



ORIGINAL RESEARCH ARTICLE

OPTIMIZATION OF PERFORMANCE PARAMETERS OF AN OFF-GRID WIND-SOLAR HYBRID POWER SYSTEM USING HOMER PRO FOR ENHANCED ENERGY RELIABILITY AT KASHIM IBRAHIM UNIVERSITY, MAIDUGURI

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ABSTRACT

Kashim Ibrahim University, Maiduguri faces persistent energy shortages due to unreliable grid supply and reliance on diesel generators. Earlier proposals for stand-alone solar PV systems overlooked wind resources and full techno-economic optimization, highlighting the need for a more resilient hybrid approach. This study aims to evaluate and optimize an off-grid wind-solar hybrid power system for reliable and sustainable electricity supply at Kashim Ibrahim University. The assessment was carried out using hourly electrical load data and validated site-specific meteorological data, including solar irradiance, wind speed, and temperature, modeled and optimized in HOMER Pro software. The optimal configuration includes 9.25 MW PV, 678 kW wind, lead-acid storage, and a bidirectional converter, which could provide 100% renewable energy with negligible unmet load. With a levelized cost of energy (LCOE) of ₦85.18/kWh and a 3.9-year payback period, the system outperforms grid and diesel alternatives by producing 17.63 GWh yearly to satisfy the 3.21 GWh demand. Over a 25-year period, the system prevents more than 308,000 tonnes of CO<sub>2</sub> emissions and reduces air and noise pollution. Strong temperature resilience is confirmed by sensitivity analysis, where temperature variation between 25–35°C results in only a 3.5% reduction in energy production. The optimized wind-solar hybrid system offers a cost effective, reliable, and environmentally sustainable energy solution for institutional power supply in northeastern Nigeria. Phased implementation is recommended for Kashim Ibrahim University and other institutions facing persistent energy insecurity.

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1. Introduction

Social welfare, institutional productivity, and the expansion of the world economy all depend on a steady and dependable power supply. However, due to poor electrical systems infrastructure, inadequate maintenance, and limited generation capacity, extremely severe electricity shortages continue to exist in many developing nations, including Nigeria. As a result, Nigeria's national grid electricity generation capacity has varied between approximately 4,000 and 5,000 MW, and it has been estimated that less than 30% of residents in Nigeria's Northeast region have access to dependable electricity, despite the country's population exceeding 220 million (Business Day, 2024; NERC, 2023). This mismatch between electricity supply and demand has a detrimental effect on the efficient operation of academic institutions like Kashim Ibrahim University in Maiduguri, where regular grid outages, inadequate infrastructure, and regional insecurity continue to be major barriers to the productivity of research and instruction.

Subsequently, off-grid renewable energy systems, mainly solar and wind hybrid systems, have become reasonable means to ensure energy access and resilience (Hamidu et al., 2025a). As a direct consequence of

persistent grid unreliability, these challenges make the institution heavily dependent on diesel generators, as evidenced by high operational costs, an increased maintenance burden, and significant greenhouse gas (GHG) emissions being associated with running these generators (Hamidu *et al.*, 2025b; Abdulrahman *et al.*, 2024). To address these technical, economic, and environmental challenges, Techno-economic optimization of these hybrids using simulation tools like HOMER Pro has globally allowed for more accurate system sizing, cost reduction, and assessment of environmental impacts (Al-Badi *et al.*, 2016). The feasibility of hybrid solar–wind systems in reducing intermittency issues and improving energy security has been demonstrated by numerous studies across diverse regions and climatic conditions. For example, Pande *et al.* (2017) optimized a PV–wind–diesel–battery system for a rural Indian community using HOMER Pro and showed that hybridization effectively reduces cost of energy and fuel consumption. Similarly, Alayande *et al.* (2025) applied a HOMER Pro–based approach for designing a grid-tied hybrid system in Nigeria and found substantial improvements in power reliability and a positive return on investment within four years. However, despite these extensive global studies, limited attention has been given to off-grid institutional applications in conflict-affected regions such as northeastern Nigeria, highlighting the need for context-specific system optimization. In this context, previous research, such as Mohammed *et al.* (2015), showed that small- to medium-sized turbines can be supported by regional wind speeds and that combining solar and wind resources improves reliability while lowering reliance on fossil fuels. Abdulrahman *et al.* (2024) created a stand-alone solar-photovoltaic system for Kashim Ibrahim University, but they did not include wind integration or complete techno-economic optimization. Similar to this, Hamidu *et al.* (2025b; 2025c) used HOMER Pro to advance institutional-scale PV modeling, but they only considered solar resources and did not perform sensitivity analysis or hybridization.

Together, these studies confirm feasibility but highlight a persistent gap: the absence of an integrated techno-economic optimization of solar–wind hybrid systems for off-grid institutional environments in conflict-prone regions. Responding directly to this gap, the present study develops and optimizes a solar–wind hybrid power system for Kashim Ibrahim University using HOMER Pro. It advances earlier solar-only models by incorporating resource complementarity and site-specific load dynamics to improve energy reliability and cost efficiency. The system integrates solar PV, wind turbines, battery storage, and converters into a unified off-grid architecture optimized for hourly load variations, addressing daily and seasonal resource fluctuations overlooked in earlier regional works. Interestingly, Maiduguri and the greater northeastern region of Nigeria offer promising opportunities for the implementation of hybrid renewable energy due to their strong solar potential (5.7–7.3 kWh/m<sup>2</sup>/day) and moderate wind resources. This resource availability provides a strong justification for hybrid system deployment in the study area. The analysis also expands environmental evaluation beyond CO<sub>2</sub> displacement to include noise reduction, elimination of NO<sub>x</sub>, SO<sub>x</sub>, and particulate matter emissions, and land-use considerations, providing a more holistic sustainability perspective. Additionally, the study assesses system adaptability under varying component temperatures, renewable resource availability, and projected load growth an analytical dimension rarely examined locally. By tackling intermittency, high diesel costs, and emissions in a conflict-prone area, this study offers a practical blueprint for reliable and sustainable power supply for academic institutions facing energy insecurity.

