GRID-SOLAR HYBRID POWER SYSTEM FOR MAIDUGURI REGION, NIGERIA: A THEORETICAL DESIGN AND SIMULATION USING HOMER®

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ABSTRACT

Regular power outages in Maiduguri, Nigeria, resulting from vandalism and old transmission infrastructure, undermine the electricity supply to critical institution. The paper presents a design and techno-economic analysis of a grid–solar photovoltaic (PV) hybrid energy system for the Senate Complex, University of Maiduguri. Based on site-specific solar resource, actual load profiles, and HOMER Pro simulations, the system was sized with 791 PV modules (700 Wp each), a 4570.71 Ah battery bank and a 248kW inverter for an annual demand of 528.74 MWh. Technical and economic parameters involved in the analysis were unmet load, over generation, annual purchase from grid, NPC (net present cost), as well as LCOE (levelized cost of energy) over 25 years lifespan of the system. The hybrid system had an NPC of ₦569.89 M, and an LCOE of ₦203/kWh in addition to reduction of unmet load to almost negligible as against grid only and PV-only. Average running cost per year was ₦29.17 million, representing significant cost savings and better supply-reliability. It is shown that PV–grid is both a technically and economically feasible approach to improving energy resilience in volatile and grid-deficient regions. This work provides one of the earliest institution-level techno-economic analyses of hybrid systems in northeast Nigeria and provides a generic model for other energy-poor regions across sub-Saharan Africa.

Keywords: Hybrid Energy Systems, Techno-Economic Assessment, Renewable Energy Integration and HOMER Pro Simulation

1 INTRODUCTION

Electric power availability is one of the most important facilitating requirements for socioeconomic development and also institutional performance. Energy insecurity is further compounded in northeastern Nigeria, particularly Maiduguri – the capital of Borno State where there have been persistent grid failures, as well as generation capacity shortages and repeated attacks on power infrastructure due to insurgent related activity. The 46 episodes of national grid collapse experienced between 2017 and April this year had thrown the country into perennial darkness, with damaging effect on virtually all sectors of Nigerian life; including security operations across many parts of the north-eastern state [1]. In Maiduguri the capital of Borno State, commercial and government activities were seriously crippled due to frequent insurgency attacks on transmission lines leading to an estimated loss tallying over ₦1.17 billion in nine months [2]. These are the challenges that continue to recur, a great reason why there is an immediate rush for decentralized energy solutions built with resilience and context in mind, particularly at critical institutions like universities; hospitals & administrative centers. To this extent, the Federal Government, through its efforts to address the persistent blackout challenges in Maiduguri, initiated the Maiduguri Emergency Power Project (MEPP). The project consisted of a 32 MW gas-fired power plant, later upgraded to a minimum output capacity of at least 50 MW. Although these capacity injections have reduced the frequency of outages, they have not been sufficient to meet the energy demands of critical institutions. In addition, a 12 MW solar PV plant was installed at the University of Maiduguri and its Teaching Hospital under the Energizing Education Programme (EEP). Despite these interventions, the provision of 24-hour electricity supply is still far from being achieved [1, 3, and 4]. Maiduguri lies within a high solar radiation zone, with prevailing seasonal average daily values ranging from about 5.8 kWh/m² (minimum) to over 7.3 kWh/m² annually [6], reaffirming the suitability of solar photovoltaic (PV) systems for off-grid applications in the region [5]. However, the intermittency of standalone PV systems necessitates costly storage solutions to ensure continuous supply, which limits their applicability [7]. Furthermore, the instability of the Yola Electricity Distribution Company (YEDC) grid exacerbates the situation. Feeder reliability remains significantly below 24-hour supply, with service bands typically within 12–16 operating hours per day on lower-priority feeders. In addition, the grid is characterized by frequent outages and unscheduled load shedding, averaging no fewer than two disruptions per hour, which severely affects power supply reliability in Maiduguri [8]. Consequently, systems that rely solely on either the grid or PV are inadequate for mission-critical facilities that require uninterrupted, round-the-clock electricity. A hybrid grid–solar power system combines solar PV as the primary energy source, battery storage to buffer supply fluctuations, and the grid as a reliable backup. This configuration provides enhanced resilience while simultaneously reducing overall costs. The approach not only lowers the operational cost of electricity supply but also improves energy security and contributes to climate change mitigation. For instance, in northern Nigeria, a hybrid PV/Wind/Biogas grid-connected system achieved a reduction of more than 68% in Net Present Cost (NPC) and an 85% decrease in the Levelized Cost of Energy (LCOE) compared to a standalone hydrogen-based system [9]. Similarly, campus-level studies conducted in Kenya demonstrated that hybrid PV/grid systems reduced annual energy costs by nearly 80%, underscoring the significant economic benefits and renewable energy integration potential of hybrid configurations [10]. Increasing amounts of international evidence demonstrate that hybrid renewable energy systems (HRES) will be more efficient and cheaper over their lifetimes. A South African case study of a residential grid-interactive solar PV system presented significant energy-cost savings, as well as demand-side advantages inherent in real tariff structures [11]. Similarly, systematic reviews concluded that PV–battery–grid hybrid systems provide more flexibility, robustness, and cost-effectiveness compared to systems based on a single supply of energy source, especially where grids are poorly developed [12]. West Africa-based modeling in Lagos found that grid-connected PV with storage could help decrease reliance on diesel fuel, save on diesel costs - as well as electricity costs - for institutional loads, and deliver better overall performance than PV alone or grid alone baselines [13]. In Nigeria, all research avenues have been focused on PV–diesel or PV–wind hybrid systems for off-grid or peri-urban customers, and an increasing amount of techno-economic studies vindicates the comparative reliability of hybrid systems over single-source systems [14]. Contrariwise, peer-reviewed papers discussing PV–grid hybridization in post-conflict and reliability-constrained regions seem limited, making the value of the present case study of Maiduguri all the more. In advancing a widening research agenda, the present investigation uses HOMER Pro to simulate and design a PV–grid hybrid system for the University of Maiduguri Senatorial Complex, and to achieve the following objectives: To conduct a detailed energy audit and load assessment of the complex. To theoretically design and simulate a hybrid PV–grid system incorporating local solar and grid performance data using HOMER Pro software. To evaluate the system's technical reliability and economic feasibility compared to grid-only and PV-only alternatives. By integrating institutional energy demand with conflict-region reliability considerations, this study contributes a unique framework for deploying hybrid systems in energy-insecure environments.

2 METHODOLOGY

2.1 Materials Description/Selection

The evaluation of the grid–solar hybrid power system was based on a mix of simulation tools, local climate data, measured energy demand, and verified cost information. HOMER Pro was used to model and optimize performance. Hourly solar irradiance for Maiduguri was obtained from the Nigerian Meteorological Agency, while the load profile was recorded on-site at the University of Maiduguri Senate Complex. Economic inputs such as grid tariffs, equipment prices, and financial parameters were taken from Yola Electricity Distribution Company reports and current market rates. The system design used high-efficiency PV modules, lead-acid batteries, a peak-rated inverter with reserve margin, and grid connection modeled for both stable and unreliable supply.

