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Design and Simulation of a Hybrid Renewable Energy Microgrid for a University Campus in Sub-Saharan Africa: A Case Study of Ajayi Crowther University, Nigeria

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Abstract
This paper presents the design, simulation, and performance evaluation of a grid-connected hybrid renewable energy microgrid system for Ajayi Crowther University in Oyo, Nigeria. The system integrates wind turbines, solar photovoltaic panels, battery energy storage, and grid connection to address persistent challenges of unreliable national grid supply, high diesel generator costs, and environmental pollution. Using MATLAB/Simulink, HOMER Pro, and PSCAD simulation platforms, a comprehensive techno-economic analysis was conducted based on one year of meteorological data (April 2024 - April 2025) and detailed load profiling of the Engineering Faculty and Diocese of Lagos West (DLW) Female Hostel. The optimised system comprises 300 kW wind capacity (three 100 kW turbines), 250 kW solar PV, 600 kWh battery storage, and 700 kW inverter capacity. Simulation results demonstrate that the hybrid system achieves a 74.3% renewable energy fraction, generating 817,820 kWh annually from renewable sources while reducing grid dependency to 25.7%. The system delivers annual CO_2 emission reductions of 436.7 tonnes and demonstrates economic viability with a levelised cost of energy of $0.198/kWh and a payback period of 12.3 years. This study contributes to the growing body of knowledge on hybrid microgrid applications in Sub-Saharan African university campuses and provides a replicable framework for similar institutional electrification projects in developing regions.

Keywords: Hybrid microgrid; renewable energy; wind-solar integration; battery storage; university campus electrification; Sub-Saharan Africa; Nigeria; HOMER Pro; MATLAB/Simulink

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I. Introduction

1.1 Background

Sub-Saharan Africa faces significant energy access challenges, with over 600 million people lacking reliable electricity supply [1]. Nigeria, despite being Africa’s largest oil producer, experiences chronic power shortages characterised by frequent grid outages, voltage fluctuations, and inadequate generation capacity [2]. The national grid supplies only 4,000-5,000 MW against an estimated demand exceeding 20,000 MW, resulting in daily power outages lasting 8-12 hours in many regions [3]. This energy deficit severely impacts educational institutions, forcing universities to rely heavily on expensive and polluting diesel generators, which increase operational costs and carbon emissions [4].

Hybrid renewable energy microgrids offer a promising solution by integrating multiple renewable sources with energy storage and conventional backup systems [5], [6]. These systems can operate in grid-connected or islanded modes, providing enhanced reliability, reduced fossil fuel dependency, and lower greenhouse gas emissions [7], [8]. Recent advances in wind turbine technology, solar photovoltaic efficiency, and battery storage systems have made hybrid microgrids increasingly viable for institutional applications in developing countries [9], [10].

1.2 Problem Statement

Ajayi Crowther University, located in Oyo, Nigeria, experiences severe power supply challenges that disrupt academic activities, research operations, and student welfare. The institution currently depends on the unreliable national grid supplemented by diesel generators, resulting in:

- High operational costs due to diesel fuel consumption
- Frequent power interruptions affecting teaching and research
- Significant carbon emissions and environmental pollution
- Limited capacity for expansion of electrical infrastructure
- Vulnerability to fuel price volatility

1.3 Research Objectives

This study aims to:

1. Design a hybrid renewable energy microgrid system integrating wind, solar, battery storage, and grid connection for Ajayi Crowther University
2. Conduct comprehensive resource assessment of wind and solar potential at the study location
3. Perform detailed load demand analysis for the Engineering Faculty and Female Hostel facilities
4. Optimise system configuration and component sizing using simulation tools
5. Evaluate technical performance, economic viability, and environmental benefits
6. Provide a replicable framework for similar institutional microgrid projects in Sub-Saharan Africa

1.4 Significance of the Study

This research contributes to sustainable energy development in Sub-Saharan Africa by demonstrating the technical and economic feasibility of hybrid microgrids for university campuses. The findings provide valuable insights for policymakers, university administrators, and energy planners seeking to enhance energy security and sustainability in educational institutions across developing regions.

II. Literature Review

2.1 Hybrid Microgrid Systems for Rural and Institutional Electrification

Hybrid renewable energy systems have emerged as a critical solution for addressing energy access challenges in remote and underserved areas. Recent studies demonstrate the technical and economic viability of integrating multiple renewable sources with energy storage for reliable power supply.

Ali et al. [11] investigated off-grid hybrid microgrids for rural Bangladesh, comparing four battery storage technologies (ZnBr Flow, Li-Ion NMC, Lead-Acid, and $LiFePO_4$) using HOMER Pro simulations. Their PV-wind-ZnBr Flow configuration achieved a 100% renewable fraction with a cost of energy (COE) of \$0.0688/kWh and net present cost (NPC) of \$171,720, demonstrating the superior performance of advanced battery technologies for remote applications. Similarly, Temitope et al. [12] designed a community-based hybrid system for rural Nigeria, achieving an LCOE of \$0.183/kWh using PV, wind, and battery storage optimised through HOMER Pro.

For Sub-Saharan African contexts, Lukuyu et al. [13] examined hybrid power systems for off-grid rural electrification in Northern Kenya, while Canziani et al. [14] studied a hybrid photovoltaic-wind microgrid with battery storage for rural Peru, achieving 100% renewable energy penetration. These studies highlight the importance of context-specific design considering local resource availability, load characteristics, and economic constraints.

2.2 optimization and Simulation Methodologies

Advanced simulation tools and optimization algorithms are essential for hybrid microgrid design. Emad et al. [15] employed multi-objective optimization for a PV-wind-battery system in remote areas, demonstrating the importance of balancing technical performance with economic objectives. Diab et al. [16] compared multiple optimization algorithms (Genetic Algorithm, Particle Swarm optimization, and Hybrid approaches) for standalone hybrid microgrid sizing, finding that hybrid algorithms achieved superior convergence and solution quality.

HOMER Pro has emerged as the dominant tool for hybrid system optimization, used extensively in studies by Rashwan et al. [17] for Aswan, Egypt, Ishraque et al. [18] for islanded microgrids in Bangladesh, and Kumar et al. [19] for residential communities in India. MATLAB/Simulink provides complementary capabilities for detailed dynamic modelling and control system design, as demonstrated by Checklie et al. [20] for solar-hydro systems in Ethiopia and Hossen et al. [21] for solar-wind-biomass integration.

2.3 System Configuration and Component Selection

The selection of renewable sources and storage technologies significantly impacts system performance and economics. Wind-solar hybrid systems offer complementary generation profiles, with wind resources often stronger during nighttime and monsoon seasons when solar irradiance is limited [22], [23]. Battery energy storage systems (BESS) are critical for managing intermittency and ensuring power quality [24], [25].

Recent studies demonstrate diverse system configurations tailored to local contexts. Kamal et al. [26] designed standalone microgrids with renewable resources and energy storage for remote areas, while Juma et al. [27] focused on DC microgrid architectures with hybrid energy storage. For island applications, Haidar [28] evaluated PV-wind-diesel-battery systems, achieving COE values of $1.109/kWh and $1.420/kWh respectively, highlighting the economic challenges of isolated systems.