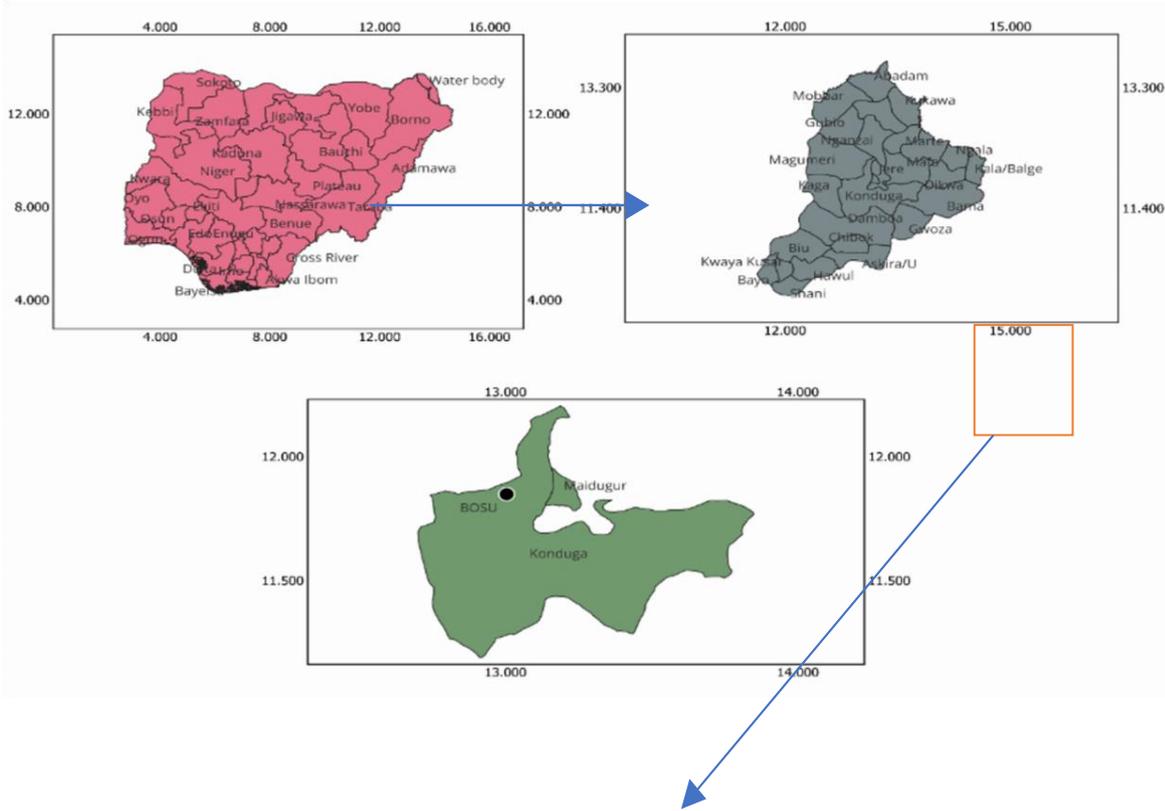
## 2. Materials and Method

### 2.1 Study Area

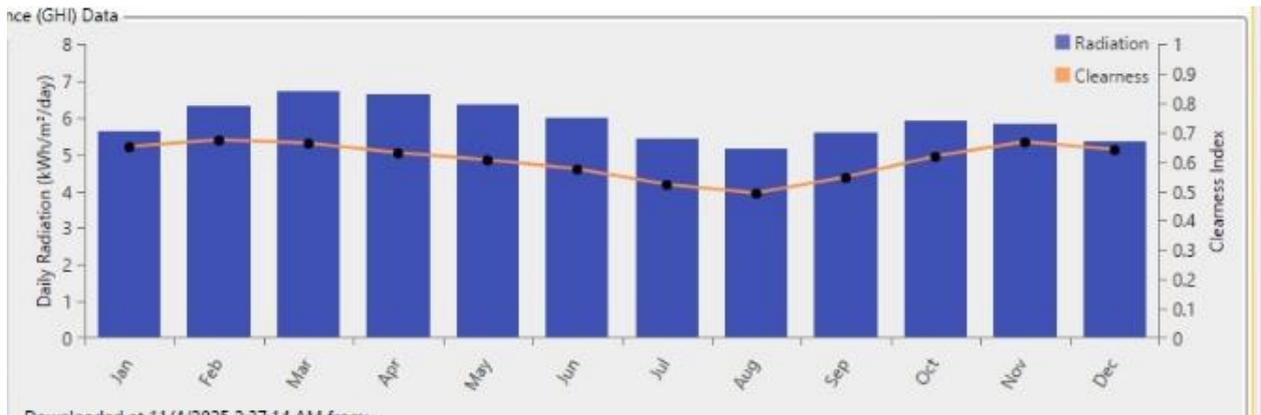
The study was conducted at Kashim Ibrahim University, Maiduguri, Nigeria (Latitude: 11°50'N, Longitude: 13°09'E, Elevation: 354 m), located within the semi-arid Sahelian zone characterized by prolonged sunshine, moderate wind potential, and high diurnal temperature variation, making it suitable for wind–solar hybrid integration, with Figure 1 presenting Nigeria, Borno State, Maiduguri, and Kashim Ibrahim University as the study area, Figure 2 showing the monthly solar radiation and clearness index for Maiduguri, Figure 3 illustrating monthly average wind speeds ranging from 4.0 m/s to 7.2 m/s with higher speeds between January and March and lower speeds during the monsoon months of August to October, and Figure 4 presenting the monthly temperature profile derived from NiMet data and NASA cross-validation in HOMER Pro.

### 2.2 Meteorological Data

Hourly meteorological data for the year 2025 were sourced from the Nigerian Meteorological Agency (NiMet). The dataset, including solar irradiance, wind speed, and ambient temperature, was validated against the NASA POWER database using a modified version of the procedure described by Hamidu *et al.* (2025d) to reflect the local climatic and system conditions.



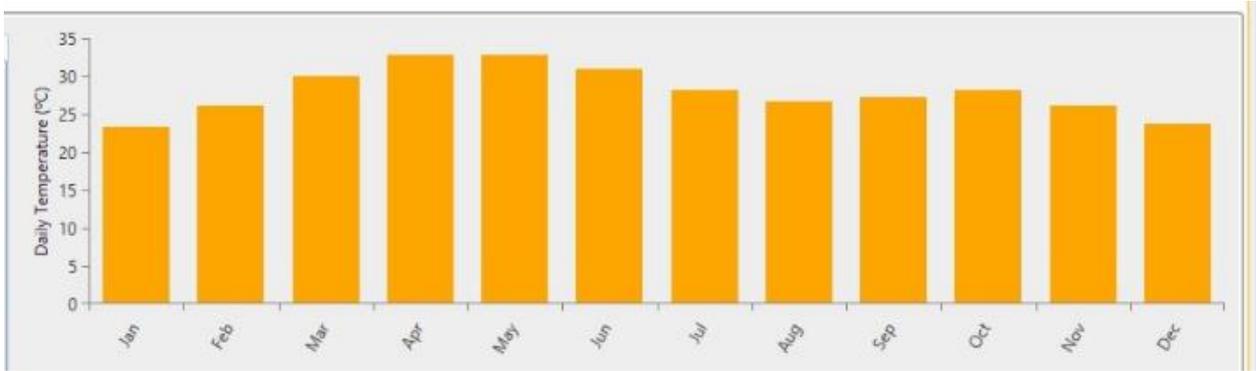
**Figure 1:** Map of Maiduguri showing the study area adopted from (Abdurahman *et al.*, 2024)