Table 1. Summary of materials, technical specifications, and data sources

Simulation Tool	HOMER Pro (v3.14); used for hybrid System simulation, optimization, and analysis	HOMER Energy (2020)
Solar Resource Data	Hourly solar irradiance; Maiduguri average 5.5–6.5 kWh/m²/day	Nimet (2021)
Load Data	Hourly demand profile for Senate Complex (lighting, AC, office equipment, elevator)	Field measurements
Economic Parameters	Grid tariff (YEDC), capital costs of PV, batteries, inverter;discount rate 8%, inflation 3%, project life 25 years	YEDC (2022); Market Survey
PV Modules	Canadian Solar CS6U-340M monocrystalline;340 W each; 17.49% efficiency; ₦250,000/kW	Canadian Solar Inc) (2021)
Battery Storage	Lead-acid; total 600 kWh; 88% efficiency; 80% depth of discharge	HOMER Energy (2019)
Inverter/Converter	Capacity for peak load +25% margin; 90% efficiency	S. Electric (2020)
Grid Connection	Continuous and intermittent supply scenarios; 1,500 outages/year; 5 hr mean repair time	(YEDC, 2024)

2.1.2 Description of the Case Study

Maiduguri, the capital of Borno State in northeastern Nigeria (11°49′59.99″ N, 13°08′60.00″ E), is characterized by chronic electricity supply challenges. The University of Maiduguri Senate Complex, funded by the Tertiary Education Trust Fund (TETFund), was selected for this study due to its continuous, high-priority electricity demand. The complex consists of a two-story Senate Building (46 × 44 m²) housing over 500 occupants across 56 offices, including core administrative units, and equipped with energy-intensive facilities such as air conditioners, elevators, office electronics, and lighting. Behind it, the 350-seat Senate Chamber hosts official meetings and is fitted with air conditioning, public address systems, and lighting. These characteristics make the site an ideal candidate for the design and techno-economic evaluation of a hybrid PV–grid–battery power system.

2.2 METHOD

The design process for the hybrid renewable energy system followed three main stages: (i) resource assessment, (ii) electrical load evaluation, and (iii) system modeling and optimization. Each power source was first analyzed individually, then integrated into the hybrid configuration to meet the complex's load demand reliably and economically.

2.2.1 Data Collection and Analysis

2.2.1.1 Solar Resource Assessment

Hourly solar radiation data were obtained from the Nigerian Meteorological Agency (NiMet), representing the long-term solar potential of Maiduguri. These data informed the photovoltaic generation model in HOMER Pro (Figure 1).

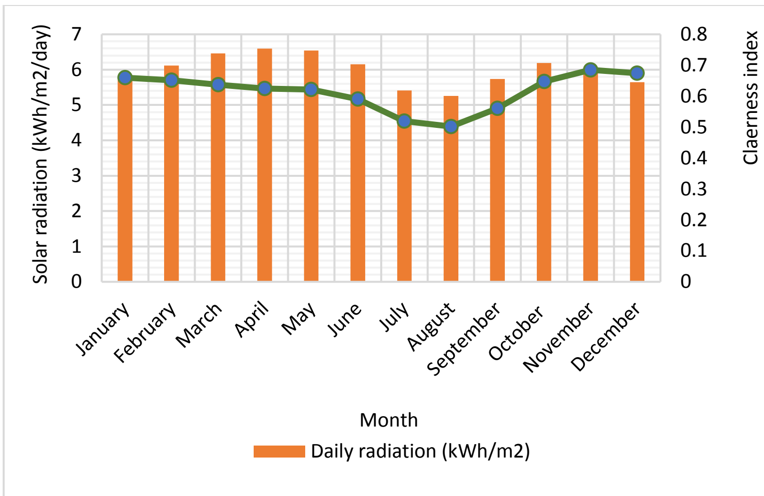


Figure 1. Monthly average solar radiation and clearness index for Maiduguri

2.2.1.2 Grid Performance Data

Operational statistics for the local grid were provided by the Yola Electricity Distribution Company (YEDC). The grid experiences an average of 1,500 outages annually with a mean repair time of 5 hours, indicating severe supply instability (Table 2).

Table 2. Grid Supply Parameters for the Senate Complex

S/N	**Parameters**	**Value**
1.	Mean output frequency (/year)	1500
2.	Mean repair time (hour)	5

Source: YEDC. 2025

2.2.1.3 Electrical Load Profile

A comprehensive on-site audit identified and recorded the power ratings and quantities of all significant electrical appliances in the Senate Complex. Major loads include air-conditioning units, refrigeration, computing devices, printers, photocopiers, elevators, water pumps, and various lighting systems. Table 3 summarizes the inventory, which was subsequently converted into an hourly demand profile for HOMER Pro simulation.

Table 3. Major electrical loads of the Senate Complex (summarized from audit).

Items	Power Ratings	Quantity	Total
Air Conditioners	2.5HP	9	79
	2HP	49	
	1.5H	15	
	1HP	6	
Refrigerator	2HP	10	31
	1HP	20	
TV sets	56Watts	19	23
	60Watts	4	
Standing Fan	56 Watts	13	13
Elevators	64919Watts (from calculation)	2	2
Computers	LCD monitors 29.8Watts	53	
	CPU 56Watts	53	106
Printers	Laser Jet 805Watts	13	18
	Desk Jet 575Watts	5	
Photocopiers	1400Watts	7	7
Pumping Machines	2HP	1	
	1HP	3	4
Lighting	Incandescent Lamps 100Watts	16	
	Compact Fluoescent lamp 18Watts	301	317

2.2.2 Theoretical Design of Photovoltaic Solar Power Plant

The design of the solar photovoltaic (PV) power plant consisted of PV module sizing, inverter sizing, battery sizing, and charge controller selection. The equations are corrected and presented below with all variables defined:

Battery Sizing

$$\text{Total daily watt hour per day} = \text{Load demand x } 24 = \frac{\text{Wh}}{\text{day}} \quad (1)$$

$$\text{Daily energy requirement} = \text{Total daily watt hour per day x power factor} = \frac{\text{Wh}}{\text{day}} \quad (2)$$

System Voltage $= 360$ V, power factor $= 1.1$, nominal Battery Voltage $= 6$ V, % Usage $=$ 80 % and battery autonomy $= 1$ day.

$$\text{Total load Ampere hour per day} = \frac{\text{Total daily load Wh/day}}{\text{System Voltage x power factor}} \quad (3)$$

$$\text{Battery Capacity (Ah)} = \frac{\text{Ampere hour per day x Days of Autonomy}}{\text{Percentage Usage}} \quad (4)$$

$$\text{Number of Batteries required} = \frac{\text{Battery Capacity}}{\text{Battery rating required}} \quad (5)$$

***Inverter Sizing*:** the size of inverter used in PV power plant depends on the total peak wattage required for the complex. The inverter must be large enough to handle the total peak requirement at any time. The inverter should be 25 - 30 % bigger than the total wattage of the appliances and machines. [15].

$$\text{Inverter size} = \text{Load demand (W)x } 0.25 + \text{ (W)} \quad (6)$$

$$\text{Number of Inverter required} = \frac{\text{Inverter size}}{\text{Rating of an Inverter}} \quad (7)$$

***Panel Generation Factor*:** panel generation factor varies with the solar intensity and sunshine period of the site [15, 16].

$$\text{Panel generation factor} = \frac{\text{solar irradiance x sunshine hours}}{\text{Solar test conditions irradiance}} \quad (8)$$

***Energy Required from PV Modules*: t**his can be calculated by multiplying peak energy requirement in kWh/day and energy lost in the system [15].

$$\text{Energy required from PV module} = \text{Total daily load x Power factor} = \frac{\text{Wh}}{\text{day}} \quad (9)$$

***Total Watt Peak Rating for PV Modules*:** This is calculated using the energy required to be produce by from solar PV modules and the panel generation factor [15].

$$\text{Total watt peak rating for PV modules} = \frac{\text{Energy required from PV modules}}{\text{Panel generation factor}} \quad (10)$$

Number of PV Modules Required

$$\text{Number of PV modules required} = \frac{\text{Total watt peak rating}}{\text{PV module maximum power}} \quad (11)$$

Regulator Rating Required

$$\text{Regular rating load side} = \frac{\text{Total DC wattage}}{\text{System Voltage}} \quad (12)$$

$$\text{Number of regulators used} = \frac{\text{Regulator rating}}{\text{regulator capacity}} \quad (13)$$

2.2.3 System Simulation and Analysis

Three distinct system configurations Grid, Solar, and Grid–Solar hybrid were simulated using the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software. The selection of the optimal system hinged on two criteria: minimizing unmet load and determining the Levelized Cost of Energy (LCOE). The decision was made through a comparative evaluation of each system's unmet loads and LCOEs.

