ASSESSMENT OF THE PERFORMANCE OF PHOTOVOLTAIC MODULE UNDER ENVIRONMENTAL CONDITIONS

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ABSTRACT

The performance of photovoltaic (or PV) modules depends on incidence solar irradiance and the temperature of the cell. This study investigates the performance of mono-crystalline photovoltaic module mounted on rooftop. This corresponds to a typical situation where the module is exposed to environmental conditions. The current – voltage characteristics and temperature of the module were obtained for the interval defined by airmass AM1.5 and AM2 and the peak power determined. The data obtained was analyzed and the results show that the efficiency at peak power is 0.0865. This is less than the efficiency from standard test condition; the slight effect of temperature on module fill-factor suggests temperature effect on module efficiency.

Keywords: Performance, efficiency, photovoltaic, irradiance, airmass, fill-factor, maximum power, solar spectrum.

INTRODUCTION

Solar Energy represents a major source of energy that drives activities on Earth. Man's demand for energy have risen steadily over time from just over 7000 Mtoe (mega tonnes of oil equivalent) in the year 1980 to about 12000 Mtoe in 2009 (Source: IEA (2011), Electrical energy demand has been increasing since the year 2000 especially in developing countries (source: IEA World Energy Outlook 2019). The emphasis has been on renewable energy sources following concerns on the effects about energy generation and consumption on the environment. The world energy consumption can be met through the conversion of 5% of the Sun's energy that reach the Earth (Shukla *et. al.*, 2015).

The use of Solar Energy for electrical power generation dates back to Space age when Solar Photovoltaic cells were used to power Satellites orbiting around the Earth. With passing time it was realized that Solar Photovoltaic can be used as a power source not just for satellites but also as an environmentally friendly source of energy on Earth.

A number of studies on photovoltaic cells and modules have focused on the effects of different environmental factors like dust, solar irradiation, shadowing and temperature on the performance. Some works make use of mathematical models to study the performance of photovoltaic modules.

Tsai (2010) suggested four different types of generalized MATLAB models to examine the effect of solar irradiance and cell temperature and to optimize the generalized model. Model verification has been confirmed through an experimental measurement. Gonz•lez-Longatt (2005) used the first complete solar photovoltaic power electronic conversion system in circuit-based simulation model to simulate the electrical behavior of the PV systems in a grid connected application has been designed.

Nema *et. al.* (2010) carried out a simulation study of PV cell, PV module and PV array under different operating conditions and load to determine their performance. Hernanz, *et. al.* (2010) have analyzed the performance of solar cells and developed a complete model to simulate the electrical behavior of the PV systems. Kumari *et. al.* (2012) have also carried out mathematical modeling and simulation of PV Cell in matlab/simulink Environment to find the parameters of the nonlinear I-V equation by adjusting the curve at three operating conditions: open circuit, maximum power, and short circuit points.

Singh and Kumar (2018) performed computer simulation using MATLAB/SIMULINK for the solar module developed considering diode PV cell model. Simulation test on solar PV module where carried out at two conditions keeping in mind the temperature condition of their location of interest (Rajasthan):

Keeping temperature constant while varying intensity of solar radiation and Keeping solar radiation constant while varying temperature of the module. They observed that the increment of irradiance increases the generation of current and power leading to higher maximum power but increasing the temperature of the solar PV module causes a challenge in maintain a constant terminal voltage across the PV panel while maintaining constant current.

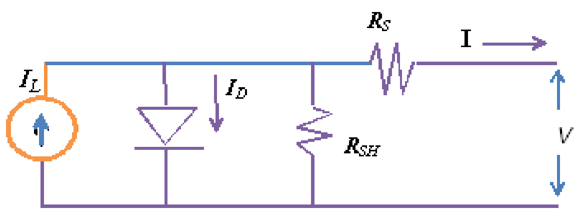

Figure 1: Single diode model of PV cell

When a solar cell (p-n junction) is illuminated, electron-hole pairs are generated and the electric current obtained I is the difference between the solar light generated current I_L and the diode dark current I_J, i.e.

$$I = I_L - I_J \tag{1}$$

$$I = I_L - I_O\left(\exp\left(\frac{e(V + IR_S)}{nkT}\right) - 1\right) - \frac{V + IR_S}{R_{SH}} \tag{2}$$

where, V is output voltage of the cell at the terminals, n is ideality factor, k is Boltzmann•s constant ($k = 1.38 \cdot 10^{-23}$ J/K), e is charge of electron ($e = -1.6 \cdot 10^{-19}$ C) and T is the temperature of solar cell.