**Figure 2:** Solar radiation potential for Maiduguri



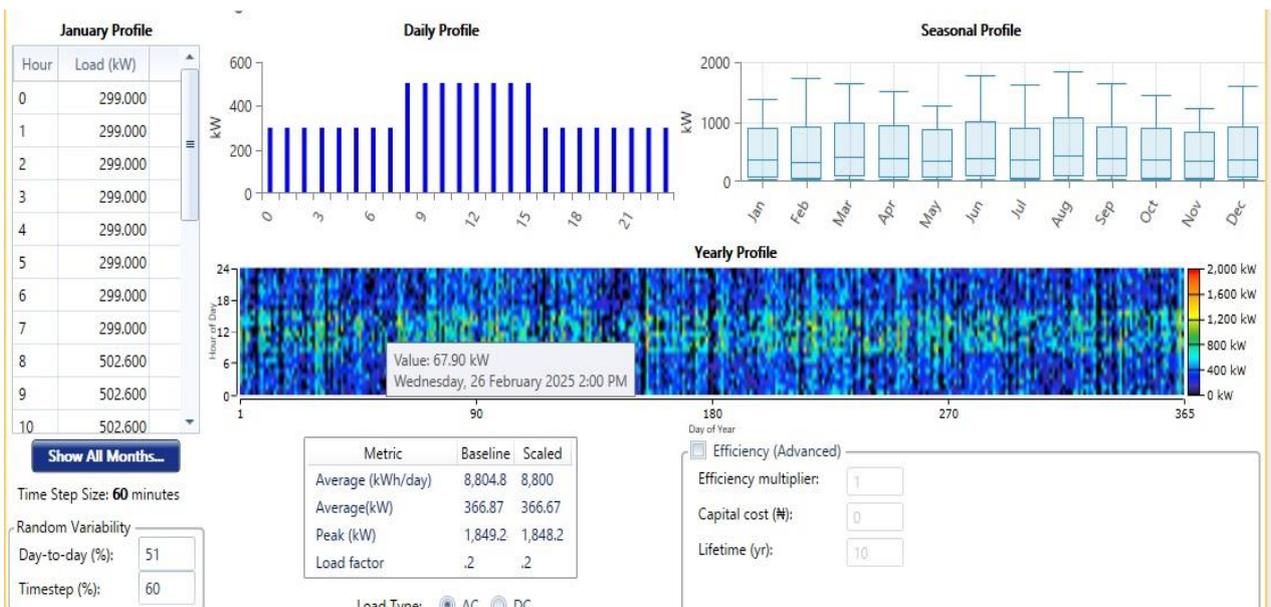
**Figure 3:** Monthly Average Wind Speed Profile for Maiduguri



**Figure 4: Monthly Temperature Profile for Maiduguri**

### 2.3 Load Profile Analysis

The facility's electrical demand patterns over a year are shown in the energy load profile (Figure 5), which also includes information on important systems such as lighting, HVAC, ICT, and laboratory loads. Because of HVAC and laboratory usage, the baseline load in January is roughly 299 kW off-peak and rises to 502 kW during peak activities. The daily load peak occurs at midday. Because of the need for cooling, seasonal variations indicate higher loads during warmer months. The university records an average daily electricity consumption of 8,804 kWh, corresponding to an annual energy demand of 3.21 GWh/year. This results in an average load of 366.87 kW, a peak demand of 1,848.2 kW, and a load factor of approximately 0.20, which are critical inputs for the hybrid system sizing and optimization.



**Figure 5: Electrical load profile of Kashim Ibrahim University**

### 3.4 System Modeling and Component Specifications

The hybrid system comprises solar PV, wind turbine, battery energy storage system (BESS), and a bidirectional inverter. Table I shows the technical specification and economic parameters for Kashim Shettima University (KSU).

#### 2.4.1 Solar PV Modeling

The system employs the Canadian Solar MaxPower CS6U-340M panel, rated at 340 W with an efficiency of 17.49%. The real electrical output from the PV array is determined using Equation (1) (Lambert et al., 2006):

$$PV_{PV} = F_{PV} \times Y_{PV} \times \left[ \frac{I_T}{I_S} \right]$$

1

In this expression,  $F_{PV}$  represents the overall derating factor accounting for losses due to dirt, partial shading, wiring, and inverter inefficiencies.  $Y_{PV}$  is the installed PV capacity (kW),  $I_T$  refers to the solar irradiance incident on the module surface (kW/m<sup>2</sup>), while  $I_s$  is the standard reference irradiance of 1 kW/m<sup>2</sup>. The equation therefore adjusts the theoretical panel rating to reflect realistic operating conditions (Lambert et al., 2006).

**Table I:** Technical specifications and cost of system parameters for KSU

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	157,500	25,000
Wind Turbine	Generic 3kW	3 kW	92%	20 yrs	15,000,000	13,000,000	170,000
Battery	Lead-acid (generic)	1 kWh	80%	10 yrs	550,000	550,000	50,000
Converter	System Generic	1 kW	96%	15 yrs	250,000	250,000	25,000

Source: Techpoint Africa (2025)

### 2.4.2 Wind Turbine Modeling

The wind turbine component was evaluated using HOMER’s standard performance model, which expresses the electrical power output as a function of the available kinetic energy in the wind. The output of the turbine is estimated using Equation (2) (Lambert et al., 2006):

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

In this equation,  $P_{WT}$  is the power generated by the wind turbine (W),  $\rho$  represents the air density (kg/m<sup>3</sup>),  $A$  is the rotor swept area (m<sup>2</sup>),  $C_p$  is the power coefficient determined by the turbine’s aerodynamic characteristics, and  $V^3$  is the hub-height wind speed (m/s). The cubic dependence on wind speed highlights the sensitivity of wind power to local resource conditions (Lambert et al., 2006).

### 2.4.3 Battery Storage Modeling

The number of batteries required for the storage bank is obtained from:

$$N_{batt} = \frac{Q_{life}}{Q_{thrpt}} \times R_{batt} \tag{3}$$

HOMER uses Equation (3) to estimate the effective lifetime of the battery bank (Lambert et al., 2006). Here,  $N_{batt}$  denotes the total number of batteries,  $Q_{life}$  is the lifetime energy throughput of an individual battery (kWh),  $Q_{thrpt}$  is the annual energy cycled through the bank (kWh/year), and  $R_{batt}$  is the float life in years. This sizing approach ensures that the storage system can reliably support energy needs during periods of low or no solar generation.

### 2.4.4 Inverter Sizing

The inverter rating is obtained using Equation (4):

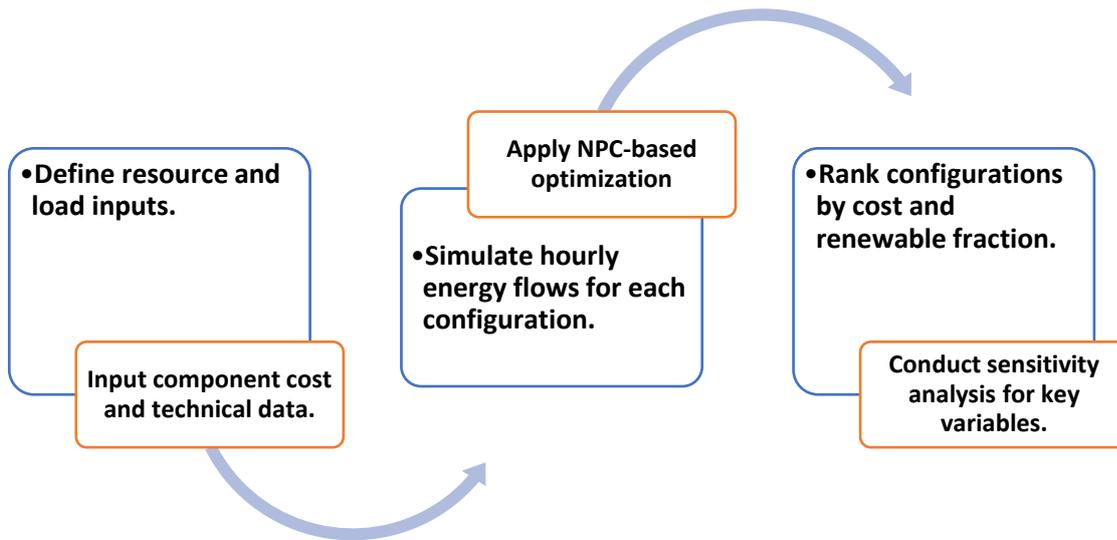
$$P_{inv} = P_{ACload} \times f_{ov} \tag{4}$$

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 (Nordin & Rahman, 2016).

