Techno-Economic and Environmental Assessment of a Solar PV-Based Microgrid for Residential Electrification in Gwange I, Maiduguri Using HOMER Pro

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Abstract

The Nigerian power sector continues to struggle with outdated infrastructure, security related disruption, climate change disruptions, and unstable grid supply. In densely populated areas like Gwange I Ward, Maiduguri, centralized electricity systems remain inadequate, forcing residents to depend on costly diesel and petrol generators. This study aims to address this issue by optimizing a solar photovoltaic (PV)–battery energy storage system (BESS) microgrid. The system for Gwange I was designed and optimized using HOMER Pro v3.14, integrating load estimation, solar resource analysis, component sizing, technical performance and economic analysis into the methodological framework. Simulation results indicate that the proposed configuration comprising a 1,085 kW PV array and 1,172 kWh of usable battery storage achieves renewable penetration above 660% and delivers an annual generation of approximately 1.95 GWh. The system's competitiveness against diesel alternatives is confirmed by economic analysis, with a levelized cost of energy (LCOE) of ₦28.68/kWh and a payback period of 2.3 years. The study also highlights the importance of thermal effects on system performance, revealing a 2.7% drop in annual PV output due to temperature increase. Environmentally, noise and air pollution are reduced, and annual CO_2 emissions are reduced by over 1,300 metric tonnes. The study confirms that decentralized solar microgrids with resilience-focused design offer a sustainable, reliable route to urban electrification in weak and climate-sensitive contexts, thus directing policy for microgrid deployment and integration of thermal management.

Keywords: *Solar PV microgrid, battery energy storage, techno-economic optimization, Homer Pro software.*

1.0 Introduction

Nigeria's power sector continues to underperform despite decades of reform, with an installed generation capacity of 13,625 MW but only about 4,854 MW reliably available in 2024 [1]. Structural challenges including aging transmission lines, inadequate gas supply, poor maintenance, and underinvestment have undermined the system, causing annual economic losses estimated at over ₦1.5 trillion [2, 3]. As a result, small-scale diesel and petrol generators have become the viable solution, now supplying approximately 44% of household electricity at an annual fuel cost of US $14 billion [4]. Beyond high costs, this reliance aggravates urban air pollution, noise, and greenhouse gas emissions, undermining Nigeria's energy transition targets.

The northeastern region of Nigeria presents unique energy security challenges, where insecurity and climate vulnerability converge. Armed insurgents have repeatedly targeted high-voltage transmission infrastructure, notably the 330 kV Damaturu–Maiduguri line, cutting off Borno State's capital from the national grid on multiple occasions since 2020 [5, 6]. These deliberate disruptions underscore the fragility of centralized grid systems in conflict-affected areas. In response, the Federal Government commissioned a 50 MW emergency gas-fired power plant in Maiduguri in March 2023 under the administration of President Muhammadu Buhari [7]. While politically significant, the plant was initially operated in simple-cycle diesel mode at about 32 MW and later shut down pending liquefied natural gas (LNG) supply infrastructure. By mid-2023, only about 12 MW was being dispatched to Yola Electricity Distribution Company, leaving Maiduguri's supply unreliable and inadequate [8, 9]. This outcome highlights the limitations of short-term fossil fuel interventions for achieving sustainable energy security. Local communities in Maiduguri continue to bear the brunt of these structural failures. In 2024, severe flooding submerged multiple low-lying substations and distribution transformers, with Gwange I Ward one of the city's poorest and most densely populated neighborhoods among the worst hit. Over 5,000 households were affected, and electricity supply was completely disrupted for weeks [10]. Such events illustrate how natural disasters now interact with insecurity to exacerbate systemic energy poverty, pushing already vulnerable communities deeper into crisis.

Despite these challenges, Maiduguri possesses significant renewable energy potential. The city receives an average global horizontal irradiance exceeding 5.5 kWh/m²/day, making solar photovoltaic (PV) technology technically viable throughout the year [11]. Evidence from techno-economic studies across Nigeria demonstrates

that solar PV–battery energy storage systems (PV–BESS) can outperform diesel generation when evaluated using Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), especially in rural and peri-urban contexts [12]. However, little attention has been paid to applying such systems in conflict- and flood-prone urban areas like Gwange I Ward, where both environmental shocks and insecurity threaten conventional power infrastructure.

By designing and simulating a context-specific PV-based microgrid for Gwange I Ward using HOMER Pro, this study fills this knowledge gap. The study assesses technical performance, economic feasibility, and environmental impacts in a local setting by combining system design parameters with an energy audit of household demand. Resilience-focused elements like sectionalized distribution, flood-tolerant system placement, and modular PV siting are all included in the suggested design. By doing this, it offers one of the earliest models of renewable energy that is specifically designed for an urban Nigerian community that is simultaneously at risk from insurgency and climate change.

2.0 Materials and Methods

In this study, a solar PV–Battery Energy Storage System (BESS) microgrid for Gwange I Ward, Maiduguri, Nigeria, was designed and optimized using HOMER Pro v3.14. Economic analysis, component sizing, load estimation, technical performance evaluation, and solar resource analysis are all integrated into the methodological framework.

2.1 Study Area

The study area, Mukadam Usman Street in Gwange I Ward, Borno State, Nigeria, is chosen due to its vulnerability to energy disruptions due to climate change flooding and conflict-related sabotage, guiding the load modeling and demand profiling of HOMER Pro simulations.

2.2 Load Profile

A bottom-up audit of residential appliances in Mukadam Usman Street in Gwange I Ward of Maiduguri Metropolitan Council was used to estimate the demand for electricity, taking into account factors like device ownership, rated power, and usage hours. With a peak of 335 kW and an overall load of 805 kWh/day, the data is consistent with demand patterns found in comparable Nigerian case studies [13].

Table 1: Estimated daily electrical load profile for Mukadam Usman Street of Gwange I Ward

Appliance	Avg. Units per Household	Power Rating (W)	Daily Usage (hrs)	Energy per HH (kWh/day)	Total for 40 HH (kWh/day)
LED Bulbs (8W)	5	8	4	0.16	6.40
Standing Fan	1	70	6	0.42	16.8
Ceiling Fan	1	60	5	0.30	12.0
TV (32" LED)	1	75	2.5	0.19	7.50
Decoder	1	15	3	0.05	1.80
Phone Charging (2x)	2	5	2	0.02	0.80
	1	10	2	0.02	0.80
Radio	0.5	100	5	0.25	10.0
Refrigerator (Small)	0.5	1000	0.2	0.10	4.0
	1	50	2	0.01	4.0
Electric Iron (Occasional)	0.1	750	0.2	0.02	0.60
Laptop				**2.3**	
Water Pump (shared)					**92**
					805
Total per Household					
Total for 40 Household					
Total for 350 Household					

The energy audit on 40 homes in Mukadam Usman Street, Gwange I, Maiduguri as shown in Table 1 revealed that the average household uses 2.3 kWh per day, with a daily community demand of 92 kWh. High temperatures, fans, lighting, refrigeration, and entertainment equipment are major energy consumers. The study projected the

entire load for 350 community households, estimating a daily energy requirement of 805 kWh/day. A solar PV-based microgrid was simulated using HOMER Pro. Due to practical limitations, only 40 households were surveyed, but the data provides a representative snapshot of residential energy use. Thus, the 40-household sample was deemed sufficient for accurate modeling and projection.

