Techno-Economic Optimization of a Hybrid PV-Wind-Waste-to Energy System for the University of Maiduguri

Hafsah A. ABDULRAHMAN[1], Muhammad M. HAMIDU[2*]

[1,2*]Department of Mechanical Engineering, University of Maiduguri, Maiduguri, Nigeria

[1]hafsamha@gmail.com, [2*]muhammadhamidu@unimiad.edu.ng

Abstract

The University of Maiduguri has struggled with power outages all the time because the national grid is unstable, diesel prices are high, and the amount of trash on campus is growing. This study examines a hybrid solar photovoltaic-wind-waste-to-energy (WTE) system as a sustainable alternative that enhances energy security and mitigates waste disposal issues. The main aim was to design and improve a reliable hybrid system that could meet the university's needs for electricity for academic, administrative, and residential purposes. HOMER Pro used hourly load profiles, solar radiation, wind speed, temperature data, and the amount of municipal solid waste available to create models. Then, it analyzed different system configurations based on Net Present Cost (NPC), Levelized Cost of Energy (LCOE), renewable fraction, and operational performance. The results show that the PV–wind–biogas–battery configuration provides the most cost-effective solution with a 100% renewable fraction. The optimal system has 16,812 kW of PV power, 2,434 kW of wind power, a 500-kW biogas generator, 17,972 kWh of lead-acid storage, and a 3,718-kW bidirectional converter. Solar PV contributes the highest annual energy output, supported by wind generation during low-irradiance months. The biogas unit, fuelled by an average of 26.5 tonnes of daily campus waste, provides stable power that keeps the system running during times when renewable energy is weak. With little unmet load and strong seasonal resilience, the total annual generation (44.65 GWh) greatly surpasses the campus load. According to the study's findings, UNIMAID can achieve a reliable power supply while converting its waste stream into an energy resource by combining PV, wind, and WTE. As future demand increases, it is advised that the university implement this configuration, enhance waste collection systems, and gradually expand the hybrid system.

Keywords: HOMER Pro Simulation, Hybrid Renewable Energy System, Solar–Wind–Biogas Integration, Techno-Economic Optimization and Waste-to-Energy (WTE).

1.0 Introduction

Continuous fundamental problems in Nigeria's power sector jeopardize energy security at important institutions like the University of Maiduguri (UNIMAID). The current energy mix is becoming more and more unsustainable due to the unstable national grid run by the Yola Electricity Distribution Company (YEDC), frequent transmission line vandalism brought on by regional insurgency, rising cost of electricity, and fluctuating diesel prices [1]. As a result, institutions such as UNIMAID depend on a fragile combination of grid power, diesel generators, and scattered standalone PV installations. Although Maiduguri benefits from abundant solar irradiation and moderate wind speeds, the intermittency of these resources continues to limit their ability to reliably meet large institutional loads. However, buildings like the UNIMAID Senate Complex solar farm and decentralized solar microgrids like the Gwange I Ward project have shown noticeably lower LCOE when compared to diesel-based systems, supporting the feasibility of renewable options [2, 3].

Beyond solar and wind, waste-to-energy (WTE) technologies offer an underutilized opportunity for improving energy reliability, reducing emissions, and addressing solid-waste accumulation in Maiduguri. The city's Municipal Solid Waste (MSW) composition has shifted substantially over time. Early assessments reported 25.8% organic content and 18.1% plastics [4], whereas recent findings show organic waste rising to approximately 55% and plastics to around 33% [5]. These increases in high-energy-yield fractions such as organic matter and plastics provide a robust feedstock base suitable for WTE pathways including anaerobic digestion, incineration, landfill-gas-to-energy (LFGTE), pyrolysis, and plasma gasification. Figure 1 highlights these compositional changes, illustrating the growing relevance of WTE technologies to Maiduguri's energy and waste-management challenges.

Globally, hybrid renewable energy systems (HRES) especially PV–wind combinations have gained attention due to their complementary generation patterns, which reduce storage requirements and improve supply stability [9, 10]. Optimization studies using HOMER Pro consistently show superior economic and environmental performance for hybrid systems compared with stand-alone configurations [11, 12]. In Maiduguri, earlier work confirmed that solar wind hybrids are feasible for small-scale facilities, such as the Engineering Faculty Workshop with daily consumption of roughly 370 kWh/day [13]. However, these studies remain limited in scale and do not address multi-megawatt institutional loads.
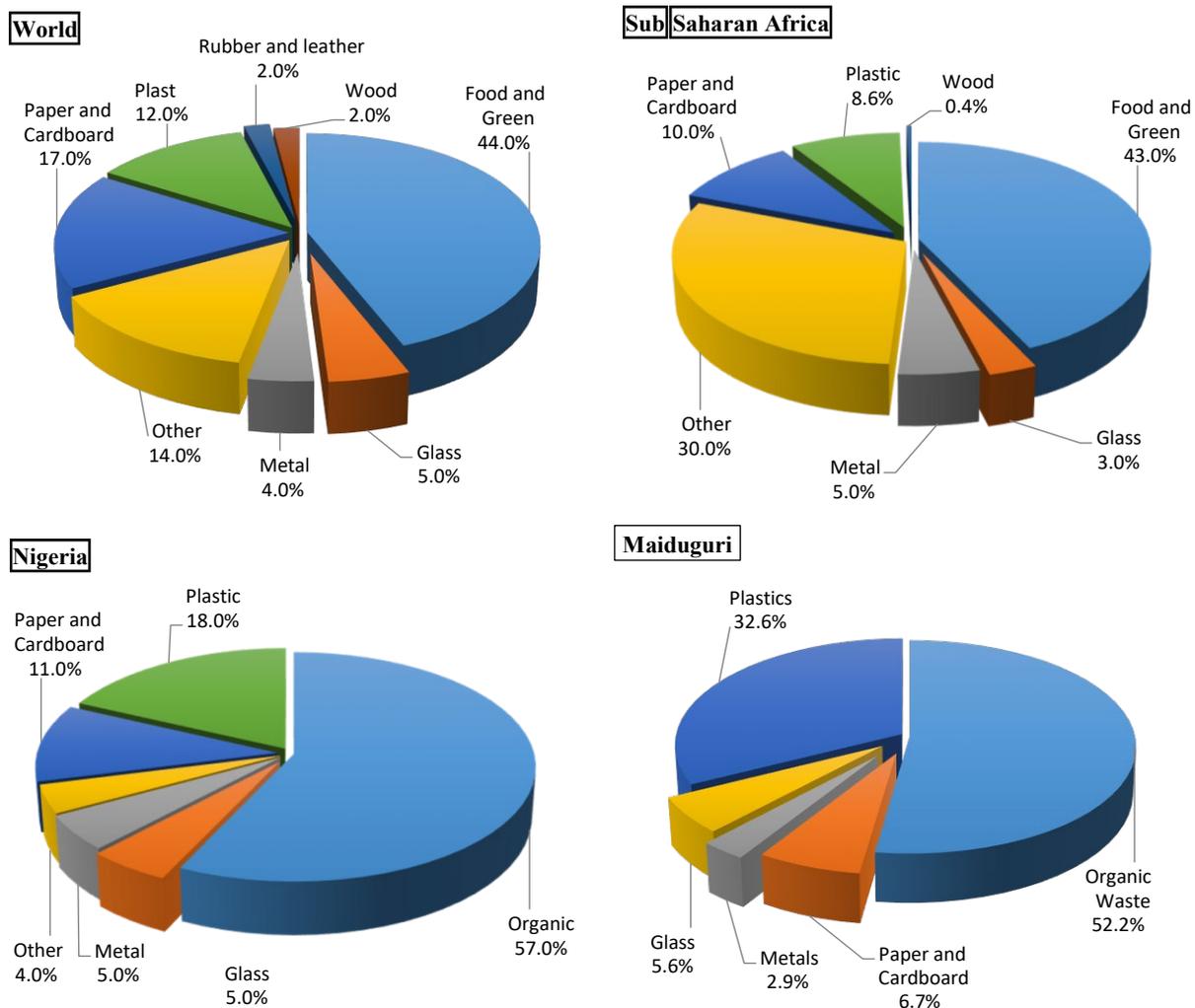
Figure 1. Composition of waste in various areas. The charts for the world and Sub-Sahara were taken from Kaza et al. (2018) [6], the chart for Nigeria was taken from Kofoworola (2016) [7], and the chart for Maiduguri was based on information from Oumarou et al. (2017) [8].

In recent years, a growing body of literature has explored hybrid systems that integrate WTE with solar and wind resources, particularly through HOMER Pro simulations. International studies such as Ishraque et al. (2022) [14], and Chandra et al. (2023) [15] demonstrate that adding WTE components (biogas generators, gasifiers, or LFGTE units) significantly enhances supply reliability by providing firm, dispatch able base load power during low solar and wind periods. Case studies across Africa and Asia show that PV–wind–biomass hybrids optimized in HOMER consistently outperform diesel-based or single-resource renewable systems. Chisale et al. (2023) [16] illustrated that hybridizing renewables with biomass significantly lowers net present cost (NPC) and improves system robustness under fluctuating fuel prices. Similarly, Moraes et al. (2024) [17] modelled landfill-gas electricity production using a LandGEM-generated methane profile imported into HOMER; their findings indicated that LFGTE can supply reliable base load power and substantially reduce methane emissions from unmanaged waste.

This gap is particularly evident in Nigeria, where hybrid renewable research remains focused on rural communities or single-building systems. WTE integration is still largely missing from Nigerian hybrid energy studies, despite the growing availability of organic and plastic waste in cities such as Maiduguri. For a large, energy-intensive, and security-sensitive institution like UNIMAID, which has an estimated peak demand of 3.5 MW [18], the potential for a tri-hybrid WTE/PV/wind system remains largely unexplored in the literature.

