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Experimental Modelling and Simulation of Stand-Alone Experimental Photovoltaic Array for Different Climatic Conditions in Bauchi Metropolis

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ABSTRACT

Standalone renewable energy based on photovoltaic systems accompanied with battery storage system are beginning to play an important role over the world to supply power to remote areas. The current state and the future potentials of renewable energy have increased globally to minimize the usage of other resources such as fossil fuel, which affect the environment. AbubakarTatari Ali Polytechnic, Bauchi (ATAP) is a case where renewable energy will count for 75% of its energy consumption. Solar energy is abundantly availabl.so we have to extract and utilize it in a very efficient way. In this research, an improved yet simple model that can simulate and accurately predict the output power of an installed photovoltaic array in school of Engineering of the AbubakarTatari Ali Polytechnic, Bauchi and for different climatic conditions was developed. The result shows the field measurement based analytical model and RFBNN architecture for PV performance evaluation yielded superior results when compared with that of the manufacturer datasheet based mathematical model.

Keywords:, Photovoltaic, PV system, Renewable energy, Solar energy, Stand-alone.

1. INTRODUCTION

Conventional fossil fuel energy sources are largely responsible for global warming which is believed to be playing an ever-increasing role in charting other energy resource utilizations and development directions into the foreseeable future. To be more specific, electrical energy generation worldwide is currently being realized via burning of fossil fuels with the attendant productions of greenhouse gases. Consequently, fossil fuel displacements via rapid penetration of renewable and environmentally friendly sources of electricity productions are central to mitigating the global warming phenomena. Some recent projections (IAEA, 2007) indicate that the total global energy will almost triple by 2050 [1]. As a consequence, renewable energy sources which currently supply somewhere between 15% and 20% of the total energy demand are expected also to grow in leaps and bounds in the twenty-first century. Figure 1 conceptualizes the schematic overview of the genesis of renewable energy sources and the underlying conversion process. It is unarguable that the Sun is the sole driver of all terrestrial based renewable energy sources being exploited by researchers for the benefit of mankind. Both industrialized and some developing countries have adopted those viable renewable resources in their national energy mix policies so as to mitigate the negative environmental impacts of fossil fuels.

Different geographical regions experience different weather patterns, so the site where we live is a major factor that affects the photovoltaic system design from many sides; the orientation of the panels, finding the number of days of autonomy where the sun does not shine in the skies, and choosing the best tilt angle of the solar panels. Photovoltaic panels collect more energy if they are installed on a tracker that follows the movement of the sun; however, it is an expensive process. For this reason, they usually have a fixed position with an angle called tilt angle β. This angle varies according to seasonal variations [2]. For instance, in summer, the solar panel must be more horizontal, while in winter, it is placed at a steeper angle.

The world focus is now on the need to have an environmentally-sound source that can be used for safe and clean energy production. Designers need a reliable tool to predict energy production from solar cells in order to make sound and appropriate decisions regarding their use. Many models of varying complexity describing the behavior of a solar cell exist. However, several factors need to be considered in choosing an appropriate model for detailed simulation studies. To minimize the computational effort which is involved in long-term performance prediction, the model should be kept as simple as possible without sacrificing the required accuracy [3].

This research was focused in AbubakarTatari Ali polytechnic Bauchi. Bauchi State occupies a total area of 49,119km^2 representing about 5.3% of Nigeria's total land mass and is located between latitudes 9^{o}3' and12^{o}3' north of the equator. Longitudinally, the state lies between 8^o 50' and 11^o east of Greenwich meridian. The latitude and longitude makes it a relatively sun-rich region with an annual solar irradiance of about 2,500kWhm^{-2}. This implies that solar energy systems would be very efficient in this part of the world.

