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Design and Sizing of an Off-Grid Solar Photovoltaic (PV) System for an Office Unit at Modibbo Adama University, Yola-Nigeria

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ABSTRACT
The average performance of a 100 W, 23.3 V monocrystalline silicon solar PV module for three days measurements were determined under Modibbo Adama University Yola climatic conditions. The performance parameters were used for more accurate sizing of a PV system of an office unit. The average values of the performance parameters of the modules were found to be 71.63 W, 16.00 V, 4.48 A, 22.53 V and 4.90 A for P_{max}, V_{mp}, I_{mp}, V_{oc} and I_{sc} respectively at an overall average solar irradiance of 667.54 W/m^2. These values differ significantly from those of manufacturer's data sheet. The average daily energy consumption of the office unit and the total rated power of the AC loads were found to be 9.78 kWh/day and 3.272 kW respectively. About 13 parallel modules, 2 series modules, 3 parallel batteries (Lithium Iron Phosphate- 48 V, 300 (Ah) and 2 voltage charge controllers are required to maintain stable power supply. The capacity of an inverter needed for stable conversion to AC supply is 4 kW. The average performance efficiency of the PV system is found to be 13.49%. The yearly energy yield and capacity utilization factor were determined as 13,297,680 Wh/year and 58.38% respectively. The initial capital cost of the proposed solar PV system is ₦ 8,853,772 and a levelized cost of electricity (LCOE) as ₦ 29.48/kWh.

INTRODUCTION

Solar energy is the energy that is gotten from the sun. It remains one of the most reliable and abundant renewable resources available for power generation. Its global availability and clean nature make it a strong alternative to fossil-fuel-based energy sources (Ballaji *et al*., 2022). Solar energy can directly be converted into useful power using photovoltaic (PV) modules, which transform sunlight into electricity through the action of a semiconductor junction exposed to sunlight. Solar photovoltaic (PV) technology is readily accessible for deployment and development in Nigeria (Sedara *et al*., 2025). Photovoltaic systems are deployed in a wide range of applications, including residential power supply, telecommunications, industrial facilities, satellites, and remote installations (Saini *et al.,* 2018). Depending on design requirements, PV systems may operate as grid-connected, hybrid, or stand-alone units (Maddileti & Cherukuri, 2019). In an off-grid configuration, the PV array functions as an independent energy source and may be paired with batteries to store excess energy for use during periods of low solar energy exposure. Charge controllers are then required to regulate battery charging and discharging, ensuring system safety and longevity. The selected batteries must have sufficient storage capacity to hold the energy generated during daylight hours for use at night and throughout the required autonomy period (Jäger *et al*., 2014). Numerous studies have examined the design and sizing of stand-alone or off-grid solar PV systems for varying energy needs across different locations (Al-shamani et al., 2015; Unwaha et al., 2016; Adebayo & Koʕyiğit, 2017; Hamza *et al*., 2018; Alaje *et al*., 2021). In most of these works, however, the sizing process depended exclusively on the manufacturer's specifications for the PV modules, which are based on standard test conditions (STC) that are not realizable under natural environmental conditions. For optimal system sizing and dependable energy delivery, it is therefore important to evaluate PV module performance under the real operating conditions of the intended installation site. The study was carried out at Modibbo Adama University, Yola, situated within the Girei area of Adamawa State in Northeastern Nigeria. The campus lies between latitudes 9°20'00" and 9°21'30" N, and longitudes 12°29'00" and 12°30'30" E. The region experiences high solar availability with sunshine hours ranging from about 5.5 hours per day during the rainy season to nearly 10 hours per day in the dry season (Silikwa et al., 2020). These climatic conditions make the area suitable for solar-energy applications and form an important basis for estimating expected system performance.

In this work, the performance of a 100-W monocrystalline PV module was comprehensively evaluated. The measured performance data was subsequently applied to the design and sizing of an off-grid solar PV system intended to meet the energy needs of an office unit within the university. This approach ensures that the system design reflects realistic module behavior rather than relying solely on manufacturer-rated parameters.