## 2.5 System Optimization and Simulation in HOMER Pro

The HOMER Pro optimization process as shown in Figure 6 begins by determining the technical-economic parameters, load profile, and resource inputs for each system component. It then runs hourly simulations for

various configurations, using NPC-based optimization to evaluate long-term economic performance. Final configurations are ranked based on renewable fraction and overall system cost, followed by a sensitivity analysis to understand the impact of changes to critical variables.



**Figure 6:** Optimization Workflow in HOMER Pro

### 2.5.1 Performance Metrics

The simulated systems undergo analysis considering both technical and economic parameters to identify the optimal solution for the case study.

#### a) Technical Indicators

System performance was characterized using HOMER Pro’s standard output metrics (Bartolucci et al., 2019; HOMER-ENERGI, 2016).

- The total annual electrical production is computed as the sum of the yearly energy outputs of all generating units, expressed in Equation (5):

$$EP = \sum_{ij}^{n,1} E_{ij} \tag{5}$$

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

- Unmet load quantifies the portion of the demand not served by the system (Masrur et al., 2020) and is given by Equation (6):

$$Unmet\ load = Total\ load - Total\ load\ met \tag{6}$$

- Excess electricity represents generation that cannot be consumed or stored (Li et al., 2018), calculated using Equation (7):

$$Excess\ Electricity = Total\ energy\ produced - Total\ load \tag{7}$$

#### b) Economic Indicators

The economic evaluation considered capital cost (CC), operating cost (OC), replacement cost (RC), salvage cost (SC), net present cost (NPC), levelized cost of energy (LCOE) and Simple Payback Period.

- Capital cost reflects the initial system expenditure (Ghigo et al., 2020) and is defined in Equation (8) (Ajeba et al., 2021):

$$C_c = \sum_{PV=1}^{N_{PV}} C_{PVG} + \sum_{G=1}^{N_G} C_G + C_P \quad 8$$

Where NPV is the number of PV units, CPVG the PV unit cost, NG the number of grid connections (0 in this study), CG the grid cost (zero), and CP the fixed project cost.

- Operating cost comprises all annualized expenditures excluding initial capital outlay (Aderemi et al., 2018):

$$OC = TAC - TCC \quad 9$$

- Salvage cost represents the residual component value at the project endpoint (Salisu & Mustafa, 2019):

$$SC = RC \left( \frac{RL}{CL} \right) \quad 10$$

With RC as the replacement cost, RL the remaining life, and CL the component lifetime.

- Replacement cost denotes the expenditure required for component renewal during operation (HOMER-ENERGI, 2016) and excludes inflation adjustments.
- The levelized cost of energy (LCOE) relates the annualized system cost to useful electricity delivered (Bartolucci et al., 2019): it can be solved using equation (11)

$$LCOE = \frac{TAC - C_{boiler} H_{serve}}{E_{serve}} \quad 11$$

Where TAC is the total annualized system cost in N/yr,  $C_{boiler}$  is the boiler marginal cost in N/kWh,  $H_{serve}$  is the total thermal load served in N/kWh, and  $E_{served}$  is the total electrical load served

- NPC aggregates all lifecycle costs including capital, replacement, O&M and salvage into a present-worth value (Abdelaziz et al., 2018):

$$NPC = \frac{TAC}{CRF} \quad 12$$

The capital recovery factor, CRF, is defined as:

$$CRF = \frac{i(1+i)^n}{i(1+i)^n - 1} \quad 13$$

Where  $i$  is the real interest rate and  $n$  the system lifetime.

- **Payback Period:** This refers to the duration required for an investment to recover its initial cost through the net cash inflows it produces (Bragg, 2025). It is determined by dividing the total project cost by the annual net cash inflow:

$$\text{Payback Period} = \frac{\text{initial investment (Cost of Project)}}{\text{Annual Net Cash Inflow}} \quad 14$$

### c) Environmental Indicators

The environmental impact of the proposed hybrid system was evaluated using a quantitative life-cycle approach, focusing on GHG emissions, air and noise pollution, and resource use.

- Greenhouse Gas Emissions

Annual CO<sub>2</sub> emissions avoided were calculated as:

$$CO_{2,avoided} = E_{PV} \times EF_{fossil} \quad 15$$

Cumulative emissions over the system lifetime (L) were:

$$CO_{2,total} = CO_{2,avoided} + L \quad 16$$

Where  $E_{PV}$  is annual PV output (kWh/year) and  $EF_{fossil}$  is the emission factor of displaced electricity (kg CO<sub>2</sub>/kWh) (Smith et al. 2024; Fthenakis, 2009)

- Air and Noise Pollution

Air pollutant reduction ( $NO_x$ ,  $SO_x$ , PM) was estimated using:

$$Pollutant_{avoided} = E_{PV} \times EF_{pollutant} \quad 17$$

Noise reduction was assessed qualitatively by comparing PV–battery operation (~0 dB) to diesel generators (~70–80 dB) (Fthenakis & Kim, 2009)

- Land Use and Resource Impact

Land occupation was calculated as: (Smith et al. 2024; Fthenakis & Kim, 2009)

$$Land\ Use\ (m^3) = N_{modules} \times Module\ Area \quad 18$$

## 2.6. Sensitivity analysis

A sensitivity assessment was conducted by applying a ±5% perturbation to key climatic variable which is the ambient temperature to examine system resilience under fluctuating environmental conditions (Lambert et al., 2006). The relative impact of these variations on performance metrics was quantified using:

$$\Delta X = \frac{X_{+5\%} - X_{-5\%}}{X_{base}} \times 100 \quad 20$$

Where X represents output indicators such as, Electric Production, Electric Consumption, Excess Electricity and Unmet Load. The results assess system adaptability to climatic fluctuations.

## 3. Results and Discussion

### 3.1 Results

Optimization of the performance parameters was carried out using HOMER Pro software by considering the load data and meteorological inputs to identify the least-cost and most reliable hybrid configuration. The HOMER Pro optimization results shown in Figure 7 indicate that the most economical hybrid system configuration is the combination of PV, wind, and battery storage with a converter, achieving the lowest Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and annual operating cost. All configurations reached a 100% renewable fraction, but their cost performances varied significantly. The third configuration, featuring a higher wind-battery share, exhibited a much higher NPC and LCOE compared to the other options. The results are in line with earlier research that highlights the importance of techno-economic optimization in enhancing system sizing and lowering costs (Hamidu et al., 2025e; Pande et al., 2017; Alayande et al., 2025).

Figure 8 depicts the schematic of the AC–DC coupled hybrid energy system set up in HOMER Pro. The wind turbine generator powers the AC bus, while the CS6U-340M PV array powers the DC bus, which is backed by a 1 kWh lead-acid storage bank. Power transfer between the two buses is coordinated by a bidirectional converter, guaranteeing steady system operation. The KIU load profile (8,800 kWh/day; peak demand: 1,848.23 kW) is supplied with electricity by the integrated configuration

Export...		Export Details...		Optimization Results							System	
Architecture							Cost				System	
CS6U-340M (kW)	G3	1kWh LA (#)	Converter (kW)	Dispatch	NPC (M)	LCOE (M/kWh)	Operating cost (M/yr)	CAPEX (M)	Ren Frac (%)			
9,624	237	12,237	1,854	CC	¥38.18	¥916.79	¥1.788	¥15.18	100			
11,674		15,410	1,807	CC	¥42.08	¥1,012	¥2.158	¥14.28	100			
	3,415	57,646	3,077	CC	¥1608	¥3,859	¥5.918	¥83.78	100			

Figure 7: Optimization results for the evaluated hybrid system configurations.

