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Performance Evaluation of a Solar Photovoltaic (PV) Module at Different Solar Irradiance

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Abstract

The primary constraint of photovoltaic (PV) systems is the relatively low conversion efficiency of PV panels (PVPs), heavily influenced by their operating temperature and sun irradiation under various configurations. The lack of precision in accounting for PV panel temperature and solar irradiation levels heightens the financial risk associated with system installation. This study examines the impact of solar irradiation, under constant temperature conditions 25^{O}C, on a monocrystalline PV panel under standard test conditions (STC) of Ilorin, North Central Nigeria. The output performance of a specific PV panel model was initially investigated by simulating it using the Scilab Xcos™ software. The current-voltage (I-V) and power-voltage (P-V) curves are utilized to evaluate the performance of PV panels, taking into account the temperature of the panels and varying solar irradiation levels. The simulation's findings demonstrate that when solar irradiation varies from 400 W/m^2 to 1000 W/m^2, there is a linear increase in both the open circuit voltage (Voc) and short circuit current (Isc). The amount of solar irradiance causes this linear increase. The results also revealed that the quantity of irradiation the PV modules are able to extract directly relates to the PV module's output power. Furthermore, the current and voltage reached their peak levels of 7.12 A and 15 V, respectively, when the solar radiation intensity was 1000W/m^2. Their minimum values were 2.95 A and 14 V, respectively, when exposed to a solar radiation of 400W/m^2. The power output of the photovoltaic (PV) panel grew in direct proportion to the rise in solar radiation. Specifically, the power output declined to 85.95 W when the solar radiation was 400W/m^2, while it was 223.64 W when the solar radiation was 400W/m^2.

Keywords: PV system, Irradiance, Monocrystalline, Short circuit, Open circuit, Power

1. Introduction

Globally power demand is steadily rising but there with limited fossil energy supply. This is a worrisome trend in the energy business as suppliers tend to look for alternative sources to offer clients to stay in business therefore, there is an urgent need for a proper energy mix. Renewable energy like solar and bioenergy plays key roles in the structural supply chain of the energy mix. Fossil energy reserves have been gradually depleting yet continuously harnessed. The fossil energy exploration like crude oil severely harmed the ecosystem and over time, increased global warming[1]. The PV systems harness solar radiation as an energy source. Using cells, it converts solar radiation into a more useful energy which is electricity. At varying efficiency ranges of 7% to 40%, the PV cells produce electricity from solar radiation[1]. The semiconductor types used for PV cell production mostly influence its conversion. PV panels typically account for the largest share of the investment cost when compared to other installation components for PV systems[2]. Therefore, making reasonable returns after investing in this system heavily relies on PV panels' (PVP's) power generation capacity. Sadly, a few deteriorating factors frequently result in low conversion efficiency for PVP's. PV panel temperature is recognized as a key component in energy production forecasting[3]. For instance, extended high-temperature and operating conditions may cause a PVP's capacity to produce power to deteriorate permanently[4]. The elevated temperature is caused by wasted energy that is created as a result of absorbing solar energy. A PVP's can mostly convert about 20% of solar radiation into electricity[2]. Most of what is still present is converted to heat. The PVP's working temperature is increased due to the stored heat energy, which reduces the panel's electrical efficiency[5]. According to standard test condition (STC), a PVP's conversion efficiency decreases by 0.40 to 0.50% for every degree of temperature increase[6].

Silica is the main component of most solar cells. The electrons that are flowing through the solar PV material because of sunlight hitting a cell are converted into direct current (DC) electricity. By attaching an inverter to the system, the DC is transformed into AC, and the AC electricity is then fed into household devices as electric power[5]. Many materials including copper and cadmium telluride are used in making PV cells. There are, however, three silicon-based materials including monocrystalline (MCS), polycrystalline (PCS), and amorphous (APS) widely used in solar PV cells[7]. Highly concentrated photovoltaic (HCPV) systems focus solar energy onto tiny solar cells using optical devices (lenses or mirrors)[8]. According to the manufacturer of semiconductor materials, there are more efficient new forms of PV modules which are about 31.8% better than the ones previously produced[9]. Just like other technologies, in the last three decades, solar cell efficiency has increased steadily. This ranges from 16.5% CdTe, 18.4% CIGS, 24.7% c-Si, to 39% GaInP/GaAs/Ge[1].

