

Technical and Economic Analysis of Hybrid Solar PV-Wind Mini-grid Power System for Sokoto Energy Research Center (SERC)

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Received on: October, 2025
2025

Revised and Accepted on: November, 2025

Published on: December,

ABSTRACT

Access to reliable electricity plays a critical role in driving the global economy by powering industries, enabling technological advancements, and supporting infrastructure. This study presents a techno-economic analysis of a hybrid solar-wind mini-grid system designed for the Sokoto Energy Research Centre (SERC) in northwestern Nigeria. The region's high solar irradiance and moderate wind speeds provide favourable conditions for renewable energy integration. Twenty-two years long-term meteorological data from National Aeronautic and Space Administration (NASA), and HOMER Pro software for simulation was utilized. The result showed the site-specific assessment has an average solar radiation of 5.99 kWh/m²/day, an annual mean wind speed of 5.17 m/s, and an average temperature of 27.71 °C, confirming the location's strong renewable energy potential. The system was modelled, optimized, and evaluated to meet an estimated daily demand of 109.33kWh and a peak load of 19.71kW. The optimal configuration comprises a 99.6 kW photovoltaic array, a 25kW wind turbine, 83 batteries, and 21.5kW of inverter size, achieving a 100% renewable fraction. The technical and economic analysis showed annual electricity production of 210,796kWh, with solar PV contributing 85% and wind 15%, with a Levelized Cost of Electricity (LCOE) of ₦125.48/kWh and a Net Present Cost (NPC) of ₦64.9 million. While producing excess electricity of 168,061 kWh annually, the system also demonstrated minimal unmet load 38.4 kWh/yr, confirming its reliability. The findings underscore the technical and economic feasibility of the hybrid system for institutional electrification in Nigeria, with potential scalability to other off-grid applications.

Keywords: Hybrid energy system, Solar PV, Wind turbine, Mini-grid.

1.0 INTRODUCTION

Wind-Solar PV implementation increases the quality of energy services, reduces dependence on fossil fuels, and consequently reduces the environmental impacts associated with the use of these fuels. As an alternative, decentralized energy solutions such as mini-grid photovoltaic (PV) systems have gained attention for their ability to provide sustainable and cost-effective power to off-grid areas (IRENA 2020). Mini-grids offer several advantages, including lower transmission losses, scalability, and the potential to integrate with local renewable energy sources (Bhattacharyya 2018).

Due to the increase in consumption, along with the unsustainable damages that fossil fuels have done to the environment, there have been efforts to develop more sustainable energy source alternatives to the traditional forms, while ensuring that a healthy life is maintained, and the environment is not polluted (Kevelaitis, & Raudonis, 2008). The initiative has driven a growing demand for environmentally sustainable energy sources that are both renewable and clean. As a result, the need for solar power has surged due to its renewable nature and minimal environmental impact.

The growing global emphasis on sustainable development and climate change mitigation has

intensified the search for clean energy alternatives to fossil fuel-based power generation. Nigeria's Energy Transition Plan (ETP) aims to achieve net-zero emissions through renewable energy integration, targeting up to 60% of energy demands from clean sources by 2050 (Adedeji *et al.*, 2023). However, implementation faces significant challenges, including inadequate policy frameworks, limited technical expertise, and insufficient funding (Ogbonnaya *et al.*, 2019). The Rural Electrification Agency (REA) has set ambitious targets for 75% electrification, though achieving these goals requires substantial policy and regulatory reforms (Aliyu *et al.*, 2020).

Despite the promising potential of hybrid renewable energy systems, limited comprehensive research has been

conducted on their technical and economic feasibility in Nigeria's specific climatic and socioeconomic context. While recent studies have begun to address individual aspects of hybrid system deployment, there remains a critical need for integrated analyses that consider the full spectrum of technical, economic, environmental, and policy dimensions (Oyedepo *et al.*, 2021). This knowledge gap hinders informed decision-making by policymakers, investors, and development organizations seeking to implement sustainable energy solutions in rural Nigeria. This study investigates the

technical and economic feasibility of a hybrid solar-wind mini-grid for SERC, providing a case model for institutional and rural electrification in resource-rich regions.

