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PERFORMANCE EVALUATION OF POLYCRYSTALLINE SOLAR PHOTOVOLTAIC MODULE IN WEATHER CONDITIONS OF MAIDUGURI, NIGERIA

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Abstract

Many Solar PV modules exhibit significant loss in their expected performance due to variations in weather conditions such as ambient temperature and solar irradiance which result in inaccurate prediction of the module performance in the field. Obviously, the Standard Test Conditions (STC) and the Nominal Operating Cell Temperatures (NOCT) do not represent real operating conditions of PV module at the site of installation. This paper evaluates the performance of commercially used polycrystalline solar photovoltaic module KD 315 under Maiduguri-Nigeria weather conditions. The model of the PV module was implemented using a MATLAB program and the model parameters are evaluated using daily data of temperature and solar irradiance obtained from Maiduguri for a period of one year. Simulation results confirm that current generated is directly proportional to solar irradiance and is almost independent of temperature. The voltage of the module decreases by about 0.5% per degree centigrade temperature increase. It was found that the power produced by the panel is dependent on the solar irradiance and ambient temperature. The manufacturer's maximum power of 315 W was achieved during the sunniest month. Thus the photovoltaic module exhibited good performance in the region under study.

Keywords: Photovoltaic module, irradiance, temperature, voltage, current, Renewable energy, cells

1. Introduction

The increasing energy demand and environmental problems in the world point out that the research and development activities in the renewable energy sources are essential. Renewable Energy (REN) resources have enormous potential and can meet the present world energy demand. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions (Ghoneim et al., 2011). One of the most promising REN technologies is the photovoltaic (PV) technology. Solar Photovoltaic (PV) system is increasingly attracting researchers due to its reliability and minimal maintenance requirements. It can be used for a wide range of electrical energy requirements, including solar home systems, water pumping, refrigeration and telecommunications to mention a few. These applications have positive social and economic impact on the lives of individual users, business and communities (Mellit, 2007).

Solar cells are devices that convert photons into electric potential in a Positive-Negative (PN) silicon junction (or other material). A PV cell is a basic unit that generates voltage in the range of 0.5 to 0.8 volts depending on the cell technology being used. Light of certain wavelengths is able to ionize the atoms in the silicon and the internal field produced by the junction separates some of the positive charges (holes) from the negative charges (electrons) within the PV device. The holes are swept into the p-layer and the electrons are swept into n-layer. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal potential energy barrier (Kanevce, 2007). There are essentially 3 different types of PV Panels, Crystalline Silicon, Amorphous Silicon and other Thin Film technology PV Panels. Crystalline Silicon panels are the oldest, most reliable and highly efficient PV panels in the market today. Crystalline Panels can be further divided into Mono-Crystalline and Poly-Crystalline panels.

Polycrystalline Solar cells are made from ingots of pure silicon, cast in manner that forms large crystalline grains. The ingot is sliced into wafers, which are then processed. The electrical output of a single cell is dependent on the design of the device and the semiconductor material(s) chosen, but is usually insufficient for most applications. In order to provide useful power for any application, the individual solar cells described above must be connected together to give the appropriate current and voltage levels and they must also be protected from damage by the environment in which they operate.

The performance of a Solar PV module is strongly dependent on some environmental conditions such as solar irradiance and temperature. Therefore, knowledge and understanding of the PV module performance under site of installation operating conditions is of great importance for correct product selection and accurate prediction of their energy performance. Many Solar PV modules exhibit a poor performance in the field due to inaccurate prediction of the module expected performance in the field. A significant part of the loss in their performance is due to variation in solar irradiance, Nominal Operating Cell Temperatures (NOCT), and other localized climatic conditions. Due to the variations of environmental conditions at each site, the Standard Test Conditions (STC) may not represent real operating conditions of PV module at the site of installation.

Several studies have been conducted on the analysis of the environmental factors that influence PV module performance (González-Longatt, 2006, Dzimano, 2008, Mustapha et al., 2009, and Kerr and Cuevas, 2003). Kerr and Cuevas , (2003) presented a new technique that can determine the current–voltage (I–V) characteristics of PV modules based on measuring the open-circuit voltage (Voc) as a function of a light intensity. Dzimano(2008) investigated the effects of temperature and radiation intensity on the performance parameters of amorphous hydrogenated silicon (a-Si:H) photovoltaic module. Likewise Mustapha et al., (2009) investigated the effect of air mass factor on the performance of different types of PV modules.