2.3 Solar Resource Assessment

Solar radiation data were obtained from Nigerian Meteorological Agency [14] and validated with NASA-POWER. Maiduguri has an average daily global horizontal irradiance (GHI) of 5.5–6.5 kWh/m²/day, with seasonal variation between dry and rainy months (Figure 1).
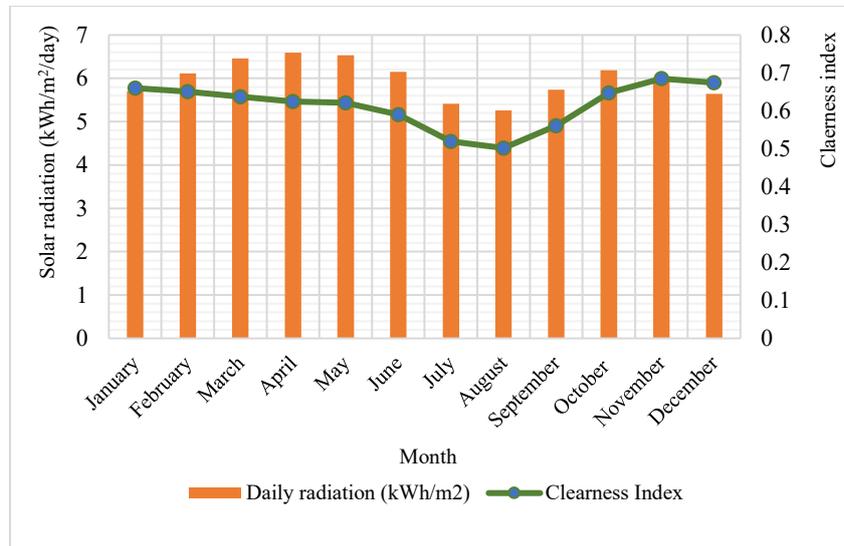

Figure 1: Average monthly solar irradiation for Maiduguri (kWh/m²/day)

2.4 System Component Specification and Cost

The HOMER software accurately simulates a solar system by specifying photovoltaic modules, battery storage, and power converters, along with their corresponding cost parameters. The analysis uses current exchange rates and an assumed 10% annual interest rate, and cost information from a reliable online vendor [15].

Table 2: System specification and cost

Component	Model	Size	Capital cost (₦)	Replacement cost (₦)	O & M cost (₦)	Lifetime
PV module	Canadian Solar CS6U-340M monocrystalline flat plate	340 W per panel	157,500	157,500	50,000	25 years
Battery	Lead-acid (generic)	1kWh	180,000	180,000	80,000	25 years
Inverter	KEHUA France KF-BCS 500K-B	500kW	72,000,000	54,000,000	1,000,000	25 years

2.5 Component Sizing

Component capacities were determined using widely adopted formulations [15]:

1. PV Array Sizing

$$Ppv = \frac{E_{load}}{H \times \eta pv} \tag{1}$$

Where Ppv the required PV capacity (kW) is, E_{load} is the average daily electrical load in (kWh/day), H is average solar irradiation on tilted surface (kwh/m²/day) and ηpv is the PV module efficiency (decimal)

2. Battery Storage Capacity (BESS)

$$C_{BESS} = \frac{E_{load} \times N_{days}}{DOD \times \eta_{BESS}} \tag{2}$$

C_{BESS} Is the required battery capacity (kWh), E_{load} is the average daily electrical load in (kWh/day), N_{days} is the days of autonomy (days), DOD is the maximum depth of discharge (decimal) and η_{BESS} is the round trip battery efficiency (decimal)

3. Inverter Capacity

$$P_{inv} \geq 1.2 \times P_{peak} \tag{3}$$

Where P_{inv} is the inverter capacity in kW, P_{peak} is peak system load demand {kW} and factor 1.2 ensures oversizing for reliability.

2.6 Simulation with HOMER Pro

The solar-battery system for Gwange 1 Ward, Maiduguri was designed and optimized using HOMER Pro as shown in figure 2, a standard software for renewable energy assessment. The system includes Canadian Solar MaxPower CS6U-340M PV modules, an inverter, and a battery storage unit. Performance was simulated hourly, and sensitivity analysis was conducted to evaluate techno-economic resilience under climatic and economic variability.
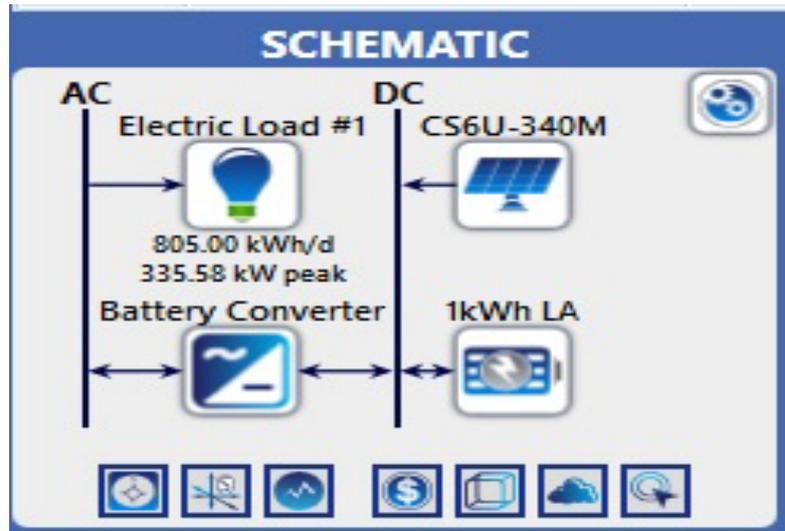

Figure 2: Architecture of the simulated PV-based microgrid system in HOMER Pro (Canadian Solar MaxPower CS6U-340M, inverter, and battery).

2.6.1 Technical Performance Indicators

Technical reliability was quantified using **HOMER Pro** indicators [17]:

1. **Electrical Production (EP)** is the total annual electrical energy generated by the system. Mathematically, it can be represented as Equation (3):

$$EP = \sum_{ij}^{n,1} E_{ij} \tag{3}$$

Where integers i to n represents the system components, j represent the period which is always treated as one year, and Ei;j represents the energy produced by the components in a year.