HOMER Pro provides a powerful platform for such an assessment by enabling detailed modelling of PV arrays, wind turbines, WTE generators and storage banks. Waste-derived fuel availability, calorific value, seasonal variation, and conversion efficiency can be incorporated through custom fuel-input profiles and generator performance definitions. International WTE-based simulations consistently show that hybridizing PV, wind, and WTE reduces greenhouse-gas emissions by capturing methane that would otherwise be released from landfills and by displacing diesel consumption.

Given the rising MSW availability in Maiduguri, strong solar resource base, moderate wind speed, and the university's multi-megawatt load, the University of Maiduguri provides a compelling case for developing an

advanced tri-hybrid WTE–PV–wind energy system. Existing studies do not provide a comprehensive assessment of such a system for an institutional environment in northern Nigeria.

To address this gap, the present study designed and evaluates a novel WTE/PV/Wind hybrid energy system optimized for the UNIMAID campus using HOMER Pro. The proposed system leverages WTE as a continuous base load, stabilizing the variability of solar and wind resources. This work contributes by:

i.   Presenting the first full-scale tri-hybrid design tailored to a multi-megawatt Nigerian university campus;
ii. Highlighting the resilience, cost, and environmental advantages of WTE integration in an arid, conflict-affected region;
iii. Applying high-fidelity techno-economic modelling; and
iv. Proposing a replicable framework for large institutions in resource-constrained areas facing chronic grid instability.

In doing so, this work addresses a critical knowledge gap in renewable energy integration for Nigerian institutions and contributes practical, policy-aligned insights toward sustainable and resilient campus energy planning.

2.0 Materials and Methods
2.1 Study Area
The research is conducted at the University of Maiduguri in northeastern Nigeria (Latitude: 11°50'N, Longitude: 13°09'E, Elevation: 354 m), a large academic campus with significant electricity demand driven by laboratories, classrooms, administrative buildings, and student residences. The frequent grid instability in the region makes the site well-suited for evaluating a wind–solar–waste-to-energy (WTE) hybrid system. Its geographic position, renewable resource availability, and campus layout provide the necessary conditions for assessing system performance and reliability; Campus population: ~50,000 persons [5]. The map of the study area used for this analysis is shown in Figure 2.
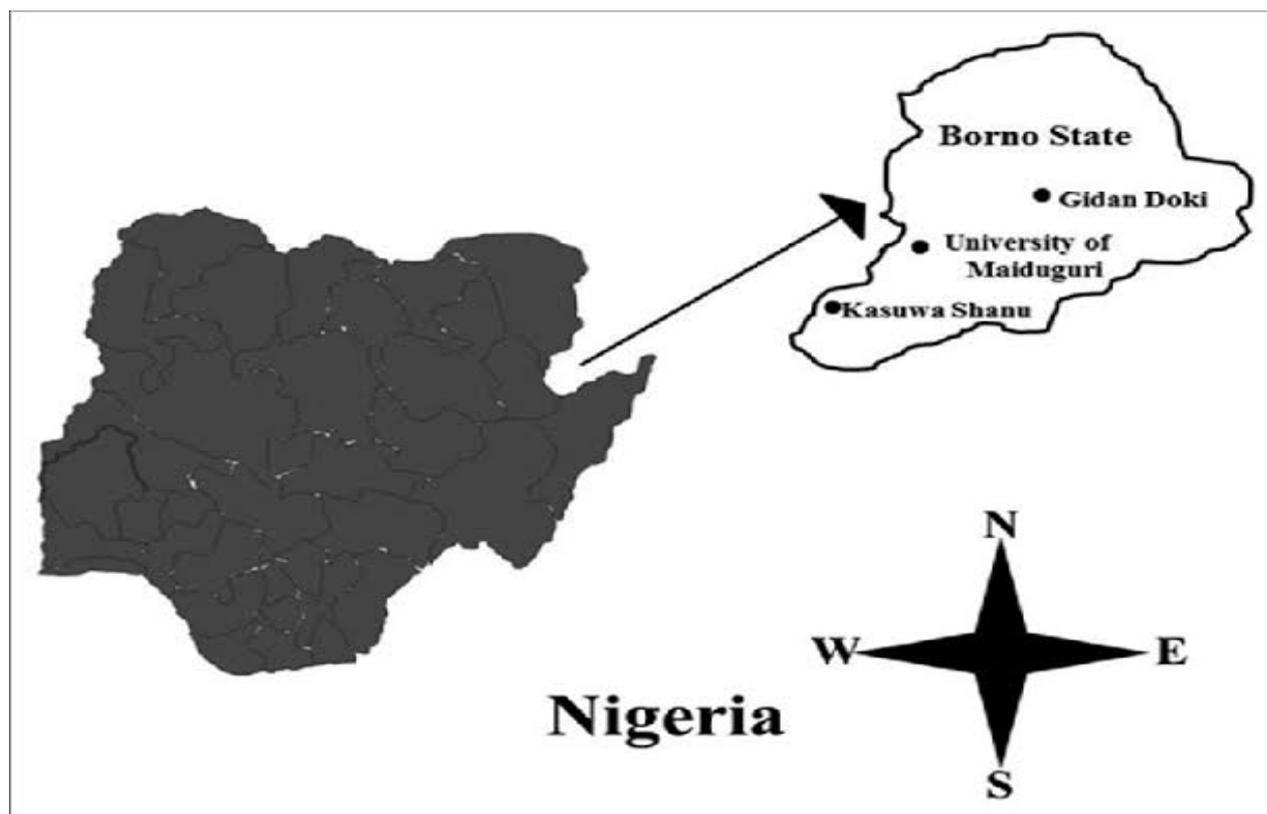

Figure 2. Map of Maiduguri showing the study area

2.2 Load Assessment and Characterizations
Electricity demand for the University of Maiduguri was disaggregated into:
- Hostels/Staff Quarters
- Academic/Administrative blocks

Measured peak load was obtained from the University's works and energy department (3.5 MW). Hourly profiles were generated using diversified load curves consistent with methodologies in Adeyanju & Manzella (2021) [19] and Igbinovia et al. (2023) [20]. The hourly load data are expressed as in equation 1.

$$L_t = L_{peak} \times D_t \tag{1}$$

Where L_t *is* the load at hour t, L_{peak} is the measured campus peak (MW) and D_t is the hourly diversity factor. The daily energy consumption is computed as shown in equation 2.

$$E_d = \sum_{t=1}^{24} L_t \tag{2}$$

Load profiles were imported into Homer under primary load = Hourly data import.

2.3 Municipal Solid Waste Assessment (Waste-to-Energy Feedstock)

Campus waste availability was estimated using population-based waste generation methodology from UNEP (2021) and Nigeria-specific studies [21] as seen in equation 3:

$$W = p \times g \tag{3}$$

Where W is the total MSW generated (kg/day) and p is the campus population of approximately 50,000 person [5]

Biogas potential from organic waste follows standard conversion ratio as shown in equation 4 [5]:

$$B = W \times Y_b \tag{4}$$

Where Y_b is biogas yield (100-200 m³/ton), we took 150 m³/ton for this work.

$$B = 26.5 \times 150 = 3975 \ ^{m^3}/_{day}$$

Energy content of biogas as expressed in equation 5:

$$E_{BG} = B \times LHV_{BG} \tag{5}$$

Using LHV = 18 MJ/m³

$$E_{BG} = 3975 \times 18 = 71,550 \ MJ/day$$

$$E_{BG}(kwh) = 18,829 \ kwh/day$$

This value was entered in HOMER under Biomass Resource → Monthly Biomass Availability (tons/day) using 2.2 ton/month variation = 26.5 ton/day fixed.

Assumptions:

- Average waste generation rate: 0.53kg/person/day, yielding a compus MSW generation of approximately 26.5 tonnes per day [5]
- Waste collection and segregation efficiency are assumed at 80%
- Biogas generator operates with electrical efficiency of 80%

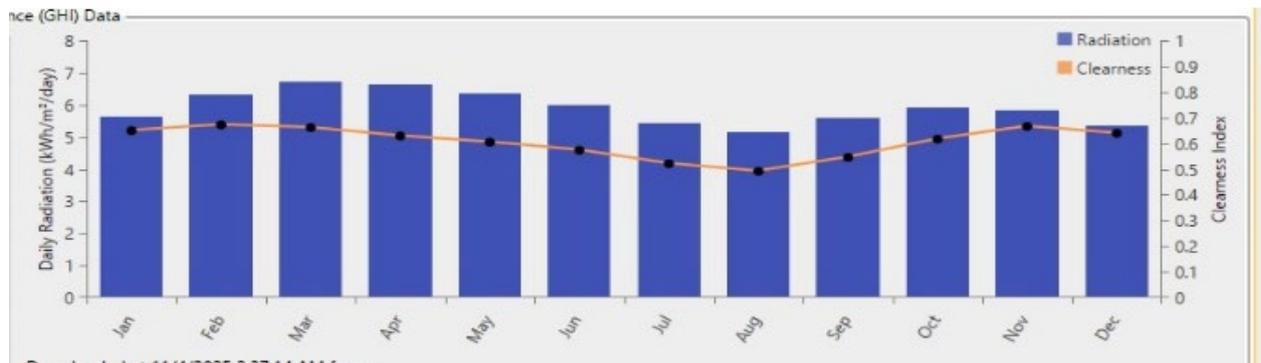## 2.4 Renewable Resource Assessment
2.4.1 Solar Resource

Figure 3. Solar radiation potential for Maiduguri

The solar resource assessment for Maiduguri indicates a high level of global horizontal irradiation (GHI), suitable for photovoltaic (PV) generation. Data from Hamidu *et al.* (2025) [22] shows an annual average GHI between 5.7–7.3 kWh/m²/day, with peak levels from February to May exceeding 6.5 kWh/m²/day. Even during monsoon months, GHI remains above 5.0 kWh/m²/day, reflecting the semi-arid Sahelian climate's low seasonal variability. This stability supports dependable year-round PV output and improves hybrid renewable-energy system simulations.