2. Description of the Experimental Photovoltaic Array

Commercial modules generally consist of 36 or 72 series connected solar cells to form cell string of designed power rating per module depending on the area of each solar cell and its fabrication technology. Herein, the M55 Siemens solar module used in this research consists of 36 series connected solar cells with rated power of 55watts. The dimension of each solar cell is 10.29cm x 10.29cm and fabricated using polycrystalline silicon technology.For the sake of operational reliability, photovoltaic modules are equipped with in-built blocking and isolation (bypass) diodes as illustrated in Fig. 1. Without these diodes, some solar cells excited by non-uniform solar irradiance pattern will consume the power generated by other cells. These diodes therefore eliminate the power loss associated with non-uniform solar irradiance scenarios arising from partial overcasts and or dust accumulations. Under ideal conditions, premised on uniform solar irradiance and dust free module assumptions, the bypass diodes are reverse biased and act as open circuits while the blocking diodes are forward biased and act as short circuits. It is therefore not essential to include such diodes in the mathematical model to be developed subsequently [4].

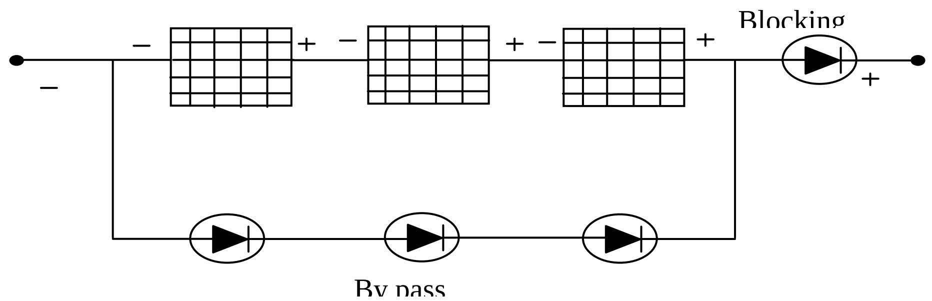

Fig. 1: Series String of Solar Cells with Bypass and Blocking Diodes

2.1. Experimental photovoltaic array used as test rig

The experimental photovoltaic array installed at the School of Engineering, ATAP Bauchi is used as test rig in this research work. The PV array comprises five M55 Siemens modules connected in parallel with rated maximum voltage of 17.4V and maximum power rating of 265Watts. The photovoltaic array is of fixed orientation at optimally determined inclination angle facing southward for all year round maximum solar energy harvest and at a location devoid of overcasts from nearby trees and building [5].

2.2 Experimental setup

The schematic representation of the overall experimental setup design is shown in Fig. 2 with all pertinent equipment clearly labeled. The critical equipment required is pyranometer for solar irradiance measurement. All other measuring instruments utilized are of digital variety so as to secure the desired accuracy in the field data acquisitions. Provisions have been made for both manual and automatic data measurement capabilities including pragmatic PV array cooling arrangement in the experimental setup.

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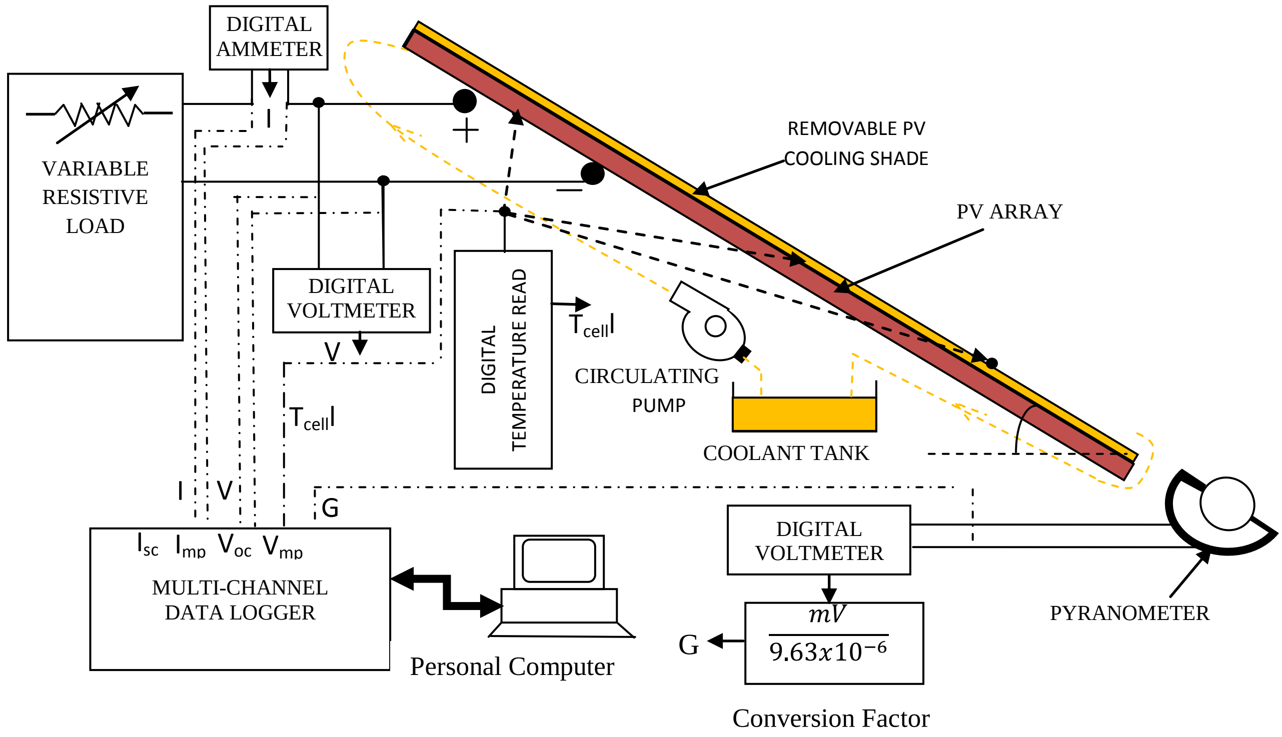