A solar module consists of individual PV cells that are connected in series for higher output voltage. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a p-n junction (Bowden *et al.* 2013).

Typically, PV cells produce low power hence several cells are connected together in a module for higher power output. Under ideal conditions a solar panel should receive an irradiance of 1000 W/m2 but unfortunately this is not true in most environments. Irradiance depends on geographical position, angle of sun to solar panel and amount of energy wasted by reflection from dust particles or from fog or clouds (Arshad *et. al.*, 2014). Nadia et al. (2020) estimated the PV panel inclination and the monthly average of temperature in Zarzis, Tunisia. They predicted the solar radiation collected by an inclined surface from daily data and geographic coordinates of Zarzis and observed that solar cell temperature has a great effect on the efficiency of a PV system. They concluded that the best solar panel performance is between 17°C and 25°C and that the most robust and efficient PV module is polycrystalline one and a low energy production of the modules is during the winter.

Effect of solar irradiance and temperature on photovoltaic module

Solar irradiance affect the short-circuit current (I_{SC}) in a direct manner. This stems from the condition that the amount of photo-generated carriers depends on the amount of available photons. An increase in irradiance is therefore expected to lead to increase in output current.

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby affecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be described as increasing the energy of the electrons in the material.

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. Open circuit voltage of photovoltaic cell decrease as temperature increase while short circuit current slightly increase as temperature increase.

Photovoltaic cell / module efficiency

The efficiency reflects the performance of the solar cell itself and it depends on the spectrum and intensity of the incident solar irradiance as well as the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another.

The electrical efficiency of the photovoltaic module depends on the efficiency of the cells that make up the module. Increases in cell/module temperature reduce the band gap of a semiconductor, thereby affecting the semiconductor parameters. The parameter most affected by an increase in temperature is the open circuit voltage (Smets *et. al.*, 2016). The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$FF = \frac{P_{MAX}}{V_{OC} I_{SC}} \tag{3}$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{IN}} \tag{4}$$

where P_{MAX} is the module maximum power which is a product of V_{MAX} and I_{MAX} , η is the module efficiency, *Voc* is the open-circuit voltage, *Isc* is the short-circuit current, *FF* is the fill factor and P_{IN} is the incident solar radiation on the surface of the module.

Various approaches have been developed by researches to improve the conversion efficiency of solar photovoltaic modules. These efforts mainly target the temperature of the module by implementing a cooling scheme and sometimes concentrating the Sun's ray on the modules. Arshad *et al.* (2014) showed that results of the experiment for improving efficiency of solar panel using mirrors as concentrator and cooling were highly encouraging. They obtained an efficiency of approximately 52%.

The measurement of cell efficiency represents the most fundamental of solar cell characterization technique which allows the comparison of devices manufactured at different companies and laboratories (Bunea *et al.*,2006). The standards for cell testing, according to Bunea *et al*, 2006 are:

- Air mass 1.5 spectrum (AM1.5) for terrestrial cells and Air Mass 0 (AM0) for space cells.
- Intensity of 100 mW/cm^2 (1 kW/m^2, also known as one-sun of illumination)
- Cell temperature of 25 °C (not 300 K)
- Four point probe to remove the effect of probe/cell contact resistance.

The electrical ratings of PV modules, as provided by the manufacturer, are derived under controlled and standard testing conditions. However, out on the test field, photovoltaic modules often performs below specification; this is the problem usually encountered by photovoltaic module users.

The objective of this work is to obtain the current-voltage curve and the power-voltage curve for the PV module as well as determine the efficiency of the PV module for cloud free conditions in airmass interval AM1.5 and AM2. The solar spectrum at AM1.5 is the standardized spectrum used by manufacturers in characterization of their solar cells. Airmass 2 (AM2) marks the point where the curvature of the earth affects how much atmosphere solar radiation has to travel through before reaching the surface of the Earth.

The present effort provides useful information about the performance of photovoltaic module under environmental conditions. This allows for the development of approaches to improve performance suitable for our environment.

MATERIALS AND METHODS

Brief description of the location

The photovoltaic module used in this study was installed on the rooftop of one of the laboratories at Faculty of Science, University of Lagos. Lagos has a significant solar and precipitation difference between the wet and dry seasons from Koppen climate classification **(Chen and Chen, 2021)**. The daytime temperature records range from below 20°C during the dry periods (from November to January) to over 30°C in March/April.