1.1 Study Location

The study location is situated in northwestern Nigeria's Sahelian climatic zone (Latitude: 13.2°N, Longitude: 5.2°E). The region exhibits high solar irradiance (5.5-6.5 kWh/m²/day, NASA-POWER 2024) and moderate wind speeds (3-6 m/s at 10m height, NREL 2023), making it an ideal location for hybrid solar-wind energy integration.

2.0 MATERIALS AND TOOL

This research adopted the quantitative research approach, using meteorological data from the (NASA), and HOMER Pro software for simulation.

3.0 METHODOLOGY

These stages are structured within a clearly defined research framework, as illustrated in the flowchart in the Figure 1, highlighting the key steps and decision-making processes undertaken during the system design and simulation phases.

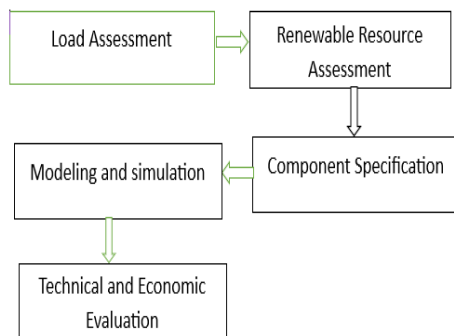


Figure 1: schematic framework of the study

Among these, the demand assessment is the most critical aspect of the sizing process. Accurate estimation of daily and peak energy loads is essential, as it determines the capacity of the solar PV panels, wind turbines, battery bank, and inverter system. Errors at this stage could result in system under-sizing, causing load shedding and unmet energy demand, or oversizing, leading to excessive capital costs without corresponding benefits. As such, special attention was given to this phase to ensure optimal system performance and cost-effectiveness tailored to the specific energy needs of the case study location.

3.1. Load Demand Assessment

Load energy demand refers to the total amount of electrical energy consumed by all connected devices, equipment, and systems within a specific location over a defined period. Understanding the load demand is critical for designing and sizing a reliable hybrid wind-solar PV mini-grid system, as it determines the capacity requirements of generation and storage components.

Accurate load profiling helps optimize system performance, reduce costs, and ensure an uninterrupted power supply.

The energy demand requirement for the location was developed based on the individual power rating of each appliance generally utilized in the office.

3.2. Renewable Energy Resource Assessment

Understanding the availability and behaviour of renewable energy resources is crucial for designing an efficient and reliable hybrid energy system. In this study, the assessment focused on solar radiation, wind speed, and ambient temperature for the location, the designated project site. To ensure a comprehensive analysis, 22 years of data (2000 to 2022) was obtained from the NASA POWER database, which provides satellite-derived meteorological data widely used in energy system planning. This long-term dataset helps to smooth out short-term fluctuations and provides a reliable picture of seasonal and annual trends in resource availability.

The data were processed and converted into monthly average values to form a clear and representative yearly profile for the location. Solar radiation data were used to determine how much energy could be harnessed from photovoltaic (PV) panels. Wind speed data at 50 meters, a standard turbine hub height, helped assess the feasibility of wind energy generation. Additionally, temperature data was analyzed to understand how heat might affect system components, particularly solar panel efficiency, which tends to drop at higher temperatures.

Equation 1, was used to assess the energy output of solar energy and wind energy, as cited by Deffie and Beckman (2013):

$$E_{PV} = G \times A \times \eta_{PV} \times PR \quad (1)$$

Where:

E_{PV} = Energy generated (kWh), G = Solar irradiance (kWh/m²), A = PV panel area (m²), η_{PV} = PV module efficiency%, PR = Performance ratio.