MATERIALS AND METHODS

Performance Parameters of Solar PV Modules

The performance of a photovoltaic (PV) module is commonly assessed using a set of electrical parameters like the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), current and voltage at the point of maximum power output (I_{mp} and V_{mp}), and the maximum power (P_{max}) the module can deliver under specific conditions (Dunlop, 2010). These parameters are typically illustrated on current–voltage (I–V) and power–voltage (P–V) characteristic curves (Figure 1). The maximum power point of a module represents the operating condition where the product of voltage and current is greatest:

$$P_{max} = I_{mp} \times V_{mp} \quad (1)$$

Another indicator of solar PV module quality is the fill factor (FF). It expresses how closely the I–V curve approaches an ideal rectangular shape (Figure 1.1) and is calculated from:

$$FF = \frac{P_{max}}{I_{sc} \times V_{oc}} \quad (2)$$

The conversion efficiency of a PV module shows how effectively it converts incident solar radiation $H(t)$ into electrical energy. It depends on both electrical output and the intensity of irradiance striking the module area A:

$$\eta_m = \frac{P_{max}}{A \times H(t)} \quad (3)$$

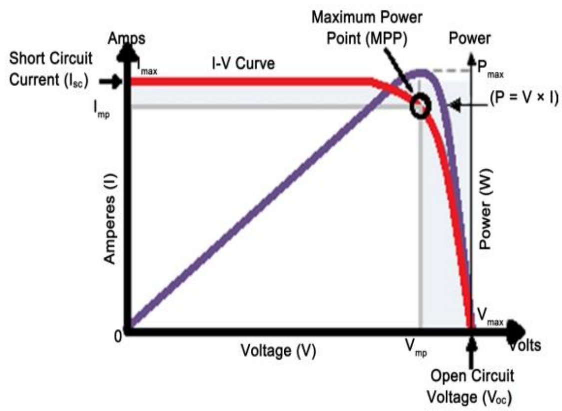


Figure 1: I-V and P-V Characteristics Curve of a Solar Cell (Coulibaly *et al*., 2019)

Performance Analysis of Solar PV System

Performance analysis of a solar PV system provides valuable information about the actual performance of a PV system at a specific site. The performance analysis parameters include solar PV system efficiency, yearly electrical energy produced, annual efficiency of the system and Capacity Utilization Factor (Owolabi *et al*., 2023; Sharma & Goel, (2017)). Other important parameters are the instantaneous power output at the AC side, and total solar energy incident on the PV system.

The instantaneous power output (AC) from the PV module is adopted and modified from (Wei, 2019):

$$P_{inst}(t) = AH(t)\eta(t)\eta_{invt}(t)\eta_{vc}(t)\eta_{others} \quad (4)$$

where $\eta(t), \eta_{invt}(t)$ and η_{vc} are efficiency of the module, inverter and voltage charge controller respectively.

The efficiency of the solar PV system is calculated using:

$$\eta_{syst}(t) = \frac{P_{inst}(t)}{A_{tot}H(t)} \quad (5)$$

where A_{tot} is the total surface the area of the PV modules.

The Electrical energy (AC) E_{yearly} produced by the PV system over the year is calculated using:

$$E_{yearly} = \int_0^{1\,year} P_{inst}(t)dt \quad (6)$$

The total solar energy S_{yearly} incident on the PV system throughout the year is calculated using:

$$S_{yearly} = A_{tot}\int_0^{1\,year} H(t)dt \quad (7)$$

The annual efficiency of the system is given by:

$$\eta_{Annual} = \frac{E_{yearly}}{S_{yearly}} \times 100\% \quad (8)$$

The Capacity Utilization Factor (C.U. F) measures how much energy the system actually delivers at the AC side relative to the energy it would have produced if the photovoltaic plant had operated at its rated power for the entire period (Tursunov *et al*., 2023).

$$C.U.F = \frac{E_{yearly}}{P_{rated} \times 24 \times 365} \times 100\% \qquad (9)$$

Materials/Equipment

In order to carried out this research effectively, the following equipment/materials were used. A 100 W, 23.3 V SUNSHINE SOLAR monocrystalline silicon PV module, KIPP & ZONEN CC20 pyranometer, MY61 MASTECH Digital multimeter, Checktemp H198501 Digital thermometer, variable resistor, Digital clinometer App 1.6.0, wrist watch and plasticine.