Fig. 2: Experimental Setup Showing Major Equipment and PV Cooling Arrangement

2.3 Measurement equipment

The measurement requirements in this research work are critical in the attainment of the model development embarked upon in this research work. The choice of equipment for the various measurements has been given due and careful consideration. In what follows, the various equipment facilities used are briefly described from the standpoints of their accuracies, specifications and calibration needs for all the measurement tasks.

2.3.1 Pyranometer

A pyranometer essentially generates voltage signal from thermopile detectors which is directly proportional to the incident solar irradiance. Most high quality pyranometers measure the total irradiance irrespective of the wavelengths in the solar spectrum and at all incident angles. The pyranometer, model No: CM6B, used in this research work for the measurement of direct solar irradiance is also capable of measuring horizontal component of solar irradiance [6]. The calibration of the pyranometer involves specification of its conversion factor to enable direct mapping of the generated voltage output, normally in millivolt range, into its corresponding solar irradiance expressed in W/m2. With respect to the model of pyranometer used, its representative conversion factor as specified by the manufacturer is $9.63x10^{-6}$ V/Wm^{-2}[7]. This is however contingent on regular cleaning of the convex glass of the pyranometer to be dust free and ensuring its firm attachment to the PV array rack [8].

2.3.2 Digital multimeters

The desirability for uninterrupted measurements throughout the measurement period engendered reliance on manual measurements of the needed field data to underpin PV array model development and performance characterizations. The core measuring instruments required are essentially dedicated multimeters of various selectable ranges for current and voltage measurements. In order to achieve the desired measurement accuracies, fluke digital multimeters are chosen for hourly measurements of PV open circuit voltages and short circuit currents as well as solar irradiance [9]. Except for the tedium of manual measurements and data logging into logbook, their measurement accuracies are not compromised. Of course, automatic data acquisition system (DAS) configured for the same purpose is naturally preferred with manual measurement arrangement as substitute in the event of DAS mal-operation particularly in a developing research environment characterized by paucity in such equipment stock [10].

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2.2.3 Thermocouples/digital thermometers

There is need to monitor PV temperatures at strategically selected locations to build credible database required as critical input into PV model development. The measurement of temperature can be accomplished by using thermocouples. The most popular thermocouple for PV temperature measurement is the k-type configured from dissimilar wires comprising chromel and alumel which is appropriately calibrated for specific temperature range of interest [11]. The thermocouple based temperature measurement is easily adaptable to DAS setup. It is also possible to manually monitor PV array operating temperatures at specific nodes using readily available hand held digital thermometers of superior quality than achieved through thermocouples. Digital thermometers of +/- 0.05^{o}C accuracy and temperature range of 0 to 100oC are available for manual measurements of PV temperatures at key selected nodes [12].