2. **Excess Electrical Energy (EEE)** is the portion of the load that cannot be met due to inadequate generation [18]. and it is mathematically expressed as Equation (4):

$$\text{Excess Electricity} = \text{Total energy produced} - \text{Total load} \tag{4}$$

3. **Unmet Electrical Load (UEL)** is the surplus electrical energy produced by the system that remains unused by the load or batteries [19]. Mathematically, it can be represented as Equation (5):

$$\text{Unmet load} = \text{Total load} - \text{Total load met} \tag{5}$$

2.6.2 Economic Performance Indicators

Economic feasibility was assessed through Net Present Cost (NPC)**,** Levelized Cost of Energy (LCOE)**,** and Payback Periods**,** consistent with [20] and HOMER financial models [21]:

1. **Net Present Cost (NPC)**: It encompasses various expenses, including capital cost, replacement cost, salvage value, and operation and maintenance costs. The NPC can be calculated using Equation (6) [20].

$$\text{NPC} = \frac{\text{TAC}}{\text{CRF}} \tag{6}$$

Where CRF is the capital recovery factor and can be further defined as follows

$$\text{CRF} = \frac{i(1+i)1^n}{i(1+i)1^n - 1} \tag{7}$$

Where TAC is the total i is the total real inflation rate n is the system lifespan

2. **Levelized Cost of Energy (LCOE)**: is a metric indicating the ratio of the annualized lifecycle cost to the electrical energy used to power the load [22]. It can be determined using Equation (6).

$$LCOE = \frac{TAC - C_{boiler}H_{serve}}{E_{serve}} \qquad (6)$$

3. **Payback Periods**: the time it takes for an investment to recover its initial cost from the net cash flow it generated. It calculated as the investment divided by the annual net cash inflow [23].

$$Payback\ Period = \frac{initial\ investment\ (Cost\ of\ Project)}{Annual\ Net\ Cash\ Inflow} \qquad (7)$$

2.6.3 Sensitivity Analysis

The study evaluated the Solar Microgrid PV-BESS configuration's reliability under different operating conditions, focusing on temperature variations. Key performance indicators like total electricity production, load consumption, surplus generation, and unmet demand were compared. The study also examined the system's adaptability to environmental variability and stability under actual thermal conditions, highlighting its ability to balance generation and demand.

3.0 Results and Discussion

3.1 System Component Design and Sizing Using HOMER Pro

A solar PV-based microgrid energy system was designed and simulated using HOMER Pro software, aiming to find the ideal size and arrangement of PV arrays, battery banks, and power electronics.

3.1.1 Photovoltaic (PV) Array Performance

Figure 3 shows the PV power output simulation and solar irradiance profile. With a mean output of 223 kW and a rated capacity of 1,085 kW, the PV system generates 1,951,446 kWh annually. This translates to a 20.5% capacity factor. The system runs 4,361 hours a year and has a maximum instantaneous output of 982 kW. With a high penetration rate of 664%, the PV system supplies a sizable amount of the load demand all year long. With no clipped production and a levelized cost of energy (LCOE) of ₦23.1/kWh, solar energy is being used as efficiently as possible.

Quantity	Value	Units
Rated Capacity	1,085	kW
Mean Output	223	kW
Mean Output	5,346	kWh/d
Capacity Factor	20.5	%
Total Production	1,951,446	kWh/yr

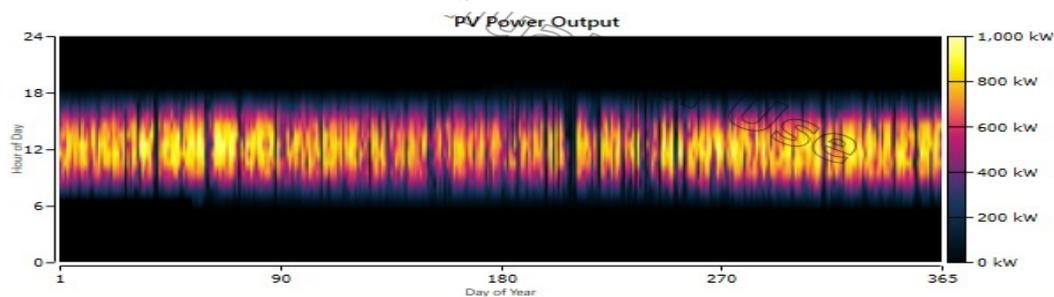| Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	982	kW
PV Penetration	664	%
Hours of Operation	4,361	hrs/yr
Levelized Cost	23.1	₦/kWh
Clipped production	0	kWh

Figure 3: PV power output and performance metrics

3.1.2 Battery Storage System

Figure 4 summarizes battery performance metrics and sizing. At a bus voltage of 48 V, the final configuration comprises 1,952 batteries organized in 488 strings of four batteries each. With a usable nominal capacity of 1,172 kWh, the system offers a nominal capacity of 1,954 kWh. During times when PV output is low, the system's approximately 34.9-hour autonomy supports energy availability. Over the course of the year, the battery bank receives 175,052 kWh of energy inflow and 140,394 kWh of energy outflow, resulting in 35,052 kWh of storage losses. Based on a total lifetime throughput of 1,561,600 kWh, a battery's expected lifespan is 9.95 years. For optimal battery health and longevity, the state charge (SOC) stays primarily above 52%.
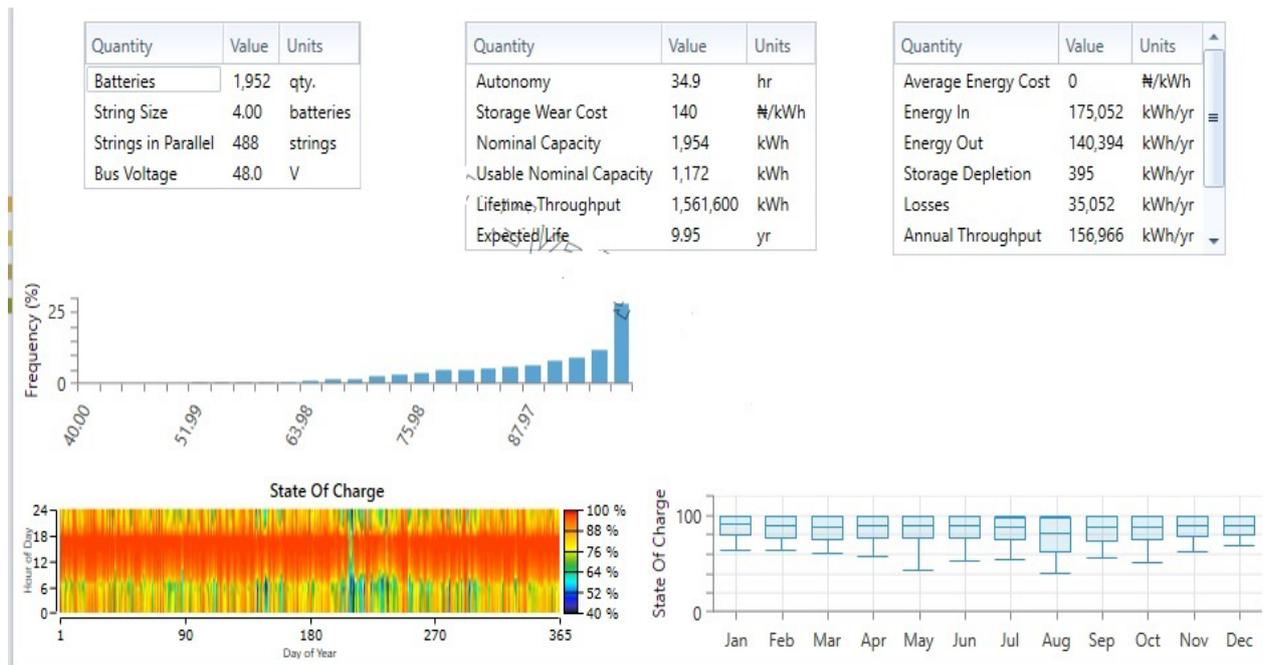
Quantity	Value	Units
Batteries	1,952	qty.
String Size	4.00	batteries
Strings in Parallel	488	strings
Bus Voltage	48.0	V