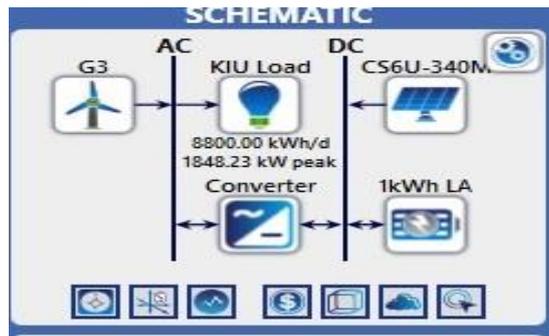


Figure 8: Optimized Hybrid System Architecture

### 3.2 System Component Model and Sizing Using HOMER Pro

#### a) PV Array Performance

Quantity	Value	Units
Rated Capacity	9,251	kW
Mean Output	1,871	kW
Mean Output	44,915	kWh/d
Capacity Factor	20.2	%
Total Production	16,393,860	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	8,402	kW
PV Penetration	510	%
Hours of Operation	4,361	hrs/yr
Levelized Cost	47.9	¥/kWh
Clipped production	0	kWh

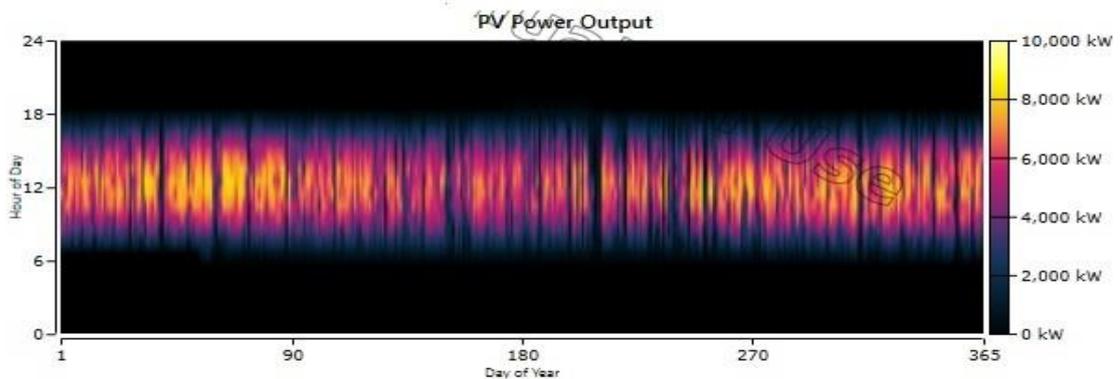
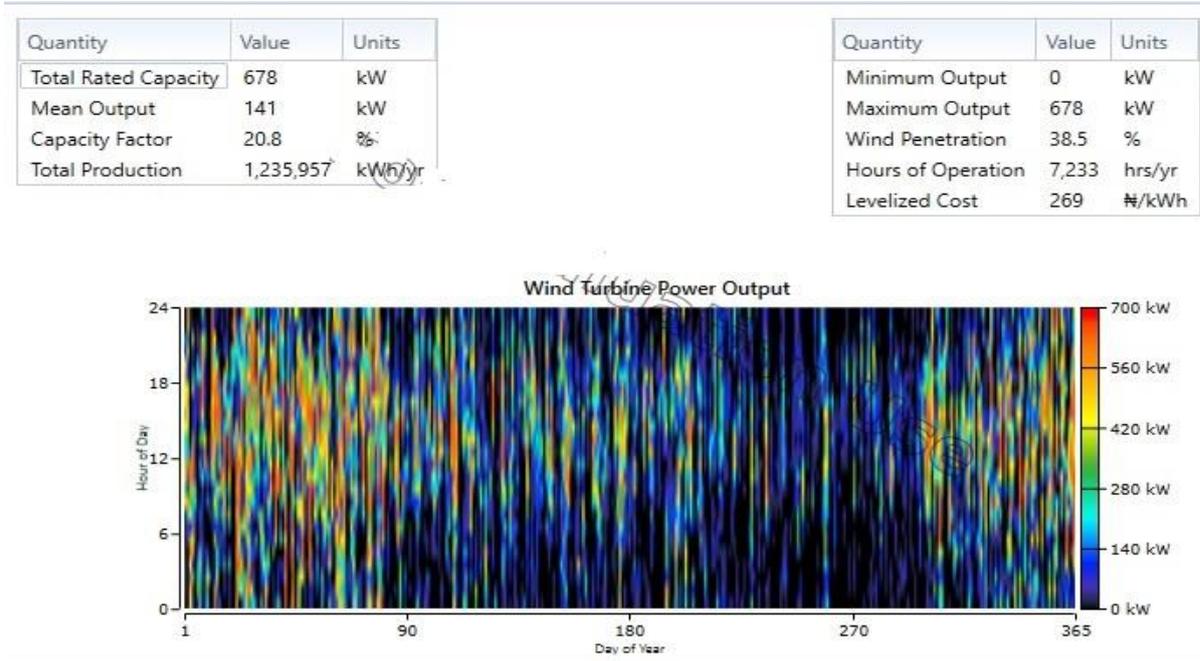


Figure 9: PV Array Performance

The Canadian Solar MaxPower CS6U-340M PV array achieves a yearly performance with a mean output of 1.87 MW, a capacity factor of 20.2%, and a total annual generation of 16.39 GWh as shown in Figure 9. The system demonstrates a PV penetration of 510%, indicating a robust renewable generation surplus. The hourly power heat map illustrates consistent diurnal generation, peaking between 10:00 and 15:00. Ideal inverter

sizing is evidenced by a maximum output of 8.40 MW and no clipped production. The levelized cost of PV electricity is 47.9 ₦/kWh, confirming the solar subsystem’s economic viability as the main energy source in a hybrid setup.

**b) Wind Turbine Power Output and Annual Performance**



**Figure 10: Wind Turbine Power Output and Annual Performance**

With an average output of 141 kW and a rated capacity of 678 kW, the wind turbine system generates 1.24 GWh of electricity annually, corresponding to a capacity factor of approximately 20.8%, as shown in Figure 10. The turbine operates for about 7,233 hours per year and exhibits output variability typical of the local wind regime. Although the instantaneous peak output (678 kW) reaches the rated capacity during short high-wind periods, this reflects normal turbine power regulation rather than full conversion efficiency, as aerodynamic performance is inherently limited by the Betz limit and system losses. Wind energy, despite its intermittent nature, achieves a penetration of 38.5% and contributes meaningfully to supply stabilization, particularly during periods of reduced solar generation.