2.2.3.1 Technical Performance Indicators

The simulation assessed parameters that represent energy production efficiency, supply reliability, and renewable contribution: Total Electrical Production (EP): Annual combined generation from all system components [17].

$$EP = \textstyle\sum_{ij}^{n,1} E_{ij} \quad (14)$$

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. **Unmet Electric Load:** Share of demand not met due to insufficient capacity [18, 19].

$$\text{Unmet load} = \text{Total load} - \text{Total load met} \quad (15)$$

Excess Electricity: Surplus generation beyond both load and storage capacity, often linked to seasonal oversizing [7].

$$\text{Excess Electricity} = \text{Total energy produced} - \text{Total} \quad (16)$$

Grid Purchases: Total electricity drawn from the utility grid per year, indicating dependency on external supply [7].

Economic Performance Indicators: The economic evaluation considered investment cost, operational expenses, and lifetime cost-effectiveness: **Capital Cost (CC):** Upfront expenditure for PV arrays, battery systems, and fixed infrastructure [20, 21].

$$CC = \sum_{PV=1}^{N_{PV}} + \sum_{G=1}^{N_G} C_G + C_P \quad (17)$$

Where NPV is the number PVs, CPVG is the unit cost of PV, NG is number of grids which is taken to be 1 in this work, CG is the grid cost which is taken to be zero for this work, and CP is the fixed cost. **Operating Cost (OC):** Annual running expenses excluding initial investment [22].

$$OC = TAC - TCC \quad (18)$$

Where TAC is the total annualized cost, and TCC is the total capital cost. Salvage Cost (SC): Residual component value at end-of-life [23].

$$SC = RC \times \left(\frac{RL}{CL}\right) \quad (19)$$

RC is the system replacement cost, RL is the system remaining lifetime, and CL is the system lifetime. **Replacement Cost (RC):** Cost to replace worn-out components [18]. **Levelized Cost of Energy (LCOE):** Average lifetime cost per kWh [17].

$$\text{LCOE} = \frac{\text{TAC} - C_{\text{boiler}} H_{\text{serve}}}{E_{\text{serve}}} \quad (20)$$

Where TAC is the total annualized system cost in N/yr, Cboiler is the boiler marginal cost in N/kWh, Hserve is the total thermal load served in N/kWh, and Eserved is the total electrical load served. **Net Present Cost (NPC)**: Total lifetime cost including capital, replacement, operational, and grid electricity costs, minus salvage value [22, 24].

$$\text{NPC} = \frac{\text{TAC}}{\text{CRF}} \quad (21)$$

With the **Capital Recovery Factor** (CRF) given by:

$$CRF \frac{i(1+i)1^n}{i(1+i)1^n - 1} \quad (22)$$

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

3 RESULTS AND DISCUSSION

3.1 Energy Audit Analysis

An energy audit of the complex, as summarized in Table 4, reveals a clear breakdown of daily energy consumption across various appliances. Air conditioners are the largest consumers, accounting for 62% of the total energy usage. Refrigerators follow with 15%, while printers and lighting each contribute 6%. Photocopiers and elevators consume 3% each, and pumping machines use 1% of the total energy. Devices like computers, TV sets, and standing fans make up a smaller portion, with computers and TV sets consuming 2% and standing fans accounting for less than 1% of total energy usage. This data highlights the disproportionate energy demand among devices, where just four device categories air conditioners, refrigerators, printers, and lighting make up approximately 89% of the total energy load. Air conditioners alone contribute the most at 62%, underscoring their significant impact on overall energy consumption. Refrigerators, at 15%, along with printers and lighting, each at 6%, collectively dominate the energy profile. The analysis further suggests several opportunities for improving energy efficiency across devices. Targeting high energy consuming devices, particularly air conditioners (62%) and refrigerators (15%), offers the greatest potential for reducing energy consumption. Implementing energy-efficient solutions such as upgrading to inverter air conditioners, ensuring proper maintenance of refrigerators, and switching to energy-saving lighting can lead to substantial reductions in overall energy use.

Table 4. Load requirement of the complex

Items	Power Ratings (W)	Quantity	Power (kW)	Daily Usage (Hours)	Daily Load (kWh/day)
Air Conditioners	1890	9	112.64	8	901.12
	1512	49			
	1134	15			
	756	6			
Refrigerator	1512	10	32.06	7	224.42
	756	21			
TV sets	56	19	1.30	10	13.0
	60	4			
Standing Fan	56	13	0.73	10	7.30
Elevators	64919	2	12.98	12	51.92
Computers (*Monitor*)	29.8	53	4.55	9	9.10
(*CPU*)	56	53			
Printers *(Laser Jet)*	805	12			
(Desk Jet)	575	5	13.34	7	93.38
Photocopiers	1400	9	9.80	5	49.00
Pumping Machines	1512	1	3.78	4	15.12
	756	3			
Lighting	100	16	7.20	12	84.24
	18	301			
Total			**198.20**		**1448.6**

3.2 System sizing (Theoretical Design)

The theoretical system design determined that the complex would require: PV Array: 791 modules of 700 Wp each (total ≈ 553.9 kWp). Battery Bank: 4,570.71 Ah at 48 V, requiring 92 batteries (12 V, 200 Ah each). Inverters**:** 3 units of 248 kW each (total ≈ 744 kW). Regulators**:** 12 units (to handle a regular load current of 550.56 A).

3.3 Homer Simulation Results

Following the resource assessment and load profile characterization, the proposed energy systems for the Senate Complex were modelled in HOMER Pro to compare technical performance and economic feasibility. The daily demand was set at 1,448.60 kWh/day with a peak of 244.54 kW, and three supply configurations were evaluated: Grid Only System – Dependent entirely on the Yola Electricity Distribution Company (YEDC). PV Only System – Standalone solar photovoltaic array with battery storage, operating off-grid. PV–Grid Hybrid System – Solar PV with battery backup, supplemented by grid electricity. Figures 2 to 4 illustrate the schematic layouts of each configuration.