Table 1: Specification of the PV Module Used

SUNSHINE SOLAR Electrical Characteristics at STC (1000 W/m^2, AM 1.5. 25^{0}C)	
Maximum power (P_{max})	100 W
Maximum Power Voltage (V_{mp})	19.43 V
Maximum Power Current (I_{mp})	5.15 A
Open Circuit Voltage (V_{OC})	23.3 V
Short Circuit Current (I_{SC})	5.51 A
Maximum System Voltage	1000 V
Maximum Series Fuse	10 A
Operating Temperature	-20 ^{0}C – 90 ^{0}C

Experimental Setup/Performance Evaluation of the PV Module

To determine realistic operating characteristics of the 100-W monocrystalline PV module under the Modibbo Adama University climatic conditions, an experiment for studying its performance was setup. The setup consisted of a multimeter, a pyranometer for logging solar irradiance, a digital thermometer to record module surface temperature, and a clinometer to establish the tilt angle. The panel was oriented due south to align with the optimal position for our location in the northern hemisphere. A rheostat and ammeter were connected in series with the module, while a voltmeter was placed across the module (Figure 2), so that current and voltage could be varied and recorded simultaneously. By adjusting the resistance, several combinations of voltage and current were obtained and recorded separately in Table 3 for three days. During the experiment, the PV module was cleaned regularly to minimize significant energy production losses caused by natural dust accumulation (Babalola *et al*., 2024).

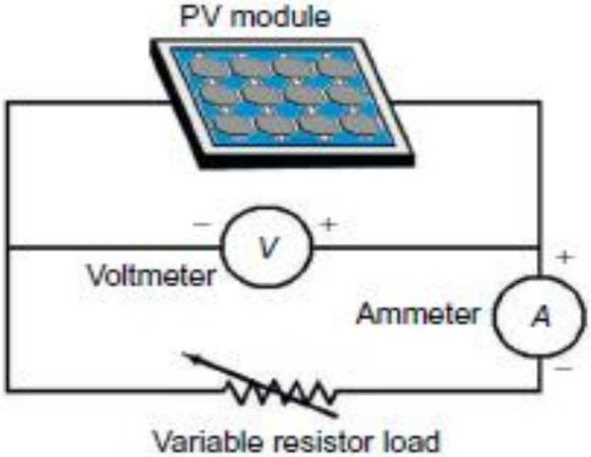


Figure 2: Circuit diagram for characterization of the PV module (Linah *et al.,* 2019).

Design and Sizing of the Off-Grid PV System

Office Unit Daily Load Estimation

The total daily energy *E* requirement of the office unit was determined by listing all appliances to be powered, their power ratings *P*, quantity *N*, and average daily operating time *t*. The energy consumed by each load was then computed using:

$$E = N \times P \times t \quad (10)$$

The energy consumption of each appliance per day is calculated and presented in Table 2.

Table 2: Estimated Daily Energy Requirements for the Office Unit

Office Appliance	Quantity	P (W)	Usage (h/d)	E (kWh/d)
Printer I	1	295	2	0.59
Printer II	1	670	2	1.34
Photocopier	1	1840	2	3.68
Standing Fan	1	120	8	0.96
Electric Bulbs	2	15	8	0.24
Ceiling Fan	2	80	8	1.28
Refrigerator	2	130	3	0.78
LED TV	2	32	3	0.19
Desktop Computer	2	90	4	0.72
Total		**3,272**		**9.78**

PV Array Sizing

To compensate for system losses, the usable energy requirement was adjusted using an overall efficiency factor. The adjusted energy (E_r) is expressed as:

$$E_r = \frac{E}{\eta_{sys}} \quad (11)$$

where E is the daily average energy consumption in Watts-hour and η_{sys} is the overall efficiency of the system, usually taken as 80% (Al-shamani *et al.,* 2015).

The peak power needed from the PV array was obtained by factoring in the average daily sunshine hours for the area:

$$P_p = \frac{E_r}{H_s} \quad (12)$$

where H_s is the average sun hours per day for the geographical location. In this case, for Modibbo Adama University, Yola-Nigeria.