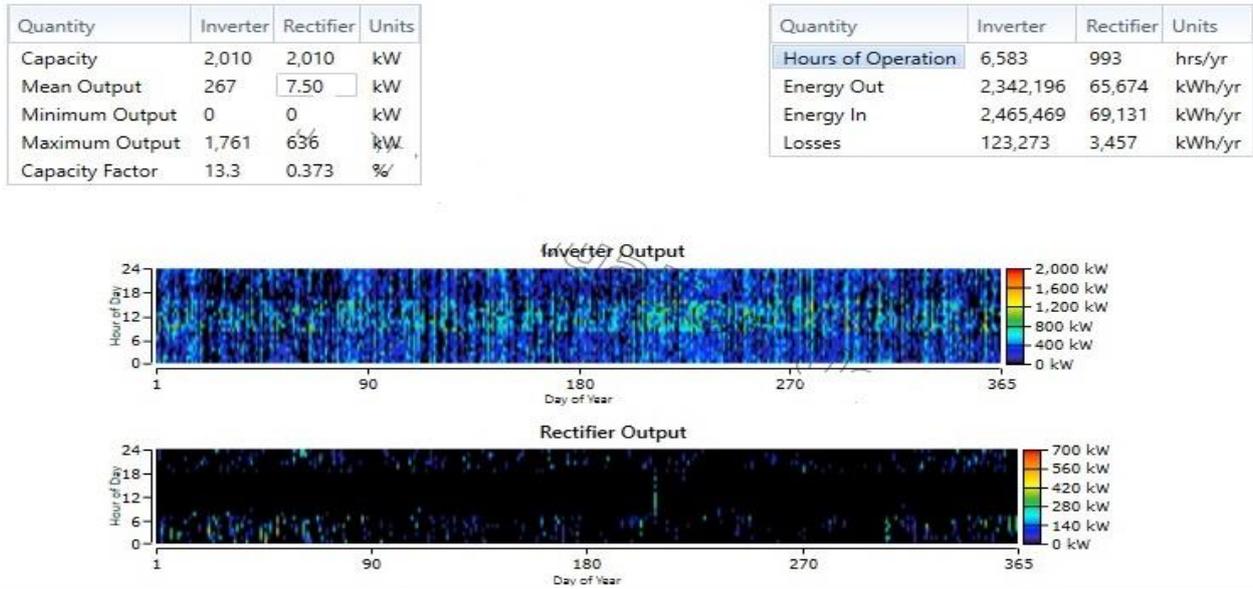
**c) Battery Bank Performance and State-of-Charge Profile**



**Figure 11: Battery Bank Performance and State-of-Charge Profile**

As shown in Figure 11, the battery subsystem is made up of 12,116 deep-cycle, 12-V units that are configured to provide a 48-V DC bus and 7,275 kWh of usable storage capacity. Even though it loses roughly 273 MWh a year, it is predicted to last for 7.9 years with a 19.8-hour autonomy capacity. The system continuously satisfies demand through renewable generation, achieving 1.37 GWh of charge input and 1.09 GWh of discharge output annually. By supporting the load during periods of low PV or wind output and ensuring a 100% renewable supply year-round, the control strategy improves system stability by ensuring the state-of-charge stays above 75%.

#### d) Converter (Inverter/Rectifier) Output Characteristics

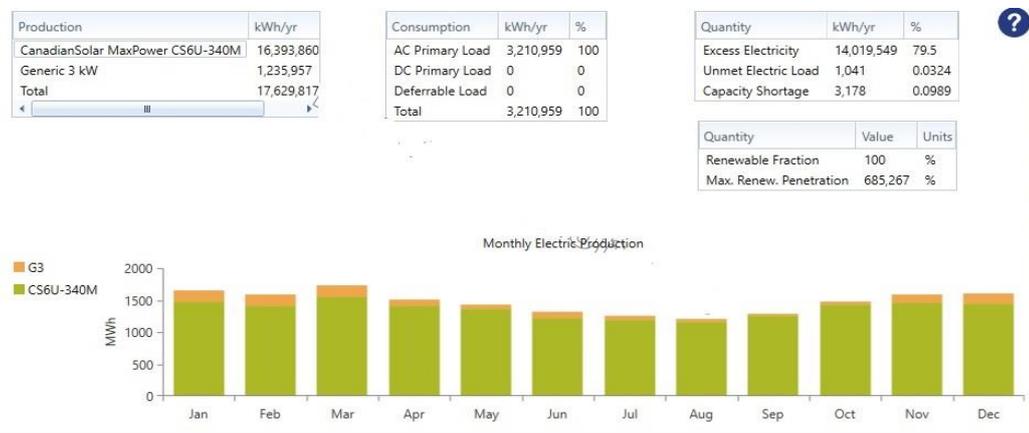


**Figure 12:** Converter (Inverter/Rectifier) Output Characteristics

The converter system performs well in terms of operation; as shown in Figure 12, the rectifier operates intermittently with a mean output of 7.5 kW and a capacity factor of 0.37%, while the inverter achieves a mean output of 267 kW and a capacity factor of 13.3% over 6,583 annual operating hours. With total conversion losses of 123 MWh, or less than 5% of the total energy processed, the inverter produces 2.34 GWh/year and the rectifier produces 65.7 MWh/year. The heat maps show continuous inverter activity all year long, supporting the analysis's findings of efficient power conditioning and reliable bidirectional energy exchange.

### 3.3 Technical Results analysis

- **Electric Production**

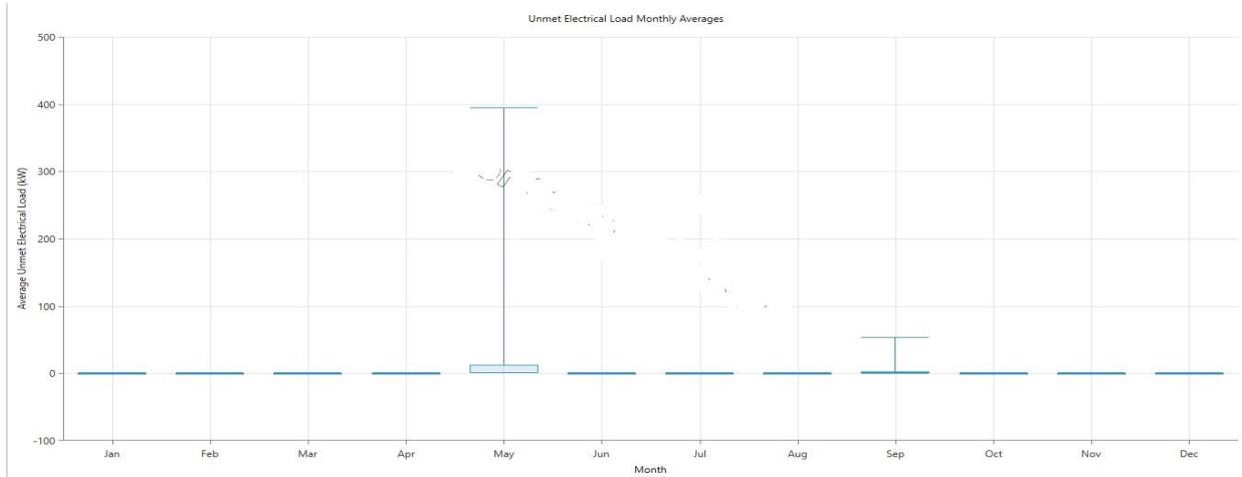


**Figure 13:** Annual Energy Balance and Monthly Production Profile

With a total generation of 17.63 GWh/yr from a PV array (16.39 GWh/yr) and wind turbine (1.24 GWh/yr), Figure 13 shows the energy production and consumption of an optimized hybrid system. The system achieves

a 100% renewable energy fraction by meeting an AC load demand of 3.21 GWh/year. It has a capacity shortage of 0.10 percent and a minimal unmet load of 0.03%, with excess electricity accounting for 79.5% of annual generation. Strong resource availability and the system's potential for full renewable adoption are indicated by monthly production, which consistently displays high PV output along with moderate wind generation.