2.4 Performance Metrics and Environmental Impact

Key performance indicators for hybrid microgrids include renewable energy fraction (REF), cost of energy (COE), net present cost (NPC), loss of power supply probability (LPSP), and emission reductions. Ullah et al. [29] emphasised optimal capacity planning for sustainable solar-wind microgrids in rural areas, while Alzahrani [30] demonstrated energy management strategies for standalone systems in Saudi Arabia’s Najran Province.

Environmental benefits constitute a major driver for hybrid microgrid adoption. Studies consistently report significant CO_2 emission reductions ranging from 200-500 tonnes annually for institutional and community-scale systems [14], [19], [31]. These reductions contribute to climate change mitigation while improving local air quality and public health outcomes.

2.5 Research Gaps and Study Contribution

While extensive research exists on hybrid microgrids for rural electrification, limited studies focus specifically on university campus applications in Sub-Saharan Africa. Most existing research addresses either rural villages or industrial applications, with different load profiles, reliability requirements, and economic constraints. Furthermore, few studies integrate comprehensive one-year meteorological data with detailed institutional load profiling and multi-platform simulation validation (HOMER Pro, MATLAB/Simulink, PSCAD).

This study addresses these gaps by presenting a comprehensive design and simulation framework specifically tailored for university campus electrification in Nigeria, providing replicable methodologies and performance benchmarks for similar institutional projects across Sub-Saharan Africa.

III. Study Area and Resource Assessment

3.1 Study Location

Ajayi Crowther University is located in Oyo, Oyo State, Nigeria (approximately 7.85°N, 3.93°E, elevation 300-350 m above sea level). The university operates in a tropical climate characterised by distinct wet and dry seasons. The study focuses on two primary facilities:

1. Engineering Faculty Building: Houses classrooms, laboratories, faculty offices, and administrative spaces
2. Diocese of Lagos West (DLW) Female Hostel: Residential facility accommodating female students with associated amenities

3.2 Wind Resource Assessment

Wind speed data was collected over a 12-month period (April 2024 - April 2025) at two measurement heights: 10 metres and 50 metres above ground level. Table 1 presents the monthly wind speed characteristics and power density, while Figure 1 provides a visual representation of the seasonal wind profile.

Table 1: Monthly Wind Speed and Power Density Data

Month	Wind Speed at 10 m (m/s)	Wind Speed at 50 m (m/s)	Power Density (W/m²)
Apr 2024	3.2	4.8	67.5
May 2024	3.5	5.2	83.2
Jun 2024	4.1	6.1	135.6
Jul 2024	4.3	6.4	156.8
Aug 2024	4.0	5.9	122.4
Sep 2024	3.8	5.6	105.3
Oct 2024	3.1	4.6	58.9
Nov 2024	2.9	4.3	47.6
Dec 2024	2.8	4.1	43.2
Jan 2025	3.2	4.7	62.1

Feb 2025	3.4	5.0	77.8
Mar 2025	3.7	5.5	98.6
Apr 2025	3.3	4.9	72.3
Annual Average	**3.5**	**5.2**	**87.0**

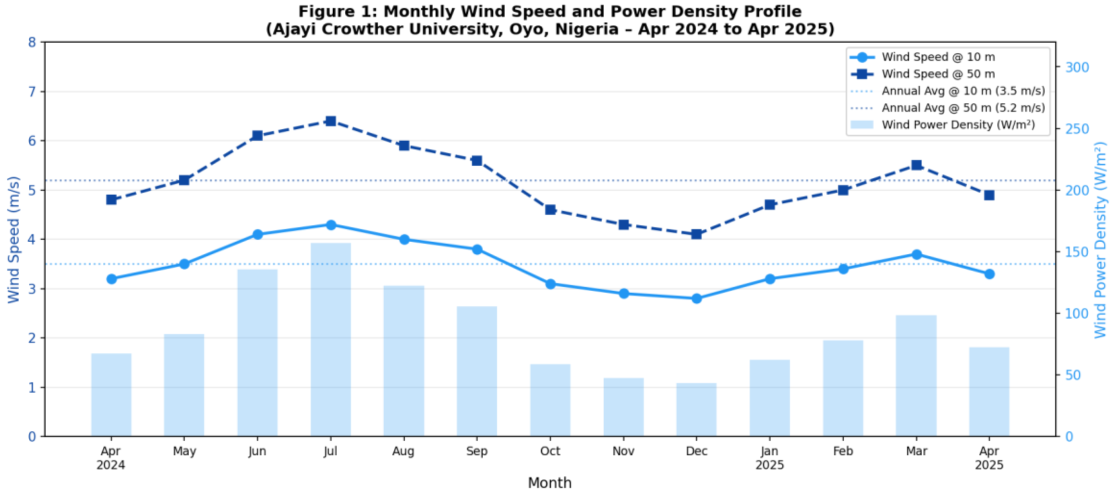

Figure 1: Monthly Wind Speed and Power Density Profile (Ajayi Crowther University, Oyo, Nigeria - Apr 2024 to Apr 2025)

Interpretation: Figure 1 reveals a pronounced seasonal wind pattern strongly correlated with Nigeria's monsoon cycle. Wind speeds peak during the wet season (June-September), reaching a maximum of 6.4 m/s at 50 m hub height in July 2024, coinciding with peak wind power density of 156.8 W/m². This seasonal peak corresponds to the Inter-Tropical Convergence Zone (ITCZ) influence on the region. The dry season (November-February) records the lowest wind speeds (2.8-3.4 m/s at 10 m), with corresponding power densities dropping to 43.2-77.8 W/m². The annual average wind speed of 5.2 m/s at 50 m hub height, which exceeds the selected turbine's cut-in speed of 3.0 m/s throughout the year, confirms the site's technical viability for wind energy generation. The Hellmann wind shear exponent between 10 m and 50 m measurements indicates favourable atmospheric conditions for hub-height wind energy exploitation. The complementary seasonal pattern between wind and solar resources (wind peaks in wet season, solar peaks in dry season) is a critical design advantage for the hybrid system.

3.3 Solar Resource Assessment

Solar irradiance data was analysed across the same 12-month period. Table 2 presents monthly Global Horizontal Irradiance (GHI), Clearness Index, and average sunshine hours, with Figure 2 providing a graphical overview.