In the past decade, numerous research have investigated the impact of solar radiation fluctuations and temperature volatility on the performance of photovoltaic (PV) panels. Suwapaet and Boonla's[10] research shows that AMS solar panels outperform MCS panels operating at elevated temperatures. Also, MCS panels supplied produce smaller power when compared to AMS at 600 W/m^2 range, despite no appreciable changes in PV panel temperature[10]. However, the targeted output size is below the expected efficiency of 31%, 50% and 54-68% for single junction, 3-cell stacks and hot carriers respectively. Only commercial modules had achieved efficiencies of 50% to 65% of these "champion" cells[10]. Ike[11] explored the impact of weather factors, such as ambient temperature, on the total efficiency of solar panels. The author asserted that there exists an inverse relationship between the ambient temperature and the output energy of the system. Additionally, the study emphasized the need to ensure proper airflow through the panels during the design process. Dash and Gupta[12] examined the correlation between temperature and the electrical output generated by various solar panels. The authors employed the temperature coefficient as a benchmark function for photovoltaic (PV) output power. The study determined that monocrystalline panels had the most average power loss, with a value of 0.446% per degree Celsius. Swapnil et al.[13] after conducting a thorough analysis of numerous research, it was shown that there is a direct correlation between temperature and both the photoelectric conversion efficiency and the output power of photoelectric modules. The researcher demonstrated that numerical parameters are contingent upon both the substance and the system simultaneously.

Chander et al.[14] used a solar simulator to research the effects of varying PV cell temperature during steady-state lighting conditions. This study discovered that the PV cell's temperature substantially impacts output parameters. It was discovered that the I_{sc} had positive coefficients for temperature, while other parameters like V_{oc} negatively impacted the temperature coefficients. The temperature impact on power with varying PV panels is reported by researchers[2], [11]. The mean power loss of monocrystalline PV panels when the temperature coefficient was considered was -0.45% per °C. Khaled et al.[15] examined the impact of shadowing on the peak power production of the photovoltaic (PV) panels and the resulting reduction in efficiency. The study determined that raising the temperature of the photovoltaic (PV) system leads to a decrease in its maximum output power. Based on the report by Temaneh-Nyah and Mukwekwe[16] elevated temperatures caused PV panels to lose power. Their findings also showed high temperatures caused a median energy waste of 37.8 kW for PV system installations for its regular 12-hour operations, which is 14.6 kWh [16]. The coefficient of temperature was found to be about 0.31% of lost energy per Kelvin [16]. Various kinds of PV panel technologies have produced output power in a variety of ways because of how sensitive they are to operating temperature ans solar irradiance. Zhe et al.[17] examined the impact of altering solar radiation intensity on the properties and efficiency of photovoltaic (PV) modules.

A number of researchers have employed mathematical models to accurately forecast the impact of variables, such as radiation intensity and temperature, across various global locations and the accuracy of the results is confirmed by comparing them to the results of real-world tests Al-Waeli et al. [18]

The present study examines the impact of variations in solar radiation and constant temperature on the overall efficiency of solar panels. An investigation was conducted to examine the connections between these variables and fundamental characteristics of photovoltaic (PV) panels, including short circuit current, open circuit voltage, output power, and efficiency. While there may exist several international studies resembling this particular study, they pertain to the conditions of different countries rather than the weather conditions specifically in Nigeria, particularly in the city of Ilorin, the capital. Ilorin exhibits a continental climate, with scorching temperatures during the summer and frigid conditions during the winter. This city experiences periodic fluctuations in relative humidity, however they are restricted in magnitude. Additionally, the wind velocity remains consistently mild, seldom surpassing 3 m/s on the majority of days throughout the year. To the best of the researchers' knowledge, no previous study of this nature has been done either domestically or abroad. The first section of this article provides background information to the research study while Section 2 provides information about the PV module's specifications. In section 3, $Scilab\ Xcos^{TM}$ software analyzed solar irradiance effects on the study’s PV module. However, section 4 discusses all the simulation's findings and results were further discussed.

2. Materials and Method

Firstly, a PV module can be arranged in series and or parallel. This corresponding arrangement gives the expected current and voltage output. In this study the analysis of the PV panel output performance was simulated using $Scilab\ Xcos^{TM}$ simulation software. By using this software, the basic data of PV panel can be explored as shown in Table 2. All data were determined under standard test conditions (STC) of Ilorin, North Central Nigeria with a rating of 25 °C, and a range of solar irradiance between 400W/m^2 and 1000W/m^2. Due to the highly unrealistic nature of the normal test settings, different data were inputted that closely resemble the actual operating conditions. The simulation programme yielded several key data points, including short circuit current, output power, open circuit voltage, and efficiency. Crucial connections can be identified to assess the overall effectiveness of PV panels, such as the correlation between efficiency and solar radiation intensity and temperature, the link between voltages and current, the relationship between voltages and output power, and other less significant connections.