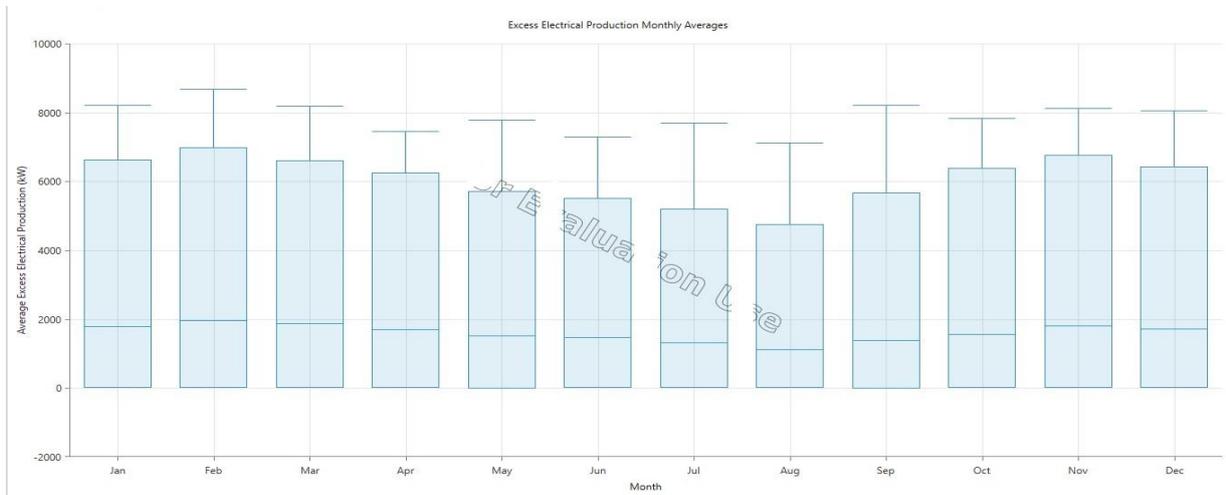
- **Unmet Load**



**Figure 14:** Monthly average unmet electrical load

The simulated system shows minimal unmet electrical load throughout the year, with only slight shortages in May and September as shown in Figure 14. These spikes occur when demand briefly exceeds generation or storage capacity, indicating high reliability in most months.

- **Excess Electricity**

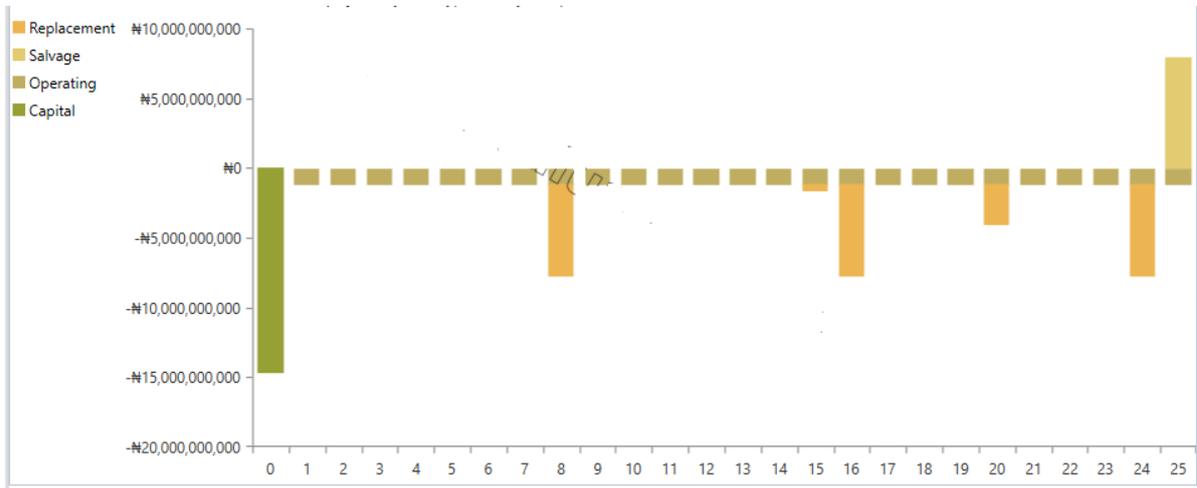


**Figure 15:** Monthly averages of excess electrical production

Figure 15 shows that the system consistently produces excess energy throughout the year, with monthly outputs averaging between 5,000 and 7,000 kW, and peak values exceeding 8,000 kW in some months. This overproduction indicates a substantial renewable generation capacity relative to load, confirming the system's design allows for sufficient capacity across all seasons. These results are consistent with research showing that hybrid PV–wind systems are more resilient and stable than single-source setups (Ma et al., 2014; Mohammed et al., 2015; Agelin-Chaab et al., 2014)..

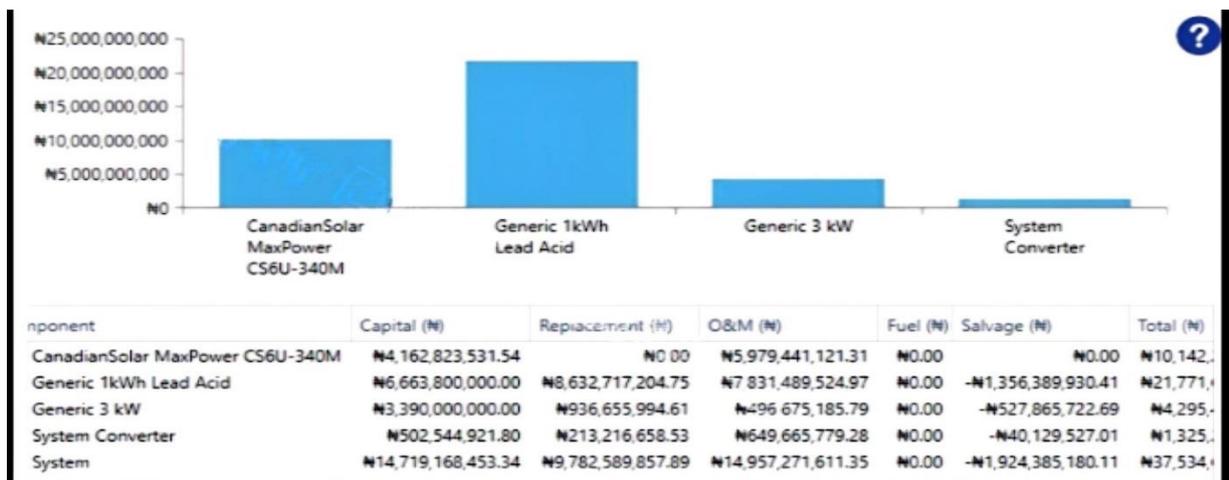
### 3.4 Economic Results analysis

To evaluate the life-cycle cost implications of the suggested system, a thorough economic analysis was conducted using HOMER Pro. A cost analysis of capital, replacement, and operation and maintenance (O&M) expenses over a 25-year project horizon was part of this.



**Figure 16:** Economic evaluation of wind-solar hybrid system

An analysis of the wind-solar hybrid system projects an initial investment of ₦15 billion, indicating a capital-intensive requirement as seen in Figure 16. The annual cost of operations and maintenance stayed around ₦1 billion over the course of 25 years, with notable peaks near years 8, 16, and 24 as a result of component replacements. This emphasizes how important it is to plan for long-term asset replacement. The system's economic viability is increased by the estimated ₦10 billion salvage value at completion.



**Figure 17:** Component-wise Cost Breakdown

The economic analysis of the hybrid system (Figure 17) indicates an initial CAPEX of ₦6.66 billion and replacement costs of ₦9.63 billion, with battery storage being the primary cost driver. The generic 3 kW wind turbine incurs ₦936.66 million in capital and ₦496.68 million in replacements, while solar PV requires ₦4.16 billion upfront. The low cost of the converter contributes to a financially balanced system, where storage and wind generation enhance long-term reliability, eliminating fuel expenses and providing significant salvage value from the storage subsystem.

