SHORT-TERM STUDY OF THE PERFORMANCE OF A PHOTOVOLTAIC MODULE

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ABSTRACT

This study attempts to evaluate the performance of a silicon polycrystalline photovoltaic module without storage (battery) by comparing the solar radiation that falls on it with the energy generated by the module on a daily basis. The efficiency of 50 watts polycrystalline module with fixed load was evaluated for some months in the years 2017 and expression obtained for module efficiency. A model was obtained for calculating the module output from solar irradiation and module temperature. The result obtained show that the module in the field of operation exhibits variation in efficiency from approximately 2% to 7.8% while the module energy output can be predicted from the model obtained with a percentage normalized RMSE of approximately 11%.

Keywords: Performance, Photovoltaic (PV), cell, module, efficiency.

INTRODUCTION

The antecedent problems associated with the world energy supply especially with crude oil and nuclear power stations; their environmental impact have made it necessary to explore environmentally friendly sources to meet energy demand. Solar photovoltaic cells provide one such alternative. Photovoltaic module is a unit that comprises series and/ or parallel interconnected solar cells. The development of photovoltaic technology has made it possible to apply it to different applications. Boukebbous *et al.*, (2021) studied the performance of a PV water pumping system for irrigation purposes under different meteorological conditions. They observed the effects of the seasons on the output of the PV system and a sensitive analysis showed that the best operating performances of the system were observed in winter and spring. Wansah *et al.*, (2015) designed, installed and evaluated solar photovoltaic modules for pumping water rural area. as an alternative source of energy for remote village dwellers is of immense economic and environmental benefits. It is also the best solution for remote rural localities and for needs such as water pumping for crops. They identified the benefits of solar photovoltaic modules for pumping water for rural the area as low operating cost, reliability and increased operational life.

Mansur *et al.* (2018) designed a standalone PV power system for a disaster relief camp from renewable energy resource to supply D.C power. They sized the PV array and battery storage using solar irradiation data and load demand and lastly simulate the designed system using PV syst. The system could meet up to 99% of load demand throughout the year except for December with 62.3% performance ratio. The loss to the system is due to temperature effect to the PV module, ohmic wiring loss, unused energy because of battery full, power converter efficiency and battery efficiency.

Bimenyimana *et al.*, (2015) compared stand-alone and grid-tied PV systems designed to supply 7.2 kWh/day, load. The results they obtained show the number of modules required, the initial investment and payback time for each type of system. The grid-tied system had lower values of these parameters. They further proposed that government adoption of smart grid technology with feed-in-tariff with solar power can be used to increase electricity supply in Rwanda.

Abdullahi *et al.* (2017)studied the performance of an 85W mono-crystalline photovoltaic module under different conditions taking measurements under indoor and outdoor conditions. They inclined the module at 25° facing south to obtain maximum irradiation under outdoor conditions. They developed a single diode electrical equivalent model using MATLAB-Simulink to investigate the I-V characteristic of the PV module and both the measured results and the simulation results were compared. Their measured results show that the module is capable of generating 17.75 W/m^2 with an efficiency of 7% and 138 W/m^2 with an efficiency of 8% from indoor and outdoor conditions, respectively during summer time in the UK.

Photovoltaic (PV) electricity is a viable and cost-effective option in many remote site applications where the cost of grid extension or maintenance of conventional power supply systems would be prohibitive (Rohouma *et. al.*, 2007). *Erdil et al.*,(2008) constructed and tested a hybrid system, composed of a photovoltaic (PV) module and a solar thermal collector and carried out an analysis on pay-back period based on energy generated by the system. Optimizing the operation of Photovoltaic system for cost-effectiveness require, among others, optimizing its operation. Moorthy *et al.*, (2020) designed and developed solar photovoltaic (PV) based direct current (DC) optimizer distributed system to enable the individual operation of maximum power point tracking (MPPT) in solar panels. This DC optimizer distributed system avoids mismatch losses and hot spots in solar PV panels during partial shadow conditions. They developed a controller that is robust against the different environmental conditions by adjusting the PV system quickly to changes in the environment. Chaibi *et al.*, (2019) examined the extent that MPPT technique could affect the yearly energy output of a solar photovoltaic field. They stated that useful conclusions about this effect can be draw by running simulations based on real meteorological and operating conditions is essential.