The number of modules required in series and parallel was then calculated to meet both voltage and current requirement (Alaje *et al*., 2021).

$$N_{series} = \frac{V_{sys}}{V_{module}} \quad (13)$$

where N_{series} is the number of series modules, V_{sys} is the system nominal voltage (in volts), V_{module} is the module rated voltage in volts.

$$N_{parallel} = \frac{P_p}{P_{module} \times N_{series}} \quad (14)$$

where $N_{parallel}$ is the Number of parallel modules, P_{module} is the module capacity.

The total number of panels, N_{total} is the product of series and parallel connected panels given as:

$$N_{total} = N_{Series} \times N_{parallel} \quad (15)$$

Battery Storage Sizing

Battery storage was sized to ensure that electrical loads can be powered during nighttime and during periods of reduced irradiance. The battery chosen for this research is Felicity LPBR48300 Battery, 48 V, 300 Ah, and 95% MDOD. The rough energy requirement for storage was calculated based on the number of autonomy days (Al-Shamani *et al*., 2015).

$$E_{rough} = E \times \mathrm{N} \quad (16)$$

where E_{rough} is the rough energy storage, E is the daily average energy consumption in Watts-hour and N is the number of days of autonomy, is taken to be 3 days in this work.

A safety-adjusted storage requirement was then determined using the maximum depth of discharge (MDOD):

$$E_{safe} = \frac{E_{rough}}{MDOD} \quad (17)$$

The battery capacity was derived from:

$$C = \frac{E_{safe}}{V_{bat}} \quad (18)$$

where C is the Capacity of the battery in Ampere-hour, V_{bat} is the rated voltage of a single battery in volts. Since the battery storage is made up of assembly of batteries, the total number of batteries used is obtained from:

$$B_{total} = \frac{C}{C_{bat}} \quad (19)$$

where B_{total} is the total number of batteries, C_{bat} is the capacity of a single battery in Ah.

The number of batteries in series and parallel was determined to satisfy voltage and capacity demands using:

$$B_{series} = \frac{V_{sys}}{V_{bat}} \quad (20)$$

$$B_{parallel} = \frac{B_{total}}{B_{series}} \quad (21)$$

Charge Controller Sizing

A charge controller was selected based on its ability to handle the maximum expected short-circuit current from the PV array. For this research, a Rover 60 A, 48 V MMPT solar charge controller is selected. The required controller current rating was determined using:

$$I_{rated} = N_{parallel} \times I_{sc} \times SF \quad (22)$$

where SF is a safety factor to accommodate potential increases in current, usually taken as 1.2 (Unwaha *et al.*, 2016).

The required number of voltage controller, N_{vc} is obtained using:

$$N_{vc} = \frac{I_{rated}}{I_{selected}} \quad (23)$$

where $I_{selected}$ is the rated current of a single controller selected.

Inverter Sizing

The inverter was sized according to the total AC load demand. The inverter selected is IVEM 5048 inverter. To ensure reliable operation under starting surges and future expansion, the inverter capacity was set at approximately 20% above the total rated AC load.

Economic Evaluation

The economic analysis involved determining the initial investment cost, which included the PV modules, batteries, inverter, charge controllers, and installation. Operation and maintenance costs over the system's lifetime were also considered. The Levelized Cost of Electricity (LCOE) was calculated to evaluate long-term cost competitiveness using (Muazu, 2016):

$$LCOE = \frac{\sum (I_{cost}+OM_{cost}+F_{cost})/(1+dr)^t}{\sum E_g/(1+dr)^t} \quad (24)$$

This allowed a comprehensive assessment of the overall economic viability of the proposed PV system.

The initial investment cost in year *t*, denoted as I_{cost}, comprises the capital required for the photovoltaic (PV) modules, battery bank, and balance-of-system (BOS) components, including the inverter, solar charge controller, and installation expenses. The total investment cost is expressed as:

$$I_{cost} = PV_{cost} + Invt_{cost} + B_{cost} + VC_{cost} + Inst_{cost} \quad (25)$$

where PV_{cost}, $Invt_{cost}$, B_{cost}, VC_{cost}, and $Inst_{cost}$ represent the costs of the PV array, inverter, battery system, voltage controller, and installation, respectively. A solar PV system incurs no fuel cost (F_{cost}) because its operation does not depend on consumable fuels. The installation cost assumes 10% of the solar PV array cost (Omorogiuwa & Oforji, 2019).