Quantity	Value	Units
Autonomy	34.9	hr
Storage Wear Cost	140	₦/kWh
Nominal Capacity	1,954	kWh
Usable Nominal Capacity	1,172	kWh
Lifetime Throughput	1,561,600	kWh
Expected Life	9.95	yr

Quantity	Value	Units
Average Energy Cost	0	₦/kWh
Energy In	175,052	kWh/yr
Energy Out	140,394	kWh/yr
Storage Depletion	395	kWh/yr
Losses	35,052	kWh/yr
Annual Throughput	156,966	kWh/yr

Figure 4: Battery bank configuration, state of charge frequency, time series, and monthly distribution

3.1.3 Inverter and Rectifier System

Converting DC output from PV arrays and batteries into AC for load consumption is a crucial function of the inverter/rectifier system. The inverter is rated at 353 kW and produces an average output of 33.5 kW, which translates to a capacity factor of 9.50%, as seen in Figure 5. With only 2,966 kWh of losses annually, the system manages an energy input of 296,597 kWh and produces 293,631 kWh, demonstrating high conversion efficiency. The inverter's 7,596 hours of operation annually further attests to its dependability in ongoing use. The rectifier component's zero output and capacity values, which indicate unidirectional DC-to-AC conversion use, show that it is not used in this system configuration.

Quantity	Inverter	Rectifier	Units
Capacity	353	353	kW
Mean Output	33.5	0	kW
Minimum Output	0	0	kW
Maximum Output	335	0	kW
Capacity Factor	9.50	0	%

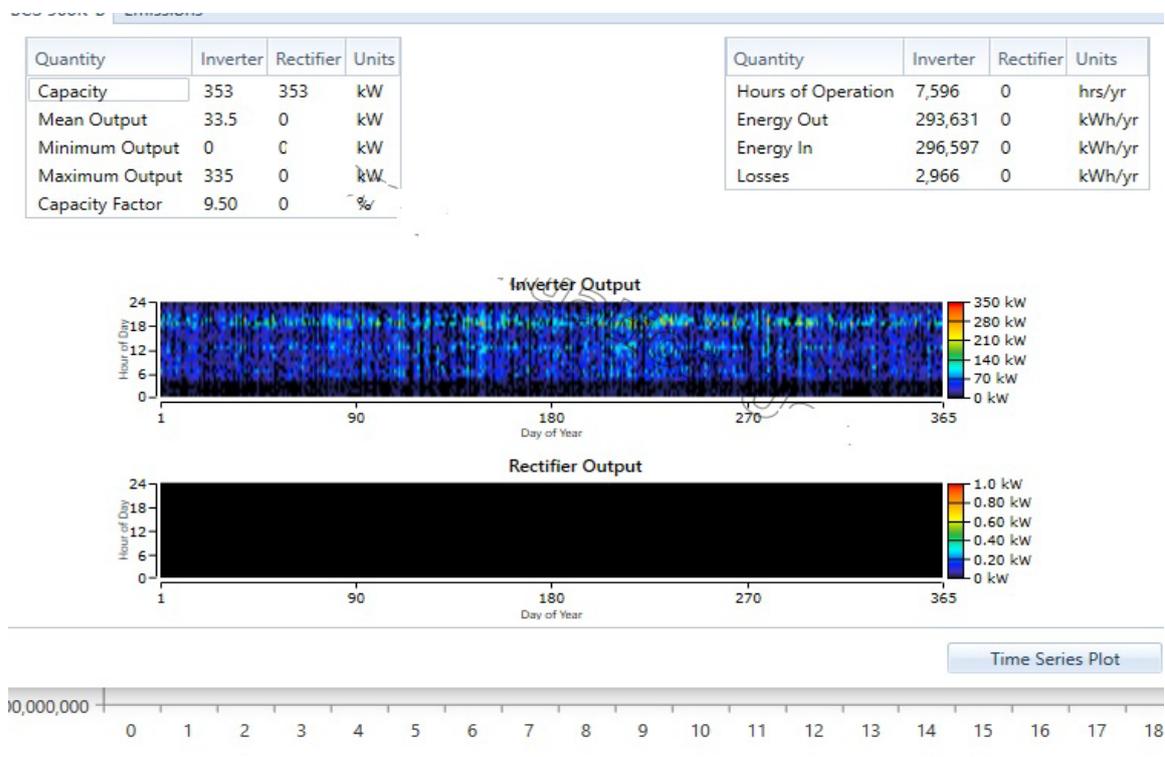| Quantity	Inverter	Rectifier	Units
Hours of Operation	7,596	0	hrs/yr
Energy Out	293,631	0	kWh/yr
Energy In	296,597	0	kWh/yr
Losses	2,966	0	kWh/yr

Figure 5: Inverter and rectifier output and performance metrics

The results of the simulation and component sizing verify that the solar PV-based microgrid system that was designed provides a dependable and economical way to meet the energy demands noted in the audit. Minimal losses, strong energy autonomy, and sustainable operation are ensured by combining a high-efficiency inverter, a

well-sized PV array, and enough battery storage. These results confirm that the suggested system design is both feasible and reliable.