The purpose of the simulation is to observe the effect of solar irradiance on PV panel output performance at constant temperature. After all parameters have been identified, the next method is to analyze the PV panel performance through the characteristics of current-voltage (I-V) and power-voltage (P-V) curves based on different amount of solar irradiance. To model the electrical characteristics in a PV module in predicting the power output, five important relevant equations need to be solved. These equations are:

i. Photo-current $\left(I_{ph}\right)$

$$I_{ph} = [I_{sc} + k_i.(T - 298)].\frac{G}{1000} \tag{1}$$

ii. Saturation current (I_o)

$$I_o = I_{rs}.\left[\frac{T}{T_n}\right]^3.\exp\left[\frac{q.E_{go}.\left(\frac{1}{T_n}-\frac{1}{T}\right)}{n.K}\right] \tag{2}$$

iii. Reverse saturation current (I_{rs})

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q.V_{oc}}{n.N_s.K.T}\right)}-1} \tag{3}$$

iv. Current through shunt resistor (I_{sh})

$$I_{sh} = \left(\frac{V+I.R_s}{R_{sh}}\right) \tag{4}$$

v. Output current (I)

$$I = I_{ph} - I_o.\left[\exp\left(\frac{q.(V+I.R_s)}{n.K.N_s.T}\right) - 1\right] - I_{sh} \tag{5}$$

Equations 1, 2 and 3 above represent the Photo-current $\left(I_{ph}\right)$ which is the output current, Saturation current (I_o) and Reverse saturation current (I_{rs}) respectively. These equations utilizes the constant values in order to produce specified output used in the block diagram as shown in Figs. 2, 3 and 4 respectively. Equations 4 and 5 will provide the current (I) and voltage (V) which are the two most important parameters of interest required by a PV module. There are numerous software that could be used to solve these equations. However, this study employed the use of Scilab Xcos^{TM} for the modeling and simulation of these complex equations. This study used this simulation tool because of its robustness in solving such complex equations [15]. For mathematical modeling and simulation of the PV module in Scilab Xcos^{TM}, Table 1 shows the required parameters used in the five equations previously mentioned.

Table 1. Photovoltaic (PV) module constants and variables

	Designation (Unit)	**Value**
I_{ph}	photo − current (A)	I_{ph}
I_{sc}	short circuit current (A)	I_{sc}
k_i	short − circuit current of cell at 25°C and 1000 W/m^2	0.0032
T	operating temperature (K)	T
T_n	nominal temperature (K)	298
G	solar irradiation (W/m^2)	G
Q	electron charge (C)	1.6×10^{-19}
V_{oc}	open circuit voltage (V)	V_{oc}
N	the ideality factor of the diode	1.3
K	Boltzmann's constant (J/K)	1.38×10^{-23}
E_{go}	band gap energy of the semiconductor (eV)	1.1
N_s	number of cells connected in series	N_s
N_p	number of PV modules connected in parallel	N_p
R_s	series resistance (Ω);	0.221
R_{sh}	shunt resistance (Ω);	415.405
V_t	diode thermal voltage (V)	……

The module rating showing the characteristics of a solar cell obtained from a Manufacturer's Datasheet [19] that will be used for modeling in Xcos^{TM} is shown in Table 2.

Table 2. Data obtained/estimated from Mitsubishi PV-TJ225GA6 at (STC) [19]

Designation	**Rating**
Maximum power rating (P_{mp})	225 W
Minimum power rating (P_{mp})	218.3 W
Tolerance of maximum power rating	+3/−3%
Voltage at maximum power (V_{mp})	30.0 V
Current at maximum power (I_{mp})	7.50 A
Open circuit voltage (V_{oc})	36.4 V
Short circuit current (I_{sc})	8.30 A
Total number of cells in series (N_s)	60
Total number of cells in parallel (N_p)	1

The Fig. 1 shows the module's circuit representation.