The prediction of the output energy from PV modules is very important from the point of view of system design energy management. This is more so for photovoltaics because the output of PV modules under outdoor operation is dependent on many factors which include solar irradiation, ambient temperature among others. Shapsough *et al.* (2019) presented a study on predicting the output of soiled solar panels using multiple linear models and artificial neural network. Inputs to both models include time period since the last cleaning cycle, date and time information, as well as irradiance and, optionally, temperature. They stated that both models were able to generate predictions with great accuracy. Chuluunsaikhan *et al.* (2021) presented a method of predict the power output of solar panels based on weather and air pollution features using machine learning methods. The created machine learning models with three kinds set of features, such as weather, air pollution, and weather and air pollution and used datasets from Seoul, South Korea, between 2017 and 2019. They showed, from their results, that they can efficiently predict the power output of solar panels from weather and air pollution. A number of literature exist on efforts at predicting the output of PV modules using artificial neural networks (ANN) (Bimenyimana *et al.*, 2017; Kim *et al.*, 2019, Faye *et al.*, 2021). The complex nature of the method of ANN may hinder its wider application for the purpose of predicting the output of PV modules. Simple regression methods that do not sacrifice accuracy may be a valuable tool for such calculations.

Presently, installation of photovoltaic technology can be employed in small or large units. Although there have been improvements in the status of photovoltaic technology, issues that stand in way of successfully deploying this technology still exist and they are being addressed (Billinton and Karki, 2001). One such issue is the conversion efficiency of photovoltaic (PV) cells / modules.

PHOTOVOLTIAC CELL GENERATION

The solar spectrum constitutes three main regions given in Table 2.1.

Table 2.1: Distribution of extraterrestrial solar irradiance in three different wavelength ranges (Iqbal, 1983)

	UV	Visible	IR
Wavelength range (μm)	<0.4	0.39 – 0.77	>0.77
Band Irradiance (W/m^2)	109.81	634.4	623
Percentage of Isc	8.03%	46.41%	46.4%

Solar radiation is modified and attenuated as it travels through the Earth’s atmosphere. The three important bands, or ranges, along the solar radiation spectrum are ultraviolet, visible (PAR), and infrared. The composition of solar radiation that reaches Earth’s surface is such that infrared radiation makes up 49.4% while visible light provides 42.3%. Ultraviolet radiation makes up just over 8% of the total solar radiation (Fondriest Environmental, Inc., 2014). The peak spectral response of silicon solar cells fall in the near infra-red region of the solar spectrum (Wirth, 2013).

The mismatch between peak spectral irradiance and peak response as can be observed in Figure 1 represents part of the limitation of silicon solar cells.

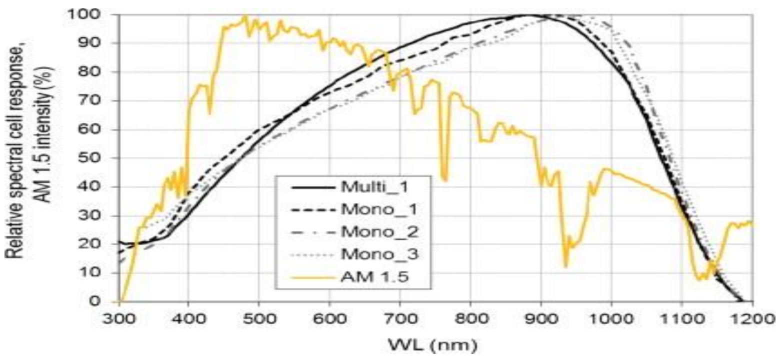

Figure 1: The spectral response of c-Si solar cells peaks between 850 and 950 nm (Wirth, 2013)

Photovoltaic Cell Conversion Efficiency

A typical silicon photovoltaic cell converts 10 to 20 percent of solar radiation that strikes its surface to electrical energy. There are a number of reasons for this relatively low conversion efficiency. Most of the photon energy below the band-gap are not absorbed and do not contribute to energy generation while photon energy above the band-gap contribute to thermalization losses (Smets*et al.*, 2016).

Electrical characteristics of a solar cell are expressed by the current-voltage curves plotted under a given illumination and temperature conditions as shown in Figure 2.