2.2.4 Multi-channel Data logger

The data logger available is delta T logger model DL2e built by Cambridge Researchers and specifically configured for solar data acquisition. It is equipped with 64 channels having calibrated sensors for voltage, current and temperature measurements. The logger sampling rate is of the order of few milliseconds and sufficiently fast for the solar data acquisition tasks. With the data logger connected to the desktop computer, all the data acquired can be stored for subsequent preprocessing and analysis. The flexibility of the DAS is clearly evident most especially its programmable capabilities to acquire the relevant PV data sequentially with minimum human intervention. It is noteworthy that the implementation of DAS can be adversely affected by unreliable power supply with the attendant problem of considerable data loss. For this reason, manual field measurements are almost always unavoidable during power supply outages.

2.2.5 Variable resistive load

The use of electronic load has become the standard approach of characterizing the power of PV array with high accuracy. However, for lack of its availability, suitably rated variable decade resistor box has been devised in this experimental setup to secure I-V curve for the PV array at constant irradiance, G and temperature, Tcell. The variable decade resistor box has the capability to sweep at discrete steps from short circuit to very near open circuit condition with corresponding PV current and voltage measured at each load point. The variable decade resistor load can be replaced by variable rheostat of rated current capacity and resistive value.

2.2.6 PV cooling arrangement

This experimental setup has incorporated a pragmatic cooling arrangement aimed at rapidly cooling the PV array to preset temperature level via conduction and forced convection processes. In this cooling arrangement, a thin layer of heat extractor/shade bearing embedded capillary pipe system is tightly overlaid on the entire PV array surface. Chilled water from reservoir tank (serving as coolant) is then circulated through the heat extractor to remove the heat trapped by the PV array. Temperature sensors at carefully selected nodes on the PV array surface are relied upon to monitor and confirm the attainment of the desired PV operating temperature level. Upon attainment of the set PV array temperature, preferably lower than the ambient temperature, the cooling arrangement is then dismantled and experimentation on the array can then be conducted as quickly as possible for every incremental rise in cell temperature. Other viable arrangements such as installation of hybridized solar collector or a pre-cooled shading/heat absorbing material could also be adopted where found expedient.

2.3 Proposed PV Array Model: Mathematical Development

The solar cell is the basic building block of any photovoltaic array and is always the starting point of PV modeling technique. Its equivalent electrical circuit earlier shown in Fig. 10(b) as model II and repeated in Fig. 15, for convenience, has been extended to represent the array model developed in this section. Applying Kirchhoff's current law on the equivalent circuit results in the current flowing to the load as is given in equation [13]

$$I = I_L - I_D - I_p \qquad \text{.........} \; (1)$$

It is obvious from the figure that the parallel (shunt) current, I_P is given by equation (2) as follows:

$$I_p = \frac{V + IR_s}{R_p} \qquad \text{.........} \; (2)$$

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Furthermore, from the theory of a p-n junction diode (Hansen, 2000), the diode current, I_D may be expressed as in equation (3):

$$I_D = I_o\left\{e^{\frac{(V+IR_S)q}{AkT}} - 1\right\} \quad \ldots\ldots\ldots (3)$$

Substituting equations (2) and (3) into equation (1) results in equation (4) as:

$$I = I_{pv} - I_o\left\{e^{\frac{(V+IR_S)q}{AkT}} - 1\right\} - \frac{V+IR_s}{R_p}\ldots\ldots \quad (4)$$