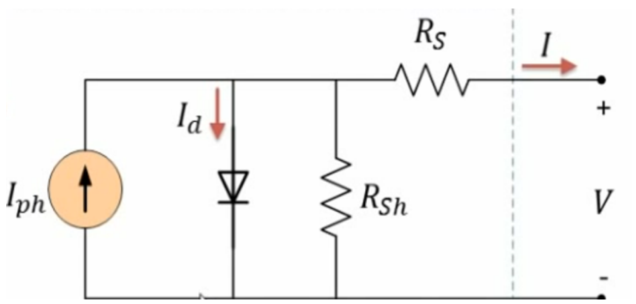


Fig. 1: Photovoltaic (PV) module cell circuit [20]

In modeling and simulating the PV module using Scilab Xcos™ with the manufacturer's specifications in Table 2, the following steps are taken:

Step one: Launch Xcos

Firstly Scilab needs to be launched, then launch *Xcos* from the general environment using  symbol or by searching for *Xcos*. By default, *Xcos* opens with two windows, a palette browser and an editing window.

Step two: Set Context

The next step is specifying in *Scilab* user's parameters. This is where values from Table 2 (i.e. Manufacturer's Specification) will be specified. This will be done from the editing window menu bar, in Simulation/Set Context.

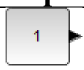
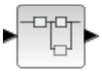
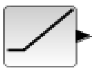
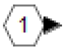
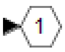
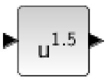
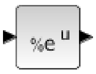
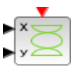
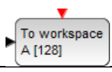
Step three: Blocks Arrangement

Instead of arranging the blocks in the editing window for the whole diagram (i.e. the five equations in block form) on one page, they can be built in small pieces in superblocks.

Step four: Modeling and Simulation

The data from Scilab Xcos™ were exported to Excel. In the palette browser, the blocks shown in Table 3 were used for the exercise:

Table 3. Set of predefined blocks

Designation	**Representation**	**Sub_Pallete**
Constant		Sources/CONST_m
Superblock		Port & *Subsystem/SUPER_f*
Ramp		Sources/RAMP
Input		Port & *Subsystem/IN_f*
Output		Port & *Subsystem/OUT_f*
Delay		Discrete time systems/DELAY_f
Power		Mathematical Operations/POWBLK_f
Exponential		Mathematical Operations/EXPBLK_m
Summation		Mathematical Operations/BIGSOM_f
Product		Mathematical Operations/PRODUCT
Clock		Sources/Clock_c
Visualization		Sinks/CSCOPXY
Mux		Recently Used Blocks/MUX_f
Matrix		Sinks/TOWS_c

Now to start arranging the blocks for each of the equation one after the other:

i. Photo-current (I_{ph})

$$I_{ph} = [I_{sc} + k_i.(T - 298)].\frac{G}{1000} \tag{6}$$

The output current is described by I_{ph}, the equation inputs are T and G with I_{sc} and k_i as constants. Fig. 2 shows the block structure for the equation.

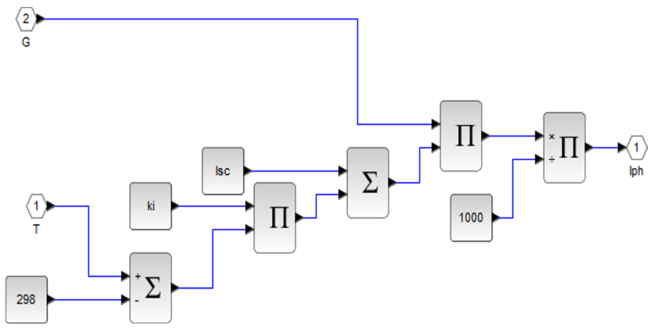


Fig. 2. Photo-current (I_{ph}) block diagram

ii. Saturation current (I_o)

$$I_o = I_{rs}\,.\left[\frac{T}{T_n}\right]^3.\exp\left[\frac{q.E_{go}.\left(\frac{1}{T_n}-\frac{1}{T}\right)}{n.K}\right] \tag{7}$$

In this equation I_o is specified as the output, T and I_{rs} are respective inputs. Also, the constants are T_n, q, E_{go}, n and K. Fig. 3 shows the block structure for the equation.

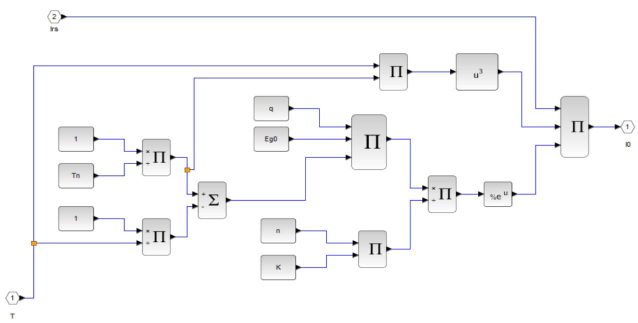


Fig. 3. Saturation current (I_o) block diagram

iii. Reverse saturation current (I_{rs})

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q.V_{oc}}{n.N_s.K.T}\right)}-1} \tag{8}$$

In this equation I_{rs} and T are specified as the respective output and input. Other parameters like I_{sc}, V_{oc}, q, n, N_s and K represent constants within the equation. Fig. 4 shows the block structure for this equation.