Calculation of solar spectra at AM1.5 and AM2

The method used involves calculating the intensity of the components of the solar spectrum using *SMARTS2* radiative transfer code. Developed by Dr. Christian Gueymard, *SMARTS* computes clear sky spectral irradiances for direct beam, circumsolar, hemispherical diffuse among others for specified atmospheric conditions (Gueymard, C. A., 2003a; Gueymard, C. A., 2003b). This is applied in the computation of the AM1.5 and AM2 solar spectra.

Photovoltaic module data acquisition system (DAS)

The photovoltaic converter used is a mono-crystalline $80W_P$ photovoltaic module. The technical characteristic of the PV module as provided by the manufacturer is given in Table 1 below:

Table 1: Technical characteristics of PV module obtained under AM1.5 spectrum (1000W/m^2 at 25°C)

TECHNOLOGY	PARAMETER	VALUE
Mono-crystalline	Maximum Power	80 W_P
	Open Circuit Voltage V_{OC}	21.5 V
	Short Circuit Current I_{SC}	4.95 A
	Maximum Power Voltage V_{mp}	17.8 V
	Maximum Power Current I_{mp}	4.55 A
	Maximum System Voltage	1000 V
	Dimension (mm)	1200*540*35
	Temperature	25°C
	Solar Irradiance @ AM1.5	1000W/m^2

Current-voltage (I-V) curves represent the most important and most direct characterization method for photovoltaic cells and modules. The open circuit voltage (Voc), short circuit current (Isc) and the shape of the I-V curve determine the efficiency, ·, of photovoltaic modules under any given condition. There are three additional important descriptors for I-V curves of solar cells:

V_{mpp} = voltage at the maximum power point (Pmax)
I_{mpp} = current at the maximum power point (Pmax)
FF = Fill-Factor: describes how well the area under the I-V curve "fills in" the maximum possible rectangle defined by the product of I_{SC} and V_{OC}.

Readings taken on a minute basis – four times in a minute each for duration of 15 seconds – with a two minutes interval break. This was carried out during the month of April 2021 from 7:00 am to 6:00 pm.

The DAS is made up of a microcontroller based timing and switching unit with suitable resistance values, and a voltage logger (4-Channel analog logger from Onset Computer Inc.). The photovoltaic module is connected across the circuit which measures the voltage produced by the module at the time the timing and switching unit is triggered.

The figure below shows a simple circuit lay out for the photovoltaic module/ Data Acquisition System setup.

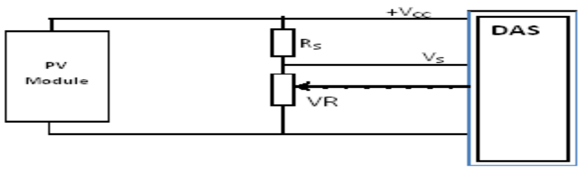

Figure 2: Circuit layout for the photovoltaic module/ Data Acquisition System (DAS) setup

When the circuit is turned on, the value of variable resistor is varied in steps from the lowest to the highest value. The current is measured through a sensing resistor R_S. . The current and power values were calculated from the data retrieved from the data acquisition system using the equations below.

$$I = \frac{V_S}{R_S} \tag{5}$$

$$P = IV_{CC} \tag{6}$$

Where V_S is the voltage across the sensing resistor, R_S is the sensing resistor and V_{CC} is the voltage of the module measured under varying load. Also, daily solar irradiation readings were taken at one minute interval for the period of the investigation.

RESULTS AND DISCUSSION

The following figures (figures 3 and 4) were obtained from calculations of solar spectra at AM1.5 and AM2. The parameters for the computation were chosen from available data and conditions that are compatible with the location of the module.