A: Diode ideality factor

Ipv: Light Current

Io : Diode Reverse Saturation Current

Rs: Series Resistance

Rp: Parallel (Shunt) Resistance

Rs

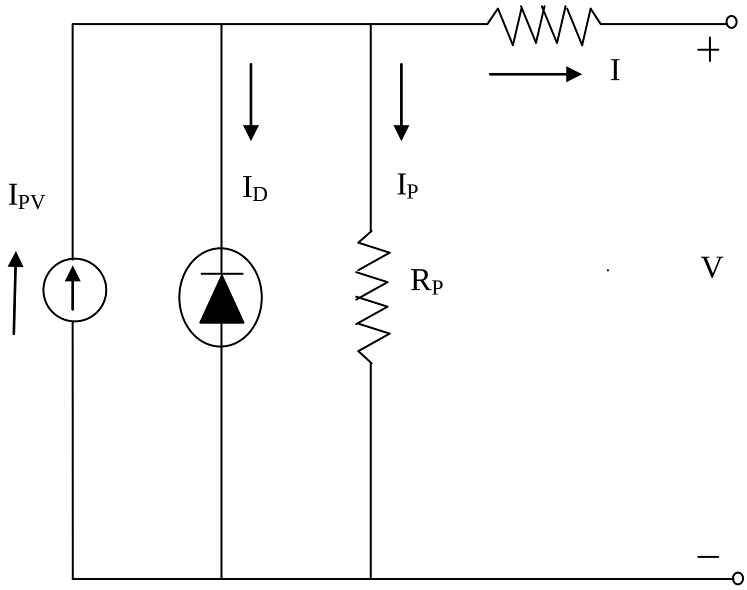

Fig. 3: Equivalent Electrical Circuit of a Solar Cell

3. EXPERIMENTAL RESULTS

Table 1 shows the minimum and maximum temperature in Bauchi for year 2022

Table 1. The monthly average values of daily global solar radiation (Wm^{-2}) in Bauchi, Nigeria.

Month	Average Monthly, (Wm^{-2})
January	2380-2520
February	2990-3230
March	3760-4000
April	4310-4680
May	5230-5690
June	6240-6890

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July	6850-7110
August	6110-6280
September	5420-5560
October	4010-4180
November	3010-3070
December	2420-2530

3.1 Results of seasonal solar irradiance and temperature variations

The solar irradiance data has been processed for the three micro-climatic conditions viz.: Harmattan, Cloudy and Clear Sunny days; thereby resulting into three seasonal solar irradiance databases. Also, the PV temperature measurements were similarly processed for each micro-weather condition. In addition, fairly comprehensive statistical characterizations of midday solar irradiance and temperatures for the three seasons are summarized in Table 2

Table 2: Summary of Statistical Characterizations of Solar Irradiance and Temperaturefor the Observed Micro-Climatic Seasons at Experimental PV Site

PV Measured Parameters	Statistical Information	Micro-climatic Seasons		
		Harmattan	Cloudy	Clear Sunny
	Maximum	605	60	965.4
	Average	586.7	600	950.8
	Minimum	560	590	927.3
Solar Irradiance (W/m^2)	Median	565.75	592.5	950.5
	Model	592	598	950.4
	Maximum	30	39.5	50
	Average	29	38	46
	Minimum	26.5	36	40.4
Temperature (^0C)	Median	30.5	37.5	45.5
	Model	30	38.5	45

3.2 Results of measurements of experimental PV array parameter variations

The experimental PV array test rig studied as earlier stated is of polycrystalline silicon technology and comprises 5 M55 Siemens solar modules connected in parallel. The leading parameters of each PV module, based on standard test conditions (STC) by the manufacturer and equivalent STC parameters of the experimental PV array test rig are presented in Table 3. The variations of these parameters with respect to temperature and solar irradiance have been exhaustively characterized from the field measurements carried out on the experimental PV array test rig.

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Table 3: PV Module and Array Parameter Values at STC

Parameter Type	M55 Siemens Solar Module Data Specification	Photovoltaic Array Rated Parameter Values
V_{oc}	21.7V	21.7V
I_{sc}	3.35A	16.75A
V_{mp}	17.4V	17.4V
I_{mp}	3.05A	15.25A
p_{pm}	53W	265W

3.3 PV array conversion efficiency computation

Efficiency is the most commonly used parameter to compare the performance of one PV array to another. Notwithstanding the earlier definition in Table 3, we repeat its definition here for convenience, as the ratio of the maximum electrical power that the PV array delivers to the load and the solar power input (Pin). This definition is expressed via equations (5) and (6).

$$\eta = \frac{P_{out}}{P_{in}} \dots (5)$$

$$\eta_{max} = \frac{P_{mp}}{P_{in}} = \frac{I_{mp}V_{mp}}{AG} \dots (6)$$

Where A = PV array cross-sectional area (m2), G = input solar irradiance (W/m2)

The experimentally determined maximum conversion efficiencies (ηmax) of the PV array operating at maximum power point for the three micro climatic conditions are also presented in Table 4.