Maiduguri metropolis is the state Capital of Borno State. It is located in the Sahel Savanna region of North-eastern Nigeria at latitude of 11^o 51' North and longitude 13^o 09' East and 350 m above sea level. It has relatively high average daily insolation ranging from 5 kWh/m^2/day to 7 kWh/m^2/day and higher solar altitude throughout the year, the average solar radiation is about 550 W/m^2. Its mean annual rainfall and temperature are about 630 mm and 32^oC respectively.

This paper evaluates the performance of commercially used polycrystalline solar photovoltaic module under Maiduguri weather conditions using solar irradiance and atmospheric temperature as inputs parameters to the model.

2. Methodology

2.1 Modelling of PV Solar cell

Modelling of Solar PV cell involve the use of either the one-diode model or the two-diode model to describe the electrical characteristics of solar cell. Each of these models establishes relationships that enable current and voltage to be evaluated according to the irradiance and temperature. The double-exponential model (with two diodes) is derived from the physics of the p-n junction and is generally accepted as reflecting the behaviour of such cells, especially those constructed from polycrystalline silicon. It is also suggested that cells constructed from amorphous silicon, usually using thick-film deposition techniques, do not exhibit as sharp a knee in the curve as do the crystalline types, and therefore the single exponential model (with one diode) provides a better fit to such cells (Nema et al., 2010).

PV cells can be modelled as a current source in parallel with a diode. When there is no light present to generate any current, the PV cell behaves like a diode i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply it generates current I_s, called diode saturation current or dark current. As the intensity of incident light increases, current is generated by the PV cell.

The equivalent circuit of the model which consists of a photo current, two diodes, a parallel resistor R_p expressing a leakage current, and a series resistor R_s describing an internal resistance to the current flow, is shown in Figure 1.

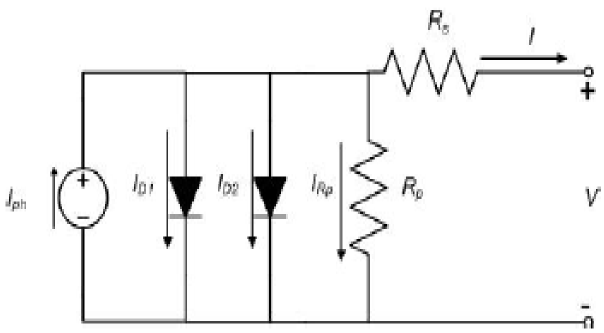

Figure 1: PV Cell Equivalent Circuit Model

Using Kirchhoff's Current Law (KVL), the terminal current of the cell is:

$$I = I_{ph} - I_{D1} - I_{D2} - \frac{V+IR_s}{R_p} \quad (1)$$

where I_{ph} is the light-generated current which is directly proportional to the light falling on the cell i.e solar irradiance G, linearly related to cell temperature T, and depends on the materials used and fabrication processes. The diodes current are noted as I_{D1} and I_{D2}. R_s and

R_p are series and shunt resistance of the solar cell respectively. I_{sat1} and I_{sat2} are the diode saturation currents of D1 (Equation 2) and D2 (Equation 3) respectively.

$$I_{D1} = I_{sat1}\left\{\exp^{\frac{q(V+IR_S)}{nkT}} - 1\right\} \quad (2)$$

$$I_{D2} = I_{sat2}\left\{\exp^{\frac{q(V+IR_S)}{nkT}} - 1\right\} \quad (3)$$

$$I = I_{ph} - I_{sat1}\left\{\exp^{\frac{q(V+IR_S)}{kT}} - 1\right\} - I_{sat2}\left\{\exp^{\frac{q(V+IR_S)}{nkT}} - 1\right\} - \frac{V+IR_s}{R_p} \quad (4)$$

where n is an ideal factor, q is the elementary charge of value $1.6\text{x}10^{-19}$ Coulombs, k is a Boltzmann's constant of value $1.38\text{x}10^{-23}$ J/K, I_{sat1} and I_{sat2} are the saturation current of the two diodes. The two diodes can be combined to simplify the equation to:

$$I = I_{ph} - I_{sat}\left\{\exp^{\frac{q(V+IR_S)}{nkT}} - 1\right\} - \frac{V+IR_s}{R_p} \quad (5)$$