3.2 Technical Results analysis

The system's performance was assessed across key indicators including renewable energy penetration, excess electrical production, and unmet load. Monthly variations in these parameters were analyzed to ensure system reliability, stability, and alignment with design expectations.
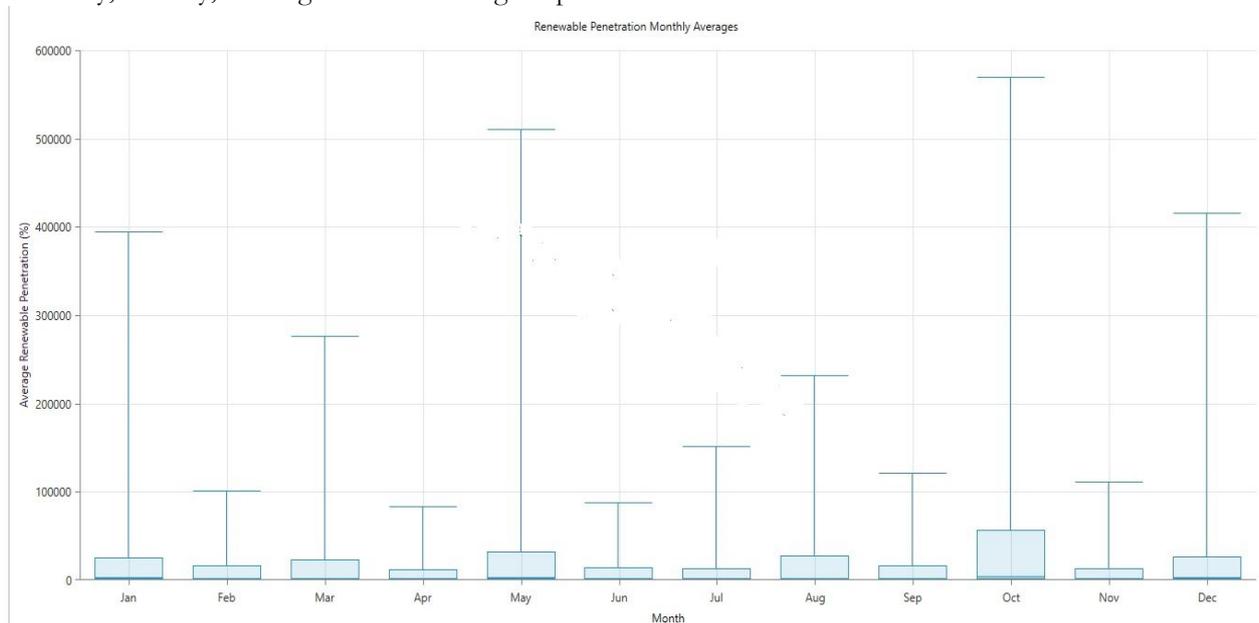

Figure 6: Renewable penetration monthly averages

Figure 6 shows monthly renewable penetration percentages, primarily photovoltaics, covering a significant portion of the electrical load. High penetration in October indicates high output or low demand, indicating an overcapacity design strategy.
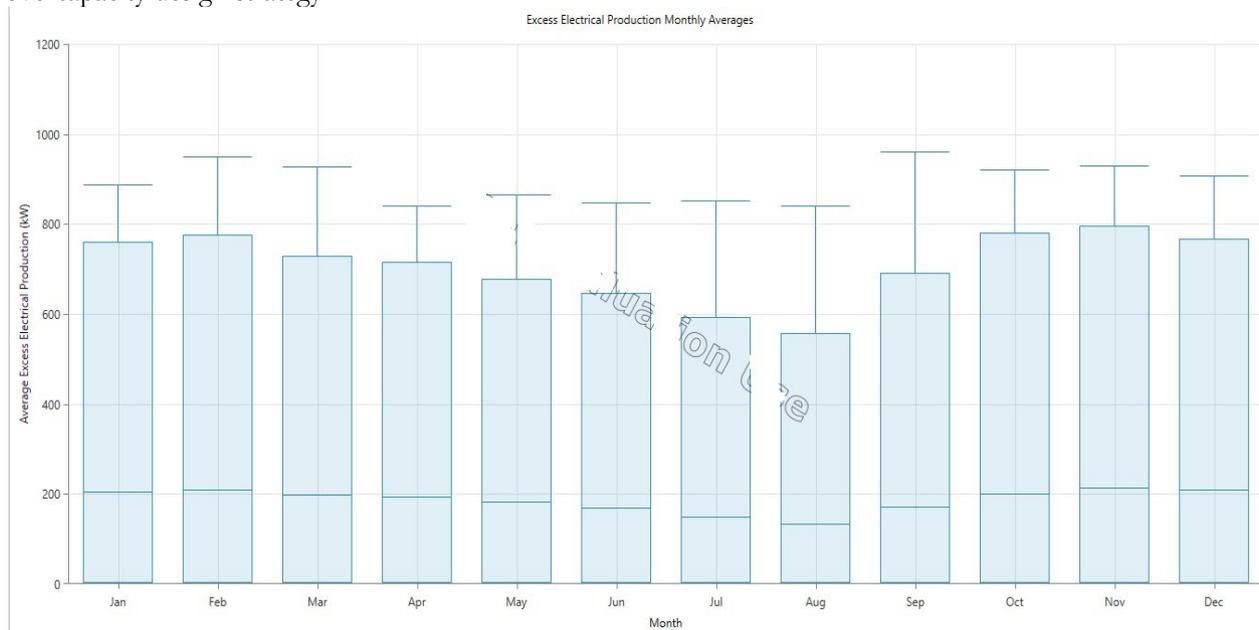

