92	80.77	76.00	0.44
700	54.78	19.18	2.10	14.64	2.17	31.77	11.62	78.88	68.38	0.52
800	57.61	18.95	2.64	14.42	2.38	34.32	10.98	68.60	64.59	0.59
900	59.29	18.92	2.76	14.36	2.45	35.18	10.01	67.37	58.89	0.67
1000	53.35	18.86	2.98	14.16	2.65	37.52	9.61	66.76	56.53	0.74

Table 2.Summary of Average Performance Response for the Monocrystalline Module at Different Irradiance levels.

Glob. Irrad. H (W/m²)	**Diffuse Irrad. H_d (w/m²)**	**V_{oc} (V)**	**I_{sc} (A)**	**V_{max} (V)**	**I_{max} (A)**	**P_{max} (W)**	**η (%)**	**FF (%)**	**MPR**	**K_T**
300	38.03	18.95	1.11	14.82	0.55	8.15	7.20	38.75	57.14	0.22
400	37.24	19.12	1.33	14.17	0.87	12.33	8.20	48.49	65.08	0.30
500	47.50	18.94	1.42	14.14	1.21	17.11	9.07	63.62	71.98	0.37
600	45.15	18.85	1.52	14.12	1.55	21.89	9.67	76.40	76.75	0.44
700	54.78	18.80	2.09	14.09	1.69	23.81	9.02	60.60	71.59	0.52
800	57.61	18.75	2.38	13.65	1.85	25.25	8.36	56.58	66.35	0.59
900	59.29	18.64	2.72	13.23	2.14	28.31	8.34	55.83	66.19	0.67
1000	53.35	18.56	2.84	12.76	2.26	28.84	7.65	54.71	60.71	0.74

Table 3. Summary of Average Performance Response for the Polycrystalline PV module at different Irradiance levels.

Glob. Irrad. H (W/m²)	**Diff. Irrad. H_d (w/m²)**	**V_{oc} (V)**	**I_{sc} (A)**	**V_{max} (V)**	**I_{max} (A)**	**P_{max} (W)**	**η (%)**	**FF (%)**	**MPR**	**K_T**
300	38.03	21.24	0.29	19.64	0.08	1.57	2.73	25.49	34.13	0.22
400	37.24	21.45	0.38	19.3	0.14	2.70	3.53	33.12	44.13	0.30
500	47.50	21.29	0.44	19.22	0.24	4.61	4.72	49.21	59.00	0.37
600	45.15	20.97	0.47	18.90	0.30	5.67	4.94	57.53	61.75	0.44
700	54.78	21.15	0.50	18.72	0.31	5.80	4.33	54.85	54.13	0.52
800	57.61	21.02	0.65	17.23	0.38	6.55	4.28	47.94	53.5	0.59
900	59.29	20.95	0.73	16.52	0.44	7.27	4.22	47.54	52.75	0.67
1000	53.35	20.80	0.76	15.08	0.46	6.94	3.62	43.90	45.63	0.74

Table 4.Summary of Average Performance Response for the Amorphous silicon PV module at different Irradiance levels.

	Monocrystalline Module			**Polycrystalline Module**			**Amorphous Silicon Module**			**Diffuse Irradiance (W/m²)**	**Global Irradiance (W/m²)**
Time	**V_{oc}**	**I_{sc}**	**T_{mod}**	**V_{oc}**	**I_{sc}**	**T_{mod}**	**V_{oc}**	**I_{sc}**	**T_{mod}**	**H_d**	**H**
800	19.02	0.59	25.48	18.19	0.62	25.48	20.45	0.16	24.98	17.68	116.26
900	19.47	0.89	28.18	18.87	0.91	28.18	21.07	0.25	26.86	31.15	259.23
1000	19.50	1.44	30.44	19.02	1.45	30.44	21.27	0.37	29.46	37.54	402.65
1100	19.38	1.69	34.54	18.96	1.62	34.54	21.21	0.46	32.26	42.41	479.37
1200	19.26	1.92	36.59	18.83	1.91	36.59	21.08	0.59	33.89	46.81	521.02
1300	19.18	2.03	37.92	18.77	1.98	37.92	21.01	0.63	35.20	45.50	542.33
1400	19.12	1.88	38.51	18.74	1.84	38.51	20.96	0.60	36.24	43.03	502.51
1500	19.05	1.58	37.24	18.54	1.55	37.24	20.86	0.47	35.65	38.38	438.20
1600	19.00	1.20	34.59	18.43	1.21	34.59	20.67	0.35	33.93	33.47	318.44
1700	18.78	0.73	32.10	18.05	0.67	32.10	20.31	0.18	31.86	23.75	170.68
1800	17.64	0.29	29.18	16.53	0.28	29.18	18.77	0.08	29.36	9.62	52.30

Table 5.Annual Hourly Average Performance of the modules.