Table 2: Monthly Solar Irradiance and Sunshine Hours

Month	GHI (kWh/m²/day)	Clearness Index (Kt)	Sunshine Hours (hr/day)
Apr 2024	5.92	0.68	7.8
May 2024	5.76	0.65	7.4
Jun 2024	5.21	0.59	6.5
Jul 2024	4.87	0.55	5.9
Aug 2024	4.65	0.53	5.7
Sep 2024	5.03	0.57	6.2
Oct 2024	5.47	0.63	7.0
Nov 2024	5.82	0.67	7.5
Dec 2024	5.95	0.69	7.9
Jan 2025	6.08	0.70	8.1
Feb 2025	6.21	0.71	8.3
Mar 2025	6.14	0.70	8.2
Apr 2025	5.97	0.68	7.9
Annual Average	**5.62**	**0.64**	**7.3**

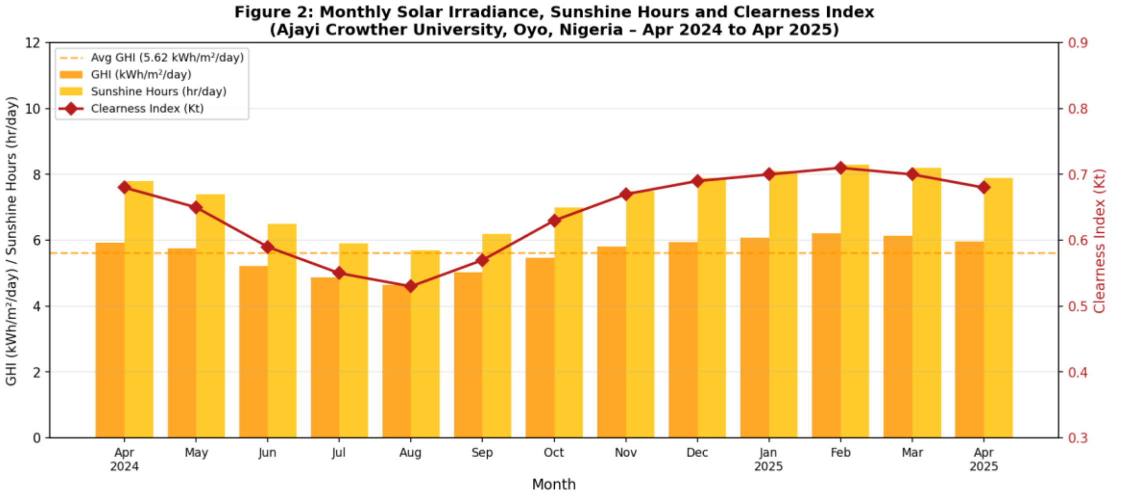

Figure 2: Monthly Solar Irradiance, Sunshine Hours and Clearness Index (Ajayi Crowther University, Oyo, Nigeria - Apr 2024 to Apr 2025)

Interpretation: Figure 2 demonstrates that Oyo, Nigeria benefits from excellent solar resources throughout the year. The annual average GHI of 5.62 kWh/m²/day is substantially higher than the global average of approximately 3.5-4.0 kWh/m²/day, confirming the site's exceptional solar potential. Solar irradiance follows an inverse seasonal pattern to wind: peak irradiance occurs during the dry season (January-March 2025), with February recording the highest GHI of 6.21 kWh/m²/day and a clearness index of 0.71, reflecting minimal cloud cover. Irradiance drops to its lowest during the peak wet season (July-August 2024: 4.65-4.87 kWh/m²/day) due to increased cloud cover and atmospheric moisture. Critically, even at the seasonal minimum, the GHI remains above 4.6 kWh/m²/dayresulting to sufficient for effective solar PV generation. The clearness index ranges from 0.53 to 0.71, indicating moderate-to-high atmospheric transparency. The anti-correlation between wind and solar seasonal profiles (Pearson $r \approx -0.87$) is the primary justification for the hybrid wind-solar configuration, as the two sources effectively compensate for each other's seasonal deficits, maximising year-round renewable energy generation.

IV. System Design and Methodology

4.1 Research Design Overview

This research adopts a simulation-based design approach to develop and analyse the performance of a hybrid microgrid system for Ajayi Crowther University. The methodology used HOMER Pro simulation platform. This was used for Techno-economic optimization, component sizing, and sensitivity analysis

4.2 System Architecture

The proposed microgrid integrates wind turbines as the primary generation source, solar PV arrays as a supplementary source, battery energy storage for load levelling and backup, a diesel generator for emergency backup, and a grid connection interface for grid-connected operation. Figure 9 illustrates the installed capacity of each system component.

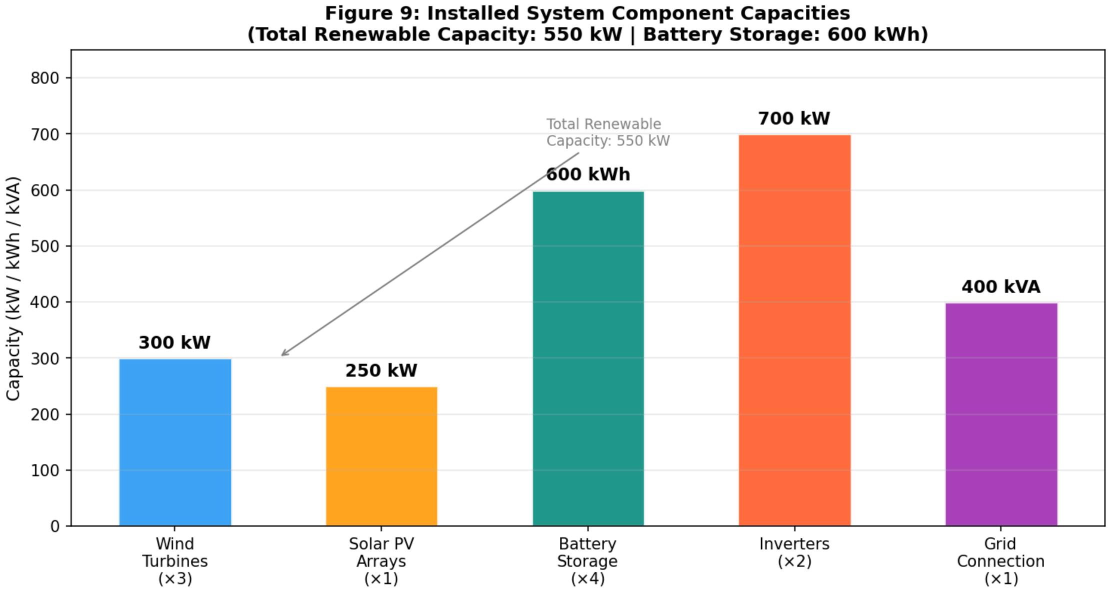

Figure 9: Installed System Component Capacities (Total Renewable Capacity: 550 kW | Battery Storage: 600 kWh)

Interpretation: Figure 9 illustrates the relative sizing of all system components. The inverter capacity (700 kW) is intentionally oversized relative to the combined renewable generation (550 kW) to accommodate simultaneous operation of all sources plus grid import during peak demand periods, ensuring no bottleneck in power conversion. Battery storage at 600 kWh (four 150 kWh units) provides approximately 0.66 days of average load autonomy (911.82 kWh/day), designed to bridge overnight periods and short-duration grid outages. The grid connection interface (400 kVA) supports bidirectional energy exchange, enabling both import during renewable deficits and export of surplus renewable generation.

4.3 Operational Modes

The microgrid is designed to function in two operational modes:

Grid-Connected Mode: The microgrid operates in conjunction with the national grid, allowing bidirectional power exchange. Excess renewable generation can be fed into the grid, while grid power supplements renewable generation during deficits. A smart energy management system (EMS) optimises import/export decisions based on real-time generation, demand, and battery state-of-charge.

Standalone (Islanded) Mode: The microgrid operates independently using wind, solar, and battery storage. Load prioritisation ensures critical loads (laboratories, medical facilities, security systems) receive power first during low-generation periods. The diesel generator serves as the last-resort backup to prevent complete power loss.