The significant points of the curve are short-circuit current, *Isc*, and open-circuit voltage, *Voc*. Maximum useful power developed by the cell is represented by the point on the curve, *Pmax* (where $P_{MAX} = I_M V_M$) and fill-factor *FF* given as follows:

$$FF = \frac{P_{MAX}}{V_{OC} I_{SC}} \qquad (1)$$

while the efficiency, η, may be expressed as:

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{IN}} \qquad (2)$$

Where P_{IN} is the incident solar radiation on the surface of the module.

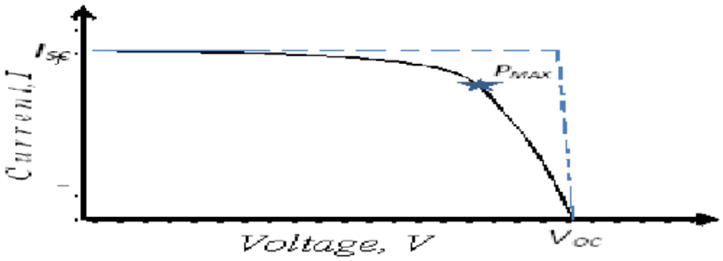

Figure 2: Current (I) – voltage (V) characteristic of solar cell

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).

Photovoltaic Module Conversion Efficiency

A typical silicon PV module converts approximately 10 to 20 percent of the sunlight that strikes its surface to electrical energy under standard test condition. The electrical efficiency of the photovoltaic module depends on the efficiency of the cells that make up the module. An increase in cell/module temperature can lead to a reduction in the band gap of the semiconductor material of the cells, 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 under operating condition falls below those obtained from test condition. There are several reasons for lower conversion efficiency under operating condition. One reason that is identified from literature may be the temperature of the module. Hosseini *et al.*, (2011) compared the combined photovoltaic (PV) module and a solar thermal collector with the conventional collector and showed that the power and the electrical efficiency of the combined system are higher than the traditional one. Also since the heat removed from the PV panel by water film is not wasted, the overall efficiency of the combined system is higher than the conventional system. Mawoli *et al.* (2017) In this study, the effect of cooling on temperature coefficient of a polycrystalline silicon solar photovoltaic module. Their results show the positive effect of cooling when the efficiencies of the test module were compared with those of a control solar module. Bambrook and Sproul(2012) carried out an investigation of a photovoltaic – photo-thermal (PVT) air system with increasing air mass flow rate. They observed thermal efficiencies in the range of 28-55% and electrical PV efficiencies between 10.6% and 12.2% at midday.

Overtime, it is observed that some stand-alone photo-voltaic systems fail to deliver the expected amount of energy within short period after installation. Although system sizing may sometimes be responsible for this, other factors which may have not been considered could be responsible for the shortfall in energy generated. Sisodia and Mathur (2020) for instance, explored the trend of dust soiling rate over different seasons in a year and its impact on the performance of solar photovoltaic (PV) system in a location in India. They stated that dust particle settlement primarily affects the optical properties of the PV modules that results in a decline their output electrical energy.

The focus of this work is to experimentally evaluate the performance of a rooftop mounted PV module in the stand-alone without storage mode. The objectives include setting up the PV – load system and the data acquisition system (DAS). It is hoped that our findings will give an insight into the response of photovoltaic modules at our location with respect to performance.

MATERIALS AND METHOD

The 50 watts module was mounted in the horizontal orientation on the roof of a laboratory at Faculty of Science, University of Lagos. This location is close to the Lagos lagoon. Temperature and humidity are lowest during the dry (harmattan) season (late November to February} and peaks in the months of March and April.

Materials

The module was connected to a fixed load and a data acquisition unit (DAS) comprising data loggers recording unit was connected to the load. Module specification, PV system design and derived characteristics are shown in Table 2 and Figures 3 and 4 are shown below.

Table 2: Module specification

PARAMETER	**VALUE**
MAXIMUM POWER	50Wp
OPEN-CIRCUIT VOLTAGE Voc	21.8V
SHORT-CIRCUIT CURRENT Isc	3.14A
VOLTAGE AT MAXIMUM POWER Vm	17.6V
CURRENT AT MAXIMUM POWER Im	2.85A 1000Wm^{-2}
IRRADIANCE UNDER STC (@ AM1.5	1000Wm^{-2}

The module was connected to the load 5 ohms/80watts and then to data acquisition unit (DAU).