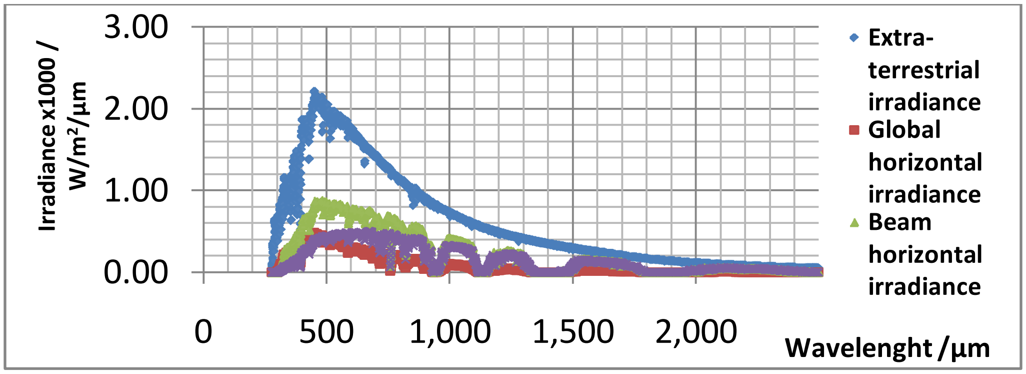

Figure 3: Solar spectral calculation at AM1.5 (Gueymard, 2003)

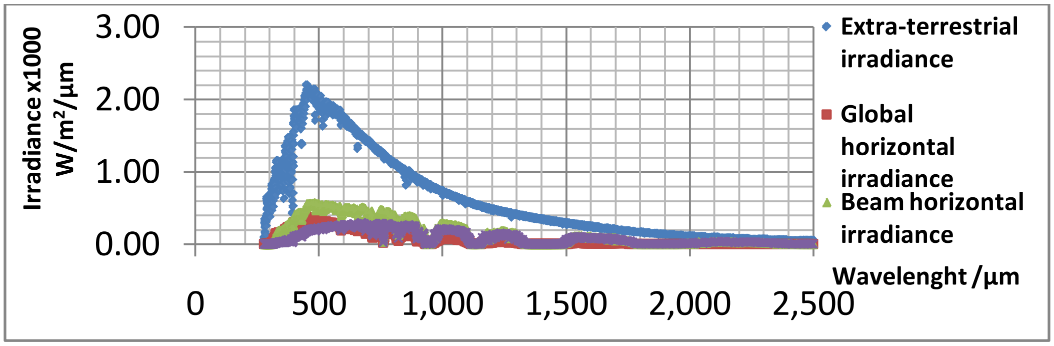

Figure 4: Solar spectral calculation at AM2 using SMARTS2 (Gueymard, 2003)

Using the extra-terrestrial spectrum (which corresponds to AM0) as reference for observation of changes in the solar intensity, it can be seen that while there is very little change in the extra-terrestrial component, the same cannot be said for the components that reach the Earth surface where a reduction of around a-third of the irradiance can be observed.

The I-V curves for selected days with clear-sky are shown below. Clear-sky is used here to imply a cloud-free atmosphere. The clearness index (or cloud-index) are sometimes used for defining these terms, however, our interest is to study the performance of the module under a sky without cloud obstruction. This method was used to obtain the I-V curves for all the day considered for analysis.

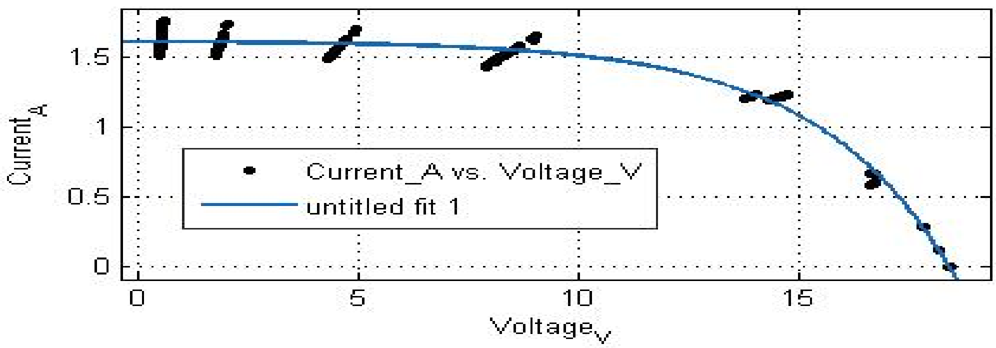

Figure 5: Current – voltage curve obtained at one minute interval for AM1.5 and AM2 past noon on 15/4/2021. R^2 = 0.9941, SSE = 0.8580, RMSE = 0.0519

The power – voltage (P-V) curves were derived from the data for I-V curve. The curves can be obtained using two methods:

- Plotting for each data set obtained during the one minute interval to get four curves;
- Plotting all data sets obtained during the one minute interval to get one curve.