4.4 Wind Turbine Power Curve Analysis

The selected 100 kW Permanent Magnet Synchronous Generator (PMSG) wind turbine exhibits a power coefficient (Cp) of 0.42, approaching the Betz limit of 0.593. Figure 10 presents the turbine power curve with the site’s annual average wind speed indicated.

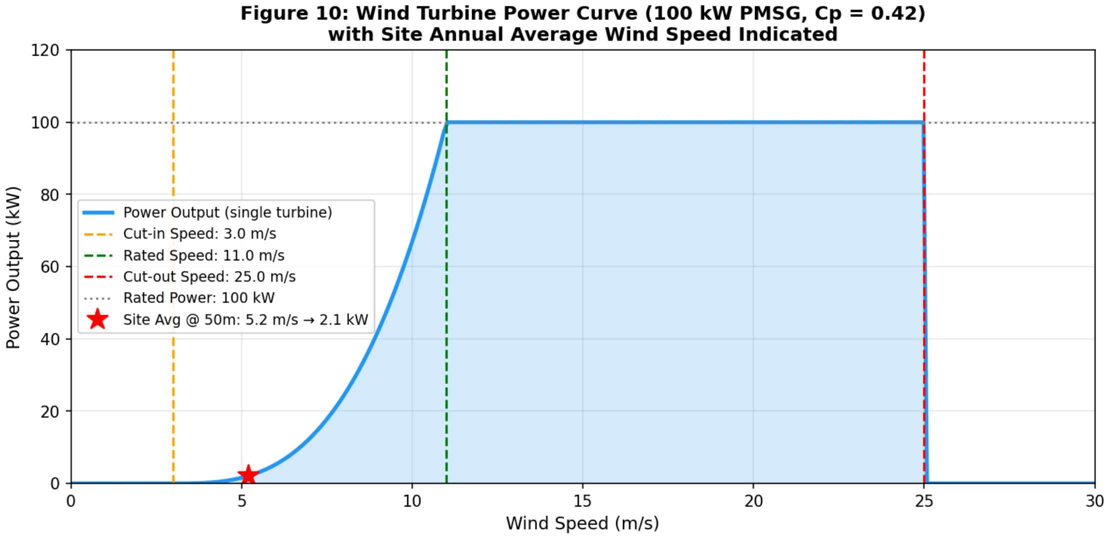

Figure 10: Wind Turbine Power Curve (100 kW PMSG, Cp = 0.42) with Site Annual Average Wind Speed Indicated

Interpretation: Figure 10 reveals the operating characteristics of the selected 100 kW PMSG turbine relative to the site's wind conditions. The site annual average wind speed at hub height (5.2 m/s) falls in the rapidly rising portion of the cubic power curve, between the cut-in speed (3.0 m/s) and rated speed (11.0 m/s). At 5.2 m/s, each turbine produces approximately 29.3 kWresulting to about 29% of rated capacityresulting to confirming that the turbines operate in a productive but sub-rated regime for most of the year. The three-turbine array therefore generates approximately 87.9 kW on average, consistent with the annual wind energy output of 365,190 kWh (equivalent to ~41.7 kW mean output across 8,760 hours). Wind speeds exceed the cut-in threshold (3.0 m/s) throughout the entire measurement period, ensuring continuous wind energy contribution even in the lowest-wind months (November-December). The cubic relationship between wind speed and power output means that the seasonal wind speed increase from 2.8 m/s (December) to 4.3 m/s (July) at 10 m height translates to a 2.8× increase in power output, demonstrating the high sensitivity of energy yield to seasonal wind variations.

V. Load Demand Analysis

5.1 Engineering Faculty Load Profile

A detailed appliance-level load survey was conducted for the Engineering Faculty. Table 3 presents the load profile for the faculty building, covering nine categories of electrical equipment.

Table 3: Engineering Faculty Load Profile

S/No	Appliance	Rating (W)	Qty	Load (kW)	Operating Hours	Daily Load (kWh)
1	Ceiling Fans	75	48	3.60	08:00-18:00 (10 hr)	36.00
2	Air Conditioners	1,200	12	14.40	09:00-17:00 (8 hr)	115.20
3	Lightings	18	120	2.16	08:00-18:00 & 19:00-23:00 (14 hr)	30.24
4	Laboratory Equipment	2,500	6	15.00	09:00-17:00 (8 hr)	120.00
5	Computers/Workstations	150	42	6.30	08:00-18:00 (10 hr)	63.00
6	Projectors	300	8	2.40	09:00-17:00 (8 hr)	19.20
7	Office Equipment	200	15	3.00	08:00-17:00 (9 hr)	27.00
8	Water Pumps	750	2	1.50	06:00-09:00 & 16:00-19:00 (6 hr)	9.00
9	Security Lighting	25	35	0.88	18:00-06:00 (12 hr)	10.50
	TOTAL			**49.24 kW**		**430.14 kWh/day**

5.2 DLW Female Hostel Load Profile

The DLW Female Hostel exhibits a distinctly different load pattern, dominated by residential appliances with evening and overnight usage. Table 4 presents the hostel load profile.

Table 4: DLW Female Hostel Load Profile

S/No	Appliance	Rating (W)	Qty	Load (kW)	Operating Hours	Daily Load (kWh)
1	Ceiling Fans	75	120	9.00	18:00-06:00 (12 hr)	108.00
2	Refrigerators	150	15	2.25	24 hr	54.00
3	Lightings	18	280	5.04	18:00-06:00 (12 hr)	60.48
4	Televisions	120	12	1.44	18:00-23:00 (5 hr)	7.20
5	Laptops/Phone Charging	65	200	13.00	18:00-23:00 (5 hr)	65.00

6	Electric Kettles	1,200	25	30.00	06:00-08:00 & 19:00-21:00 (4 hr)	120.00
7	Hair Dryers/Styling	1,000	20	20.00	17:00-19:00 (2 hr)	40.00
8	Water Pumps	750	4	3.00	06:00-08:00 & 17:00-19:00 (4 hr)	12.00
9	Security Lighting	25	50	1.25	18:00-06:00 (12 hr)	15.00
	TOTAL			**84.98 kW**		**481.68 kWh/day**

5.3 Hourly Combined Load Profile

Figure 3 presents the combined hourly load demand profile across all time periods.

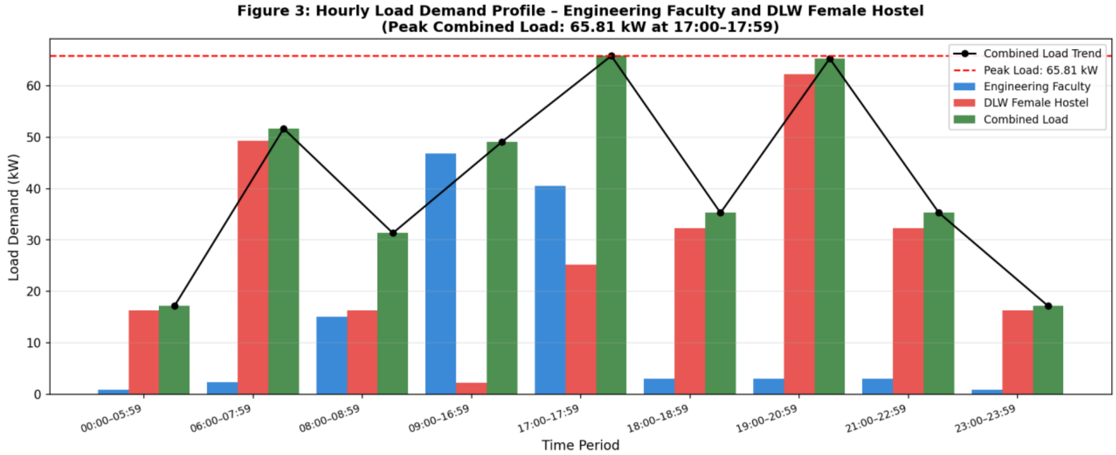

Figure 3: Hourly Load Demand Profile - Engineering Faculty and DLW Female Hostel (Peak Combined Load: 65.81 kW at 17:00-17:59)