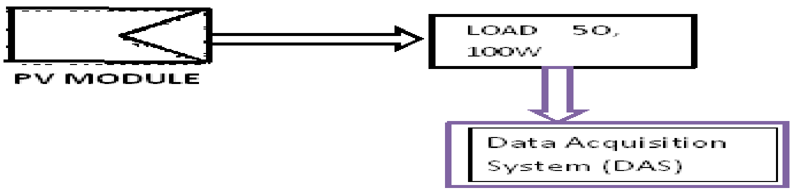

Figure 3: Photovoltaic system (without storage)

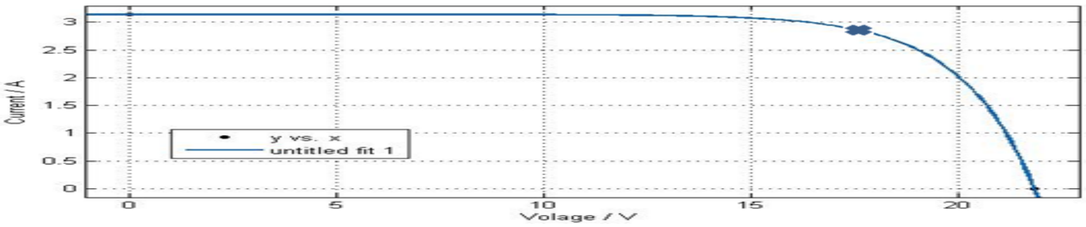

Figure 4: The current voltage curve of the 50watts PV module. Point marked on the curve represents maximum power point

A pyranometer is located at the site for the measurement of global solar irradiation.

Method

The module was connected to the load (5 Ohms/100 Watts). The load was determined from the specified module peak power in Gable 2. The DAS samples the output voltage generated by the module every second and logs the average value as well as module temperature every minute. Module efficiency is calculated as follows:

$$\text{Efficiency} = \frac{\text{Energy\_generated\_by\_the\_module}}{\text{Solar..radiation..incident..on..the..module}} \tag{3}$$

RESULTS AND DISCUSSION

Results

Data for parameters measured were acquired for the period from the month of January to May, 2017. A total of 24 days downtime in the DAS occurred during the period (10 days from 22nd to 31st January and 14 days from 25th February to 10th March). The advantages of a test period shorter than a year are that it can be completed in a shorter time, it can provide earlier results regarding system performance that can be used to improve system performance and it may be of adequate accuracy if the model gives consistent predictive quality at all times during the year and if there are no intermittent problems (Kurtz *et. al*., 2013). Figures 5 and 6 show the profiles of energy generated by the module and solar radiation incident on the module while Figure 7 is the combined profile from Figures 5 and 6 on the same axis.

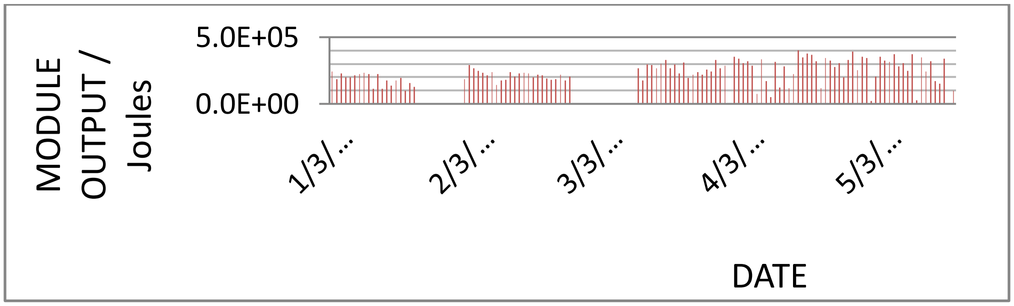

Figure 5: Energy generated by the module for the period (January to May, 2017)

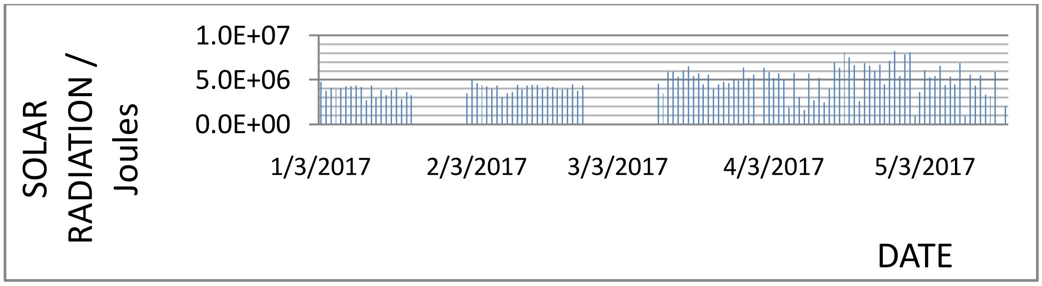

Figure 6: Solar radiation incident on the module for the period (January to May, 2017)