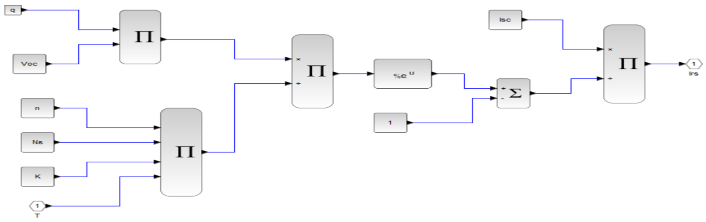


Fig. 4. Block diagram for I_{rs}

iv. Current through shunt resistor (I_{sh})

$$I_{sh} = \left(\frac{V+I.R_s}{R_{sh}}\right) \tag{9}$$

In this equation I_{sh} is specified as the output, and I and V as input with R_s and R_{sh} as the equation constants. Fig. 5 shows the block structure for the equation.

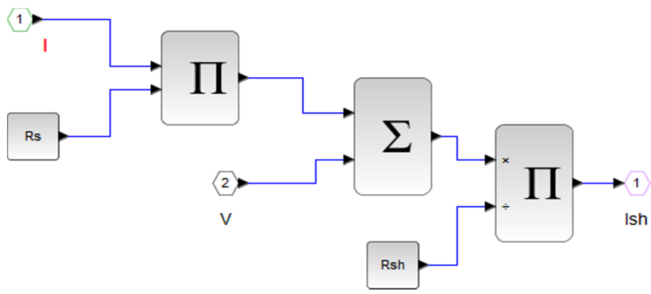


Fig. 5. Block diagram for I_{sh}

v. Output current (I)

$$I = I_{ph} - I_o.\left[\exp\left(\frac{q.(V+I.R_s)}{n.K.N_s.T}\right) - 1\right] - I_{sh} \tag{10}$$

In this equation V, T, I_o, I_{ph} and I_{sh} are specified as the inputs, with $q, R_s, n, K,$ and N_s as the equation constants. Fig. 6 shows the block structure for the equation.

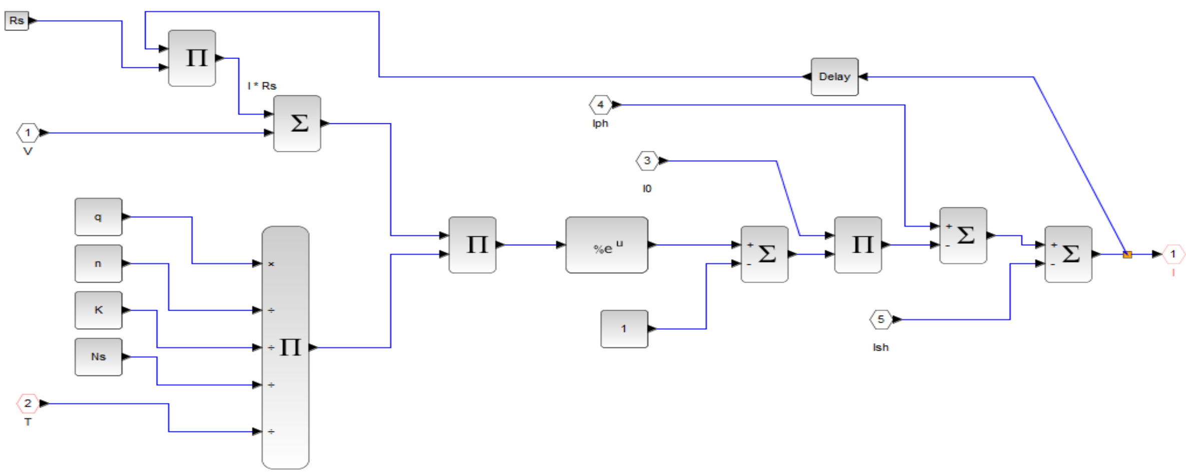


Fig. 6. Block diagram for the output current (I)

These individual blocks are connected to form a superblock in Fig. 7.