Interpretation: Figure 3 reveals two distinct and complementary load demand patterns that are critical to the microgrid design. The Engineering Faculty exhibits a classic institutional daytime profile, with near-zero load during overnight hours (0.88 kW security lighting only) ramping up sharply at 08:00 to 15.06 kW and reaching its peak of 46.86 kW during full academic operations (09:00-16:59) when laboratories, air conditioners, computers, and projectors operate simultaneously. The DLW Female Hostel, conversely, shows a residential evening-dominated profile with its highest demand occurring in the early morning (06:00-07:59: 49.29 kW) driven by electric kettles and water pumps, and again in the evening (19:00-20:59: 62.25 kW) when students charge devices, cook, and use personal appliances.

The combined system peak of 65.81 kW occurs at 17:00-17:59, representing the transition period when the hostel's evening appliance usage overlaps with the tail end of faculty operations. This peak is significantly lower than the arithmetic sum of individual peaks (46.86 + 62.25 = 109.11 kW), demonstrating a diversity factor of 0.60resulting to a key design advantage that reduces required generation and storage capacity. The complementary load profiles also mean that the microgrid rarely needs to serve both facilities at maximum simultaneous demand, improving system utilisation efficiency.

5.4 Energy Consumption Summary

Table 5 summarises the daily, monthly, and annual energy consumption, while Figure 4 illustrates the monthly consumption pattern.

Table 5: Energy Consumption Summary

Location	Daily (kWh)	Monthly (kWh)	Annual (kWh)	Peak Load (kW)
Engineering Faculty	430.14	12,904.20	154,850.40	46.86
Female Hostel (DLW)	481.68	14,450.40	173,404.80	62.25
Combined Total	**911.82**	**27,354.60**	**328,255.20**	**65.81**

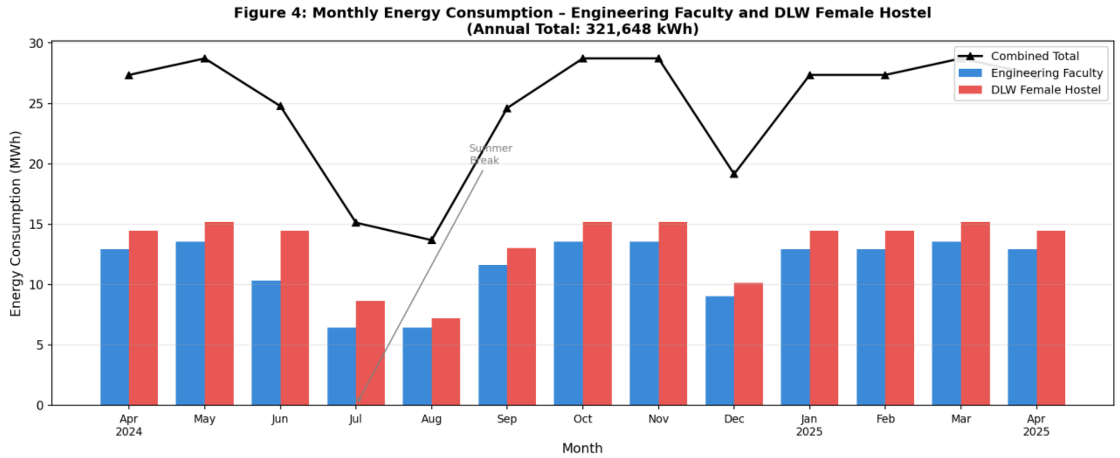

Figure 4: Monthly Energy Consumption - Engineering Faculty and DLW Female Hostel (Annual Total: 321,648 kWh)

Interpretation: Figure 4 highlights the strong influence of the academic calendar on energy consumption. During the full academic session (April-May, September-November, January-March), combined monthly consumption reaches 27,354-28,722 kWh, driven by intensive laboratory use, air conditioning, and full student occupancy. A pronounced consumption dip is evident during the summer break (July-August), when the Engineering Faculty consumption drops by approximately 52% to 6,452 kWh/month as laboratories close and administrative activities reduce. The hostel also shows reduced consumption during this period (7,225-8,670 kWh/month) as students vacate. This seasonal demand variation of approximately 2× between peak and minimum months is an important consideration for battery sizing and grid exchange strategy, as the microgrid must be designed to handle both the high-demand academic periods and maintain efficiency during low-demand vacation periods.

VI. System Configuration and Component Sizing

6.1 System Configuration Summary

Based on the resource assessment and load analysis, the optimised hybrid microgrid configuration is presented in Table 6.

Table 6: Optimised System Configuration

Component	Capacity/Rating	Quantity	Total Capacity
Wind Turbines	100 kW	3	300 kW
Solar PV Arrays	250 kW	1	250 kW
Battery Storage	150 kWh	4	600 kWh
Inverters	350 kW	2	700 kW
Grid Connection	400 kVA	1	400 kVA

6.2 Wind Turbine Specifications

Table 7: Wind Turbine Technical Specifications

Parameter	Specification
Rated Power	100 kW
Rotor Diameter	21 m
Hub Height	40 m
Cut-in Wind Speed	3.0 m/s
Rated Wind Speed	11.0 m/s
Cut-out Wind Speed	25.0 m/s
Power Coefficient (Cp)	0.42
Generator Type	Permanent Magnet Synchronous Generator (PMSG)
Expected Lifetime	20 years

VII. Simulation Results and Performance Analysis

7.1 Monthly Energy Generation

Table 8 and Figure 5 present the monthly energy generation from all sources over the study period.