The photo generated current is given as :

$$I_{ph} = I_{sc}^{*}\left(\frac{G}{G^{*}}\right)(1 + K_o(T - T^{*})) \quad (6)$$

where I_{sc}^{*}, G^{*}, T^{*} are the cell's short-circuit current , solar irradiance and cell's temperature at Standard Test Conditions (STC) respectively. $I_{sc}(T1)$ is the short circuit current at temperature T_1, K_o is the cell's short-circuit current temperature coefficient.

$$K_o = \frac{I_{sc(T_1)} - I_{sc}^{*}}{T_1 - T^{*}} \quad (7)$$

On the other hand, the cell's saturation current varies with the cell temperature, which is described as

$$I_{sat} = \frac{I_{sc}^{*}\left(\frac{T}{T^{*}}\right)^{\left(\frac{3}{n}\right)} \exp\left[\frac{-qE_G}{nk}\left(\frac{1}{T} - \frac{1}{T^{*}}\right)\right]}{\exp\left(\frac{qV_{oc}^{*}}{nkT^{*}}\right) - 1} \quad (8)$$

where V_{oc}^{*} is the open circuit voltage at Standard Test Conditions (STC) E_G is the bang-gap energy of the semiconductor used in the cell. Band gap of silicon is 1.12eV and that of germanium 0.66 eV (Parthasarathy et al., 2011).The saturation current I_{sat} depends on the diffusion coefficient of electrons and holes and is highly sensitive to temperature changes. The saturation current at reference temperature T^{*} is given as:

$$I_{sat}^{*} = \frac{I_{sc}^{*}}{e^{\frac{qV_{oc}^{*}}{nkT^{*}}} - 1} \quad (9)$$

Series resistance inside each cell is :

$$R_s = -\left[\left.\frac{dV}{dI}\right|_{V=V_{oc}} + \frac{1}{X_V}\right] \quad (10)$$

$$X_v = I_{sat}^{*} \cdot \frac{q}{nkT} e^{\frac{qV_{oc}}{nkT}} - \frac{1}{X_V} \quad (11)$$

The most important parameters widely used for describing the cell electrical performance is the open-circuit voltage V_{oc} and the short-circuit current I_{sc} . Short circuit current is the greatest value of the current generated by a cell. It is produced by the short circuit conditions i.e V=0. Since normally I_{ph} >> I_{sat} and ignoring the small diode and ground-leakage currents under zero-terminal voltage, the short-circuit current I_{sc} is approximately equal to the photocurrent I_{ph}.

$$I_{sc} = I_{ph} \tag{12}$$

Open circuit voltage correspond to the voltage drop across the diode (p-n junction) when it is transverse by the photocurrent I_{ph}, namely when the generated currents I = 0. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{I_{sat}}\right) \tag{13}$$

where V_t is the thermal voltage

$$V_t = \frac{nkT}{q} \tag{14}$$

The temperature of solar cell T significantly affects the output power of a solar module and it depends exclusively on the irradiation G and on the ambient temperature T_a, according to the equation:

$$T = T_a + \beta G \tag{15}$$

where β is a constant given as

$$\beta = \frac{T^* - T_1}{G^*} \tag{16}$$

The maximum power can be expressed as

$$P_{max} = V_{max} I_{max} = \gamma V_{oc} I_{sc} \tag{17}$$

where V_{max} and I_{max} are terminal voltage and output current of PV module at Maximum Power Point (MPP), and γ is the cell Fill Factor (FF) and is given as the maximum power that can be delivered to the load divided by the product of V_{oc} and I_{sc}.

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} = \frac{I_{max} V_{max}}{V_{oc} I_{sc}} \tag{18}$$

2.2 Solar PV Module

In most commercial PV products, PV cells are generally connected in series configuration to form a PV module in order to obtain adequate working voltage. PV modules are then arranged in series-parallel structure to achieve desired power output.

Let N_s and N_p be the number of cells in series and in parallel in one PV panel respectively. The output voltage V_p and current I_p of the panel are given by:

$$V_p = N_s \cdot V \tag{19}$$

$$I_p = N_p \cdot I \quad (20)$$

3. Results and discussion

The KD 315 PV module was chosen for the evaluation due to its wide applications in developing countries such as Nigeria. The KD 315 module provides 315W maximum power at STC, and it has 80 polycrystalline silicon cells connected serially. The key specifications of the module are shown in Table 1.