Figure 7: Excess electrical production monthly average

The average amount of excess electricity produced each month is depicted in figure 7; values usually fall between 600 and 800 kW. High PV penetration directly leads to excess generation, which guarantees system resilience. If it isn't diverted to storage or ancillary loads, it also amounts to wasted energy. The comparatively constant excess energy in every month points to an oversized system that prioritizes minimizing unmet loads over maximizing generation-to-demand ratios.
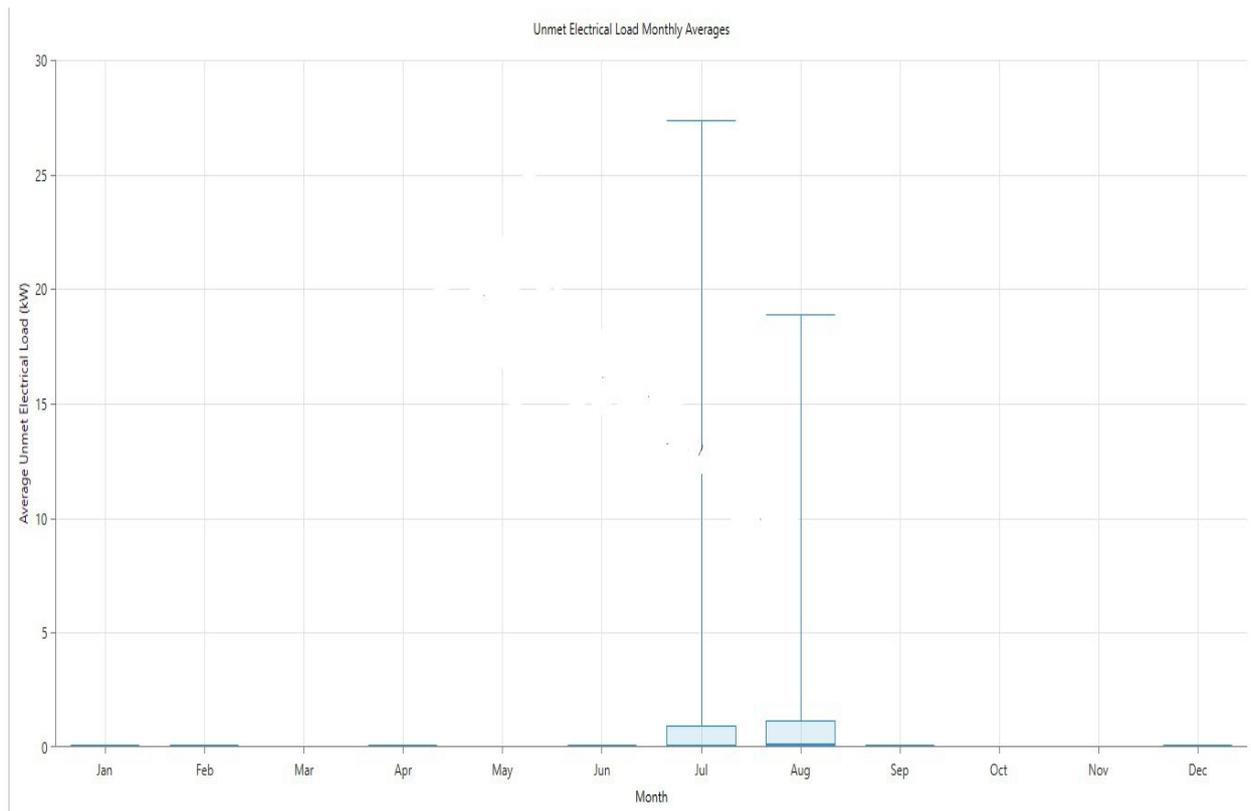
Figure 8: Unmet electrical load monthly averages

The monthly unmet load levels are shown in Figure 8. All other months exhibit little to no unmet load, with the exception of July and August, when there is a slight unmet demand (peaking at about 25 kW in July). With a few minor exceptions that are probably caused by seasonal decreases in solar irradiance or higher consumption, this performance demonstrates that the system can meet demand all year long. These findings confirm that the PV and storage system sizes are sufficient for dependable service delivery.

3.4 Economic Results analysis

A comprehensive economic analysis was carried out using HOMER Pro to determine the life-cycle cost implications of the proposed system. This included an evaluation of capital, replacement, and operation & maintenance (O&M) costs across a 25-year project horizon.
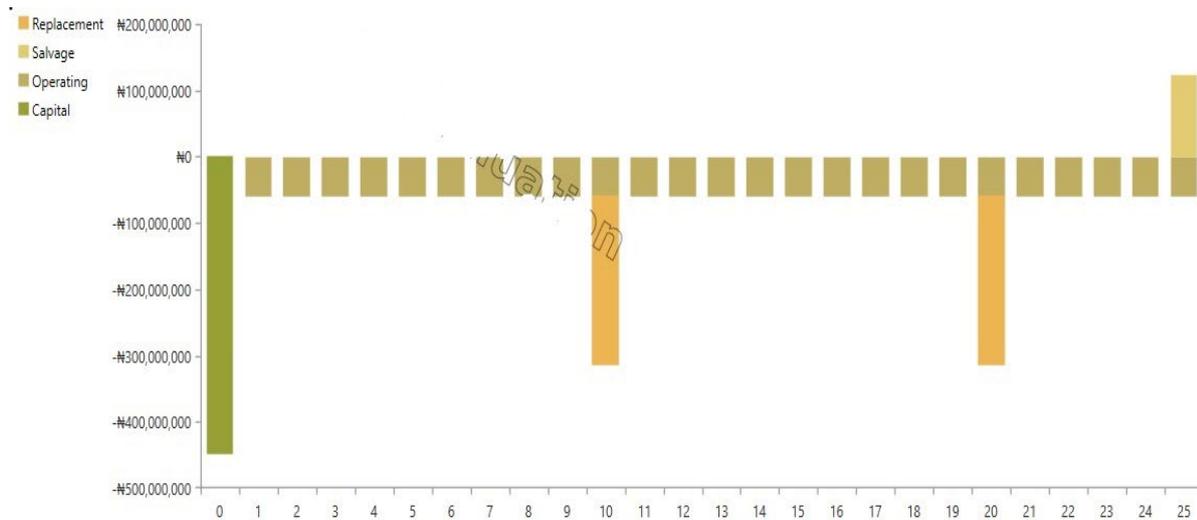

Figure 9: Projected cash flow over 25-year system lifetime

The anticipated annual cash flow of the solar PV-based microgrid is displayed in Figure 9. Year 0 sees the initial capital investment (about ₦449 million). While major replacement costs are planned for Years 10 and 20, which correspond to the anticipated lifecycle of the battery bank and inverter units, annual O&M expenses stay

comparatively constant. The remaining useful value of system components at the end of the project life is represented by the salvage value, which is recovered in Year 25.
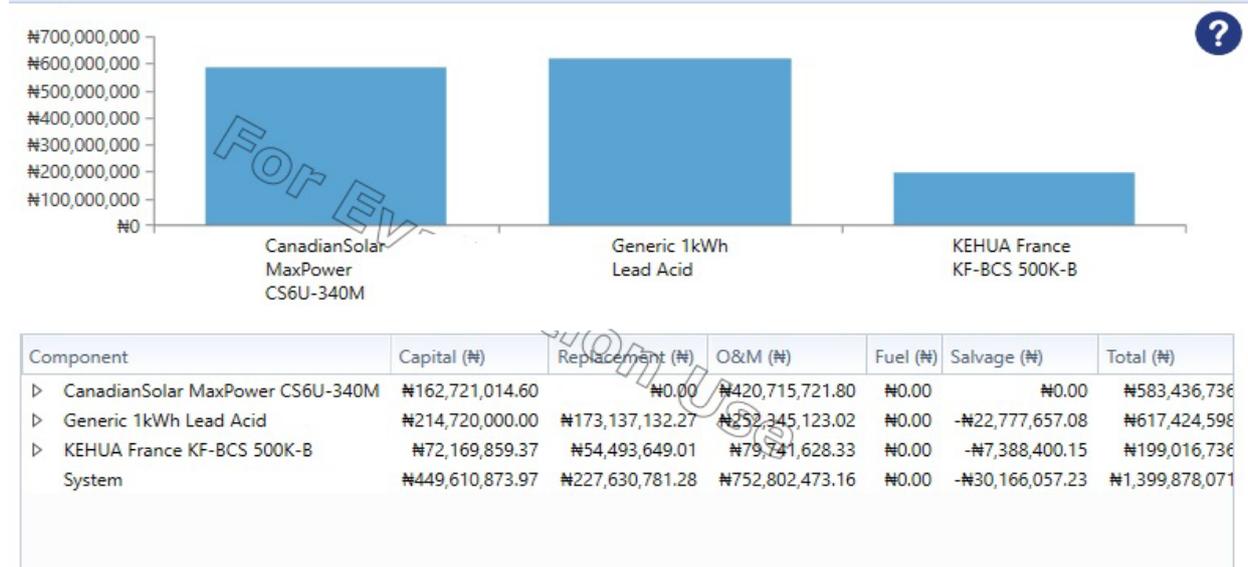