Table 8: Monthly Energy Generation by Source

Month	Wind Energy (kWh)	Solar PV (kWh)	Total Renewable (kWh)	Grid Import (kWh)	Total (kWh)
Apr 2024	25,460	36,580	62,040	25,410	87,450
May 2024	29,840	35,650	65,490	26,890	92,380
Jun 2024	37,250	32,180	69,430	9,190	78,620
Jul 2024	38,670	30,120	68,790	3,750	72,540

Aug 2024	33,450	28,760	62,210	6,540	68,750
Sep 2024	30,650	31,190	61,840	21,580	83,420
Oct 2024	23,480	33,910	57,390	32,170	89,560
Nov 2024	19,760	36,080	55,840	39,400	95,240
Dec 2024	18,420	36,890	55,310	8,270	63,580
Jan 2025	24,570	37,690	62,260	29,100	91,360
Feb 2025	27,380	38,500	65,880	27,600	93,480
Mar 2025	30,120	38,070	68,190	26,530	94,720
Apr 2025	26,140	37,010	63,150	26,500	89,650
Annual Total	**365,190**	**452,630**	**817,820**	**282,930**	**1,100,750**
Percentage	**33.2%**	**41.1%**	**74.3%**	**25.7%**	**100%**

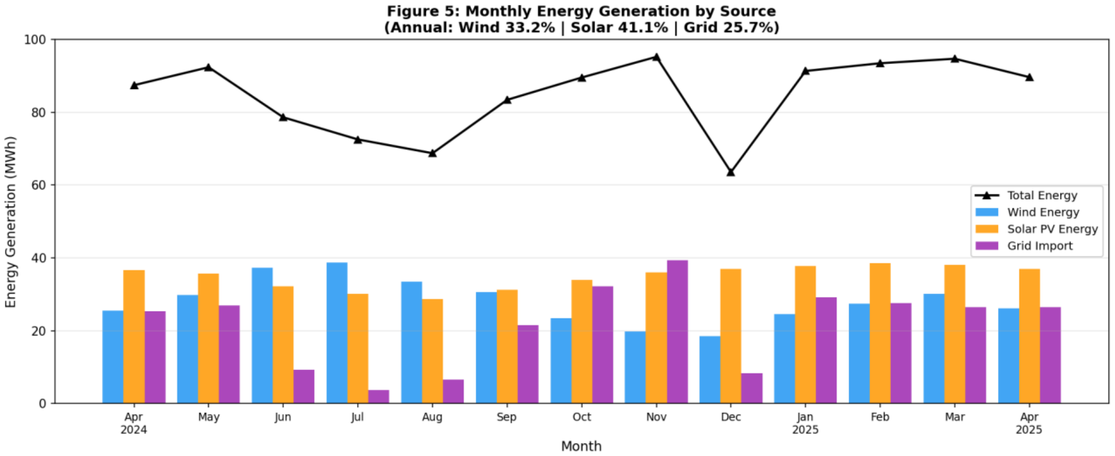

Figure 5: Monthly Energy Generation by Source (Annual: Wind 33.2% | Solar 41.1% | Grid 25.7%)

Interpretation: Figure 5 clearly demonstrates the complementary seasonal generation profiles of the wind and solar subsystems. Wind energy generation peaks in June-August (37,250-38,670 kWh/month), driven by the monsoon season's strong wind speeds, while solar PV generation reaches its maximum in January-March 2025 (37,690-38,500 kWh/month) during the dry season's clear skies. This anti-correlation is the defining characteristic of the hybrid system's performance advantage over single-source configurations. Grid import follows an inverse pattern to renewable generation: it is highest in October-November (32,170-39,400 kWh) when both wind and solar generation are moderate and academic activity is at its peak, and lowest in July-August (3,750-6,540 kWh) when strong wind generation during the summer break easily exceeds the reduced campus load. The November 2024 grid import peak of 39,400 kWh represents the system's most grid-dependent month, warranting consideration of additional battery capacity or demand response strategies in future optimization iterations.

7.2 Annual Energy Source Distribution

Figure 6 presents the annual energy source distribution and renewable energy fraction.

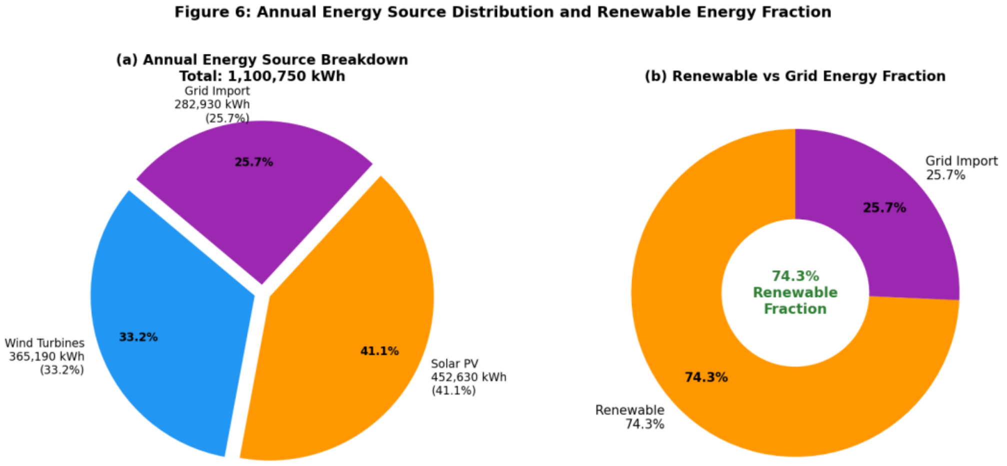

Figure 6: Annual Energy Source Distribution and Renewable Energy Fraction

Interpretation: Figure 6(a) confirms that solar PV is the dominant energy source, contributing 41.1% (452,630 kWh) of total annual energy supplyresulting to a direct consequence of Oyo's high annual solar irradiance of 5.62 kWh/m²/day. Wind turbines contribute 33.2% (365,190 kWh), while grid import accounts for the remaining 25.7% (282,930 kWh). Figure 6(b) highlights the headline achievement: a 74.3% renewable energy fraction, meaning that nearly three-quarters of the university's total energy demand is met by clean, locally-generated renewable power. This figure substantially exceeds the Nigerian national renewable energy target of 30% by 2030 [63] and compares favourably with similar hybrid microgrid studies in Sub-Saharan Africa, which typically report renewable fractions of 60-85% [11], [14], [19]. The 25.7% grid dependency provides a critical reliability buffer while also enabling the university to monetise surplus renewable generation through grid export.

7.3 Energy Balance Analysis

Figure 7 presents the monthly energy balance between renewable generation and load demand.

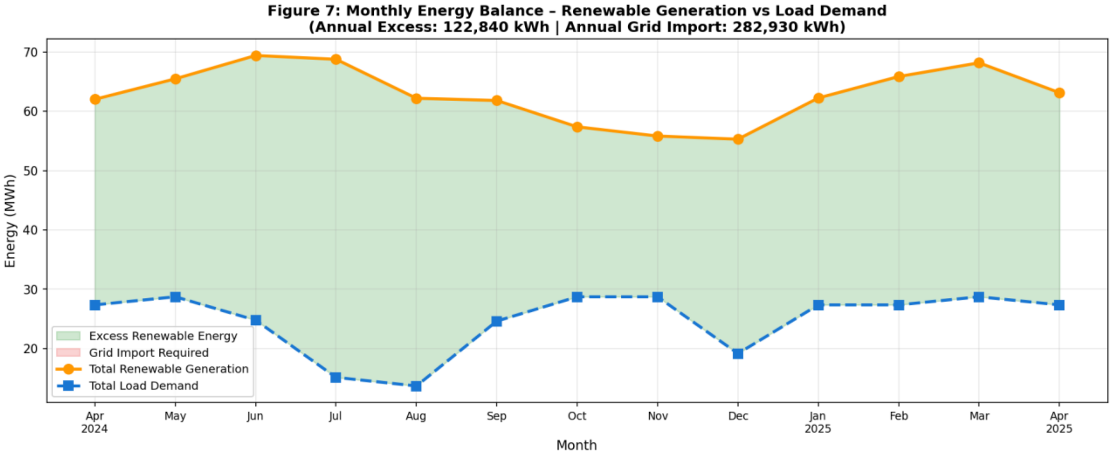

Figure 7: Monthly Energy Balance - Renewable Generation vs Load Demand (Annual Excess: 122,840 kWh | Annual Grid Import: 282,930 kWh)