2.4.2 Wind Resource

Figure 4. Monthly average wind speed profile for Maiduguri

Maiduguri's monthly average wind speeds range from 4.0 m/s to 7.2 m/s as shown in figure 4, with higher speeds between January and March and lower speeds during the monsoon months of August to October. The wind resource is generally strong, exceeding 5 m/s in most months, making the region suitable for small to medium-sized wind energy projects. The early-season high wind speeds enhance solar generation and improve the reliability of hybrid PV–wind power systems.

2.4.3 Biomass Resource

Figure 5. Monthly average biomass availability for the University of Maiduguri (tonnes/day).

The monthly average biomass availability for the university community is presented in Figure 5. The values range between 17.83 tonnes/day and 32.69 tonnes/day, with an annual mean of 26.50 tonnes/day. High-availability months (January–May, September–November) correspond to periods of full academic occupancy, examinations, and peak cafeteria operations. Lower values in June–July align with reduced student activities during semester breaks.

2.4.4 Temperature Profile

Figure 6. Monthly temperature profile for Maiduguri

The monthly temperature profile of Maiduguri as shown in figure 6, was analyzed through NiMet data and NASA cross-validation in HOMER Pro, shows typical semi-arid conditions. Temperatures peak at about 32–34°C

from February to May before tapering off. While high temperatures may cause slight derating of PV modules, they remain within acceptable limits for modern PV technology. This stable thermal pattern supports reliable PV performance estimations and system design considerations.

2.5 Optimization and Dispatch Strategy

As illustrated in Figure 7, the optimization workflow in HOMER Pro begins with defining all technical parameters, economic inputs, load characteristics, and resource profiles for the proposed hybrid system. The software then conducts hour-by-hour simulations across multiple configuration options, evaluating each through long-term economic indicators such as Net Present Cost. Once the simulations are completed, HOMER Pro ranks the viable system setups based on their renewable contribution and overall cost-effectiveness. The process concludes with an environmental assessment, which examines the system's potential for emission reduction and its broader ecological benefits.
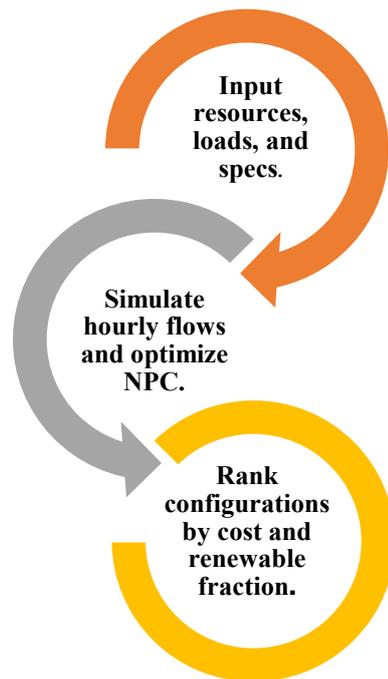

Figure 7. Optimization workflow in HOMER Pro

2.6 Component Modeling and Specification

The integrated hybrid system includes solar PV, a wind turbine, a waste-to-energy unit, a battery storage bank (BESS), and a bidirectional inverter. The technical and economic specifications for these components are summarized in Table 1

Table 1: Technical specifications and cost parameters of system components

Component	Model	Rated Power	Efficiency	Lifetime	Capital Cost (₦/unit)	Replacement Cost (₦)	O&M Cost (₦/year)
PV Module	Canadian Solar CS6U-340M monocrystalline flat plate	0.34 kW	17.49%	25 yrs	157,500	130,500	25,000
	Generic 3kW Generic 500kW						
Wind Turbine		3kW	25%	20 yrs	1,500,0000	1,300,000	17,000
	Lead-acid (generic)	500kW	80%	10 yrs	54,000,000	40,000,000	40,000

Component	Model	Rated Power	Efficiency	Lifetime	Capital Cost (₦/unit)	Replacement Cost (₦)	O&M Cost (₦/year)
Biogas Gen	System Generic	1 kWh	80%	10 yrs	340,000	300,000	34,000
Battery		1 kW	96%	15 yrs	180,000	150,000	20,000
Converter							

Source: Techpoint Africa (2025) [23]

2.6.1 Photovoltaic System (Canadian Solar CS6U-340M)

PV output modeled using Homer equation:

$$P_{PV,t} = P_{rated}\left(\frac{G_t}{G_{STC}}\right)[1 - \beta(T_c - 25\ oC] \tag{6}$$

The PV module output was estimated using HOMER's standard formulation, which expresses the instantaneous power $P_{PV,t}$ as a function of the rated capacity, the incident solar irradiance, and the cell temperature. In this model, G_t is the solar radiation at time t, G_{STC} is the reference irradiance at standard test conditions, β is the temperature coefficient of the PV module, and T_c represents the operating cell temperature. This relationship accounts for both irradiance variation and temperature effects on PV performance.

2.6.2 Wind Turbine (3kW)

$$P_{WT} = \frac{1}{2}\rho \times A \times C_p \times V^3 \tag{7}$$

The wind turbine was analyzed using HOMER's built-in performance model, which relates its electrical output to the kinetic energy contained in the incoming wind. As shown in Equation (7), the turbine power P_{WT} depends on air density, the swept area of the rotor, the turbine's power coefficient, and the cube of the wind speed [24].

2.6.3 Biogas Generator (500kW)

The biogas generator performance was characterized using established models reported in the literature [25, 26]. Its fuel consumption F_{BG} is determined from the generated power output, the generator efficiency, and the lower heating value (LHV) of the biogas, as expressed in Equation (8).

$$F_{BG} = \frac{P_{gen}}{\eta_{gen} \times LHV} \tag{8}$$

2.6.4 Battery Storage (Lead Acid 1 kWh)

The battery state of charge (SOC) was modeled to account for charging and discharging dynamics. The SOC at the next time step SOC_{t+1} is calculated based on the current SOC as shown in equation 9, the charged power P_{ch} multiplied by the charging efficiency η_{ch}, and the discharged power P_{dis} divided by the discharging efficiency η_{dis}, normalized by the battery capacity E_{bat} [24]

$$SOC_{t+1} = SOC_t + \frac{P_{ch}\eta_{ch} - P_{dis}/\eta_{dis}}{E_{bat}} \tag{9}$$

2.6.5 Converter (Generic)

The inverter rating is obtained using Equation (10):

$$P_{inv} = P_{ACload} \times f_{ov} \tag{10}$$

In this equation, P_{inv} is the required inverter capacity (kW), P_{ACload} is the total alternating-current demand (kW), and f_{ov} is the oversizing factor typically set at 1.25. This allowance ensures the inverter can handle continuous operating loads as well as short-duration surges [27].

2.7 Techno-Economic Modeling in Homer Pro
2.7.1 Total Production

The total yearly electricity generated is obtained by summing the energy outputs of all system components Equation (11).

$$EP = \sum_{ij}^{n,1} E_{ij}$$ (11)

Where i to n denote system components, j represents the annual period, and E_{ij} is the energy produced.

2.7.2 Excess Electricity
Excess electricity represents the energy generated that cannot be used or stored [28], calculated using Equation (12).

$$Excess\ Electricity = \ Total\ energy\ produced - Total\ load$$ (12)

2.7.3 Unmet Load
The unmet load measures the fraction of the energy demand that the system fails to supply [29] and is calculated using Equation 13.

$$Unmet\ load = Total\ load - Total\ load\ met$$ (13)

2.7.4 Net present Cost
The NPC represents the total lifecycle cost of the system, including capital, replacement, operation and maintenance, and salvage costs, expressed in present value terms [30]. It is calculated as expressed in equation 14.

$$NPC = \frac{TAC}{CRF}$$ (14)

Where the Capital Recovery Factor (CRF) is defined as:

$$CRF = \frac{i(1+i)1^n}{i(1+i)1^n - 1}$$ (15)

In these expressions, i is the real interest rate and n is the system lifetime in years.

2.7.5 LCOE
The LCOE represents the ratio of the system's annualized cost to the total useful electricity delivered [31]. It is calculated using equation 16.

$$LCOE = \frac{TAC - C_{boiler}H_{serve}}{E_{serve}}$$ (16)

Where TAC is the total annualized system cost (₦/yr), C_{boiler} denotes the boiler's marginal cost (₦/kWh), H_{serve} is the total thermal load served (₦/kWh), and E_{serve} is the total electrical energy supplied.

2.7.6 Payback Period
The payback period is the time needed for an investment to recoup its initial cost from the net cash inflows generated by the project [32]. It is calculated as shown in equation 17.

$$Payback\ Period = \frac{initial\ investment\ (Cost\ of\ Project)}{Annual\ Net\ Cash\ Inflow}$$ (17)

3.0 Results and Discussion
3.1 Load Profile Analysis
A comprehensive load assessment for the University of Maiduguri identified hourly and seasonal demand characteristics across academic/administrative buildings, student hostels, and staff residential quarters. The academic blocks display a daytime load with an average consumption of 12,187 kWh/day and peak demand of 2,213.6 kW during academic hours (10:00–14:00) (see Figure 8). In contrast, the hostels and staff quarters exhibit a residential load profile, averaging 23,236 kWh/day with peaks between 18:00 and 22:00 due to evening activities as shown in Figure 9.

Seasonal load analysis indicates that academic energy loads fluctuate more due to school calendars and breaks, while residential loads remain stable year-round, influenced by continuous campus residency. A chronological heat-map created in HOMER Pro illustrates peak daytime demand in academic buildings, contrasted with steady, high evening demand from residential areas throughout the day.