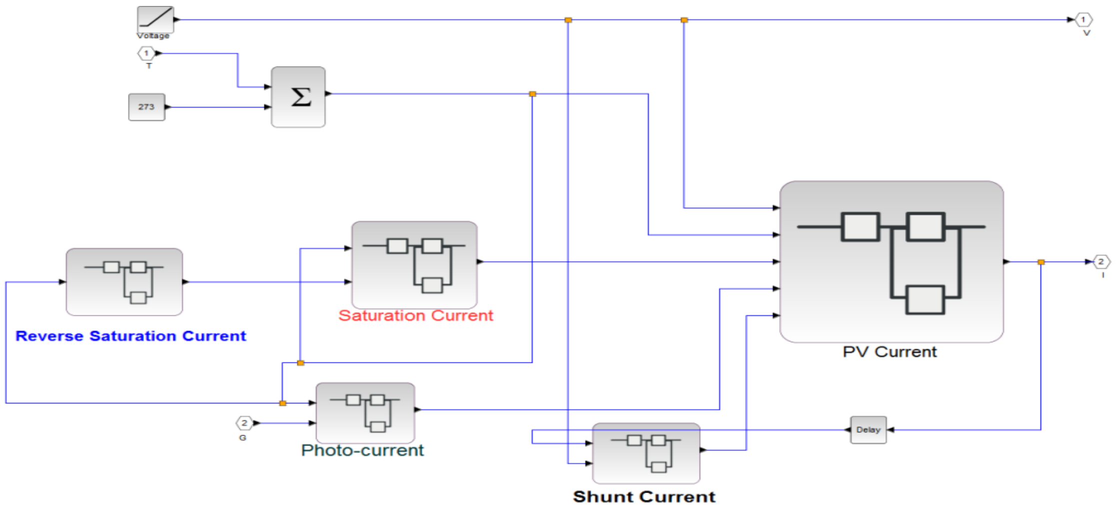


Fig. 7. Photovoltaic (PV) module sub-superblocks

For the system to produce the expected power output, certain T and G as seen in Fig. 8 are required in the system. Next section of this study shall discuss the results of modeling and simulation of the photovoltaic (PV) module.

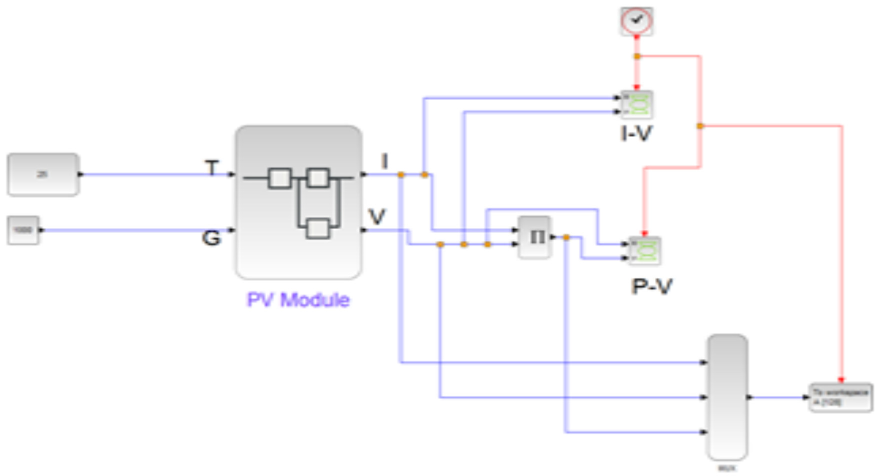


Fig. 8. Photovoltaic (PV) Module Visualization

3. Results and Discussion

The results obtained using Scilab Xcos^{TM} were exported to Excel Worksheet as shown in Table 4. The modeling and simulation operating parameters at various sun irradiances are displayed in Table 4. The results shows that, the increase in Isc through the open circuit of the PV module grows at a constant voltage, which increases the output power in the PV modules due the increase in the amount of solar in irradiance. In contrast, the output power in the PV modules rises sequentially as the voltage across their circuit increased. Also, the results further revealed that the current drops as the time interval increases. These data were used to generate a P-V vs. I-V curves at varying solar irradiance as shown in Figure 9 which was also used for the performance analysis of this study