### 3.4.1 Levelized Cost of Energy

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 solar PV system. The LCOE was calculated using the estimated lifetime energy generation of 17,626,817 kWh annually over 25 years and the total life-cycle expenditure of ₦37,534,644,742.46.

$$LCOE = \frac{\text{Total Life – Cycle Cost (₦37,534,644,742.46)}}{\text{Total Energy Produced Over 25 Years (17,626,817 kWh/year} \times 25 \text{ years)}}$$

An LCOE of ₦85.18/kWh is obtained by substituting the values. This price is even more affordable than typical Nigerian grid tariffs, which typically range between ₦90 and ₦210/kWh, and significantly less expensive than

the current cost of diesel-generated electricity. The outcome shows that the suggested system can provide electricity at a significantly lower and more consistent long-term cost, making it a financially feasible substitute for conventional sources.

### 3.4.2 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 17,626,817 kWh, the yearly financial savings were computed as:

$$\text{Annual Cost Offset} = 17,626,817 \text{ kWh/year} \times \text{₦}209/\text{kWh} = \text{₦}3,684,004,753 \text{ kWh/year}$$

The initial capital cost of the system is ₦14,719,168,453.34. Thus, the simple payback period is:

$$\text{Payback Period} = \frac{\text{₦}14,719,168,453.34}{\text{₦}3,684,004,753 \text{ kWh/year}} \approx 3.9 \text{ Years}$$

This relatively short recovery time shows that the investment becomes financially beneficial early in its operational life, further reinforcing the system's economic attractiveness. The viability and scalability of comparable hybrid systems are supported by these results (Hamidu *et al.*, 2025f; Abraham *et al.*, 2023).

## 3.5 Environmental Impact Assessment

The environmental performance of the hybrid system was assessed using the quantitative indicators outlined in the methodology. The results demonstrate substantial reductions in greenhouse gas emissions, significant improvements in local air quality, and a modest land-use footprint consistent with sustainable energy system design.

### 3.5.1 Greenhouse Gas Emission Reduction

Using the annual hybrid energy production of 17,628,817 kWh/year and the diesel emission factor of  $EF_{fossil} = 0.7, \text{ kg CO}_2/\text{kWh}$ , greenhouse gas avoidance was calculated using Equation (15).

$$CO_{2,avoided} = 17,628,817 \times 0.7$$

This corresponds to approximately 12,340 tonnes of CO<sub>2</sub> avoided annually. Over the 25-year system lifetime (Equation 16):

$$CO_{2,total} = 12,340 \times 25$$

$$CO_{2,total} = 308,504,300 \text{ kg CO}_2$$

Thus, the hybrid system prevents over 308,000 tonnes of CO<sub>2</sub> from being released, confirming the system's substantial contribution to climate mitigation.

### 3.5.2 Reduction of Air Pollutants and Noise

By successfully eliminating NO<sub>x</sub>, SO<sub>x</sub>, CO, and particulate matter emissions, wind-solar generation improves air quality and lowers risks to public health. Furthermore, noise pollution is greatly reduced, as diesel generators run at 70–80 dB, while solar PV panels and battery storage operate at 0 dB and contemporary wind turbines operate at 40–50 dB. Because of this, the hybrid system is perfect for use in healthcare, education, and residential settings.

### 3.5.3 Land Use and Resource Impact

Land-use requirements were calculated using Equation (18) and the annual PV production of 16,393,860 kWh/year. The PV subsystem uses Canadian Solar 340-W modules with a typical area of 1.96 m<sup>2</sup> per module,  $E_{pv} = 16,393,860 \text{ kWh/year}$  and PV annual yield (Maiduguri typical) = 1400 kWh/kW/year,

$$PV \text{ Capacity} = \frac{E_{pv}}{1400}, PV \text{ Capacity} = \frac{16,393,860}{1400} \approx 11,710 \text{ kW, Number of 340 W modules needed}$$

$$N_{\text{modules}} = \frac{11,710}{0,34} \approx 34,441 \text{ modules}$$

$$\text{Land Use} = 34,441 \times 1.96 \approx 67,508 \text{ m}^2 (\approx 6.75 \text{ hectares})$$

Large amounts of land are needed for utility-scale photovoltaic (PV) systems that produce more than 16 GWh a year. The preservation of nearby vegetation and agriculture is made possible by wind turbines' low land impact, which only requires foundation pads and spacing corridors. As a result, this hybrid system keeps its ecological and spatial environmental footprint less substantial. These results are consistent with life-cycle studies that demonstrate hybrid renewable systems have minimal effects on land and provide significant environmental and noise benefits (Fthenakis & Kim, 2009; Smith et al., 2024)

### 3.6 Sensitivity Results analysis

A temperature-based sensitivity assessment was conducted to evaluate the influence of thermal conditions on system performance. Four ambient temperature scenarios 25 °C, 28 °C, 30 °C, and 35 °C were simulated in HOMER Pro. The outcomes focused on annual generation, delivered load, surplus electricity, and the extent of unmet demand.

**Table 2:** Temperature-Based Sensitivity of Major System Outputs

S/N	Temperature (°C)	Production (kWh/year)	Consumption (kWh/year)	Excess Electricity (kWh/year)	Unmet Load (kWh/year)
1	25	17,789,154	14,174,513	3,211,020	980
2	28	17,629,817	14,019,549	3,210,959	1,041
3	30	17,323,068	13,717,028	3,210,839	1,161
4	35	17,163,734	13,526,066	3,210,778	1,222

Table 2 shows that the total energy production drops by approximately 3.5% as the temperature rises, from 17.79 GWh at 25 °C to 17.16 GWh at 35 °C. Because there is less supply at higher temperatures, annual consumption decreases even though there is a steady surplus of electricity of about 3.21 GWh. With a slight decline in system adequacy in hotter conditions, unmet load increases from 980 kWh/year at lower temperatures to 1,222 kWh/year at 35 °C. Higher temperatures have a slight detrimental effect on reliability and lower photovoltaic output, even though the system maintains a steady surplus overall. Nonetheless, the consistent excess electricity in every scenario suggests that the system is naturally protected from thermal stress by the solar-wind mix. This confirms previous research on hybrid systems' ability to withstand heat (Lambert et al., 2006; Hamidu et al., 2025f)

### 4. Conclusion

The optimized solar–wind hybrid system shows that the electricity demand of Kashim Ibrahim University can be reliably met using locally available renewable energy resources. Operating fully on renewables with only minor supply shortfalls, the system improves energy security and demonstrates reliability that is suitable for institutional use. The joint contribution of solar and wind resources further confirms that hybridization is effective in reducing intermittency and supporting continuous power supply. From an economic point of view, the system remains competitive when compared with grid electricity and diesel-based generation. Although the initial investment is relatively high, the reduction in operating costs over time supports its overall economic viability throughout the project lifetime. In environmental terms, the hybrid system offers clear advantages by reducing greenhouse gas emissions, eliminating common air pollutants, and operating with very low noise levels, which is appropriate for a university environment. The land requirement is also moderate, supporting sustainable campus development. Results from the sensitivity analysis show that the system continues to perform reliably under different temperature conditions, with only slight reductions in output at higher ambient temperatures. For implementation, a phased deployment starting with key facilities such as laboratories and ICT centers is considered practical. Routine battery replacement planning, continuous system monitoring, the use of photovoltaic-thermal options, and supportive government policies are expected to further strengthen long-term performance and scalability.

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