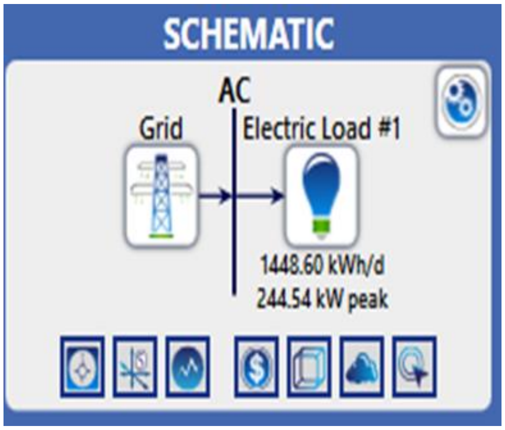


Figure 2. Schematic layout of Grid only configuration (HOMER Pro simulation)

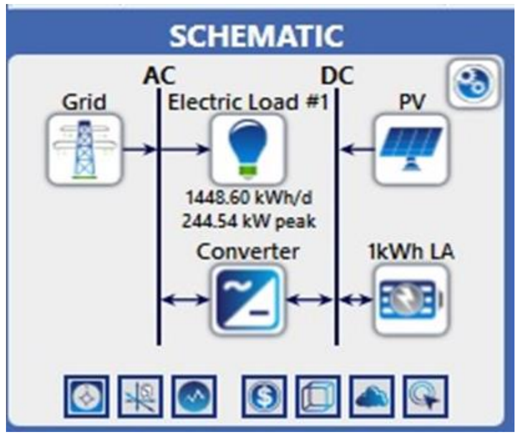


Figure 3. Schematic layout of PV only configuration ((HOMER Pro simulation)

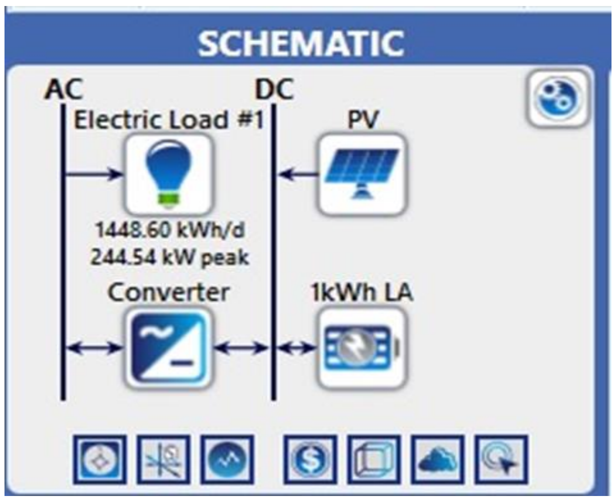


Figure 4. *Schematic layout of Grid-PV hybrid configuration ((HOMER Pro simulation)*

3.4 System Analysis

This section presents a cohesive analysis of the three energy system configurations Grid Only**,** PV Only**,** and Grid–PV Hybrid evaluated through both technical and economic lenses and compared against relevant literature.

3.4.1 Technical Performance Evaluation

The simulation outcomes (detailed in Figures 5–17) reveal notable contrasts among the configurations:

3.4.1.1 Grid Only System:

The utility grid showed unreliable supply with frequent outages (Figure 5), monthly electricity production peaking at ~10.3 MWh (August) and falling to ~4.3 MWh (February) (Figure 6). Unmet demand remained persistently high, averaging ~145 kW annually, with peaks of ~170 kW in April (Figure 7). These findings reflect longstanding challenges tied to grid instability and infrastructure limitations in Sub-Saharan Africa [26].

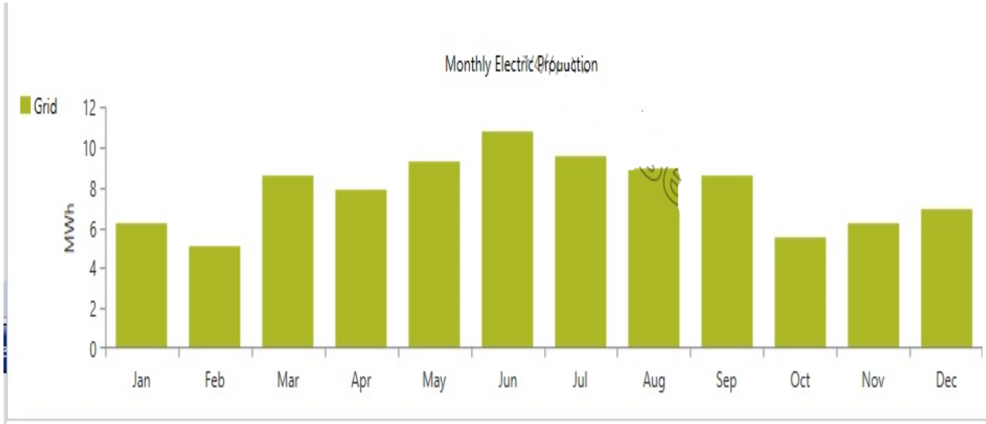


Figure 5. Monthly grid outages at the Senate complex *(based on HOMER Pro Simulation)*.

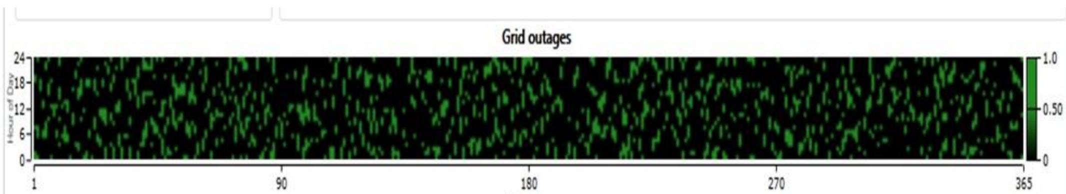


Figure 6. Monthly electric production by the grid only system *(HOMER Pro results)*

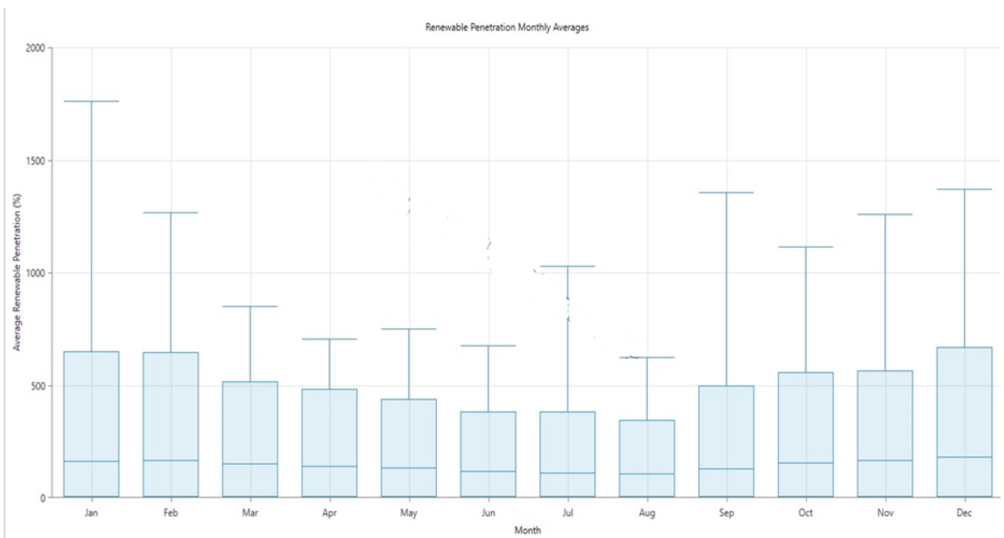


Figure 7. Monthly Averages of unmet electrical load by the grid (HOMER Pro results)