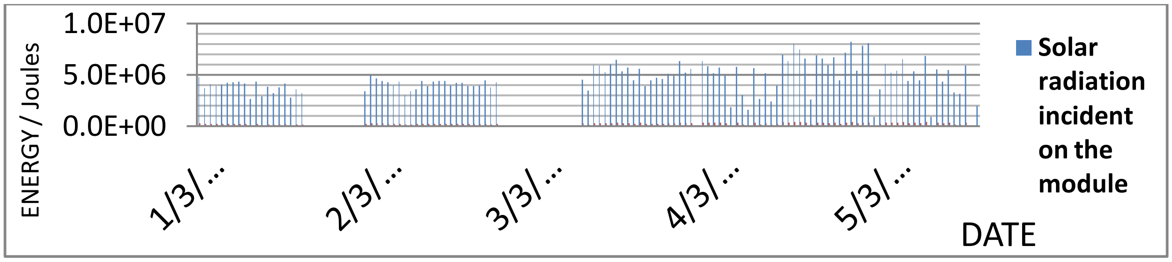

Figure 7: Energy generated and solar radiation for the whole period (January to May, 2017)

Figure 8 is a profile of the variation in calculated day efficiency for each day during the period of study while Figure 9 is a plot of energy generated by the module against solar radiation incident on the module.

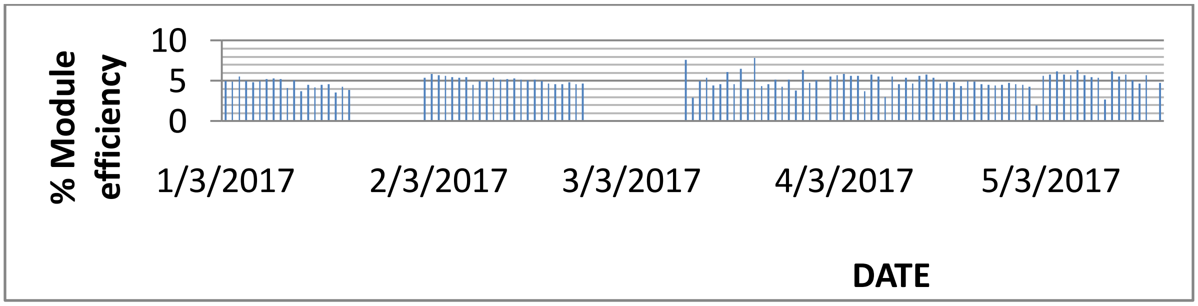

Figure 8: Module efficiency variation for the period (January to May, 2017)

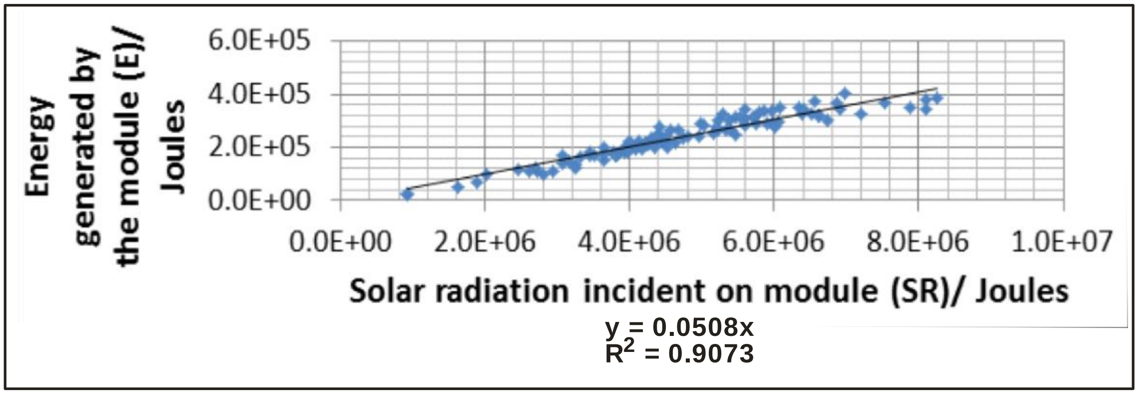

Figure 9: Energy generated by module plotted against solar radiation incident on the module for the period (January to May, 2017)

An important aspect of this work is the prediction of the energy generated by the PV module from quantities that determine the performance of the module. These quantities are solar radiation and module temperature. The month of April was used to obtain a model for the PV module that can predict the total output for any day. The regression statistics is show on Table 3.