The system's economic lifetime, *n*, is assumed to be 25 years. The annual operation and maintenance cost, OM_{cost}, is estimated using the method proposed by Omorogiuwa and Oforji (2019):

$$OM_{cost} = 0.02 \times PV_{cost}\left(\frac{1+i_r}{1+d_r}\right)\left[\frac{1-\left(\frac{1+i_r}{1+d_r}\right)^{25}}{1-\left(\frac{1+i_r}{1+d_r}\right)}\right] \quad (26)$$

The discount rate d_r is calculated using (Kellison, 2009)

$$d_r = \frac{i_r}{1+i_r} \quad (27)$$

The interest rate is taken as $i_r = 27.5\%$ (Trading Economics, 2024).

E_g is annual energy generated by the PV module over the period (kWh/year).

RESULTS AND DISCUSSION

Performance Characteristics of the PV Module

The Voltage V and current I readings from the set up (Figure 2) taken under varying load conditions along with their 3-day average values, corresponding irradiance levels G and module surface temperatures T are recorded in Tables 3(a) & 3(b). The maximum recorded power output over the 3-day experiments was 73.28 W, occurring at a maximum voltage of 16.00 V and current 4.58 A. These values represented the maximum power point (MPP) under the prevailing averaged irradiance of 680 W/m².

Table 3(a): Performance Test Result on Day 1 & 2

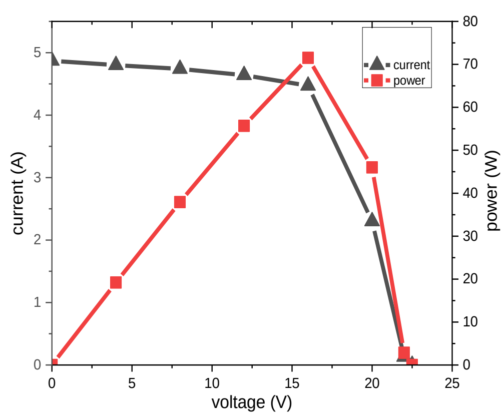
Performance test result on Day 1					Performance test result on Day 2				
I (A)	V (V)	P (W)	G (W/m^2)	T (^{o}C)	I (A)	V (V)	P (W)	G (W/m^2)	T (^{o}C)
4.87	0.00	0.00	660	57.80	4.79	0.00	0.00	657	51.20
4.80	4.00	19.20	662	57.90	4.71	4.00	18.84	656	52.50
4.74	8.00	37.92	662	58.60	4.55	8.00	44.40	659	53.40
4.64	12.00	55.68	661	57.00	4.51	12.00	54.12	655	54.80
4.47	16.00	71.52	663	56.90	4.38	16.00	70.08	658	53.70

Performance test result on Day 1					**Performance test result on Day 2**				
2.30	20.00	46.00	664	55.70	2.81	20.00	56.20	661	54.50
0.13	22.00	2.86	665	55.50	0.30	22.00	6.60	660	55.60
0.00	22.50	0.00	666	54.50	0.00	22.30	0.00	662	55.70

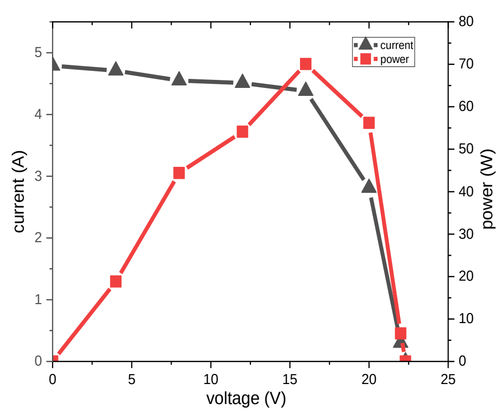
Table 3(b): Performance Test Result on Day 3 & Average Performance Result over 3 days