Before simulation, load datasets were pre-processed in HOMER Pro, with a 60-minute time step and variability consistent with Nigerian university energy-modelling studies Hamidu et al., (2025) [33]. Loads were categorized into two streams: academic/admin (Load 1) and residential (Load 2), aiding accurate sizing of PV, wind, and WTE components. Mid-day academic peaks inform PV sizing, while evening residential loads necessitate wind and biogas generation. The combined campus peak demand of ~3.4 MW sets the minimum generation capacity required for system reliability.
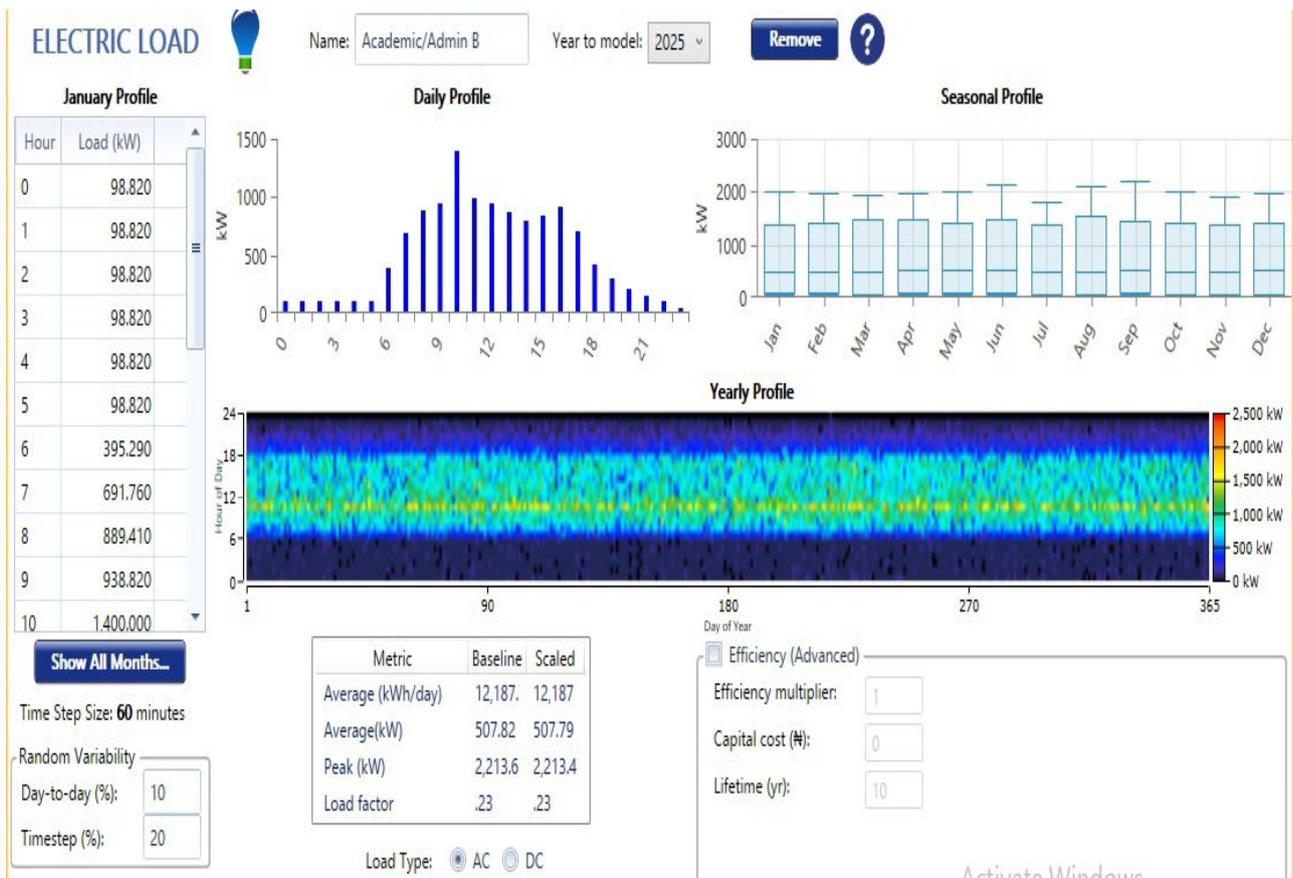
Figure 8. Hourly and monthly load profile for Academic and Administrative Buildings at the University of Maiduguri
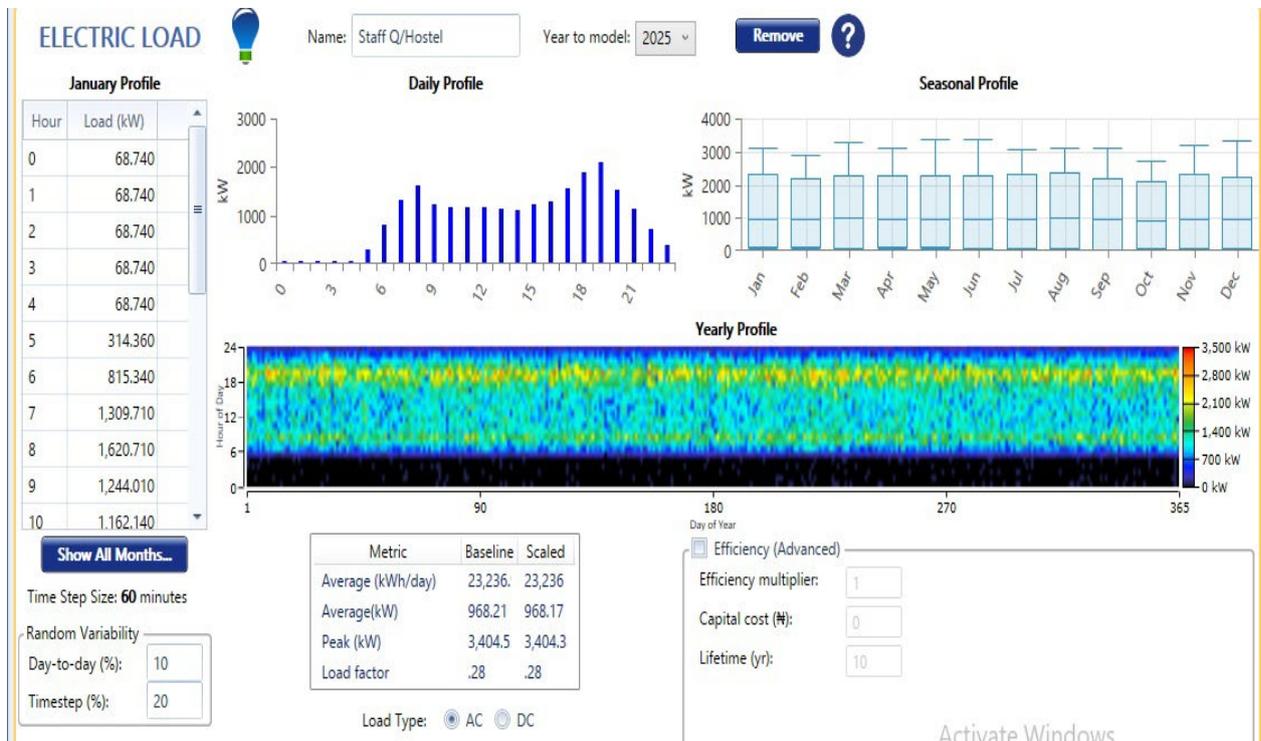

Figure 9. Hourly and monthly load profile for Hostel and Staff Residential Quarters at the University of Maiduguri

3.2 HOMER Pro Optimization Results

The HOMER Pro optimization was conducted using the load data and meteorological inputs to identify the least-cost and most reliable hybrid configuration.

Figure 10. HOMER Pro Optimization results for the evaluated hybrid system configurations

The HOMER Pro optimization results in Figure 10 identify the PV–wind–battery–converter-Biogas (WTE) configuration as the most techno-economically viable system among the examined options. The optimal configuration consists of 16,812 kW PV, 2,434 kW wind, 500 kW biomass, 17,972 kWh lead-acid storage, and a 3,718-kW bidirectional converter. This system achieves the lowest Net Present Cost (NPC), LCOE, and annual operating cost, making it the most cost-effective option with a 100% renewable fraction. Although it includes biomass fuel consumption (6,518 tons/year), the system still maintains full renewable penetration because biomass is classified as a renewable resource in HOMER. Alternative configurations with larger PV capacities or increased battery storage demonstrated significantly higher NPC, CAPEX, and LCOE values. For instance, systems with PV capacities above 30 MW and battery banks exceeding 50,000–90,000 kWh showed sharp increases in CAPEX and LCOE, making them economically unattractive despite achieving similar renewable fractions. These cost escalations are mainly due to oversizing of storage and converter capacities, leading to diminishing economic returns.
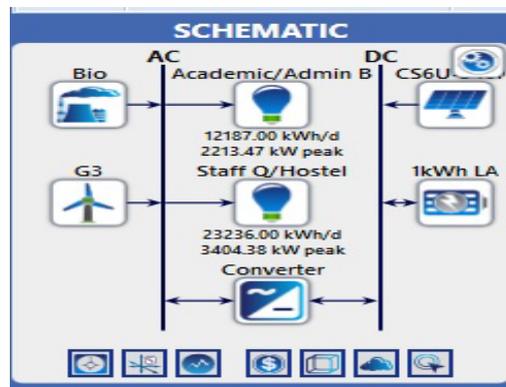

Figure 11. Optimized hybrid system architecture

The schematic in Figure 11 illustrates the AC–DC hybrid architecture used in HOMER Pro. The wind turbine (G3) and biomass generator supply the AC bus, while the CS6U-340M PV array feeds the DC bus, which is supported by the 1 kWh lead-acid battery bank. A bidirectional converter coordinates power exchange between the AC and DC buses. The two major load centers Academic/Admin Block (12,187 kWh/day, 2,213.47 kW peak) and Staff Quarters/Hostel (23,236 kWh/day, 3,404.38 kW peak) are efficiently supplied through this integrated topology. The optimization confirms that a balanced PV–wind–battery system with moderate storage offers the best trade-off between cost and performance. Increasing storage or PV capacity beyond the optimal point sharply increases NPC and LCOE without improving renewable penetration or system reliability.