Table 1 KD 315 module specifications

KD 315 PV Module Parameters (Zdanowicz et al., 2004)		
Standard Test Conditions (STC) STC = 1000 W/M^2 irradiance, 25^{o}C module temperature, AM 1.5 spectrum*		
Maximum Power	P_{mp}	315 W
Voltage @ V_{mp}	V_{mp}	39.8 V
Current @ i_{mp}	I_{mp}	7.92 A
Open circuit Voltage	*Voc*	49.2 V
Short circuit Current	*Isc*	8.50 A
Power Tolerance	$P_{tolerance}$	+5/-3%
Nominal Operating Cell Temperature Conditions (NOCT) NOCT = 800 W/M^2 irradiance, 20^{o}C ambient temperature, AM 1.5 spectrum*		
Temperature	T_{NOCT}	45 ^{o}C
Maximum Power	P_{mp}	226 W
Voltage @ V_{mp}	V_{mp}	35.8 V
Current @ i_{mp}	I_{mp}	6.34A
Open circuit Voltage	*Voc*	45.0 V
Short circuit Current	*Isc*	6.88 A
Temperature Coefficients		
Maximum Power	P_{mp}	-0.51 %/ ^{o}C
Voltage @ V_{mp}	V_{mp}	-0.52 %/ ^{o}C
Current @ i_{mp}	I_{mp}	0.0064 %/ ^{o}C
Open circuit Voltage	*Voc*	-0.36 %/ ^{o}C
Short circuit Current	*Isc*	0.061 %/ ^{o}C
Cell Operating Temperature	*Toc*	-40 to +90

The model of the PV module was implemented using a MATLAB program. Newton-Raphson method was used to solve systems of nonlinear equations. The model parameters which included voltage current and power were evaluated using daily temperature and solar irradiance data obtained from Nigerian Meteorological Department, Maiduguri. The data covered the twelve months (January to December) of the year 2010.

Figures 2 and 3 show the solar irradiances with respect to day and month respectively, for the year 2010. The Figure 2 shows that the average daily insolation varied largely with periods. The sunniest month in the year which was April (Figure 3) had an average insolation of 0.8 kW/m^2, which was about 37.5% more than the least sunny month in the year, August, which received an average insolation of 0.5 kW/m^2 . Also the average insolation throughout the year was about 0.6 kW/m^2.

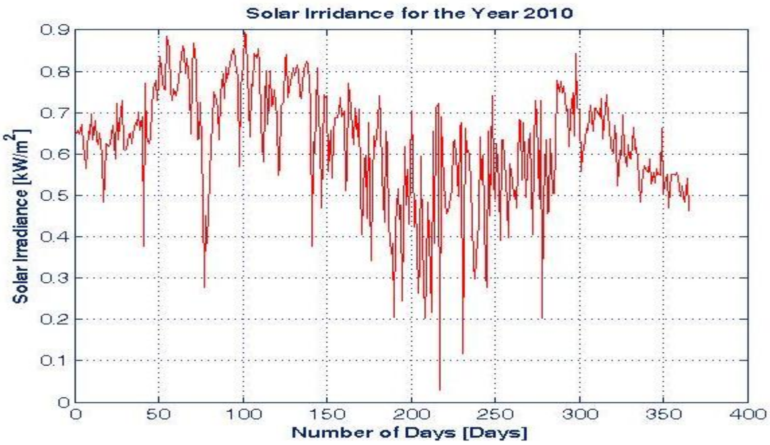

Figure 2: Annual daily solar irradiance

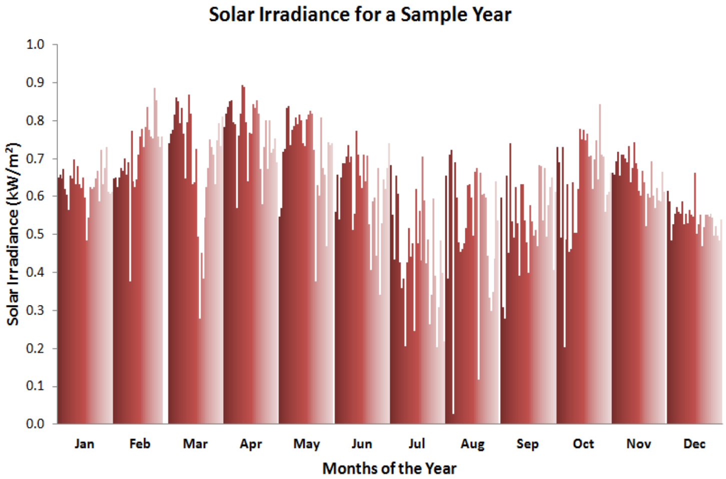

Figure 3: Solar irradiance vs month

Figures 4 and 5 show the ambient temperatures with respect to day and month respectively, for the year 2010. The Figures reveal that month of April had the highest average temperature of about 43^{o}C while month of August had the lowest average temperature of about 31^{o}C which was 38.7% less than the highest average temperature. The average temperature of the year was 37^{o}C, about 48% more than the temperature at STC.