3.3. Capacity factor for solar PV

$$CF_{PV} = \frac{E_{PV}}{P_{rated} \times 8760} \quad (2)$$

The Wind power potential of the location was analyzed using the wind power density equation (WPD) in equation (3), as cited by (Manwel *et al.*, 2010)

$$P = \frac{1}{2} \rho A v^3 \quad (3)$$

P = Wind power (w), ρ = Air density (kg/m^3), A = Swept area of turbine blades (m^2), V =Wind speed (m/s)

The Weibull probability distribution for speed analysis, as shown in equation (4), cited by (Mostafaeipour *et al.*, 2014):

$$f(V) = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k} \quad (4)$$

k = Shape factor, c = Scale factor

3.4 System Components, Characteristics, and Costs

The hybrid energy system analyzed in this study comprises the following key components: photovoltaic (PV) modules, a wind turbine, a diesel generator, battery storage, and converters. Each component was selected based on the system’s overall configuration and operational requirements. Cost data for the PV modules, inverter, and batteries were primarily sourced from local suppliers where available. In instances where local pricing was not accessible, manufacturer and international retail prices were utilized as references.

Comprehensive technical specifications and cost estimates for these components are presented in the subsequent sections. It is important to note that each system component has a different operational lifespan, as specified by the manufacturers. For consistency in analysis, the overall project lifetime is assumed to be 25 years, aligning with standard practice for long-term techno-economic evaluations.

3.5. Photovoltaic Panels

The physical examination of the site shows that the PV panels can be installed on the rooftops of the buildings on a fixed axis, at an angle equivalent to the latitude of the site, for optimum solar radiation capturing. Factors including the size of the panel, types, the brand manufacturer, the retailer, and the country in particular affect the cost of PV modules. In this research, the Generic flat plate Solar was selected for the simulation, with the characteristics given in Table 1. Panels with equivalent traits are available in the Nigerian markets.

Table 1: Characteristics of the selected PV panel

Manufactural	Generic
Model	Generic flat plate
Cell type	Mono-crystalline
Panel type	Flat plate
Rated power (W)	550
Operating temperature	45
Efficiency %	17.49
Temperature coefficient	-0.41
Initial cost	₦135,000
Replacement cost	₦115,000
O&M	₦10,000

3.6 Wind turbine

The wind turbine serves as a complementary energy generation source in the hybrid mini-grid system

designed for (SERC). While solar energy remains the primary source due to Sokoto’s high solar irradiance, the inclusion of wind power enhances the system’s resilience, particularly during non-daylight hours and cloudy conditions. The turbine is expected to operate at a capacity factor of around 20-30%, contributing significantly to energy generation during nighttime and the Harmattan season, when wind speeds are typically higher. The characteristics of the type of wind turbine used for this simulation is described in Table 2.

Table 2: Characteristics of the wind turbine

Name:	Generic 1Kw
Manufacturer	Generic
Rated capacity (kW)	1
Life time	20years
Hub height	50m
Initial cost	₦200,000.00
Replacement cost	₦160,000.00
O&M	₦10,000

3.7 Battery Storage selection

For energy storage in this research, the Generic lead-acid battery model type was selected due to its standardization within HOMER software and compatibility with hybrid renewable energy systems. This battery type offers reliable performance for both solar PV and wind-based systems and is suitable for applications requiring moderate energy storage capacity with consistent cycling. The battery is characterized on Table 4 by the following specifications used in the software.

Table 4: Characteristics of the battery

Name	Generic lead acid
Model	Generic 1
Nominal Capacity(kWh)	1
Nominal voltage (V)	12
Maximum capacity (kWh)	83.4
Capacity ratio	0.403
Rate constant (1/hr)	0.827
Round-trip efficiency %	80
Maximum charge current (A)	16.7
Maximum discharge current (A)	24.3
Maximum charge rate (A/Ah)	1

The software was utilized to determine the optimal quantity of batteries needed to satisfy the daily energy demand of the location. The software considered load variability, generation patterns, and autonomy days to ensure a balance between system reliability and cost-effectiveness. The use of standardized batteries such as the Generic model also aids in scalability, easy maintenance, and cost estimation during simulation,

making it an ideal choice for system design and optimization in remote or semi-urban energy project.

3.8 Inverter Selection and Cost Estimation

In hybrid mini-grid systems, inverters are essential for converting DC power from the PV panels and batteries into AC power for the load, and vice versa, such as converting AC power from the diesel generator to charge the battery bank when necessary. Unlike older system configurations that required separate grid-tied and off-grid inverters, modern hybrid systems benefit from advanced inverter technologies that combine both functions into a single device. Capital cost of converter cost was inputted as ₦300,000, and replacement cost was set to be ₦260,000. The efficiency of the converter is 95% and the lifetime of the converter was given by the manufacturer as 15 years.