3.3 System Component Model and Sizing Using HOMER Pro
a. PV Array Performance

Quantity	Value	Units
Rated Capacity	16,812	kW
Mean Output	3,401	kW
Mean Output	81,628	kWh/d
Capacity Factor	20.2	%
Total Production	29,794,319	kWh/yr

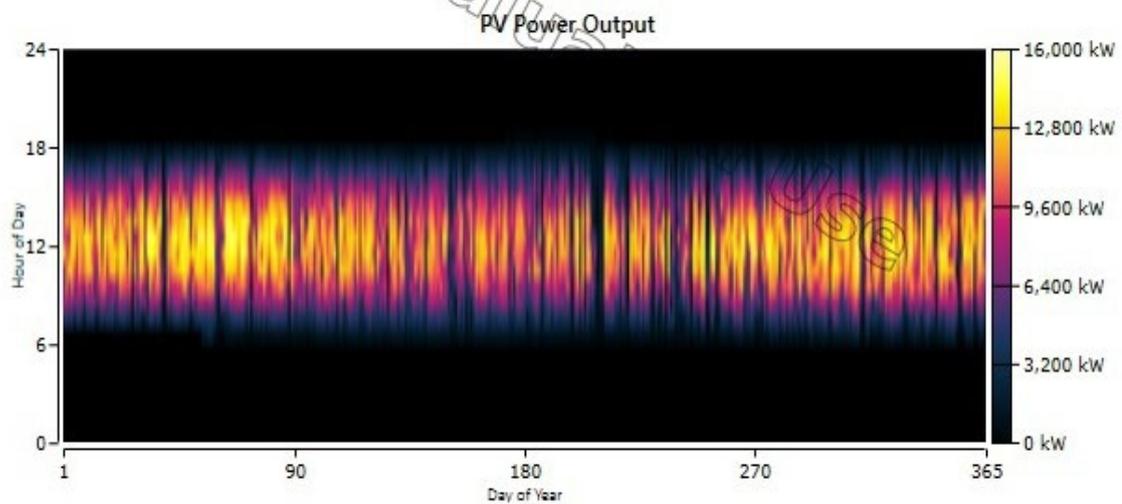| Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	15,269	kW
PV Penetration	230	%
Hours of Operation	4,361	hrs/yr
Levelized Cost	39.4	₦/kWh
Clipped production	0	kWh

Figure 12. PV power output: Annual diurnal distribution and performance metrics

Figure 12 presents the year-long diurnal variation for PV power output, visualized through a color plot (0–16,000 kW) mapped against hour of day and day of year. The PV configuration has a rated capacity of 16,812 kW and achieved a mean output of 3,401 kW, corresponding to a capacity factor of 20.2%. Annual PV energy production totaled 29,794,319 kWh. PV penetration is reported at 230%, indicating substantial resource availability relative to the electrical demand profile. The maximum instantaneous output was 15,269 kW, with minimum recorded as 0 kW, mapping directly to nighttime hours. Total operational hours equaled 4,361 per annum, accompanied by a levelized cost of energy of 39.4 ₦/kWh. Notably, no energy clipping was observed, confirming appropriate system sizing and inverter configuration. The annual profile demonstrates predictable diurnal generation peaks and consistent seasonal performance, supporting the reliability and economic viability of large-scale PV integration within the hybrid system, which aligns with recent technoeconomic studies reporting comparable PV performance and cost behaviour in Nigeria and Sub-Saharan Africa [34. 35].

b.   Wind Turbine Power Output and Annual Performance

Quantity	Value	Units
Total Rated Capacity	7,302	kW
Mean Output	1,520	kW
Capacity Factor	20.8	%
Total Production	13,311,150	kWh/yr

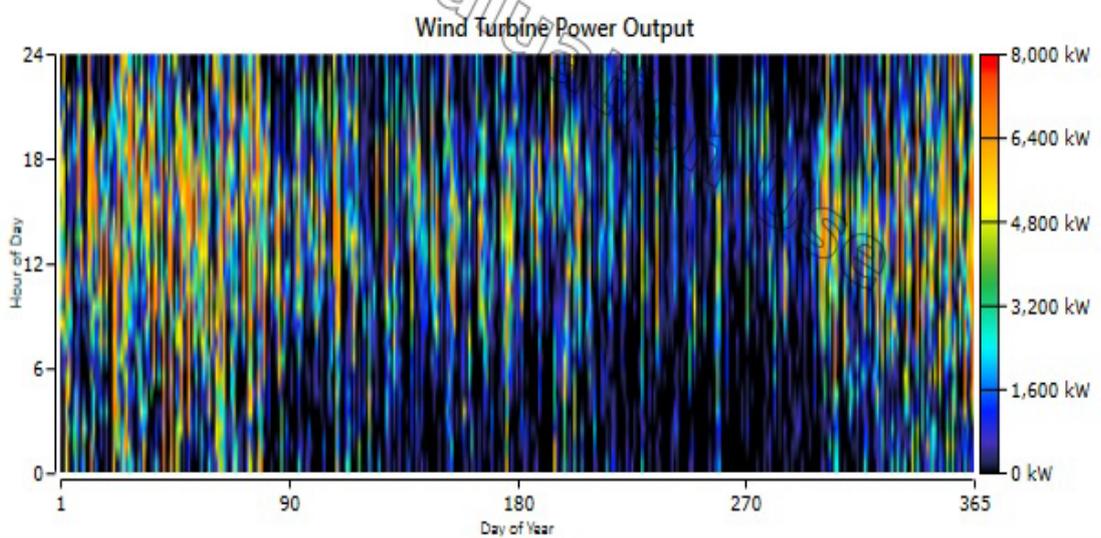| Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	7,302	kW
Wind Penetration	103	%
Hours of Operation	7,233	hrs/yr
Levelized Cost	32.7	₦/kWh

Figure 13. Wind turbine power output: annual diurnal distribution and performance metrics

Figure 13 displays the annual distribution of wind turbine power output, with a detailed color density plot showing hourly power generation (0–8,000 kW) for each day across the year. The corresponding summary statistics report a total rated capacity of 7,302 kW, mean output of 1,520 kW, and an annual capacity factor of 20.8%. Total wind production reached 13,311,150 kWh/yr, with wind penetration at 103%. Maximum output coincided with the rated capacity (7,302 kW), while the minimum was 0 kW, reflecting periods of low or absent wind resource. The turbine operated for 7,233 hours per year, with a calculated levelized cost of energy at 32.7 ₦/kWh. These results underline the significant temporal variability in wind generation and its capability to meet system demand during high-resource intervals, consistent with recent wind-energy assessments that report similar capacity factors, variability patterns, and techno-economic performance in Nigeria and Sub-Saharan Africa [36, 37].

c. The annual operational profile and key performance indicators of the Generator

Quantity	Value	Units
Hours of Operation	3,280	hrs/yr
Number of Starts	565	starts/yr
Operational Life	6.10	yr
Capacity Factor	35.3	%
Fixed Generation Cost	42,000	₦/hr
Marginal Generation Cost	0	₦/kWh

Quantity	Value	Units
Electrical Production	1,547,383	kWh/yr
Mean Electrical Output	472	kW
Minimum Electrical Output	150	kW
Maximum Electrical Output	500	kW

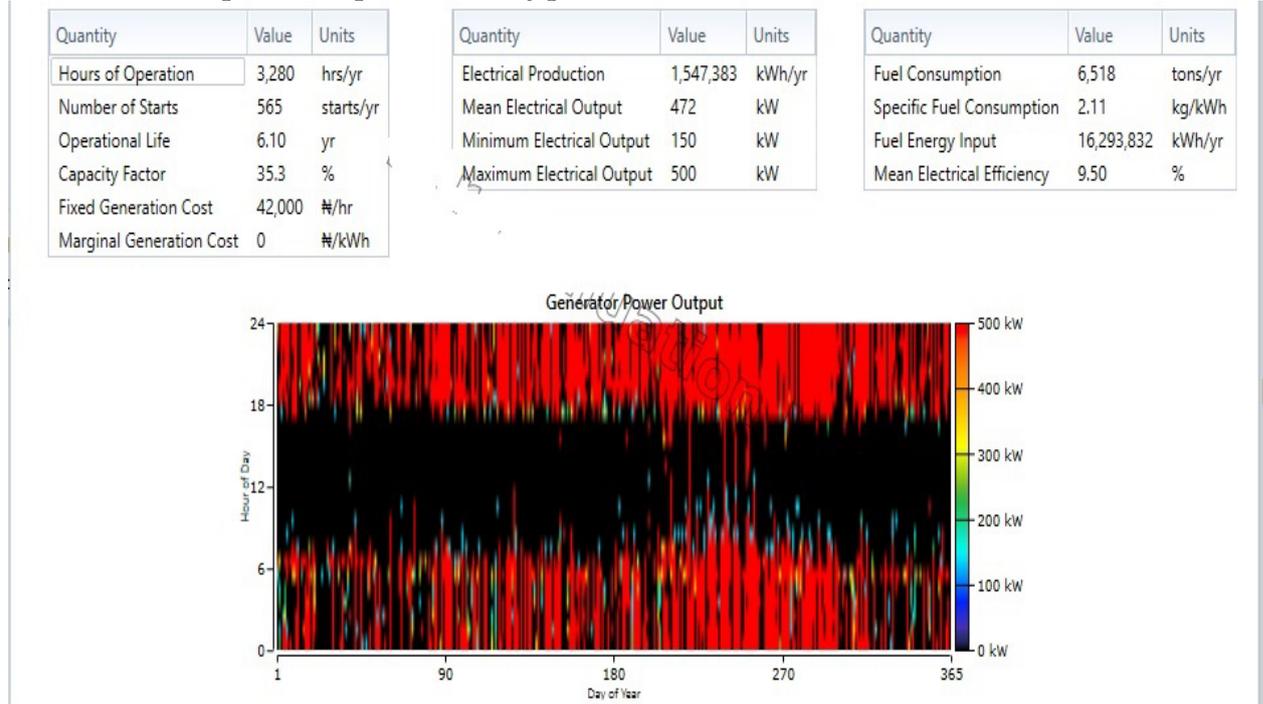| Quantity	Value	Units
Fuel Consumption	6,518	tons/yr
Specific Fuel Consumption	2.11	kg/kWh
Fuel Energy Input	16,293,832	kWh/yr
Mean Electrical Efficiency	9.50	%