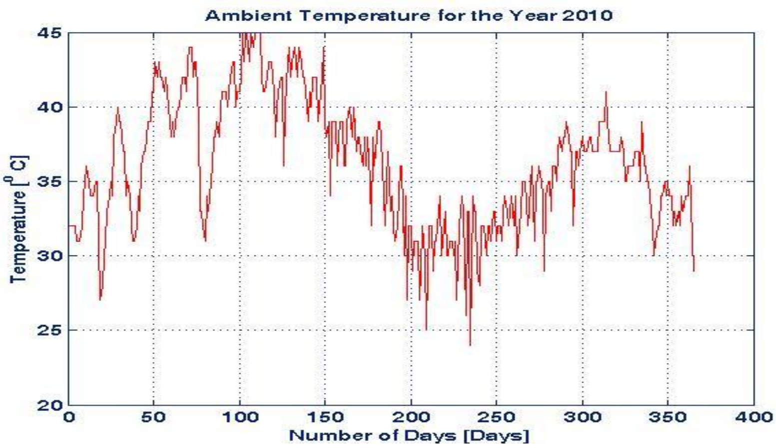

Figure 4: Annual dailyambient temperature

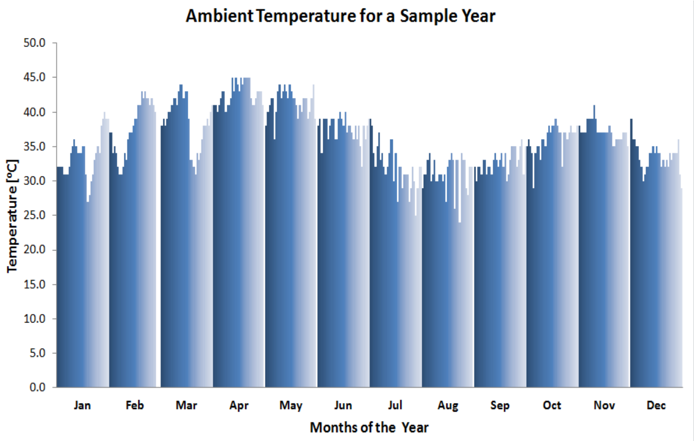

Figure 5: Ambient temperature vs months

Figures 6 7 show that power generated varied with seasons. For example more power was generated in the dry season (February to May) than in the rainy season (June to September). It was also observed that power generated in the sunniest month of the year (April) was 39% more than the power generated in August which was the least sunny month of the year. Power generated in the sunniest month of the year was close to the theoretical maximum power level assumed in solar panel specifications at STC. This suggests that the module can function normally in this part of the country without difficulties.