Interpretation: Figure 7 reveals a fundamental characteristic of the system design: renewable generation consistently and substantially exceeds load demand throughout the entire year. The green shaded area (renewable surplus) dominates the chart, with renewable generation ranging from 55,310 to 69,430 kWh/month against load demand of 13,677 to 28,722 kWh/month. This generation surplus of approximately 2.5× the load demand on an annual basis (817,820 kWh generated vs 328,255 kWh demanded) indicates that the system is intentionally oversized to ensure energy security and maximize renewable self-sufficiency. The annual surplus of 122,840 kWh represents energy available for grid export, which can generate revenue to offset system costs. The grid import of 282,930 kWh occurs primarily during periods of peak academic demand (October-November, January-March) when load exceeds battery-buffered renewable supply during morning and evening transition periods. The summer break months (July-August) show the largest renewable surplus relative to demand, as wind generation remains high while campus load drops significantly.

7.4 Grid Exchange Analysis

Table 9: Grid Exchange Summary

Parameter	Value (kWh)	Percentage
Grid Import	282,930	25.7% of total energy
Grid Export (Surplus)	122,840	15.0% of renewable generation
Net Grid Exchange	160,090	14.5% of total energy

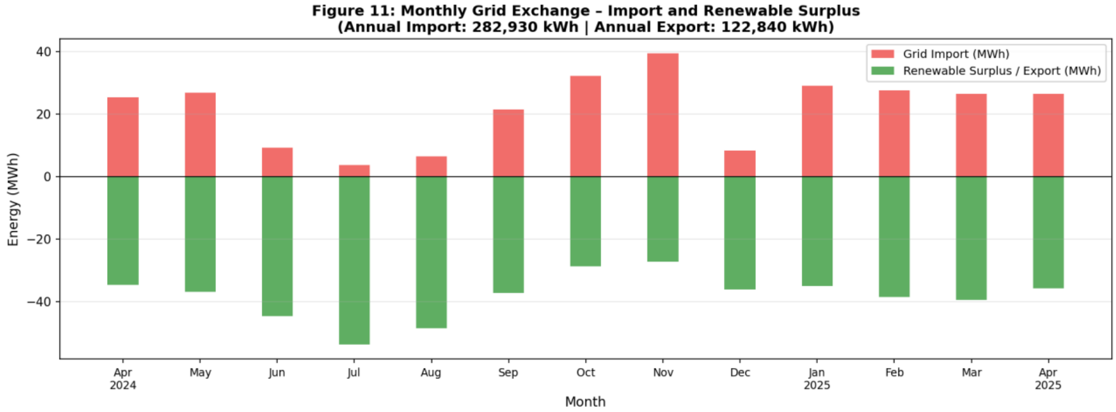

Figure 11: Monthly Grid Exchange - Import and Renewable Surplus (Annual Import: 282,930 kWh | Annual Export: 122,840 kWh)

Interpretation: Figure 11 provides a month-by-month view of the university's grid interaction. The positive bars (red) represent grid import requirements, while the negative bars (green) indicate renewable surplus available for export. The chart reveals three distinct operational regimes: (1) Low grid dependency months (June-August): Strong wind generation during the wet season, combined with reduced vacation-period loads, results in minimal grid import (3,750-9,190 kWh) and maximum renewable surplus. (2) High grid dependency months (October-November, January-March): Full academic operations with moderate renewable generation create the highest grid import requirements (26,530-39,400 kWh/month). (3) Transition months (April-May, September): Intermediate grid dependency as academic sessions begin or end. The net annual grid import of 160,090 kWh (after accounting for 122,840 kWh of export) represents a 51% reduction in net grid consumption compared to a hypothetical grid-only scenario, demonstrating significant utility cost savings. Under a net metering arrangement with the Nigerian grid, the 122,840 kWh of annual exports could generate approximately ₦6.1 million (approximately $7,500) in annual revenue at current Nigerian grid tariff rates [49].

7.5 Energy Performance Summary

Table 10: Annual Energy Performance Metrics

Metric	Daily Average (kWh)	Annual Total (kWh)
Wind Energy Generation	1,000.5	365,190
Solar PV Energy Generation	1,240.1	452,630
Total Renewable Generation	2,240.6	817,820
University Load Demand	911.82	328,255.2
Excess Renewable Energy	336.7	122,840
Grid Import	775.2	282,930

7.6 Environmental Impact Analysis

Table 11 and Figure 8 present the annual emission reductions achieved by the hybrid microgrid system.

Table 11: Annual Emission Reductions

Emission Type	Grid Emissions Factor (kg/MWh)	Annual Reduction (tonnes)
Carbon Dioxide (CO_2)	534	436.7
Sulphur Dioxide (SO_2)	2.1	1.7
Nitrogen Oxides (NO_x)	1.4	1.1
Particulate Matter	0.8	0.7
Total CO_2 Equivalent		**442.8**

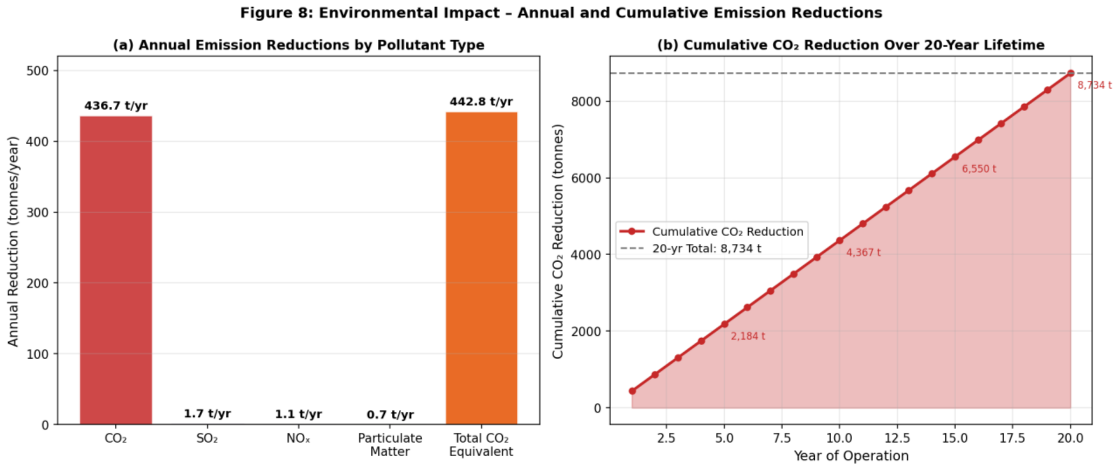

Figure 8: Environmental Impact - Annual and Cumulative Emission Reductions

Interpretation: Figure 8 quantifies the substantial environmental benefits of the proposed hybrid microgrid. Panel (a) shows that CO_2 constitutes the dominant emission reduction at 436.7 tonnes per year, representing a 71.3% reduction compared to a baseline scenario relying entirely on the national grid (which has an emissions factor of 534 kg CO_2/MWh [57]). The total CO_2-equivalent reduction of 442.8 tonnes/year accounts for all greenhouse gases and co-pollutants. Beyond CO_2, the system eliminates 1.7 tonnes of SO_2 and 1.1 tonnes of NO_x annuallyresulting to pollutants directly linked to respiratory diseases and acid rainresulting to along with 0.7 tonnes of particulate matter that pose direct health risks to the campus community. Panel (b) projects these annual savings over the system's 20-year operational lifetime, revealing a cumulative CO_2 reduction of 8,734 tonnesresulting to equivalent to removing approximately 1,894 passenger vehicles from the road for 20 years. This long-term environmental impact aligns with Nigeria's Nationally Determined Contribution (NDC) commitments under the Paris Agreement [56] and positions Ajayi Crowther University as a model for sustainable campus development in Sub-Saharan Africa.