3.9 Charge Controller Selection

The Controller component in the software used defines how the hybrid wind-solar PV mini-grid system operates during the simulation by specifying the control algorithms or dispatch strategies used to manage energy flows. The software allows multiple Controller components to be tested, enabling comparison of different control strategies to identify the most efficient system operation. For this research, the Controller is set to the “optimize” mode, allowing the software to automatically determine the optimal dispatch decisions for power output, thereby supporting the techno-economic feasibility analysis of the system.

3.10 Modelling and Technical and Economic simulation of the hybrid System

The modelling and simulation phase is central to evaluating the technical and economic viability of the proposed hybrid wind-solar PV mini-grid system for the location. This stage involves the selection and sizing of system components, including photovoltaic (PV) panels, wind turbines, battery banks, and inverters, based on site-specific energy demand and available renewable energy resources. Using the simulation software, several system configurations were modelled to identify the optimal setup in terms of cost-effectiveness, reliability, and energy performance. Key input parameters included the electrical load profile, solar irradiance data, wind speed profiles, component technical specifications, and relevant economic factors.

The simulation provided outputs such as energy production, component sizing, (NPC), (LCOE), and renewable energy fraction, allowing for a comprehensive assessment of the system’s feasibility under multiple design scenarios. In this research, the Solar PV sizing is a critical step to ensure that the photovoltaic array can effectively meet the daily

energy demand. The sizing is calculated by equation 5. cited by (Guda and Aliyu., 2015).

$$PV \text{ Array Size (kW)} = \frac{E_{total}}{PSH \times PR} \quad (5)$$

PSH is the peak sunshine hour.

Wind Turbine Sizing

This research involves selecting the appropriate turbine capacity and number of units needed to complement solar generation, based on Sokoto’s average wind speeds, load demand, and the turbine’s power curve to ensure reliable energy output, using equation 6.

$$\text{Wind turbine sizing} = \frac{\text{Daily load}}{24 \times Vr} \quad (6)$$

Battery sizing also involves determining the total storage capacity required to meet SERC’s energy demand during periods of low solar and wind generation, ensuring sufficient backup power while optimizing the number of battery units for cost-effectiveness and long lifespan. This is calculated using the expression in equation 7, (Guda and Aliyu 2015, El-Shemaway *et al.*, 2017)

$$\text{The size of the battery (Ah)} = \frac{\text{Daily load} \times \text{Autonomy day}}{\text{DoD} \times Be} \quad (7)$$

Selecting an inverter with a rated capacity equal to or slightly higher than the location’s peak load to efficiently convert DC from the solar PV and batteries into AC for the load, while ensuring compatibility with the hybrid system by using equation 8. The inverter must handle the peak load and ideally have a 20-25% safety margin.

$$\text{Inverter} = \text{Peak Load} \times 1.25 \quad (8)$$

Charge Controller Sizing involves determining a controller that can handle the maximum current and voltage from the solar PV array while efficiently regulating power flow to the battery bank, preventing overcharging or deep discharging, and ensuring reliable operation of the hybrid wind–solar system. For the charge controller sizing, equation 9 was applied,

$$\text{Charge Controller Current} = \frac{PV \text{ array power}}{\text{Battery Voltage}} \quad (9)$$

3.11 Economic Criteria for System Simulations

The following economic indicator was used to assess the economic simulation system to determine the most cost-effective, reliable, and sustainable.

3.12 Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is a key economic indicator used to assess the average cost of electricity generated by the hybrid energy system over its entire operational lifetime. It provides a

Figure 4, shows the temperatures of the selected location. The annual monthly temperature of 27.71 was analyzed, which range from 22.7 °C in January to 33.0 °C in May, showing a clear seasonal trend. These variations impact PV module efficiency which decreases with rising temperature and affect battery charging/discharging behaviour. HOMER Pro utilizes this data to apply temperature derating to PV output and adjust battery performance accordingly, ensuring realistic modelling of the hybrid system. Ambient temperature plays a crucial role in the performance of solar PV and battery systems. In this study, monthly average temperature data from 2000 to 2022 of the location was sourced from the NASA POWER database and incorporated into HOMER software to enhance simulation accuracy.