Figure 14. Annual Operational Profile and key Performance indicators of the Generator

Figure 14 illustrates the annual operational profile and key performance indicators of the generator, highlighting a total electrical production of 1,547,383 kWh/yr at a mean output of 472 kW and a capacity factor of 35.3%. The time-series plot reveals that the generator predominantly operates near its rated capacity (up to 500 kW) throughout the year, as indicated by the high-density regions in the output profile. This consistent performance, despite 565 annual starts and variable load conditions, underscores the unit's operational reliability and efficiency, essential for hybrid energy system integration at scale, and this behaviour aligns with documented operational patterns and techno-economic characteristics of diesel generators used in hybrid PV–diesel systems across the Sahel and broader developing regions [38], [39].

a) Battery Bank Performance and State-of-Charge Profile

Quantity	Value	Units
Batteries	17,972	qty.
String Size	4.00	batteries
Strings in Parallel	4,493	strings
Bus Voltage	48.0	V

Quantity	Value	Units
Autonomy	7.31	hr
Storage Wear Cost	419	₦/kWh
Nominal Capacity	17,986	kWh
Usable Nominal Capacity	10,792	kWh
Lifetime Throughput	14,377,600	kWh
Expected Life	9.88	yr

Quantity	Value	Units
Average Energy Cost	0	₦/kWh
Energy In	1,626,660	kWh/yr
Energy Out	1,301,328	kWh/yr
Storage Depletion	0.340	kWh/yr
Losses	325,332	kWh/yr
Annual Throughput	1,454,929	kWh/yr

Figure 15. Battery bank performance and state-of-charge profile

As shown in Figure 15, the battery subsystem is characterized by a high capacity configuration of 17,972 cells arranged with a 4.493 parallel string factor and a nominal storage capacity of 17,986 kWh, with an expected life of approximately 9.88 years. The frequency histogram and time-series plot indicate that the battery state of charge (SOC) is predominantly maintained above 80% throughout the year, reflecting effective charge management and

minimizing deep cycling events that contribute to wear cost (₦419/kWh) and storage depletion (0.340 annual units). Monthly SOC boxplots confirm stable battery operation, with minimal deviations across all months, supporting the overall system's reliability and storage efficiency, which is consistent with documented performance behaviour of lithium-based storage systems in hybrid renewable microgrids operating under similar climatic and techno-economic conditions [40], [41].

d. Annual Performance Metrics and Diurnal Variation of Inverter and Rectifier Outputs

Quantity	Inverter	Rectifier	Units
Capacity	3,718	3,718	kW
Mean Output	631	87.4	kW
Minimum Output	0	0	kW
Maximum Output	3,718	3,718	kW
Capacity Factor	17.0	2.35	%/

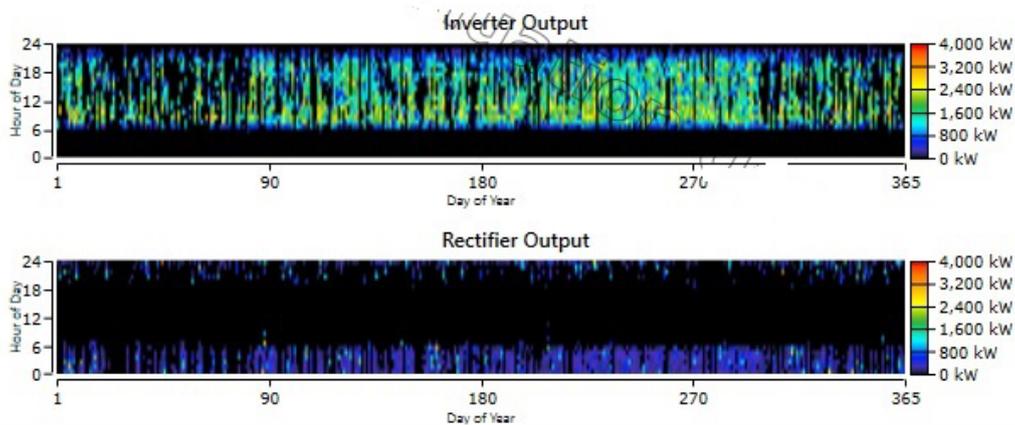| Quantity	Inverter	Rectifier	Units
Hours of Operation	4,213	3,088	hrs/yr
Energy Out	5,524,636	765,422	kWh/yr
Energy In	5,815,406	805,708	kWh/yr
Losses	290,770	40,285	kWh/yr

Figure 16. Annual performance metrics and diurnal variation of inverter and rectifier outputs

Figure 16 presents the annual operational analysis of both inverter and rectifier subsystems, including key quantitative performance indicators and time-resolved output profiles. The rated capacities for inverter and rectifier units are both 3,718 kW, with observed mean outputs of 631 kW and 87.4 kW, respectively. Annual capacity factors were calculated as 17.0% for the inverter and 2.35% for the rectifier, signifying marked differences in utilization rates. Instantaneous outputs ranged from 0 up to their rated capacity (3,718 kW) for each device. For the inverter, total annual energy out was 5,524,636 kWh, based on 4,213 hours of operation. Energy in reached 5,815,406 kWh, resulting in measured conversion losses of 290,770 kWh/year. The rectifier subsystem generated 765,422 kWh/year, with corresponding energy input of 805,708 kWh/year, and losses totaling 40,285 kWh/year across 3,088 hours of operation. The lower color-density plots visualize the hourly variation in output over the entire year. The inverter output profile displays persistent, temporally heterogeneous operation typical of variable renewable source coupling, while the rectifier output is active for a more limited number of hours and at significantly lower levels, reflecting its ancillary or backup role within the hybrid system, which aligns with documented characteristics of bidirectional power-electronics interfaces in PV–battery hybrid microgrids, particularly regarding conversion efficiency ranges, loss behaviour, and operational asymmetry between inverter and rectifier modes [42], [43].

3.4 Techno-Economic Results analysis
a. Total Production

Figure 17. Annual energy balance and monthly production profile

As shown in Figure 17, the annual electricity production is primarily driven by the PV array, which generates 29.79 GWh/yr, forming the backbone of the hybrid system. The 3-kW wind turbine contributes a substantial 13.31 GWh/yr, making it the second-largest energy source in the configuration and providing valuable complementarity to solar output, especially during periods of reduced irradiance. The 500-kW biogas Genset adds 1.55 GWh/yr, operating mainly as a stabilizing and dispatch-support resource rather than a base load unit. Together, these components yield a total generation of 44.65 GWh/yr, far above the annual load requirement of 12.92 GWh/yr. This result is in a high renewable penetration, substantial excess electricity (≈31.1 GWh/yr) and it has a capacity shortage of 0.09 percent and a minimal unmet load of 0.06%, reflecting significant oversizing an outcome driven by the system's design priority on reliability in a critical institutional environment. The monthly production pattern shows consistently strong PV and wind contributions, with wind generation helping to smooth seasonal dips in solar output around June–August. Biogas generation remains steady throughout the year, offering operational flexibility during low-wind or low-solar intervals, a performance trend consistent with documented multi-source hybrid systems where PV–wind complementarity and biofuel-based dispatchable generation significantly enhance reliability in high-variability regions [36], [44].
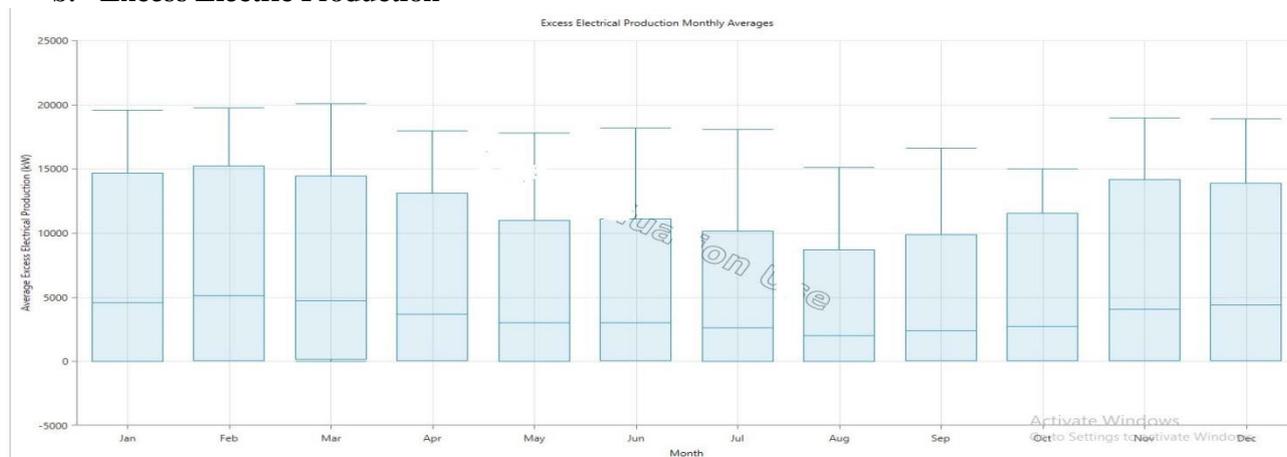
b. Excess Electric Production