Table 4. Inputs and Outputs Parameters after Modeling and Simulation

Solar Irradiance		@ 400 W/m^2		@ 600 W/m^2		@ 800 W/m^2		@ 1000 W/m^2	
Time [s]	V [volt]	I [amps]	P [watt]	I [amps]	P [watt]	I [amps]	P [watt]	I [amps]	P [watt]
0.1	1	3.317593	3.317593	4.977593	4.977593	6.637593	6.637593	8.297593	8.297593
0.3	3	3.312778	9.938333	4.972778	14.91833	6.632778	19.89833	8.292778	24.87833
0.5	5	3.307962	16.53981	4.967962	24.83981	6.627962	33.13981	8.287962	41.43981
0.7	7	3.303146	23.12202	4.963146	34.74202	6.623146	46.36202	8.283146	57.98202
0.9	9	3.298325	29.68492	4.958325	44.62492	6.618325	59.56492	8.278325	74.50492
1.1	11	3.291717	36.20889	4.950827	54.45909	6.609934	72.70928	8.26904	90.95944
1.3	13	3.286841	42.72893	4.945937	64.29718	6.60503	85.86538	8.264117	107.4335
1.5	15	3.281853	49.2278	4.940914	74.11372	6.599965	98.99947	8.259001	123.885
1.7	17	3.276568	55.70166	4.935535	83.90409	6.594471	112.106	8.253371	140.3073
1.9	19	3.270474	62.13901	4.929183	93.65448	6.58781	125.1684	8.246339	156.6804
2.1	21	3.262189	68.50597	4.920201	103.3242	6.577991	138.1378	8.235514	172.9458
2.3	23	3.247964	74.70316	4.904087	112.794	6.559609	150.871	8.21441	188.9314
2.5	25	3.217635	80.44089	4.868638	121.716	6.518012	162.9503	8.165432	204.1358
2.7	27	3.143669	84.87906	4.780794	129.0814	6.413507	173.1647	8.040921	217.1049
2.9	29	2.951446	85.59193	4.550969	131.9781	6.138536	178.0175	7.71175	223.6408
3.1	31	2.438846	75.60422	3.936524	122.0322	5.401835	167.4569	6.828297	211.6772
3.3	33	1.058938	34.94494	2.281105	75.27646	3.415813	112.7218	4.445613	146.7052