Performance test result on Day 3					**Average Performance test result over 3 Days**				
I (A)	**V (V)**	**P (W)**	**G (W/m^2)**	**T (^{o}C)**	**I (A)**	**V (V)**	**P (W)**	**G (W/m^2)**	**T (^{o}C)**
5.05	0.00	0.00	684	52.10	4.90	0.00	0.00	667.00	53.70
4.99	4.00	19.96	686	53.40	4.83	4.00	19.33	668.00	52.50
4.85	8.00	38.80	683	57.10	4.71	8.00	40.37	668.00	53.40
4.63	12.00	55.60	681	58.70	4.59	12.00	55.13	665.67	54.80
4.58	16.00	73.28	680	57.80	4.48	16.00	71.63	667.00	53.70
2.55	20.00	51.00	682	57.60	2.55	20.00	51.07	669.00	54.50
0.65	22.00	14.30	679	57.80	0.36	22.00	7.92	668.00	55.60
0.00	22.80	0.00	675	58.50	0.00	22.53	0.00	667.67	56.00

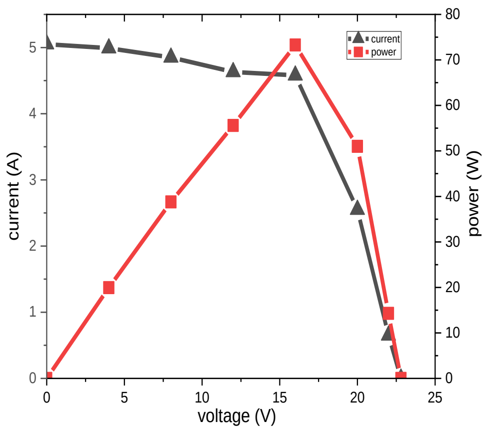
Figures 3 (a-d) give the plot of the I–V and P–V characteristic curves of the PV module. Figure 3(d) represented the 3-day average value plots and used for the sizing of the unit system. The open-circuit voltage and short-circuit current were measured as 22.53 V and 4.90 A respectively.

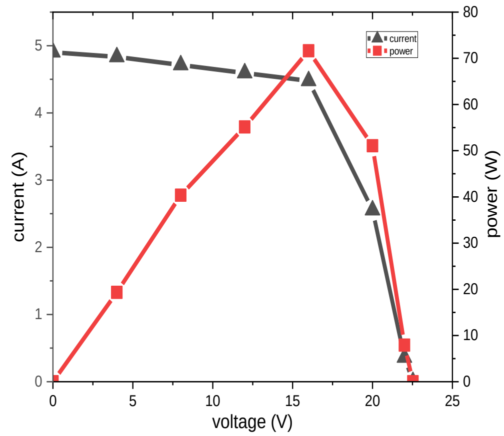


(a)



(b)





(c) (d)

Figure 3: I-V and P-V Characteristics Curves (a) Day 1 (b) Day 2 (c) Day 3 (d) Average

The I–V and P–V curves clearly show the module's reduced performance relative to its Standard Test Condition (STC) ratings. While the manufacturer specifies a P_{max} of 100 W at 1000 W/m², the location's reality of decreased irradiance and elevated module temperature have significantly decreased the output levels of the PV module. This obviously emphasizes the importance of characterizing PV modules under realistic site conditions before sizing than solely relying on manufacturers STC values.

Table 4: Maximum Power, Fill Factor and Module Efficiency over 3 days Experimental Period

Day	P_{max} (W)	FF (%)	η_m (%)
Day 1	71.52	65.27	16.65
Day 2	70.08	65.61	16.42
Day 3	73.28	63.64	17.56
Average values	**71.63**	**64.84**	**16.87**

From Table 4, the highest maximum power was found to be 73.28 W recorded on the third day of the experiment however, with the lowest fill factor. This is expected as light intensity (irradiance) increases, the modules generate more power such that the increased short current (I_{sc}= 5.05A) increases cell series resistance losses (I^2R) leading to a decreased in fill factor. The efficiency of the module ranges from 16.65-17.56% over the 3-day experimental period. These values are consistent with typical performance ranges for monocrystalline modules operating under non-ideal environmental conditions.