Figure 8. Monthly electric production by the Solar PV *(HOMER Pro results)*

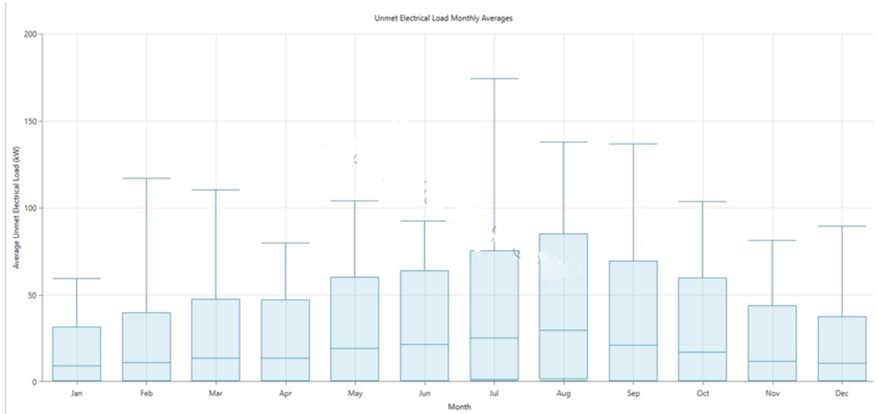


Figure 9. Monthly Averages of renewable penetration by the Solar PV. (HOMER Pro results)

3.4.1.2 PV-Only System

Electricity generation (Figure 8) was seasonal, with the highest output (~95 MWh) in dry seasons and lowest (~70 MWh) during the rainy months, closely mirroring solar resource variability across Nigeria [25]. Excess generation peaked in February (~330 kW) and dipped in mid-year (~230 kW) (Figure 10). However, unmet load escalated during July–August (~85 kW; Figure 11), underscoring PV vulnerability under adverse weather conditions [27]. Although renewable penetration was very high (~540% annual average), reliability was compromised due to intermittency and storage limits.

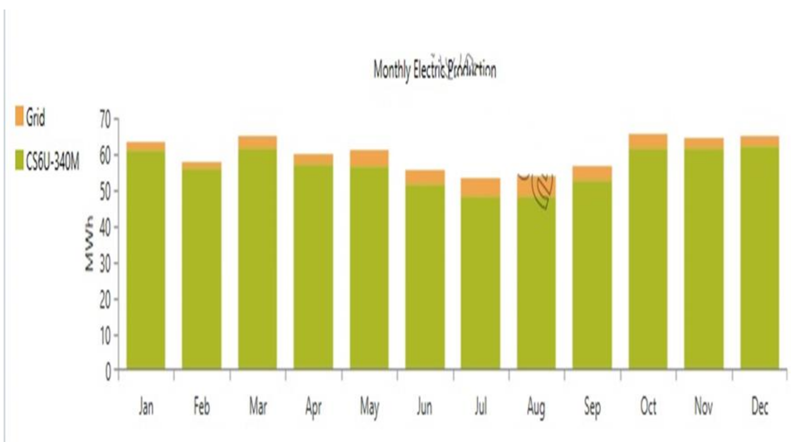


Figure 10. Monthly Averages of excess Electric production by the Solar PV *(HOMER Pro results)*.

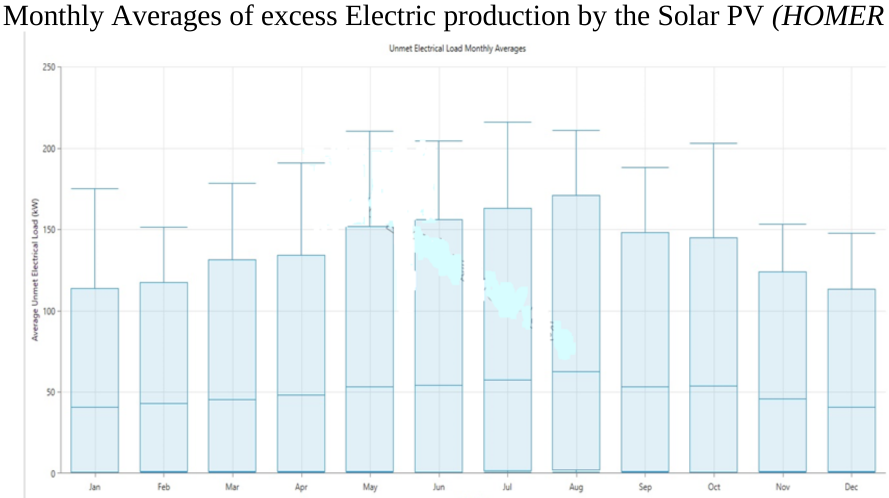


Figure 11. Monthly Averages of unmet electrical load by the Solar PV *(HOMER Pro results)*

3.4.1.3 Grid–PV Hybrid System

This configuration achieves significant improvements in both generation stability and reliability. As shown in Figures 12–15, solar covers most demand, with grid support during low irradiation months. Unmet load drops near zero, and grid purchases are more moderate (~30–75 kW range), while excess production remains controlled (e.g., ~380 kW in October). Such hybrid effectiveness aligns with observations in Nigerian tertiary institutions and power-constrained environments using HOMER optimization [9, 28].

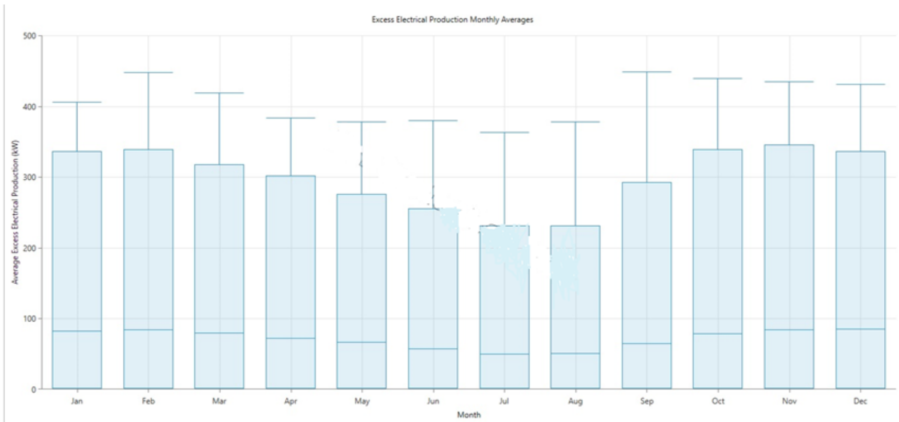


Figure 12. Monthly electric production of grid-solar hybrid system (HOMER Pro results)

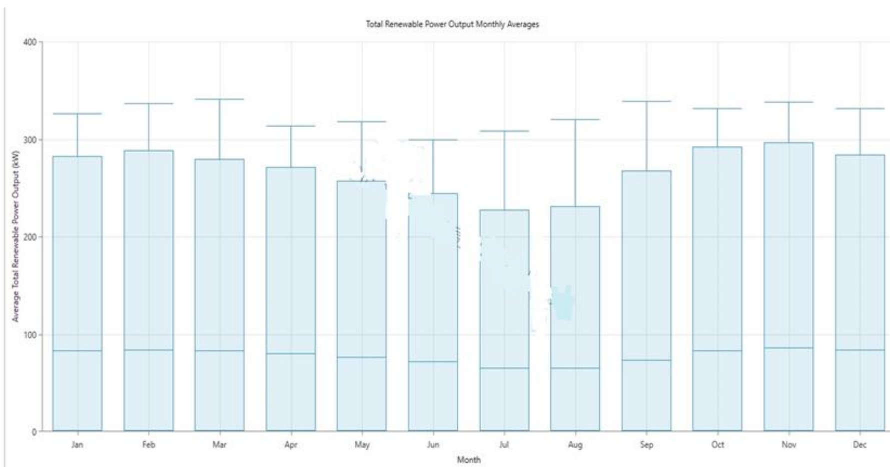


Figure 13. The monthly average of the total renewable power output of the Grid-Solar hybrid system *(HOMER Pro results)*