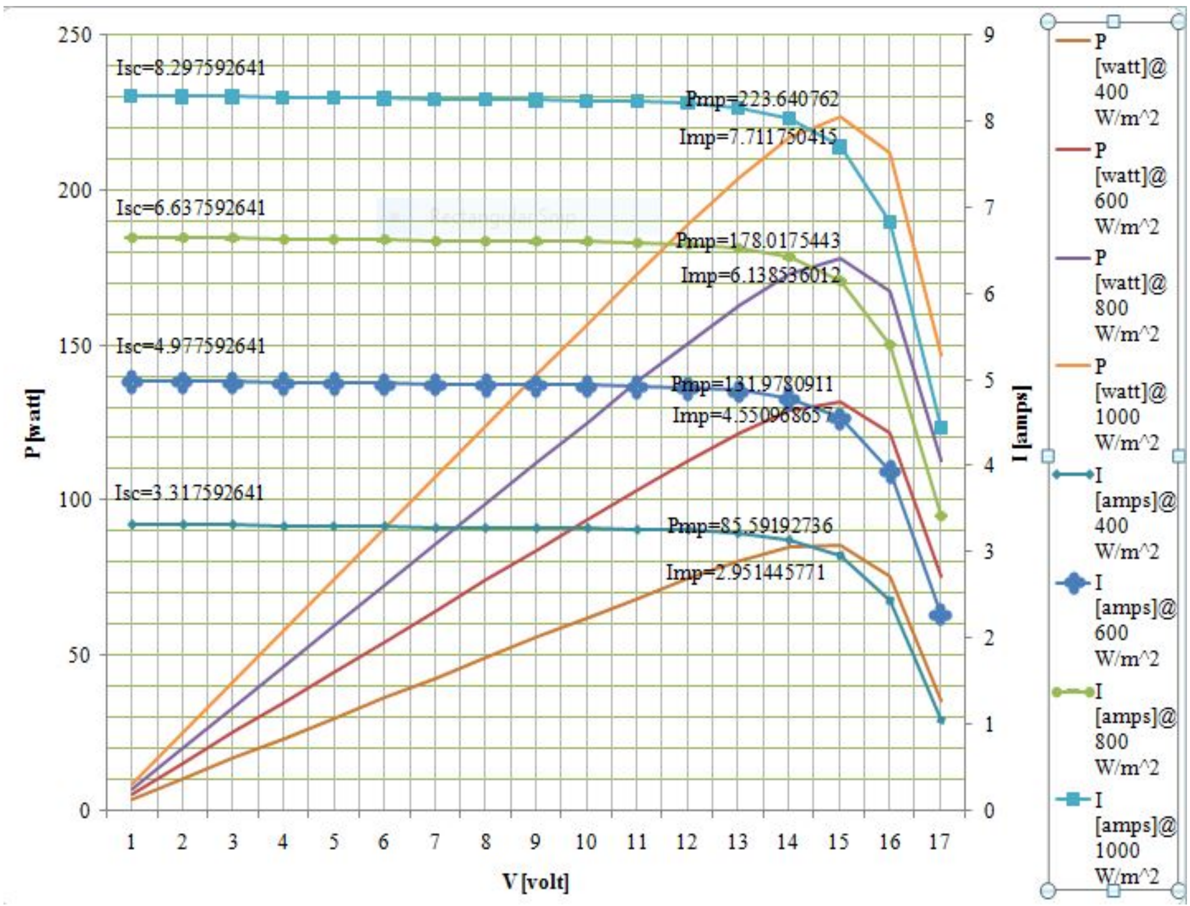


Fig. 9. Variation in (P-V) and (I-V) curves at varying solar irradiance

Figure 9 illustrates the correlation between the current, voltage, and output power under a consistent temperature of 25 °C and a fluctuating solar radiation ranging from 1000 W/m^2 to 400W/m^2. This is a theoretical scenario that cannot be implemented under actual operational circumstances. The current and voltage reached their peak levels of 7.12 A and 15 V, respectively, when the solar radiation intensity was $1000\mathrm{W/m^2}$. Their minimum values were 2.95 A and 14 V, respectively, when exposed to a solar radiation of $400\mathrm{W/m^2}$. The power output of the photovoltaic (PV) panel grew in direct proportion to the rise in solar radiation. Specifically, the power output declined to 85.95 W when the solar radiation was $400\mathrm{W/m^2}$, while it was 223.64 W when the solar radiation was $400\mathrm{W/m^2}$.

It is important to note that the the characteristics I-V and P-V alter during the day in tandem with the increase in solar insolation. PVPs current, voltage, and output power rose as the solar radiation increased, while the temperature remained constant. The photovoltaic panel achieved its highest performance under standard test conditions (STC). The findings align with the research conducted by [1], [2], [6].

4. Conclusion

The performance evaluation of a PV module at different solar irradiance for power generation was carried out with Scilab Xcos™ simulation software with data under STC for Ilorin North Central, Nigeria. The block diagrams and equations for each of the PV modules' subsystems and components were examined. The simulation's findings demonstrate that when solar irradiation varies from 400 $\mathrm{W/m^2}$ to 1000 $\mathrm{W/m^2}$, there was a linear increase for both the Voc and Isc. This linear increase is caused by the amount of solar irradiance. Furthermore, the solar irradiation that the PV modules can capture determines output power of the PV modules. The quantity of irradiation the PV modules are able to extract directly relates to the output power of the PV module as seen in Figure 9, it also shows that the current and voltage reached their peak levels of 7.12 A and 15 V, respectively, when the solar radiation intensity was $1000\mathrm{W/m^2}$. Their minimum values were 2.95 A and 14 V, respectively, when exposed to a solar radiation of $400\mathrm{W/m^2}$. The power output of the photovoltaic (PV) panel grew in direct proportion to the rise in solar radiation. Specifically, the power output declined to 85.95 W when the solar radiation was $400\mathrm{W/m^2}$, while it was 223.64 W when the solar radiation was $400\mathrm{W/m^2}$.

The outcome of this study opens new avenues for designing a PV modules as well as PV arrays that would produce the highest possible power output at different solar irradiance which is the major problem faced by the particular geographical location chosen for this study.

Future research on the impact of dirt or shade on solar PV arrays as well as other algorithm setups for improved maximum power point tracking (MPPT) are suggested.

Author Contributions

Anas Bala: Conceived and designed the analysis, Methodology, Software, Validation, Analysis, Investigation, Data curation, Writing Original draft, Visualization, and Supervision.
Babatunde Moshood Alao: Methodology, Software, Validation, Analysis, Investigation, Data curation
Oyedun Aliu Olamide: Writing Original draft, Validation, Visualization, Supervision
Oluwaseyi Omotayo Alabi: Data curation, Writing Original draft, Visualization
Mohammed Adamu: Data curation, Writing Original draft, Visualization

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