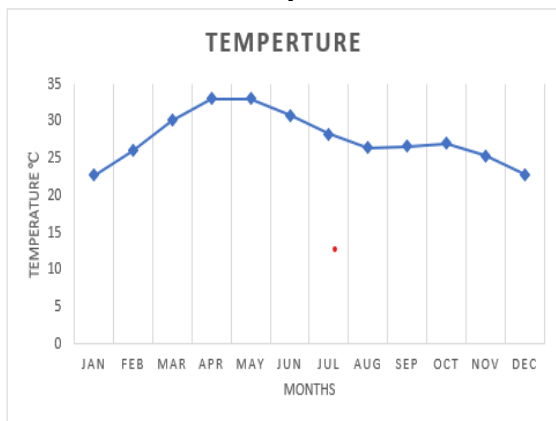


Figure 4: Average monthly Temperature (°C) for the location

4.5 System Design and Optimization Results

The details of the optimization results for the selected hybrid renewable energy system, designed to meet a peak load demand. The software was used to run several simulations before a feasible system was identified based on the required output.

Architecture		Cost				System			
PV (kW)	G1	1kWh LA	Converter (kW)	NPC (M)	COE (M)	Operating cost (M/yr)	Initial capital (M)	Ren Frac (%)	Total Fuel (L/yr)
99.6	25	83	21.5	#64.9M	#125.88	#1.49M	#45.7M	100	0
119	96	21.9		#79.5M	#154.03	#2.54M	#46.7M	100	0

Figure 5: Configurized optimizations of hybrid systems

In this simulation result, the system design is shown in Figure 6. A 25kW wind turbine contributes 15% of the total annual supply, generating 31,594 kWh/year, at a capacity factor of 14.4%. Meanwhile, the 85% contribution from the solar PV system corresponds to 179,202 kWh/year, operating at a capacity factor of 20.5%. The system achieves a renewable energy fraction of 100% and produces an excess electricity output of 168,061 kWh/year. Monthly electricity production is presented in Figure 7. Details of the system design and the specific costs associated with each component, such as total NPC, capital cost, and O&P, are provided in Tables 5 and Figure 8.

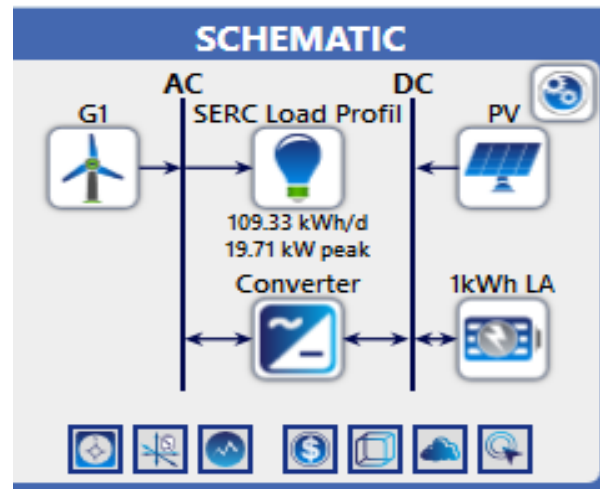


Figure 6: Schematic diagram of wind-solar

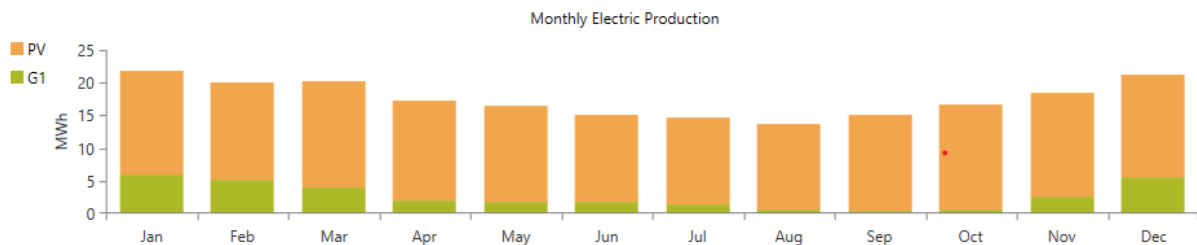


Figure 7: Monthly electric production

Table 5: The system design for the PV-Wind system

PV	Wind	Battery	Converter	COE (M)	NPC	Operating cost
99.6 Kw	25 Kw	83	21.5 kW	125.48	64,933,756.00	1,487,556.00