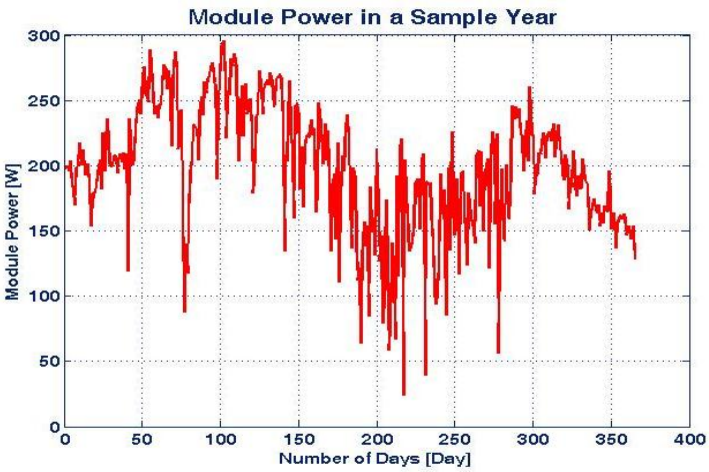

Figure 6: Current vs time for a sample day

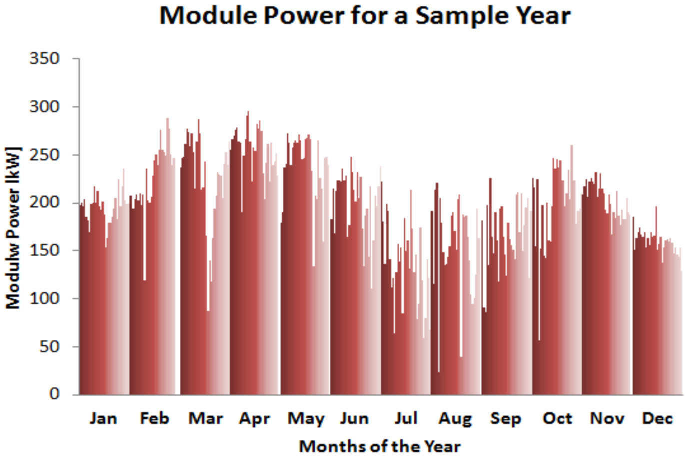

Figure 7: Power vs time for a sample month

Figures 8 and 9 show the effect of temperature on the voltage, current and power output respectively, of a solar module. It was observed that module current increased by 0.1 A/^{o}C with increase in temperature, while module voltage decreased by 0.05 V/^{o}C. On the other hand, power increased with increase in temperature. It can be observed that currents increased more rapidly than the voltage per degree rise in temperature. The consequence was that the power (the product of the two) increased with temperature.

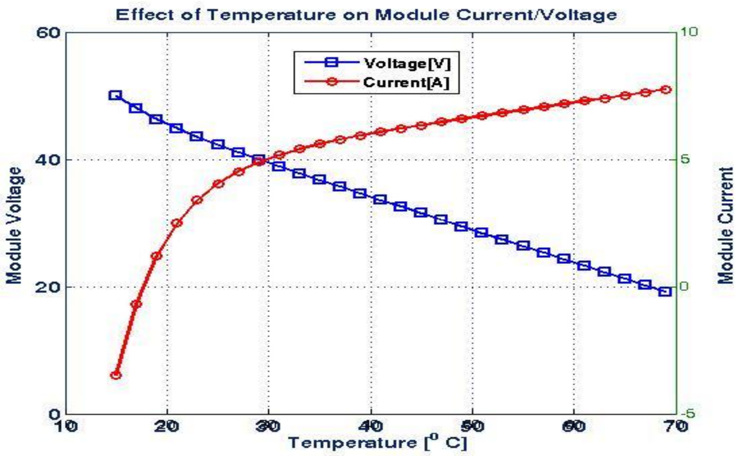

Figure 8: Module voltage/current vs temperature

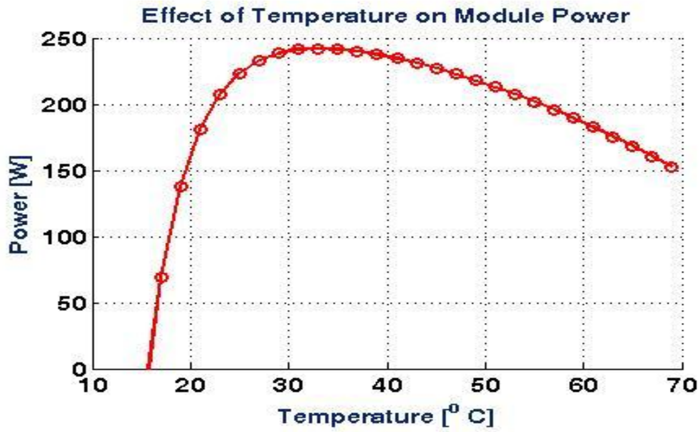

Figure 9: Module power vs temperature

Figures 10 and 11 show Cell and Module I-V curves at different insolations. The results reveal that as irradiance increased from 200 W/m^2 to 1000 W/m^2 at constant temperature, both the cell and the module output current increased rapidly while the voltage remained almost constant. For example, an increase in irradiance from 0.6 kW/m^2 to 0.8 kW/m^2, increased the module current by 36%. This indicates that irradiance has insignificant effect on the output current than the output voltage.