Table 5: Calculated Values from the PV System Performance Analysis

Parameter	Calculated value
$P_{inst}(t)$	1.518 Kw
η_m	16.87%
$\eta_{syst}(t)$	13.49%
E_{yearly}	13,297,680 Wh/year
S_{yearly}	98,521,600 Wh/year
C.U. F	58.38

Sizing Results for the Solar PV System

Tables 6 presents the calculated values of parameter required for PV array, Battery storage, charge controller and inverter sizing for the office unit.

Table 6: Calculated Values of the Solar PV Array, Battery Storage, Charge Controller and Inverter Sizing Parameters

Solar PV Array		Battery Storage		Charge Controller & inverter	
Parameter	**Calculated value**	**Parameter**	**Calculated value**	**parameter**	**Calculated value**
E	9.78 kWh/day	E_{safe}	30.88 kWh	I_{rated}	76.44 A
E_r	12.23 kWh/day	C	644 Ah	N_{vc}	2 (in parallel)
P_p	1.75 Kw	$B_{parallel}$	3	$P_{rated\ AC}$	3.272 kW
$N_{parallel}$	13	B_{series}	1	I_C	4 kW
N_{series}	2	B_{total}	3		
N_{total}	26				

From the Tables 6, the total daily energy demand (9.78 kWh/day) of the office unit is increased to 12.23 kWh/day after accounting for system inefficiencies. Based on the average sunlight hours in Yola, the required peak array power is calculated as 1.75 kW. To meet this requirement, 2 modules series connections and 13 parallel strings making a total of 26 PV modules are needed.

To ensure three days of autonomy, the safe energy storage requirement was calculated to be 30.88 kWh. A parallel connection of three 48-V, 300-Ah Lithium Iron Phosphate battery with a total storage capacity of 644 Ah is needed. The maximum expected current from the PV array resulted in a required controller rating of 76.44 A. Consequently, two 60-A charge controllers connected in parallel were selected. The total AC load rating of 3.272 kW required an inverter of 4 kW, providing adequate headroom for start-up surges and load variability.

Economic Assessment

The cost analysis of the proposed solar PV system was analyzed and presented in Table 7.

Table 7: Cost Analysis of the Proposed Solar PV System

Item	Unit price (₦)	Quantity	value (₦)
Solar PV array cost	37,000	26	962,000
Voltage regulator cost	433,986	2	867,972
Battery cost	2,149,200	3	6,447,600
Inverter cost	480,000	1	480,000
Installation cost			96,200
Initial Investment cost			8,853,772
Operation & maintenance cost over 25 years			947,164.78
Fuel cost			
LCOE			0.00
			29.48/kWh

The estimated initial investment cost of the complete PV system is ₦8,853,772, covering the PV modules, battery bank, inverter, charge controllers, and installation. Operation and maintenance over a 25-year lifespan added ₦ 947,164.78 while fuel costs remained zero for the free solar energy. Using these values, the Levelized Cost of Electricity (LCOE) for the system was computed to be ₦ 29.48/kWh. This value is far below the lowest official tariff charged by electricity companies in the Yola, Adamawa state making the proposed PV system not only technically viable but also economically competitive for long-term energy supply within the university environment. The financial performance suggests that, despite higher upfront costs, a properly sized solar PV system offers substantial savings and reliability over its lifetime.

CONCLUSION

The experimental results demonstrate how environmental conditions—particularly irradiance and temperature directly impact PV module performance. The significant deviation between manufacturer-rated and measured values highlights the necessity of assessing real-world module behavior when designing off-grid systems. If STC values alone had been used, the system might have been undersized, leading to inadequate energy supply. The sizing analysis shows that the largest cost components of the system are the battery storage unit and PV modules. Battery selection is critical because it determines system reliability during periods of low solar availability. The chosen lithium iron phosphate batteries provide high cycle life and deep-discharge capability, making them suitable for the local climatic conditions. The economic comparison indicates that solar PV offers a cost-effective alternative to grid electricity for the studied office unit. The LCOE aligns well with current energy market trends, further supporting the adoption of solar PV solutions in locations with high solar resource availability such as Yola.

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