Figures 6 and 7 show the outcomes for the former and latter methods. The latter method was adopted because it showed good representation of the behavior of the module and it represents a faster way of analyzing the large amount of data that would result from a day to a few months of data acquisition.

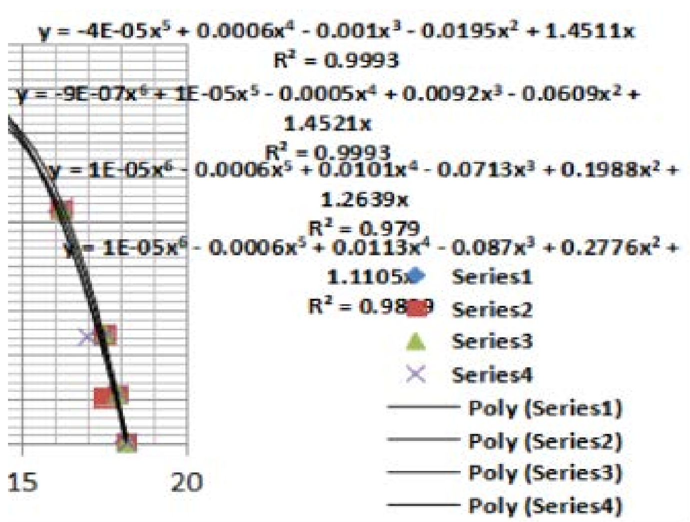

Figure 6: Power-voltage curve obtained for four data sets within one minute interval for AM1.5 and AM2 past noon on 15/4/2021

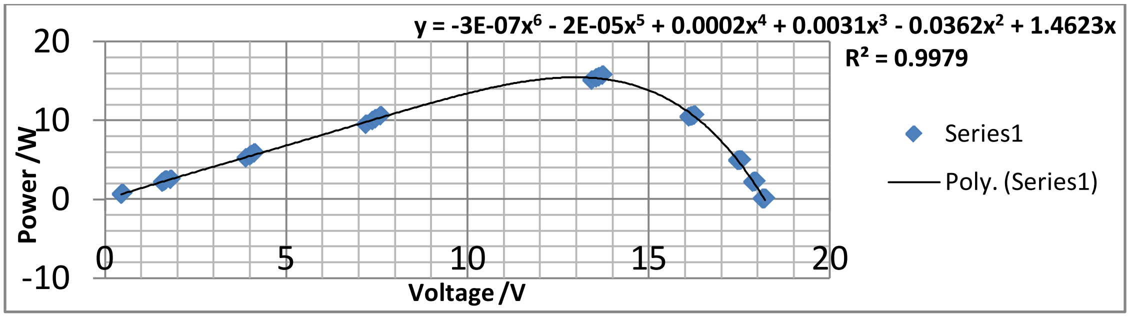

Figure 7: Power-voltage curve obtained for all data sets within one minute interval for AM1.5 and AM2 past noon on 15/4/2021

The effect of temperature on module performance was also investigated. As noted by other authors, the main parameter affected by module temperature is the open-circuit voltage. This links with the fill-factor as shown in equation 3 and with efficiency in equation 4. The effect of module temperature on fill-factor is shown in figure 8. The correlation is not strong but reflects the performance of photovoltaic module when the effect of temperature is considered as also can be seen in equation 4.

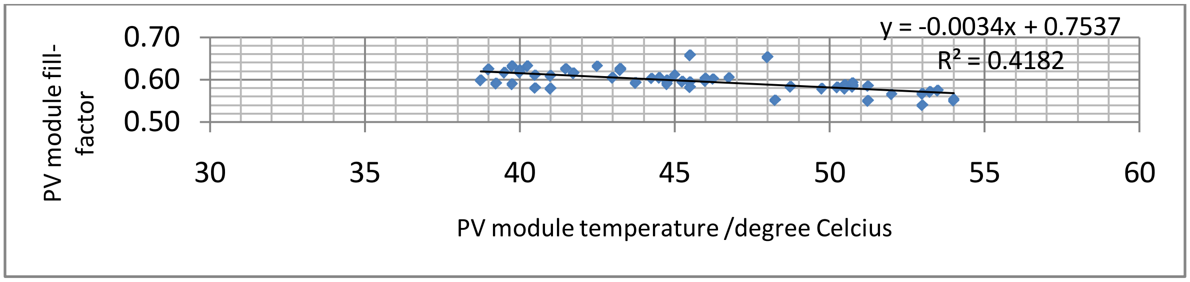

Figure 8: Variation of PV module fill-factor with module temperature for the period of study

Figure 9 shows the plot of module peak power against incident solar radiation on the module. The incident radiation on the module is determined from the product of solar irradiance and module effective area. The efficiency for the period of study is 0.865 (or 8.65%); this falls short of the efficiency calculated from the manufacturers specification which gives 13.88% (a short-fall of approximately 38%).