Figure 18. Monthly averages of excess electrical production

As shown in Figure 18, the system records consistently high excess electricity throughout the year, with monthly averages oscillating between roughly10-20 MW and wider hourly variability captured in the box-plot spread, signaling substantial over generation driven mainly by the oversized PV–wind combination relative to the institutional load. This surplus present even in the traditionally low-resource months of June–August highlights a

resilient generation margin that ensures uninterrupted supply even under worst-case demand or resource fluctuations, a behaviour consistent with documented hybrid PV–wind systems where deliberate oversizing improves reliability and resilience in microgrids with variable renewable resources [45], [36].
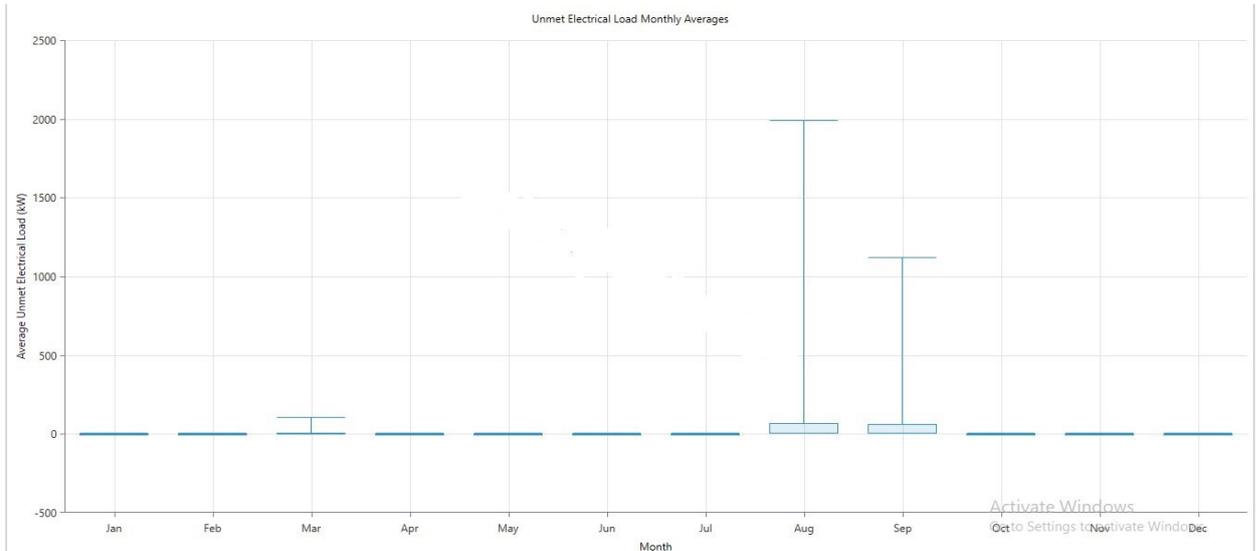
c. Unmet Load

Figure 19. The monthly averages of unmet electrical

As shown in Figure 19, the monthly averages of unmet electrical load remain negligible for most of the year, except for significant spikes observed in August and September. This pattern reveals that the system consistently satisfies the electrical demand under typical conditions, but may experience temporary shortages during peak loads or seasonal disturbances. The pronounced increase in unmet load during late summer highlights critical periods where system resilience or backup strategies should be reinforced to ensure uninterrupted power supply, reflecting the importance of robust hybrid system design and proactive reliability planning. , a trend consistent with documented findings in hybrid PV–wind–diesel systems where unmet load remains minimal under optimal design but may spike during low-resource or high-demand periods [44], [45].

d. NPC

Figure 20. Component-wise cost breakdown

As shown in Figure 20, the annualized cost analysis by component reveals that the Generic 1kWh Lead Acid batteries and Canadian Solar Max Power CS6U-340M modules account for the highest expenditures, with total lifecycle costs of ₦18,209,613,256.94 and ₦15,164,219,006.66, respectively. The detailed table indicates that the battery system's costs arise mainly from capital (₦10,140,000,000.00) and replacement (₦4,807,090,685.04), while the PV module is driven primarily by its capital investment (₦9,078,654,575.86). Other components such as the Generic 3 kW module, biogas genset, and system converter show considerably lower total costs of ₦6,075,845,969.69, ₦2,684,027,682.08, and ₦4,453,608,818.29, respectively, underscoring the cost-intensive nature of energy storage within hybrid energy systems, , a pattern consistent with techno-economic studies

indicating that battery storage and PV modules dominate lifecycle costs in hybrid PV–wind–diesel or PV–biogas systems [45], [36].
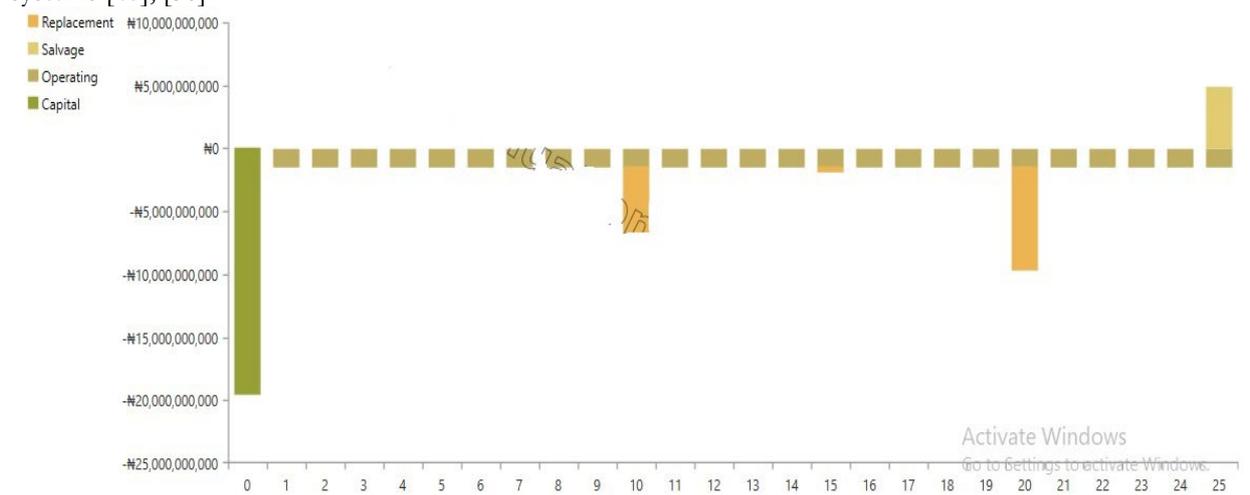

Figure 21. The project's cost flow profile

Figure 21 presents the project's cost flow profile, where the dominant upfront capital investment is clearly visible in Year 0, followed by relatively stable operating expenses over the system lifetime and periodic replacement costs around Years 10 and 20. The salvage value appearing at the end of the project horizon offsets part of the long-term expenditure, illustrating a typical lifecycle pattern of high initial CAPEX followed by predictable OPEX and scheduled component renewals, a pattern consistent with documented lifecycle cost analyses of hybrid PV–wind–diesel and PV–biogas systems, where initial capital dominates and component replacement and salvage are key drivers of long-term economic performance [45], [36].

Levelized Cost of Energy (LCOE)
Over the course of its 25-year lifespan, the Levelized Cost of Energy estimates the average cost per kilowatt-hour produced by the suggested hybrid system. The LCOE was calculated using the estimated lifetime energy generation of 44,652,852 kWh annually over 25 years and the total life-cycle expenditure of ₦42,640,933,283.21.

$$\text{LCOE} = \frac{\text{Total Life} - \text{Cycle Cost (₦42,640,933,283.21)}}{\text{Total Energy Produced Over 25 Years (44,652,852 kWh/year} \times \text{25 years}}$$

An LCOE of ₦38.2/kWh is obtained by substituting the values. This price is even more affordable than typical Nigerian rid tariffs, which typically range between ₦90 and ₦210/kWh, and significantly less expensive than the current cost of diesel-generated electricity. These results are consistent with both Hamidu *et al.* (2025b) [2] and the Hamidu, *et al* (2025d) [46] which confirmed that PV-based hybrid systems provide electricity at a substantially lower and more stable long-term cost compared to conventional supply

Simple Payback Period
The simple payback period was used to determine how quickly the project can recover its initial capital outlay. With a local grid tariff of ₦209/kWh (Band A) and an annual system output of 44,652,852 kWh, the yearly financial savings were computed as:

$$\text{Annual Cost Offset} = 44,652,852 \text{ kWh/year} \times ₦209/\text{kWh} = ₦9,332,446,068 \text{ kWh/year}$$

The initial capital cost of the system is ₦19,563,434,225.77. Thus, the simple payback period is:

$$\text{Payback Period} = \frac{₦19,563,434,225.77}{₦9,332,446,068 \text{ kWh/year}} \approx 2.1 \text{ Years}$$

This relatively short recovery time shows that the investment becomes financially beneficial early in its operational life, further reinforcing the system's economic attractiveness. This trend aligns with the findings of Hamidu *et al.* (2025b) [2] which reported a short payback time due to high avoided diesel expenses.

4.0 Conclusion and Recommendation
4.1 Conclusion
This study set out to design a reliable and cost-effective hybrid energy system capable of meeting the University of Maiduguri's growing electricity needs in the face of persistent grid instability, rising diesel costs, and the increasing burden of municipal solid waste. The system offers a workable solution to campus energy security and

environmental management issues by combining solar PV, wind power, and a waste-to-energy biogas generator into a single AC–DC coupled architecture. The PV–wind–WTE–battery configuration offers the best balance of cost, reliability, and renewable penetration, according to the HOMER Pro optimization results. The system maintains very low unmet demand, produces significantly more energy than the annual load, and reaches a 100% renewable fraction. Solar PV forms the backbone of generation, wind provides strong seasonal support, and the biogas generator serves as a dependable dispatch able unit, especially during periods of low solar and wind availability. Although the battery bank and PV array account for most of the lifecycle cost, their contribution is essential in achieving high reliability for a critical institution like UNIMAID.

4.2 Recommendation

1. Adopt the PV–wind–WTE configuration as the primary campus energy strategy, as it offers the lowest NPC and LCOE while ensuring high reliability.
2. Develop a structured waste-collection and segregation program to sustain biogas production and improve the efficiency of the WTE component.
3. Gradually expand the PV and wind capacities in phases, using the surplus energy potential to support future campus expansion or ancillary services.
4. Improve energy-use management, especially during peak periods in August–September when unmet load is highest.
5. Consider integrating a smart-monitoring and demand-response system to ensure better control of load fluctuations across academic and residential areas.
6. Conduct periodic performance reviews to reassess component lifetimes, replacement schedules, and operational costs as technology prices continue to fall.

Acknowledgements

References

[1] M. M. Hamidu, A. M. El-Jummah, and M. Shuwa, "An assessment of power sources for improved energy supply in University of Maiduguri," FUDMA Journal of Engineering and Technology, vol. 1, no. 2, pp. 597–606, 2025.