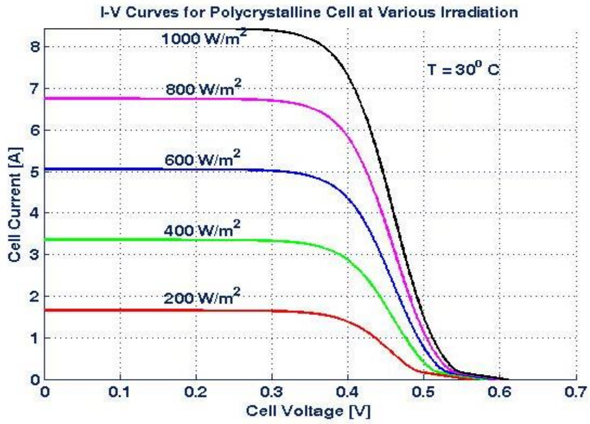

Figure 10: I-V curves of solar cell at different irradiance levels

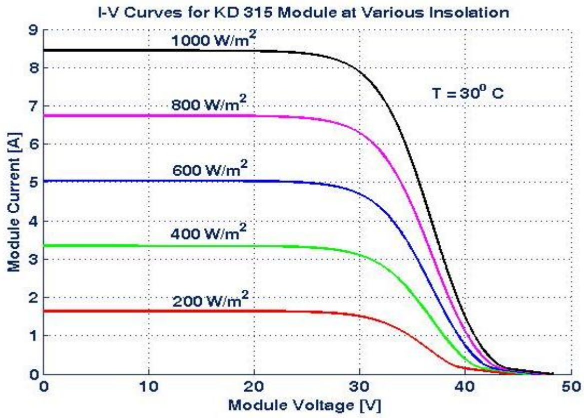

Figure 11: I-V curves for solar module at different irradiances

Figures 12 and 13 show cell and module I-V curves respectively, at various temperatures. It was observed that as the cell and module temperature rose above the standard operating temperature of 25^{o}C, the output current increased significantly while the output voltage decreased slowly. Generally between 25^{o}C and 55^{o}C, the module voltage decreased by 9.5% which is approximately 0.32% per degree Celsius while module current increased by 30.1%. This indicates that the generation of electron-hole pair in the photovoltaic module which leads to increase in the mobility within the p-n junction, increased the current of the module.

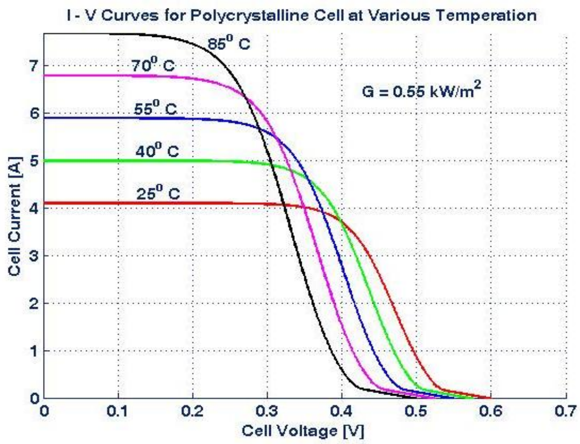

Figure 12: I-V curves of solar cell at various temperatures

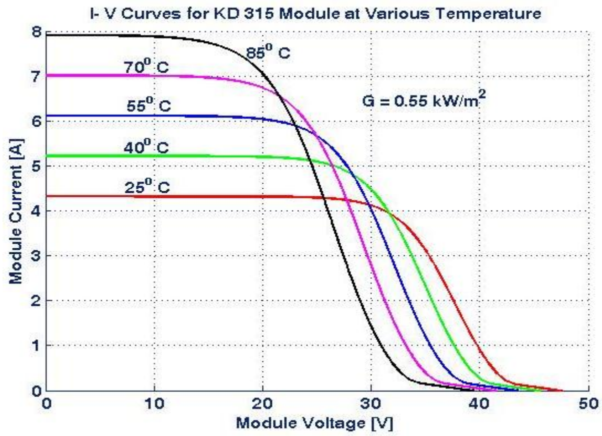

Figure 13: I-V curves of solar module at various temperatures

Figures 14 and 15 show Cell and Module PV curves at different irradiances. These curves reveal that as irradiance increased from 200 W/m^2 to 1000 W/m^2 at constant temperature, both the cell and the module output power increased rapidly while the voltage remained almost constant. For example, when the irradiance increased from 0.6 kW/m^2 to 0.8 kW/m^2, the module power increased by 22.2%. This indicates that module power is directly dependent on the amount of solar irradiation striking the surface of the PV module.