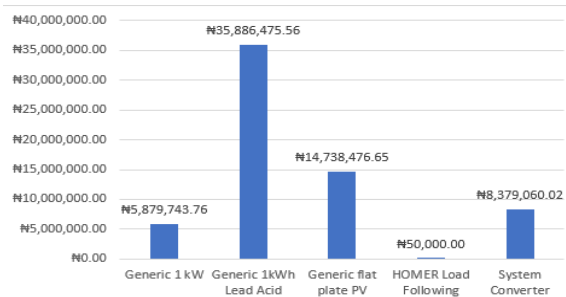


Figure 8: NPC cost of each of the components of the system

4.6 Effect of renewable energy on the selected system (solar-wind).

This is the influence of renewable energy penetration on the operational and economic performance of the chosen solar-wind configuration

4.7 PV Panels

The solar panel selected have penetration percentage of 449 and are expected to be operational for 4376 hours per year. Figure 4.18 indicates that solar irradiance is more prevalent from 8am to 4pm throughout the year.

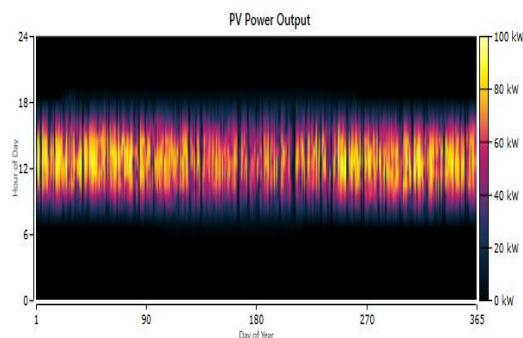


Figure 9: PV output

4.8 Wind Turbine

The wind turbine penetration was simulated to be 79.2% and expected to operate for 6,771 hours in a year. In the winter the speed is higher as illustrated in figure 4.18, and solar radiation is less making it possible to fully utilize the hybrid system for electric power generation. Solar and wind can supplement each other during lean periods.

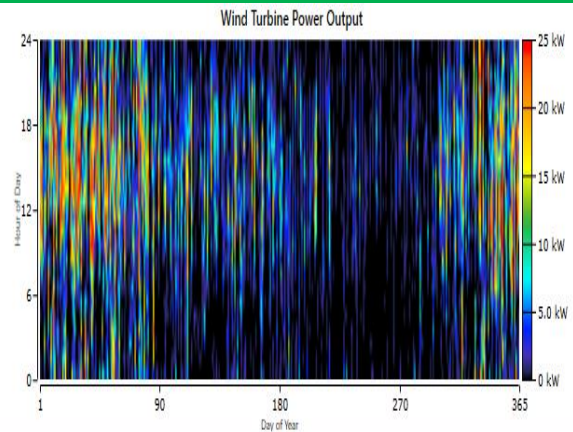


Figure 10: Wind output

4.9 Generic Lead Acid Battery

The battery has maximum capacity of 8333Ah and rated at 12V. and the batteries have yearly throughput and losses of 1,492 kWh/yr and 6,674 kWh/yr respectively.