[2] M. M. Hamidu, M. Katambi, and O. Faruq, "Techno-economic and environmental assessment of a solar PV-based microgrid for residential electrification in Gwange I, Maiduguri using HOMER Pro," FUDMA Journal of Engineering and Technology, vol. 1, no. 2, pp. 513–525, 2025.

[3] M. M. Hamidu, A. M. El-Jummah, and M. Shuwa, "Modeling and simulation of a solar farm using HOMER Pro software for University of Maiduguri Senate Complex," Arid Zone Journal of Engineering, Technology and Environment, vol. 21, no. 3, pp. 811–819, 2025.

[4] M. Dauda and O. O. Osita, "Solid waste management and re-use in Maiduguri, Nigeria," 2003. [Online]. Available: https://hdl.handle.net/2134/30546

[5] N. C. Amulah, M. B. Oumarou, and A. B. Muhammad, "Exergy analysis of waste-to-energy technologies for municipal solid waste management," Environ. Nat. Resour. J., vol. 22, no. 3, pp. 232–243, 2024, doi: 10.32526/ennrj/22/20240023.

[6] S. Kaza, L. Yao, P. Bhada-Tata, and F. Van Woerden, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, Washington, DC: World Bank, 2018.

[7] O. F. Kofoworola, "Comparative assessment of the environmental implication of management options for municipal solid waste in Nigeria," Int. J. Waste Resour., vol. 7, no. 1, Article 1000259, 2016.

[8] M. B. Oumarou, S. Shodiya, G. M. Ngala, and M. A. Bashir, "Artificial neural network modelling of the energy content of municipal solid wastes in Northern Nigeria," Arid Zone J. Eng., Technol. Environ., vol. 13, no. 6, pp. 840–847, 2017.

[9] F. Pande, H. Thakre, S. Ladukar, and D. Radke, "Designing and optimizing a hybrid renewable system using HOMER for a site selected," IJSRSET, vol. 3, no. 2, pp. 165–170, 2017.

[10] R. Yasmin, M. N. Nabi, F. Rashid, and M. A. Hossain, "Solar, wind, hydrogen, and bioenergy-based hybrid system for off-grid remote locations," Clean Technologies, vol. 7, no. 2, p. 36, 2025.

[11] O. Krishan and S. Suhag, "Techno-economic analysis of a hybrid renewable-energy system for an energy-poor rural community," J. Energy Storage, vol. 23, pp. 305–319, 2019.

[12] T. Ma, H. Yang, L. Lu, and J. Peng, "Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong," Renewable Energy, vol. 69, pp. 7–15, 2014.

[13] A. B. Muhammad, S. Shodiya, and G. N. Ngala, "Feasibility of solar-wind hybrid power system for Maiduguri area of Nigeria," Univ. Maiduguri Seminar Series, 2015.

[14] S. A. Ishraque, F. Shezan, and M. M. Rahman, "Design and implementation of a hybrid solar–wind–biomass renewable energy system considering meteorological conditions," Int. J. Photoenergy, vol. 2022, Art. 8792732, 2022.

[15] S. Chandra, A. Gupta, R. Singh, and A. Kalamdhad, "Assessment of landfill gases and energy recovery potential using LandGEM: A case study," Sci. Rep., vol. 13, Art. 6782, 2023.

[16] S. W. Chisale, K. J. Gondwe, and L. S. Ziba, "Optimization and design of hybrid renewable energy systems using HOMER Pro," Energy Reports, vol. 9, pp. 358–370, 2023.

[17] C. A. Moraes, L. S. de Carvalho, and G. Vieira, "Biogas-based electricity production from landfills using LandGEM methane modelling and HOMER optimization," Appl. Energy, vol. 352, Art. 121999, 2024.

[18] M. M. Hamidu, A. M. El-Jummah, and M. Shuwa, "An assessment of power sources for improved energy supply in University of Maiduguri," FUDMA J. Eng. Technol., vol. 1, no. 2, pp. 597–606, 2025.

[19] O. Adeyanju and L. Manzella, "Electric load modeling for university microgrids in developing countries," Energy Sustain. Develop., vol. 65, pp. 92–102, 2021.

[20] I. Igbinovia, C. Emetere, and O. Oladimeji, "Characterization of electricity consumption patterns in Nigerian educational institutions," Heliyon, vol. 9, no. 1, e12851, 2023.

[21] O. M. Amoo and O. A. Fagbenle, "Relationship between municipal solid waste composition and calorific value for energy generation," Int. J. Energy Environ. Eng., vol. 4, no. 2, pp. 1–7, 2013.

[22] M. M. Hamidu, "Development of MATLAB-based model for solar radiation prediction and photovoltaic panel tilt optimization angle for Maiduguri region, Nigeria," FUDMA J. Eng. Technol., vol. 1, no. 2, pp. 649–657, 2025.

[23] Techpoint Africa, "Price list of solar PV and battery components in Nigeria," 2025.

[24] T. Lambert, P. Gilman, and P. Lilienthal, *Micropower System Modeling with HOMER*, NREL/TP-710-39154, 2006.

[25] A. J. Onwuegbuzie, E. D. Onwuegbuzie, and S. C. Okeke, "Electricity generation from organic municipal waste: A Nigerian scenario," Energy Convers. Manage., vol. 251, 115003, 2022.

[26] P. Sahu, V. Patel, and T. Hiloidhari, "Biogas-based power generation: A review on techno-economic assessment," Renewable Sustain. Energy Rev., vol. 102, pp. 449–464, 2019.

[27] N. D. Nordin and H. A. Rahman, "A novel optimization method for designing standalone photovoltaic systems," Renewable Energy, vol. 89, pp. 706–715, 2016.

[28] C. Li, D. Zhou, and Y. Zheng, "Techno-economic comparative study of grid-connected PV power systems in five climate zones, China," Energy, vol. 165, pp. 1352–1369, 2018.

[29] H. Masrur et al., "Analysis of techno-economic-environmental suitability of an isolated microgrid system located in a remote island of Bangladesh," Sustainability, vol. 12, no. 7, 2880, 2020.

[30] M. Abdelaziz, M. Ali, and M. Eltamaly, "Modeling and simulation of smart grid integrated with hybrid renewable energy systems," *Studies in Systems, Decision and Control*, vol. 121, Springer, 2018.

[31] L. Bartolucci et al., "Fuel cell-based hybrid renewable energy systems for off-grid telecom stations: Data analysis and system optimization," Appl. Energy, vol. 252, 113386, 2019.

[32] S. Bragg, "Payback method: Payback period formula," AccountingTools, 2025. [Online]. Available: https://www.accountingtools.com/articles/payback-method-payback-period-formula

[33] M. M. Hamidu, A. M. El-Jummah, and M. Shuwa, "Modeling and simulation of a solar farm using HOMER Pro software for University of Maiduguri Senate Complex," Arid Zone J. Eng., Technol. Environ., vol. 21, no. 3, pp. 811–819, 2025.

[34] A. O. Adeniran, A. M. Akinyemi, and M. A. Olatunji, "A comprehensive analysis on the grid-tied solar photovoltaics for clean energy mix and supply in Nigeria's on-grid power," J. Eng. Sci., vol. 10, no. 2, pp. 75–88, 2023.

[35] S. Singh, M. Bhargava, and S. Muneer, "Comparative techno-economic analyses and optimisation of standalone and grid-tied renewable energy systems for South Asia and Sub-Saharan Africa," Energy Nexus, vol. 15, 100391, 2024.

[36] M. S. Adaramola, "Assessment of wind power potential and wind electricity generation using WECS in north-central Nigeria," Energy Convers. Manage., vol. 87, pp. 384–394, 2014.

[37] O. Ajayi and O. O. Ohijeagbon, "Wind energy potential in Nigeria: A review of data and techno-economic evaluation," Renewable Energy, vol. 133, pp. 1100–1113, 2019.

[38] A. S. Maiga, C. Bocci, M. B. Dia, S. Coulibaly, and A. M. Thiam, "Renewable energy options in the Sahel: Hybrid solar–diesel systems," Renewable Energy, vol. 33, no. 11, pp. 2339–2343, 2008.

[39] R. Sen and S. C. Bhattacharyya, "Off-grid electricity generation with renewable energy technologies in India: An application of HOMER," Energy, vol. 52, pp. 256–265, 2013.

[40] D. Parra, M. Gillott, G. S. Walker, and L. F. Toledo, "An overview of battery storage systems for stationary applications in the smart grid and energy system," Appl. Energy, vol. 230, pp. 1747–1761, 2018.

[41] A. Divya and J. Østergaard, "Battery energy storage technology for power systems—An overview," Electr. Power Syst. Res., vol. 79, no. 4, pp. 511–520, 2009.

[42] H. Wang, X. Qin, and X. Lin, "A review of bidirectional DC/AC converters for energy storage systems," Renewable Sustain. Energy Rev., vol. 135, 110119, 2021.

[43] T. Zhao, G. Wang, S. Bhattacharya, and A. Q. Huang, "Performance of medium-voltage high-power bidirectional solid-state transformer based on 15-kV SiC MOSFETs," IEEE Trans. Ind. Appl., vol. 49, no. 4, pp. 1892–1905, 2013.

[44] S. Rehman, L. M. Al-Hadhrami, and M. M. Alam, "Pumped-hydro energy storage system: A technological review," Renewable Sustain. Energy Rev., vol. 44, pp. 586–598, 2015.

[45] A. Mohamed, S. Al-Saadi, and S. M. Shaahid, "Techno-economic assessment of PV–wind hybrid systems for reliable off-grid electricity supply in rural areas," Renewable Energy, vol. 119, pp. 112–123, 2018.

[46] M. M. Hamidu, O. Faruq, and M. Katambi, "Design and optimization of standalone solar PV system for the Department of Mechanical Engineering, University of Maiduguri using HOMER Pro," DUJOPAS, vol. 11, no. 3e, pp. 359–374, 2025.