Figure 10: Component-wise cost breakdown

Component	Capital (₦)	Replacement (₦)	O&M (₦)	Fuel (₦)	Salvage (₦)	Total (₦)
▷ CanadianSolar MaxPower CS6U-340M	₦162,721,014.60	₦0.00	₦420,715,721.80	₦0.00	₦0.00	₦583,436,736
▷ Generic 1kWh Lead Acid	₦214,720,000.00	₦173,137,132.27	₦252,345,123.02	₦0.00	-₦22,777,657.08	₦617,424,598
▷ KEHUA France KF-BCS 500K-B	₦72,169,859.37	₦54,493,649.01	₦79,741,628.33	₦0.00	-₦7,388,400.15	₦199,016,736
System	₦449,610,873.97	₦227,630,781.28	₦752,802,473.16	₦0.00	-₦30,166,057.23	₦1,399,878,071

Each system component's economic breakdown is shown in Figure 10: inverter (KEHUA France KF-BCS 500K-B), battery storage (Generic 1kWh Lead Acid), and PV modules (CanadianSolar MaxPower CS6U-340M). After deducting salvage values, the system's total life-cycle cost comes to ₦1,399,878,071.18, which includes capital, replacement, and O&M expenses. The biggest contributors to capital and replacement costs are the batteries and PV modules, while inverters eventually result in significant O&M costs. According to the analysis, the system's low unmet load, high penetration of renewable energy sources, and predictable maintenance profile make it economically justified over the course of its operational life, despite its high initial cost.

3.4.1 Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) represents the average cost per kilowatt-hour (kWh) of electricity generated over the entire life cycle of the system. It is calculated as:

$$\text{LCOE} = \frac{\text{Total Life} - \text{Cycle Cost (₦1,399,878,071.18)}}{\text{Total Energy Produced Over 25 Years (₦1,951,446 kWh/year} \times 25 \text{ years}}$$

₦28.68/kWh is significantly lower than current diesel generator costs and even below typical Nigerian grid tariffs, which range from ₦80 to ₦150/kWh. Therefore, the system offers a financially competitive and sustainable alternative energy source.

3.4.2 Simple Payback Period

To evaluate how quickly the initial capital investment can be recovered through savings on energy bills, the simple payback period is calculated. Assuming a local grid electricity tariff of ₦100/kWh and an annual energy production of 1,951,446 kWh/year, the annual savings amount to:

$$\text{Annual Cost Offset} = 1,951,446 \text{ kWh/year} \times \text{₦100/kWh} = \text{₦195,144,600 kWh/year}$$

The initial capital cost of the system is ₦449,610,873.97. Thus, the simple payback period is:

$$\text{Payback Period} = \frac{\text{₦449,610,873.97}}{\text{₦195,144,600kWh/year}} \approx 2.3 \text{ Years}$$

3.5 Environmental Impact Assessment

The adoption of the proposed solar PV-based microgrid system comprising solar photovoltaic (PV) panels, battery energy storage, and supporting inverters yields significant positive environmental outcomes when compared to conventional fossil-fuel-based energy generation.

3.5.1 Lowering Emissions of Greenhouse Gases

The system's significant decrease in greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), is one of its main environmental advantages. With an estimated yearly production of 1,951,446 kWh from PV sources, the system successfully replaces emissions that would otherwise come from fossil fuel-based grid power or diesel

generators. The yearly CO_2 emissions offset can be roughly calculated as follows using an emissions factor of 0.7 kg CO_2 per kWh (typical for diesel generation):

CO_2 Offset = 1,951,446 kWh/year × 0.7 kg CO_2/kWh = 1,366,012 kg CO_2/year (≈ *1,366 metric tonnes of CO_2 avoided annually).*

This amounts to more than 34,000 metric tonnes of CO_2 emissions avoided over the system's 25-year lifespan, significantly aiding in the fight against climate change.

3.5.2 Air and Noise Pollution Mitigation

Since solar PV systems don't burn fossil fuels to generate electricity, they don't release harmful pollutants like sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), which are known to cause respiratory illnesses and environmental degradation. Additionally, because PV and battery systems are silent, they considerably reduce noise pollution, which is a significant benefit, especially in residential, educational, and healthcare settings where conventional generators are disruptive.

3.5.3 Land Use and Resource Considerations

With little effect on nearby ecosystems, the PV modules are usually installed on rooftops or open spaces. Battery systems have a minimal environmental impact when in use, but at the end of their useful lives, they need to be disposed of and recycled properly to avoid contaminating soil and groundwater with lead or other heavy metals. This is addressed by including recyclable lead-acid batteries in the system design and establishing appropriate end-of-life disposal procedures in coordination with accredited recycling companies.

3.6 Sensitivity Results analysis

To determine how variations in the surrounding temperature impact the solar PV system's technical performance, a sensitivity analysis was carried out. Four temperature conditions 26°C, 28°C, 30°C, and 32°C were used in HOMER Pro simulations. These temperatures represent realistic environmental variations in tropical and sub-tropical areas. Annual energy production, excess electricity, and unmet electrical load are among the parameters evaluated.

Comparison of Consumption, Excess Electricity, Production and Unmet Load at 28 °C and 30 °C