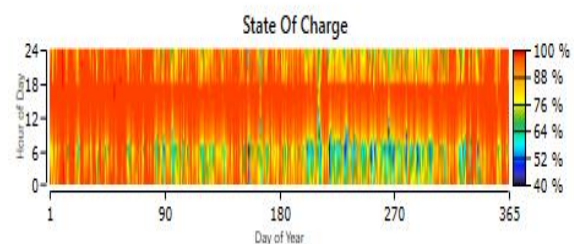


Figure 11: Battery state of charge

4.10 Converter

The converter comprises of the inverter and rectifier units each having capacity of 21.5kW. the converter is expected to operate for 6,230 hours in a year with losses of 1,301 kWh per year

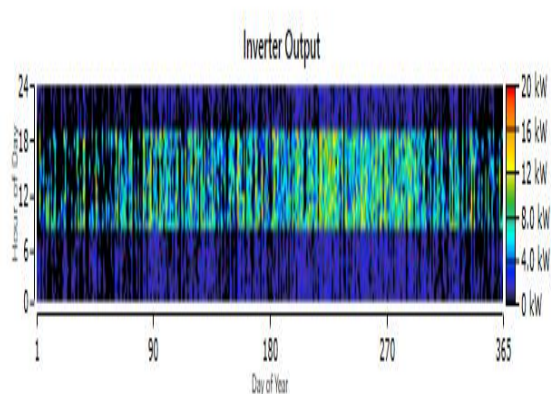


Figure 12: Inverter output.

4.11 Energy Generation and Excess Energy

A key factor in selecting the recommended hybrid system configuration for the study location was its ability to generate significant excess electricity. Based on the simulation results, the system is capable of

producing approximately 168,061 kWh of excess energy annually, as detailed in Table 7. This surplus is primarily generated during periods of high solar irradiance and favourable wind conditions, especially when the energy demand is lower than the supply.

To ensure the economic viability of this system, it is crucial that there are supportive government policies, particularly around feed-in-tariff (FiT) programs and Power Purchase Agreements (PPA). Such policies would allow SERC to sell excess electricity to the grid. Also, the issue of unmet load will remain an important consideration. The results indicate an annual capacity shortage of approximately 38.4 kWh, which occurs during periods of very low solar irradiance, sometimes as low as 1.71 kWh/m²/day, particularly in the rainy season. During such periods, the output from the renewable components may fall short of meeting the load demand, leading to temporary supply gaps.

Table 6: Electricity Generation, Excess Energy, and Unmet Load

Quantity	Value	Unit
Excess electric load	168,061	kWh/yr
Unmet electric load	1.71	kWh/yr
Capacity shortage	38.4	kWh/yr

4.12 PV-Wind Electrical Power Production and Supply

The performance and contribution of the solar PV and wind turbine to the overall electricity production are presented in Table 8. According to the simulation output, the PV array contributes 85% of the total annual energy generation, while the wind turbine accounts for the remaining 15% share. This distribution results in a combined total energy production of 210,796 kWh/year, which is nearly double the estimated load demand of the location.

On a daily basis, the PV system alone produces an average of 491kWh/day, which is well above the centre's daily consumption. This indicates that under normal solar conditions, the PV system is capable of meeting the entire load requirement with a significant surplus. The extra energy is especially valuable during daylight hours, which align with the centre's operational schedule, and can be used to charge the battery system or be redirected for productive use in other departments or faculties that are close by.

Table 7. PV-Wind Electrical Power Production and Supply Analysis

Component	Production (kWh/yr)	Unit %
Generic flat plate PV	179,202	85
Generic 1 kW	31,594	15
Total	210,796	100

AC Primary load	39,904	100
DC primary load	0	0
Deferrable load	0	0
Mean output	491	kWh/d

5.0 CONCLUSION

This research has demonstrated that a hybrid solar-wind system represents the most reliable and cost-effective pathway for meeting the electricity needs of SERC. The optimized configuration not only satisfies the centre's demand but also generates substantial excess energy, positioning the system as a potential revenue stream under supportive policy frameworks. Although the initial capital investment is significant, the long-term savings in operating costs, coupled with the environmental benefits of reducing fossil fuel dependence, reinforce the sustainability of the proposed design. The study validates the technical feasibility of hybrid renewable systems under Sokoto's climatic conditions and provides evidence that such systems can address Nigeria's rural and institutional energy challenges. By adopting enabling policies such as feed-in tariffs and grid-integration incentives, Nigeria can accelerate its transition to cleaner energy sources, strengthen energy security, and contribute meaningfully to global climate goals. This work therefore contributes both practically and academically by offering a replicable model for hybrid energy deployment in resource-rich regions.

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