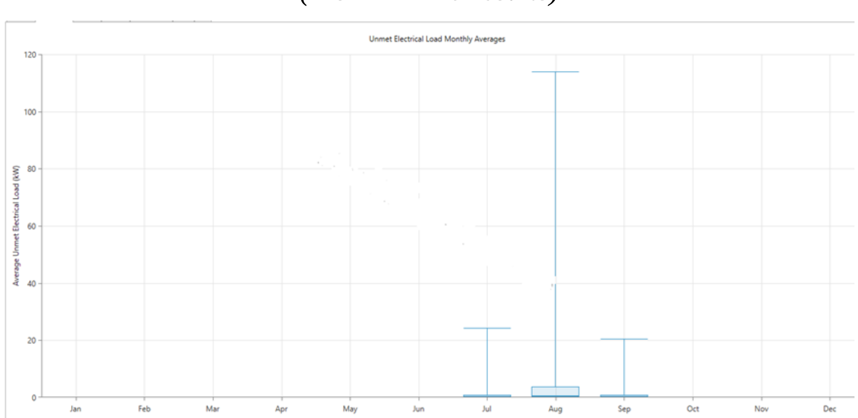


Figure 14. The monthly average of excess electrical production of the Grid-Solar hybrid system *(HOMER Pro results)*

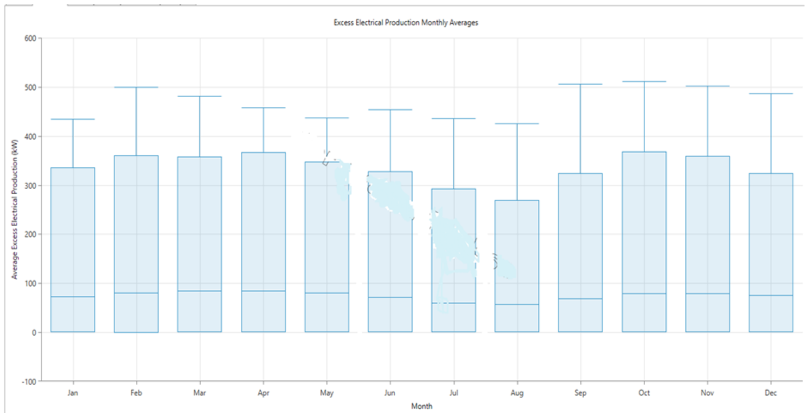


Figure 15. Monthly average of the unmet electrical load of the Grid-Solar hybrid system *(Generated from HOMER Pro results)*

Table. 5 Comparative Technical Ranking

Metric	Grid-Only	PV-Only	Hybrid
Avg. Unmet Load (kW)	145.8	62.3	8.5
Avg. Excess Energy (kW)	0	285.4	148.2
Renewable Penetration (%)	0	540	360
Avg. Grid Use (kW)	100.4	0	52.1
Reliability Index (%)	68.3	82.7	97.1

The Hybrid system clearly outperforms others in balancing reliability and renewable usage, ranking first overall. PV Only leads in renewable penetration but falls short on stability. Grid only lags in all performance metrics.

3.4.2 Economic Performance and Cost-Benefit Analysis

Economic simulation results (Figures 16–18) show that: **Grid-only:** Lowest capital cost (₦0) but highest lifetime operating cost (~₦6.36 million/year), making it cost-intensive over the long term as shown in Figure 16. The Grid-only configuration (Figure 16 and 17) is characterized by negligible capital, replacement, and salvage costs, with the primary expenditure being the annual operating cost of ₦6,355,658.00, resulting in a Net Present Cost (NPC) of ₦82,162,860.00 and a Levelized Cost of Energy (LCOE) of ₦68.00/kWh. **PV-only:** Highest initial investment (₦635.0 million) with recurring battery replacement costs (₦155.52 million every four years) but no grid costs as shown in figure 17. These findings are consistent [29], who reported that while standalone PV-battery systems in Nigeria require significant upfront and recurring expenditures, hybrid configurations and grid-supported models substantially reduce lifetime costs due to lower dependence on battery storage and grid-balancing advantages.

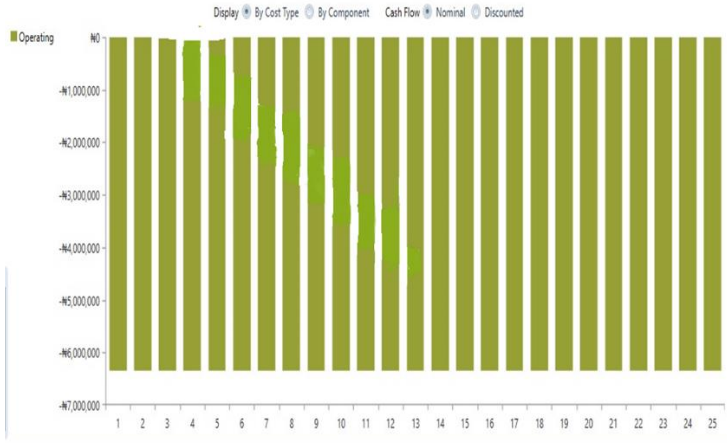


Figure 16. The system cost for the grid *(Generated from HOMER Pro results)*

Figure 17. NPC, LCOE and OC for the grid system (Generated from HOMER Pro results)

The Solar PV only system (Figure 18 and 19) entails a substantial initial investment of ₦635,005,271.00. This is accompanied by an annual operating and maintenance (O&M) cost of ₦32,626,409.24 for routine panel cleaning and terminal upkeep. Major battery replacements, valued at ₦155,520,000.00, occur every four years (4th, 8th, 12th, 16th, 20th, and 24th years). At the end of its operational life, the system retains a salvage value of ₦102,426,840.32. These factors culminate in an NPC of ₦1,518,933,000.00 and an LCOE of ₦251.72/kWh. Grid-Solar Hybrid: Lower capital cost than PV-only (₦569.9 million), reduced battery replacement cost (₦120.24 million every four years), and a moderate annual operating cost (~₦29.17 million). This aligns with findings by [29], who demonstrated that hybrid PV–grid systems in Nigeria achieve significantly lower Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) compared to standalone PV-battery systems, primarily due to reduced battery cycling and the opportunity to offset operating costs through grid integration.