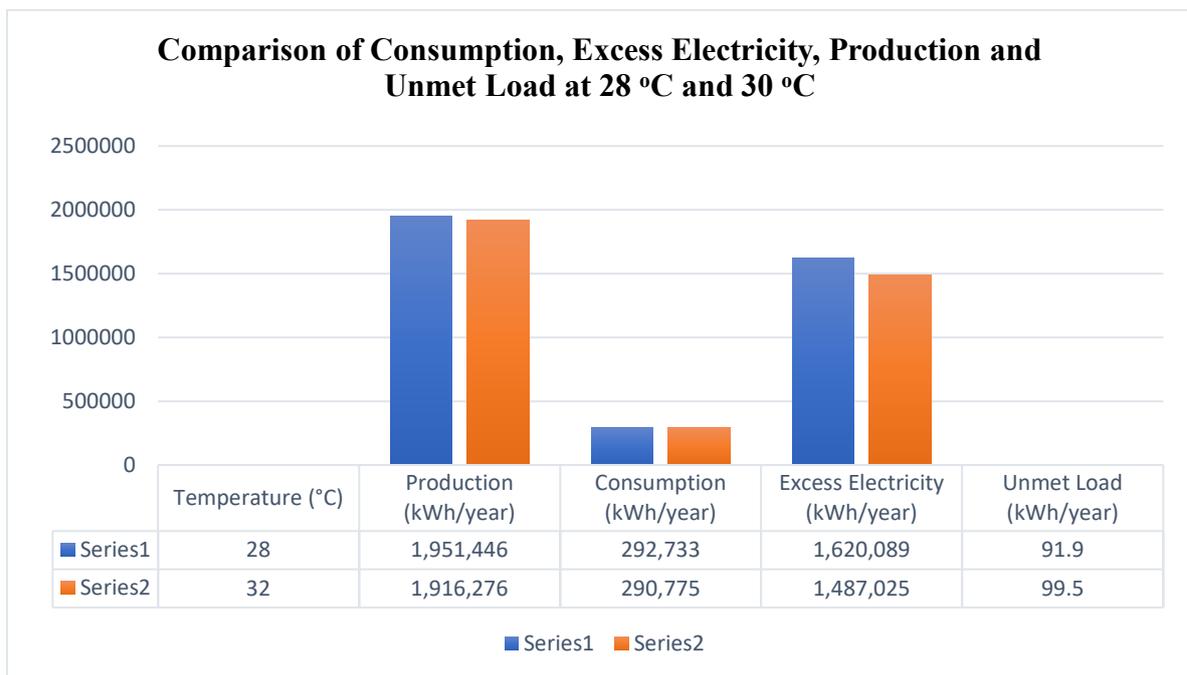|	Temperature (°C)	Production (kWh/year)	Consumption (kWh/year)	Excess Electricity (kWh/year)	Unmet Load (kWh/year)
Series1	28	1,951,446	292,733	1,620,089	91.9
Series2	32	1,916,276	290,775	1,487,025	99.5

Figure 10: Comparison of system production, consumption, excess electricity, and unmet load at 28 °C and 32 °C

The plot highlights the decline in production and excess electricity, alongside a slight increase in unmet load, as ambient temperature rises from 28 °C to 32 °C, while consumption remains nearly constant.

Table 3: Sensitivity of production, consumption, excess electricity, and unmet load to temperature

S/N	Temperature (°C)	Production (kWh/year)	Consumption (kWh/year)	Excess Electricity (kWh/year)	Unmet Load (kWh/year)
1	26	1,969,286	293,712	1,716,621	86.2
2	28	1,951,446	292,733	1,620,089	91.9
3	30	1,933,616	291,754	1,553,557	95.1
4	32	1,916,276	290,775	1,487,025	99.5

Figure 10 and Table 3 show how system performance is impacted by ambient temperature. The annual production decreased by approximately 2.7% (≈0.45%/°C) from 1,969,286 kWh/year at 26 °C to 1,916,276 kWh/year at 32 °C. While unmet load increased marginally from 86.2 to 99.5 kWh/year, excess electricity also decreased from 1,716,621 kWh/year to 1,487,025 kWh/year; consumption stayed relatively stable. These changes are illustrated by the comparative plot between 28 and 32 °C, which shows decreased production and excess energy with a slight rise in unmet demand

3.7 Discussion of Key Findings

This section interprets the results of the technical, economic, and environmental assessments of the proposed hybrid solar PV microgrid for Mukadam Usman Street, Gwange I, Maiduguri. The findings are evaluated in the local context and compared with recent studies.

3.7.1 Technical Feasibility and System Reliability

With a daily load of 805 kWh and a low unmet demand (<0.03%), the suggested microgrid exhibits strong technical viability. High renewable penetration (~664%) is ensured by the 1,085 kW PV array, which produces roughly 1.95 GWh annually. Resilience is improved by such overcapacity, especially in the face of seasonal demand fluctuations or climatic variability. Similar research supports this strategy: [24] underlined the importance of high renewable penetration in guaranteeing supply security in conflict-prone areas, while [25] noted that expanding solar microgrids enhances reliability in Nigeria.

3.7.2 Component Sizing and Energy Autonomy

The 353 kW inverter achieves 98.9% efficiency, and the battery bank (1,952 units, 1,172 kWh usable capacity) offers 34.9 hours of autonomy. When solar output is low, this configuration maintains loads and reduces conversion losses. According to [26], this design surpasses the minimum storage autonomy of 30 hours and the stability requirement of >90% inverter efficiency for Sahelian microgrids.

3.7.3 Economic Performance

The system's Levelized Cost of Energy (LCOE) of ₦28.68/kWh is competitive with the ₦25–₦30/kWh range for community-scale PV systems in Nigeria [27] reported. Initial capital and recurring battery and inverter replacements account for the majority of the 1.4 billion naira lifecycle costs. The long battery lifespan (~9.95 years), efficient sizing, and minimal unmet load all contribute to the favorable LCOE, which maximizes economic viability.

3.7.4 Environmental Impact

Over the course of its lifetime, the system avoids SO_x, NO_x, and particulate emissions from diesel generators while offsetting approximately 1,366 metric tonnes of CO_2 annually, or over 34,000 tonnes. These outcomes are consistent with [28] research showing that hybrid solar systems in the Lake Chad Basin cut emissions by 90–95% when compared to diesel alternatives. The quality of life in residential areas is improved by silent operation, which further lowers urban noise pollution.

3.8 Sensitivity to Temperature

According to the sensitivity analysis, PV output drops as the temperature rises, falling by roughly 2.7% (≈0.45%/°C) from 1,969,286 kWh/year at 26 °C to 1,916,276 kWh/year at 32 °C. As a result, excess electricity decreases and unmet load rises marginally from 86.2 to 99.5 kWh/year; consumption stays relatively stable. This effect is demonstrated by a comparative plot (Figure 4.8.1) between 28 °C and 32 °C. These results are consistent with PV temperature coefficients of -0.4 to -0.5%/°C that have been reported [29]. Similar findings are supported by local research: [30] demonstrated that cooling PV modules in Maiduguri increased efficiency by 2–3%, [31]

reported voltage losses in Jos above 25 °C, and [32] reported output reductions in Kaduna. Together, these results confirm that temperature significantly affects PV reliability in hot climates

4.0 Conclusion

This study demonstrates that for residential electrification in Gwange I, Maiduguri, a hybrid solar PV–battery microgrid provides a technically sound, financially viable, and ecologically friendly option. The system achieves a favorable LCOE of ₦28.68/kWh, provides over 34 hours of storage autonomy, and meets daily demand with very little unmet load. Additionally, it offsets over 1,300 tonnes of CO_2 per year, indicating a substantial positive impact on the climate. Sensitivity analysis demonstrates that overall system resilience is maintained under local climatic conditions, even though higher temperatures marginally reduce PV output. Governments should promote community-scale PV-battery microgrids through subsidies, loans, and regulatory frameworks. Future designs should incorporate passive cooling and module mounting, and expand to other northern Nigerian communities.

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