The profile of efficiencies calculated from data for the period of study is shown in Figure 10. The values approximate range is from 6.2% to 9.8%.

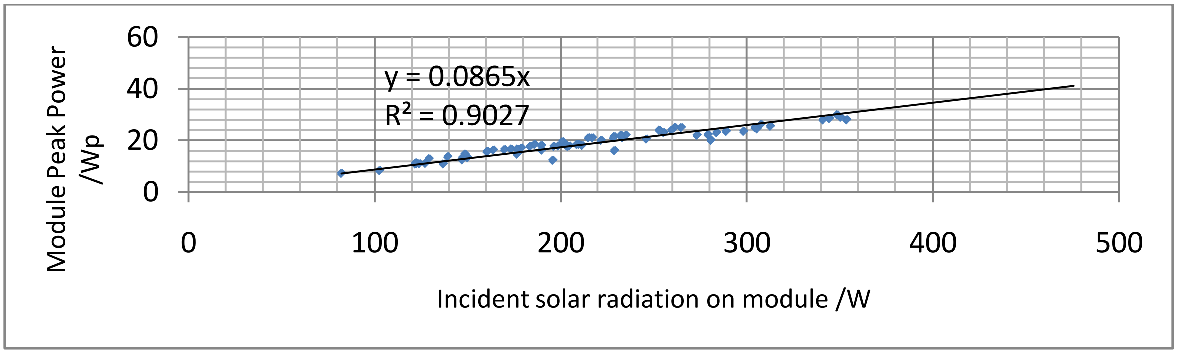

Figure 9: Plot of PV module maximum (or peak) power against incident solar radiation on module for the period of study

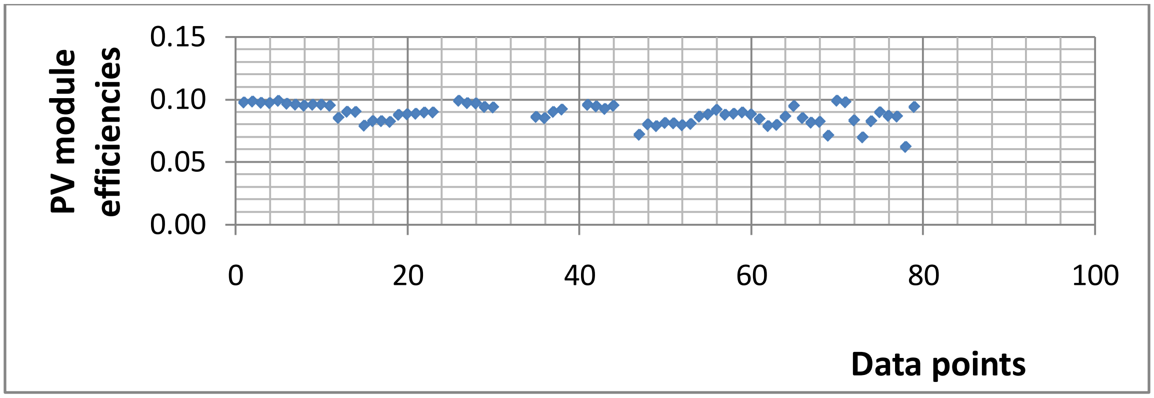

Figure 10: Plot of PV module efficiencies for the period of the study

CONCLUSION

The performance of mono-crystalline photovoltaic module was studied under environmental situation during the dry season at Akoka/Lagos. The effect of temperature on the performance of the module was observed. The shortfall in the efficiency of the module with respect to that calculated using the manufacturer's specification is approximately 38%. This value appears significant enough to necessitate some form of intervention like the type carried out by Singh and Kumar (2018). Another option would probably be to go for more stable technology such the polycrystalline modules suggested by Nadia et. al. (2020). The outlook for generation of electrical energy from the Sun using photovoltaics remains promising as efforts are continually made to reduce the cost per peak Watt such as can bring it closer to being a competitive technology for energy generation.

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