Table 3: Regression results for module temperature and solar irradiation for the month of April

Regression Statistics	
Multiple R	0.9947
R Square	0.9894
Adjusted R Square	0.9533
Standard Error	31122.1kJ
Observations	30

The model obtained is dependent on incident solar irradiation and the module temperature. It is expressed as:

$$\text{Module\_energy\_generated} = X..T_{MOD} + Y..R_{SOLAR} \quad (4)$$

The linearity of predicted module energy output and measured values is presented in Figure 10.

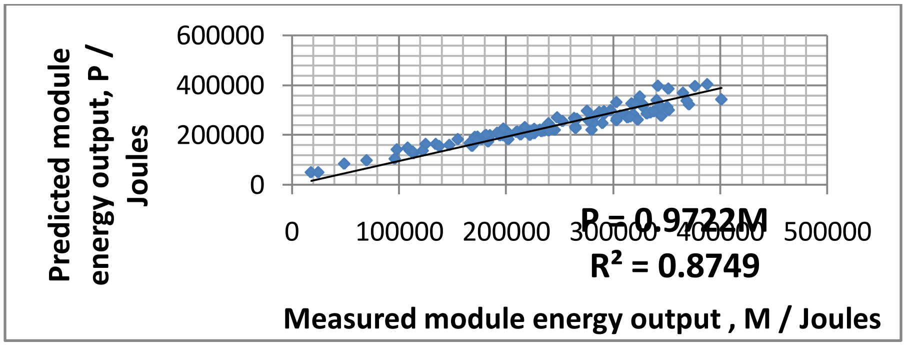

Figure 10: Predicted PV module energy output plotted against measured values

where T_{MOD} is module temperature, R_{SOLAR} is solar irradiation, while X and Y are constants where X=246.09 J/°C and Y = 0.005812 m/day. This equation was applied to all the days in the months considered. The results obtained are shown on Table 4.

Table 4: Summary of result for all the months

Measured total energy generated	Predicted total energy from the model	Mean Bias Error (MBE)	RMSE	Percentage normalized RMSE
26.4MJ	26.1MJ	2.3kJ	25.7kJ	10.8%

The RMSE is normalized with respect to the measured total energy generated to obtain percentage normalized RMSE.

DISCUSSION

The variations observed in figure 8 show that the daily energy conversion efficiency vary from approximately 2% to 7.8%. The lower end (approximately 2%) is due to lower solar irradiation for the day due to cloud presence. These converters (silicon PV modules) perform better when the beam component of solar radiation is present. The slope of Figure 9 gives the overall efficiency for the period of study. The implication is that the total energy conversion from solar radiation to electrical energy is 5.08%. This is significantly lower than the efficiency 14.4% that is obtained from Table 2 and represents a reason for improvement in PV technology. The model for the prediction of module energy output expressed in equation 4 can assist in the evaluation of the performance of the module over its useful life span. The performance indices are shown on Table 4. The correlation value and the values on table 4 agree with those found in literature (Bimenyimana *et al.*, 2017; Yadav and Chandel, 2017). Two constraints will however need to be addressed; these are first, obtaining a method for predicting the module temperature for rooftop mounted modules and second, account for depreciation in PV cell performance with time which can affect the performance of the module. One way round the first constraint is to use ambient temperature. This is possible for freely mounted modules but not for rooftop mounted modules which do not have the benefit of convective action on both front and rear surfaces. Ambient temperature for rooftop mounted modules may be a combination of air temperature and roof temperature.

CONCLUSSION

The assessment of performance of silicon polycrystalline photovoltaic module was carried out with a view to obtain the conversion efficiency of the module during a limited period of operation. A model that can facilitate the estimation of the energy output of the module from the available solar irradiation and the temperature of the module was obtained. The results obtained can provide an insight into the option for adoption of photovoltaics as a source – or alternate source – of energy with respect to installation and operation of photovoltaic systems.

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