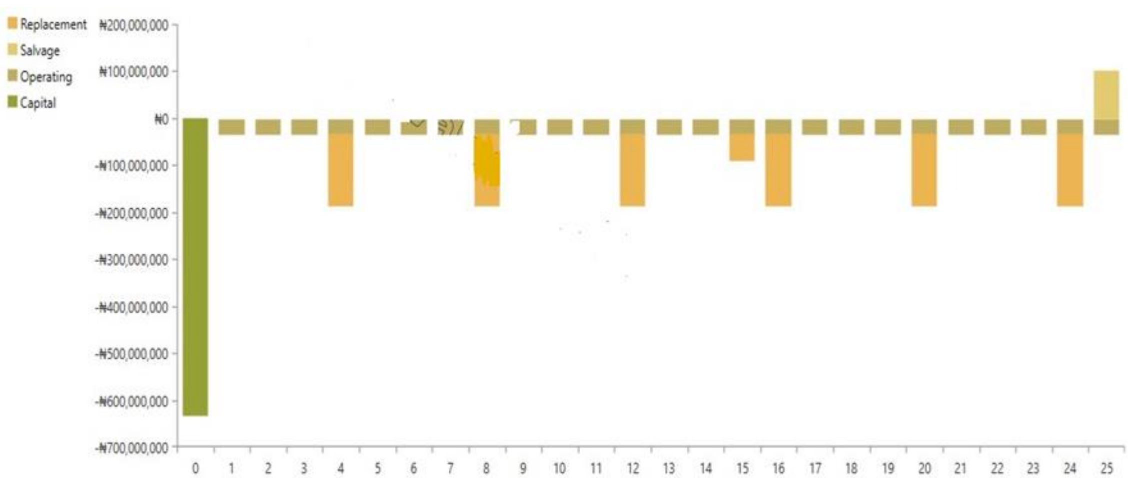


Figure 18. The system cost for the Solar PV system *(Generated from HOMER Pro results)*

Figure 19. NPC, LCOE and OC for the Solar PV system (Generated from HOMER Pro results)

The Grid–PV hybrid configuration (Figure 20 and 21) offers a lower capital cost than the PV-only system at ₦569,890,280.66. It incurs an annual O&M cost of ₦29,169,919.54 and reduced cyclical battery replacement costs of ₦120,240,000.00 every four years, alongside an additional mid-life replacement expenditure of ₦56,788,632.09 in year 15. Its end-of-life salvage value is ₦94,024,491.72. This configuration yields an NPC of ₦1,302,427,000.00 and an LCOE of ₦203.49/kWh.

Figure 20. The system cost for the Grid –Solar Hybrid system (Generated from HOMER Pro results)

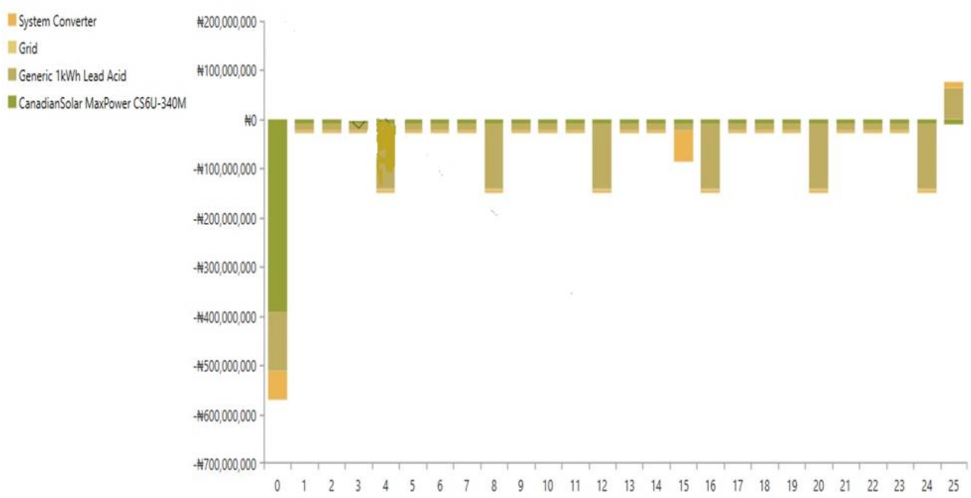
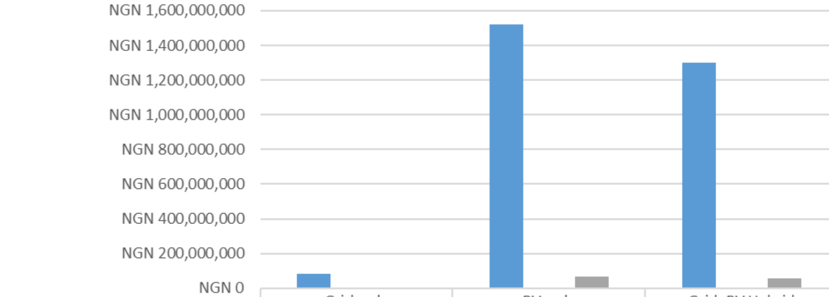


Figure 21. NPC, LCOE and OC for the hybrid system (Generated from HOMER Pro results)

3.4.2.1 Comparative Metrics

A consolidated comparison of NPC, LCOE, and annual O&M cost is presented in Figure 22. Figures 22 shows the comparative analysis. The Grid-only system records the lowest NPC, LCOE, and O&M, but at the cost of supply reliability. The PV-only system has the highest cost metrics due to its capital and storage requirements, while the Grid–PV hybrid offers a mid-point compromise, reducing NPC by 14.25 % and LCOE by 19.2 % relative to PV-only, while maintaining strong reliability. These findings align with previous sub-Saharan Africa microgrid studies, which consistently report that PV–grid hybrids deliver the most balanced trade-off between cost efficiency and reliability [9, 30]. While PV-only systems excel in renewable penetration, their high storage and capital costs limit feasibility in grid-adjacent contexts. Conversely, grid-only configurations suffer from unreliable supply, making them less suitable for critical loads such as hospitals and schools in regions with unstable grids [31].



	Grid-only	PV-only	Grid–PV Hybrid
Net Present Cost (NPC, ₦)	82,162,860	1,518,933,000	1,302,427,000
Levelized Cost of Energy (₦/kWh)	68	251.72	203.49
Annual O&M Cost (₦)	6,355,658	68,375,680	56,664,920

Figure 22. Comparative Economic Performance (Generated from HOMER Pro results)

4 CONCLUSIONS

A comprehensive energy audit, theoretical system design, and integrated technical–economic evaluation using HOMER Pro software reveal that a grid–solar hybrid system delivers the most sustainable balance of reliability, renewable penetration, and lifecycle cost for the University of Maiduguri Senate Complex. In contrast with grid-only and PV-only solutions, the hybrid system achieved: Close to zero unmet load (high availability). Moderate operating and capital costs, without adopting the extremes of PV only and grid only systems. In addition to economic and technological advantages, hybridization gives essential resilience benefits to conflict-prone areas and grid insecure environments where uninterruptible supply of electricity is very important for administrative, medical, and educational activities. The study therefore recommends the use of PV–grid hybrid systems in institutions in regions with poor grid supply.

REFERENCES

1. The Guardian Nigeria. (2021). NNPC, others begin 50 MW emergency power project in Borno. The Guardian. https://guardian.ng/news/nnpc-others-begin-50mw-nnpc-maiduguri-power-project-in-borno.
2. The Electricity Hub. (2021). Nigeria: Maiduguri businesses affected by 9 months power outage. The Electricity Hub. https://theelectricityhub.com/nigeria-maiduguri-businesses-affected-by-9-months-power-outage/.
3. Daily Trust. (2023). Buhari commissions 32 MW NNPC Maiduguri power plant. Daily Trust. https://dailytrust.com/buhari-commissions-32mw-nnpc-maiduguri-power-plant.
4. Vanguard. (2024). We generate 12 MW solar to power varsity, teaching hospital – UNIMAID VC. Vanguard Nigeria. https://www.vanguardngr.com/2024/05/we-generate-12-mw-solar-to-power-varsity-teaching-hospital-unimaid-vc/.
5. ProfileSOLAR. (2025). Solar output per kW of installed solar PV by season in Maiduguri. profileSOLAR. https://profilesolar.com.
6. Medugu, D.W. (2014). Assessment of global solar radiation absorbed in Maiduguri, Nigeria. *International Journal of Sustainable and Green Energy*, vol. 3, no. 5, pp. 108–114. https://doi.org/10.11648/j.ijrse.20140305.14.