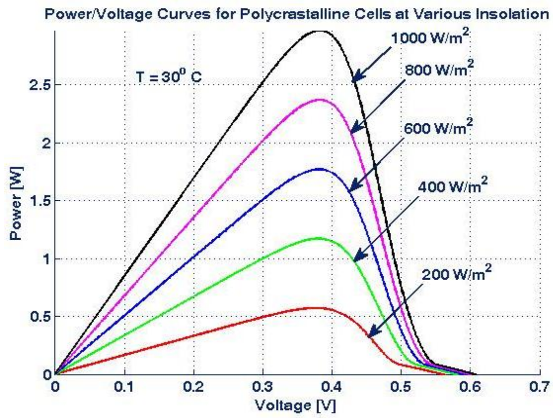

Figure 14: I-V curves of solar cell at various irradiances

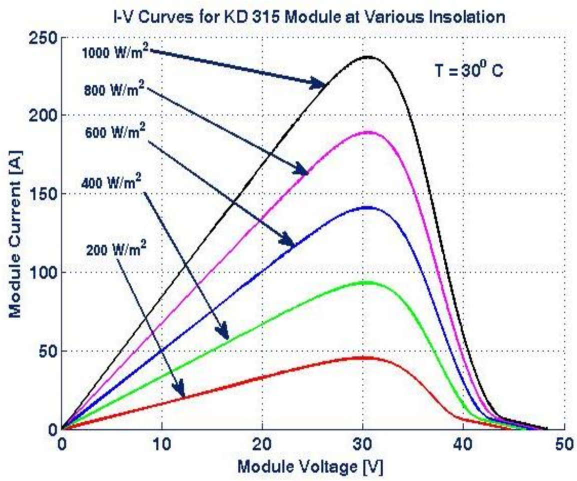

Figure 15: PV curves of solar module at various irradiances

Figures 16 and 17 show the cell and module PV curves respectively, at various temperatures. It can be seen from these Figures that as the cell and module temperature rose above the standard operating temperature of 25^{o}C, the output power increased significantly while the output voltage decreased slowly. Generally increase in temperature from 25^{o}C to 75^{o}C increased the power by 10.7%. This indicates that increase in temperature increased electron-hole mobility within the p-n junction which lead to increase in power of the module.

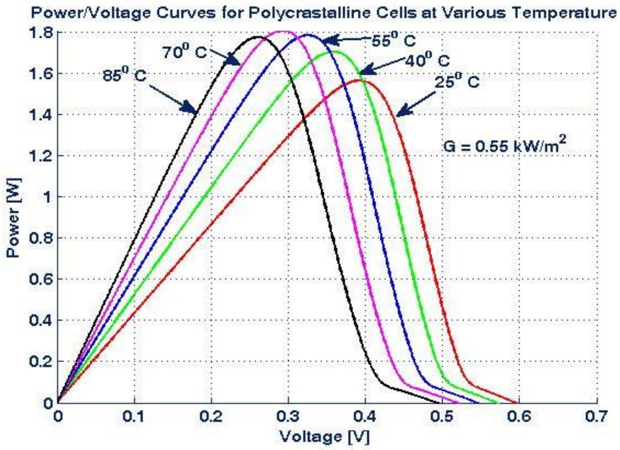

Figure 16: PV curves of solar cell at various temperatures

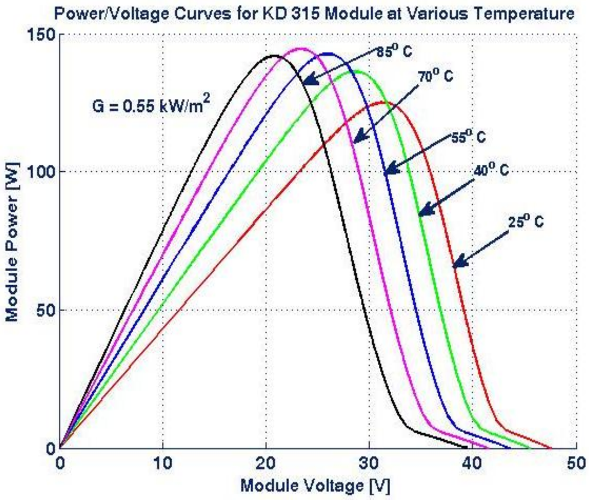

Figure 17: I-V curves of solar module at various temperatures

4. Conclusions

The effect of environmental factors such as temperature and solar irradiation on the performance of polycrystalline PV module in Maiduguri was examined. Simulation results show that there is a direct proportionality between solar irradiation, temperature, output current and power of the photovoltaic module. Also, the manufacturer's nominal power of 220 W was achieved under the Maiduguri operating conditions. Thus it can be concluded that the PV module investigated can be safely deployed without difficulty here in Maiduguri.

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