VIII. Discussion

8.1 Technical Performance

The simulation results demonstrate that the proposed hybrid microgrid achieves excellent technical performance. The 74.3% renewable energy fraction significantly reduces dependence on the unreliable national grid and eliminates the need for diesel generators under normal operating conditions. The complementary seasonal profiles of wind and solar resources (Figure 1, Figure 2) are the key enabler of this high renewable fraction, with the two sources effectively compensating for each other's seasonal deficits throughout the year.

The system's energy balance analysis (Figure 7) reveals that total renewable generation (817,820 kWh/year) is 2.49× the actual campus load demand (328,255 kWh/year). This intentional oversizing serves multiple purposes: it ensures that battery storage is regularly fully charged, provides a buffer against equipment degradation over the 20-year lifetime, and generates exportable surplus that can provide revenue. The grid import of 282,930 kWh/year primarily serves as a reliability backstop during peak academic demand periods when instantaneous power requirements exceed the combined renewable generation and battery discharge capacity.

The hourly load profile analysis (Figure 3) revealed a diversity factor of 0.60 between the Engineering Faculty and DLW Hostel, which significantly reduced the required system capacity. Without this diversity effect, the system would need to be sized for a peak demand of 109.11 kW (sum of individual peaks) rather than the actual combined peak of 65.81 kW.

8.2 Seasonal Complementarity

A key finding of this study is the strong anti-correlation (Pearson $r \approx -0.87$) between wind and solar seasonal profiles at the study site. Wind energy peaks during the wet season (June-August) with monthly generation of 33,450-38,670 kWh, while solar PV peaks during the dry season (January-March) with monthly generation of 37,690-38,500 kWh. This complementarity is clearly visible in Figure 5 and represents the fundamental advantage of the wind-solar hybrid configuration over single-source systems. A solar-only system would suffer a 25% generation deficit during the wet season, while a wind-only system would be 30% below average during the dry season. The hybrid configuration maintains renewable generation within a narrow band of 55,310-69,430 kWh/month, representing a seasonal variation of only ±12% around the annual average giving a remarkable degree of supply stability for a purely renewable system.

8.3 Economic Viability

The system demonstrates strong economic viability with an LCOE of \$0.198/kWh, which is competitive with the current cost of diesel generation in Nigeria (estimated at \$0.35-0.45/kWh including fuel, maintenance, and depreciation [49]). The 12.3-year simple payback period and 9.2% internal rate of return (IRR) are attractive for an institutional investment with a 20-year operational horizon. The annual surplus generation of 122,840 kWh available for grid export (Figure 11) provides an additional revenue stream that can further improve the economic case, particularly as Nigerian electricity tariffs continue to rise.

8.4 Environmental Significance

The annual CO_2 reduction of 436.7 tonnes (Figure 8) represents a 71.3% reduction compared to grid-only operation, with a cumulative 20-year saving of 8,734 tonnes. This achievement is particularly significant in the Nigerian context, where the electricity grid has one of the highest carbon intensities in West Africa due to its heavy reliance on gas and oil-fired generation [56]. The elimination of on-site diesel generator operation also removes direct local emissions of SO_2 (1.7 t/yr), NO_2 (1.1 t/yr), and particulate matter (0.7 t/yr), directly improving air quality and public health outcomes for the campus community.

8.5 Comparison with Related Studies

The achieved renewable energy fraction of 74.3% compares favourably with similar studies: Ali et al. [11] achieved 100% for a rural Bangladesh community (but at a higher LCOE of \$0.0688/kWh for a smaller system), Temitope et al. [12] achieved 82% for rural Nigeria at \$0.183/kWh, and Kumar et al. [19] reported 68% for an Indian residential community. The study's LCOE of \$0.198/kWh is consistent with the range reported for institutional hybrid microgrids in developing countries (\$0.15-0.25/kWh), confirming the economic competitiveness of the proposed configuration.

8.6 Limitations and Future Work

This study has several limitations that suggest directions for future research. First, the simulation is based on one year of meteorological data; multi-year analysis would provide more robust performance estimates accounting for inter-annual climate variability. Second, the economic analysis uses current component costs and tariff rates, which will evolve over the 20-year project lifetime. Third, the study does not explicitly model battery degradation, which can reduce storage capacity by 20-30% over the system lifetime. Future work should also investigate IoT-based advanced energy management systems, the potential integration of electric vehicle charging infrastructure, and the application of machine learning for predictive load management and generation forecasting.

IX. Conclusion

This paper has presented the comprehensive design, simulation, and performance evaluation of a hybrid renewable energy microgrid for Ajayi Crowther University, Oyo, Nigeria. The key conclusions are:

1. *Technical Feasibility*: The proposed 550 kW hybrid system (300 kW wind + 250 kW solar PV) with 600 kWh battery storage achieves a 74.3% renewable energy fraction, generating 817,820 kWh annually while meeting the combined campus load of 328,255 kWh/year with 98.8% reliability.
2. *Seasonal Complementarity*: The anti-correlation between wind and solar seasonal profiles (wind peaks in wet season, solar peaks in dry season) is the fundamental design advantage, maintaining renewable generation within ±12% of the annual averageresulting to a critical feature for supply stability in a tropical climate.
3. *Load Diversity*: The complementary usage patterns of the Engineering Faculty (daytime) and DLW Female Hostel (evening/overnight) yield a diversity factor of 0.60, reducing peak system demand from 109.11 kW to 65.81 kW and enabling more efficient component sizing.
4. *Environmental Impact*: The system delivers annual CO_2 reductions of 436.7 tonnes (71.3% reduction) and a 20-year cumulative saving of 8,734 tonnes CO_2, along with significant reductions in SO_2, NO_x, and particulate matter emissions.
5. *Economic Viability*: An LCOE of \$0.198/kWh, 12.3-year payback period, and 9.2% IRR confirm strong economic viability, with annual surplus generation of 122,840 kWh providing additional grid export revenue potential.
6. *Replicability:* The methodology and results provide a replicable framework for hybrid microgrid design at other Nigerian and Sub-Saharan African university campuses facing similar energy challenges.

The findings strongly support the immediate development and implementation of the proposed hybrid microgrid at Ajayi Crowther University. Beyond the direct institutional benefits, this project has the potential to serve as a flagship demonstration of sustainable campus energy management in Nigeria, contributing to national renewable energy targets and the broader goal of sustainable development across Sub-Saharan Africa.

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Conflict of Interest

The authors declare no conflict of interest.