7. Li, J., Zhou, Y. and Zheng, Y. (2018). Performance analysis of PV intermittency in hybrid renewable systems. *Renewable Energy*, vol. 127, pp. 871–882. https://doi.org/10.1016/j.renene.2018.05.031.
8. Yola Electricity Distribution Company (YEDC). (2025). Customer service bands. YEDC. https://yedc.com.ng.
9. Jumare, I., Bhandari, R. and Zerga, A. (2020). Assessment of a decentralized grid-connected photovoltaic/wind/biogas hybrid energy system in northern Nigeria. *Energy, Sustainability and Society*, vol. 10, pp. 1-16. https://doi.org/10.1186/s13705-020-00260-7.
10. Katche, M.L., Makokha, A.B., Zachary, S.O. and Adaramola, M.S. (2024). Techno-economic assessment of solar–grid–battery hybrid energy systems for grid-connected university campuses in Kenya. *Electricity*, vol. 5, no. 1, pp. 61-74. https://doi.org/10.3390/electricity5010004.
11. Numbi, B.P. and Malinga, S.B. (2017). Optimal energy cost and economic analysis of a residential grid-interactive solar PV system: Case of eThekwini municipality, South Africa. *Applied Energy*, vol. 186, pp. 28-45. https://doi.org/10.1016/j.apenergy.2016.10.084.
12. Rehman, S., Al-Hadhrami, L.M. and Alam, M.M. (2020). Hybrid renewable energy systems for power generation: A review. *Renewable and Sustainable Energy Reviews*, vol. 119, Article 109546. https://doi.org/10.1016/j.rser.2019.109546.
13. Enongene, K.E., Oladokun, V. and Akingbade, K. (2019). Techno-economic analysis of a grid-connected PV system for Lagos, Nigeria: A HOMER-based study. *Energy Reports*, vol. *5*, pp. 1243-1253. https://doi.org/10.1016/j.egyr.2019.08.017.
14. Abdulkarim, B., Olatomiwa, L. and Popoola, O. (2021). Techno-economic assessment of hybrid PV-diesel-battery systems for Nigerian institutions. *Energy Reports*, vol. 7, pp. 455-466. https://doi.org/10.1016/j.egyr.2021.02.043.
15. Chandel, M., Agrawal, G.D., Mathur, A. and Mathur, S. (2017). Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city. *Case Studies in Thermal Engineering*, vol. 10, pp. 73-81. https://doi.org/10.1016/j.csite.2017.03.005.
16. Osueke, C.O., Uzendu, P. and Ogbonna, I.D. (2013). Study and evaluation of solar energy variation in Nigeria. *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 3, pp. 387-396.
17. Bartolucci, L., Cordiner, S., Mulone, V., Santarelli, M. and Sciubba, E. (2019). Fuel cell-based hybrid renewable energy systems for off-grid telecom stations: Data analysis and system optimization. *Applied Energy*, vol. 252, no. 113386, pp. 1-18. https://doi.org/10.1016/j.apenergy.2019.113386.
18. HOMER Energy (2016). HOMER Pro version 3.7 user manual. *HOMER Energy*. https://www.homerenergy.com.
19. Masrur, H., Zaman, F., Rokonuzzaman, M., Al-Mamun, M.R., Islam, M.S. and Ghosh, A. (2020). Techno-economic-environmental suitability of an isolated microgrid system located in a remote island of Bangladesh. *Sustainability*, vol. 12, no. 7, 2880, pp. 1-20. https://doi.org/10.3390/su12072880.
20. Ghigo, A., Cazzola, M., Bracco, G., Mattiazzo, G. and Collu, M. (2020). Platform optimization and cost analysis in a floating offshore wind farm. *Journal of Marine Science and Engineering*, vol. 8, no. 11, pp. 1-18. https://doi.org/10.3390/jmse8110835.

21. Ajeba, W., Adebanji, B. and Fasina, T. (2021). Comparative analysis of off-grid small hydro–solar PV–diesel hybrid system in Southwest Nigeria. *Energy & Environment*, vol. 32, no. 6, pp. 1148-1163. https://doi.org/10.1177/0958305X20985438.

22. Aderemi, B.A., Chowdhury, S.P.D., Olwal, T.O. and Abu-Mahfouz, A.M. (2018). Techno-economic feasibility of hybrid solar photovoltaic and battery energy storage for a mobile base station in Soshanguve, South Africa. *Energies*, vol. 11, no. 6, pp. 15-21. https://doi.org/10.3390/en11061521.

23. Salisu, S. and Mustafa, M.M.O. (2019). Technoeconomic feasibility analysis of an off-grid hybrid energy system for rural electrification in Nigeria. *Alexandria Engineering Journal*, vol. 58, no. 1, 261-270. https://doi.org/10.1016/j.aej.2019.09.013.

24. Abdelaziz, M., Ali, M. and Eltamaly, A.M. (2018). Modeling and simulation of smart grid integrated with hybrid renewable energy systems. *Studies in Systems, Decision and Control*, vol. 121, pp. 123-146. https://doi.org/10.1007/978-3-319-74361-9_7.

25. Deichmann, U., Meisner, C., Murray, S. and Wheeler, D. (2011). The economics of renewable energy expansion in rural Sub-Saharan Africa. *Energy Policy*, vol. 39, no. 1, pp. 215-227. https://doi.org/10.1016/j.enpol.2010.09.034.

26. Akinyele, D.O. and Rayudu, R.K. (2016). Techno-economic and life cycle environmental performance analyses of a solar photovoltaic microgrid system for developing countries. *Energy*, vol. 109, pp. 160-179. https://doi.org/10.1016/j.energy.2016.04.061.

27. Duffie, J.A. and Beckman, W.A. (2013). *Solar engineering of thermal processes* (4th ed., p. 250). Hoboken, NJ: John Wiley & Sons.

28. Adefarati, T. and Bansal, R.C. (2017). Techno-economic analysis of sustainable hybrid mini-grid systems in northern Nigeria. *Energy, Sustainability and Society*, vol. 7, Article 30. https://doi.org/10.1186/s13705-017-0137-0.

29. Ismaila, Z., Falode, O.A., Diji, C.J., Kazeem, R.A., Ikumapayi, O.M., Petinrin, M.O. and Akinlabi, E.T. (2023). Evaluation of a hybrid solar power system as a potential replacement for urban residential and medical economic activity areas in southern Nigeria. *AIMS Energy*, vol. 11, no. 2, pp. 319-336. https://doi.org/10.3934/energy.2023017.

30. Akinyele, D.T., Rayudu, R.K. and Olatunde, G.K. (2022). A review of renewable off-grid mini-grids in Sub-Saharan Africa. *Frontiers in Energy Research*, vol. 10, Article 871289. https://doi.org/10.3389/fenrg.2022.871289.

31. Odetoye, O.A., Olulope, P.K., Olanrewaju, O.M., Alimi, A.O. and gbinosa, O.G. (2023). Multi-year techno-economic assessment of a proposed zero-emission hybrid community microgrid in Nigeria using HOMER. *Heliyon*, vol. 9, no. 9, e19189. https://doi.org/10.1016/j.heliyon.2023.e19189.