Table 4: PV array Fill Factor and Conversion Efficiency for Harmattan, Cloudy and Clear Sunny Seasons

Climate Type	PV array Performance Parameters		Typical Operating Parameters	
	Fill Factor	Efficiency (%)	Temperature (^{o}C)	Irradiance (W/m^2)
Harmattan	0.718	13.11	29	586.6
Cloudy	0.711	12.50	38	600.0
Clear Sunny	0.708	12.43	46	950.8

3.4 Effects of temperature on array fill factor and conversion efficiency

The effects of temperature on the array Fill Factor and Conversion Efficiency for the three micro-climatic seasons of harmattan, cloudy and clear sunny have been determined. The results are presented in Table 5.

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Table 5: Effects of Temperature on Fill Factor and Conversion Efficiency for the Three Climatic Seasons

Temperature (^{0}C)	Micro-Climatic Variant Harmattan		Cloudy		Clear Sunny	
	Fill Factor	Conversion Efficiency (%)	Fill Factor	Conversion Efficiency (%)	Fill Factor	Conversion Efficiency (%)
25	0.733	13.52	0.724	13.44	0.732	13.98
30	0.720	13.07	0.718	13.07	0.727	13.62
35	0.715	12.66	0.713	12.69	0.721	13.24
40	0.706	12.28	0.709	12.34	0.716	12.87
45	0.703	11.94	0.704	11.97	0.711	12.50
50	0.699	11.58	0.698	11.62	0.705	12.12
55	0.692	11.22	0.691	11.22	0.670	11.76
60	0.687	10.86	0.687	10.88	0.691	11.35
65	0.684	10.50	0.681	10.53	0.687	11.01
70	0.676	10.14	0.675	10.16	0.681	10.65
75	0.669	9.78	0.669	9.81	0.674	10.28

3.5Effects of solar irradiance on array fill factor and conversion efficiency

Similarly, the effects of solar irradiance on array Fill Factor and conversion efficiency for the three weather conditions have been equally determined. The results are presented in Table 6.

Table 6: Effects of Irradiance on Fill Factor and Conversion Efficiency for the Three Climatic Seasons

Irradiance (W/m^2)	Micro-Climatic Variant Harmattan		Cloudy		Clear Sunny	
	Fill Factor	Conversion Efficiency	Fill Factor	Conversion Efficiency	Fill Factor	Conversion Efficiency
200	0.642	10.84	0.586	9.47	0.604	9.39
300	0.679	11.86	0.675	11.28	0.669	10.75
400	0.685	12.19	0.692	11.83	0.683	11.24
500	0.712	12.87	0.704	12.22	0.696	11.63

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600	0.719	13.13	0.711	12.50	0.702	11.90
700	0.756	13.36	0.715	12.69	0.707	12.12
800	0.725	13.59	0.717	12.84	0.709	12.26
900	0.727	13.63	0.719	12.99	0.711	12.39

4 CONCLUSION

Increased energy utilization and global pollution awareness have made green/renewable energy more and more valuable recently. In this paper, renewable energy has been briefly explored and solar energy has been highlighted. It is concluded that among several renewable energy resources, the photovoltaic (PV) effect is the most fundamental and feasible way because of the abundance and easy access to solar radiant energy. In conclusion, with the government's further supports on solar PV systems to urban areas, it would make it a more popular choice and enhance sustainable development thereby reducing dependence on grid power and reducing carbon footprints. The field measurement based analytical model and RFBNN architecture for PV performance evaluation yielded superior results when compared with that of the manufacturer datasheet based mathematical model. Although the results analyzed appear to be location specific, they could be adapted to other locations with similar climatic conditions most especially in the northeast zone and other zones in Nigeria.

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