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Design, Fabrication, and Experimental Performance Evaluation of a Low-Cost Vertical-Axis Wind Turbine-Photovoltaic Hybrid System for Rural Electrification in Northern Nigeria

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ABSTRACT
Reliable electricity remains inaccessible to many rural communities in Nigeria due to inadequate grid infrastructure and the high cost of conventional energy systems. Hybrid renewable energy systems that combine wind and solar resources provide an effective alternative for decentralized electricity generation, particularly in regions with complementary renewable energy profiles. This study presents the design, fabrication, and experimental evaluation of a low-cost vertical-axis wind turbine (VAWT) integrated with a photovoltaic (PV) subsystem for rural electrification in northern Nigeria. The prototype consists of a three-bladed H-type Darrieus VAWT employing a NACA 0021 symmetrical airfoil coupled to a permanent-magnet alternator and a 300-W photovoltaic module through a battery-supported hybrid energy management system. Performance testing was conducted under wind speeds ranging from 2.8 to 6.5 m s^{-1} and solar irradiance between 420-910W m^{-2} in Mubi, Adamawa State, Nigeria. Wind speed, rotor speed, voltage, current, and solar irradiance were continuously monitored using calibrated sensors connected to an Arduino-based data acquisition system. Experimental results showed that the turbine attained a cut-in wind speed of approximately 2.8 m s^{-1} and produced a maximum electrical output of 68.4 W at a wind speed of 6.5 m s^{-1}, corresponding to an overall electrical conversion efficiency of approximately 29.3% and a power coefficient within the expected operating range for small H-rotor VAWTs. The hybrid configuration generated an average daily electrical energy of approximately 3.2 kWh, improving power availability during periods of low solar irradiance through complementary wind generation. The total fabrication cost of approximately ₦1.50 million demonstrates the economic feasibility of locally manufactured hybrid renewable energy systems for rural communities. The findings confirm that locally fabricated VAWT-PV hybrid systems represent a technically viable and economically attractive solution for decentralized rural electrification in low-wind regions of northern Nigeria.

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INTRODUCTION

Universal access to affordable, reliable and sustainable electricity remains one of the major challenges facing developing countries, particularly in sub-Saharan Africa. Although Nigeria possesses abundant renewable energy resources, electricity supply remains unreliable, especially in rural communities where grid extension is technically difficult and economically prohibitive. According to the International Renewable Energy Agency (IRENA, 2023), decentralized renewable energy technologies are increasingly recognized as practical solutions for achieving universal energy access while reducing greenhouse gas emissions and dependence on fossil fuels.

Among decentralized renewable technologies, hybrid renewable energy systems (HRES) combining photovoltaic (PV) and wind energy have received considerable attention because of their ability to exploit the complementary nature of solar radiation and wind resources. Solar photovoltaic systems generally produce maximum power during daylight hours under clear atmospheric conditions, whereas wind resources often exhibit higher availability during evening, nighttime, and cloudy conditions. Integrating these energy sources therefore enhances system reliability, improves energy availability, reduces battery cycling, and minimizes fluctuations associated with single-source renewable systems (Hassan et al., 2023; León Gómez et al., 2023; Zebra et al., 2021; Bagdadee et al., 2024).

Small-scale wind turbines are generally classified into horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). Although HAWTs dominate commercial electricity generation because of their relatively high aerodynamic efficiency, they require consistent wind direction, sophisticated yaw mechanisms, tall towers, and regular maintenance. In contrast, VAWTs possess several characteristics that make them attractive for decentralized rural applications. These include omni-directional wind acceptance, lower installation height, simpler mechanical construction, reduced maintenance requirements, quieter operation, and improved performance under turbulent and multidirectional wind conditions frequently encountered around buildings and rural settlements (Paraschivoiu, 2019; Islam et al., 2021; Chong et al., 2014; Fiedler & Tullis, 2020).

Despite these advantages, VAWTs also present several engineering challenges. Conventional Darrieus turbines generally exhibit poor self-starting capability, relatively lower aerodynamic efficiency than horizontal-axis turbines, cyclic blade loading that may reduce structural lifespan, and lower tip-speed ratios under low Reynolds number conditions. These limitations have motivated recent investigations into blade optimization, improved airfoil selection, hybrid

Savonius-Darrieus configurations, active pitch control, and advanced computational fluid dynamics (CFD) optimization techniques aimed at enhancing aerodynamic performance and starting characteristics (Bang et al., 2024; Shen et al., 2024; Eltayeb et al., 2024; Castelli et al., 2012; Kumar & Bansal, 2020). Nevertheless, many published investigations remain computational or laboratory based, with relatively few studies providing long-term experimental validation of locally fabricated hybrid systems operating under the low-wind conditions typical of northern Nigeria.

Several studies have investigated hybrid renewable energy systems for rural electrification using optimization software such as HOMER Pro and MATLAB/Simulink. While these investigations demonstrate the techno-economic feasibility of PV-wind hybrid systems, they frequently rely on simulated meteorological datasets and imported equipment, with limited attention given to fabrication using locally available materials or field validation under actual environmental conditions (Mas'ud et al., 2024; Bouregba et al., 2024; Amuta et al., 2024; Okelola et al., 2025; Thango & Obokoh, 2024). Consequently, uncertainties remain regarding the practical performance, affordability, maintainability, and long-term sustainability of locally manufactured hybrid renewable energy systems suitable for rural Nigerian communities.

The present study addresses these gaps through the design, fabrication, installation, and experimental evaluation of a low-cost hybrid renewable energy system consisting of a locally fabricated H-type Darrieus vertical-axis wind turbine integrated with a photovoltaic subsystem. Unlike previous simulation-oriented investigations, this work emphasizes practical fabrication techniques using locally sourced materials, real-time field measurements, and experimental validation under naturally occurring wind and solar conditions in northern Nigeria.

The study considered the design and fabrication of a low-cost H-type Darrieus vertical-axis wind turbine using locally available materials, and the integration of the wind turbine with a photovoltaic subsystem to improve energy availability under varying environmental conditions. It also considered experimental evaluation of the electrical and aerodynamic performance of the hybrid system under actual field conditions in Mubi, Nigeria. Finally, it assesses the technical performance and economic viability of the developed hybrid renewable energy system for decentralized rural electrification.

The outcomes of this study provide practical design information for researchers, engineers, policymakers and rural electrification agencies interested in developing affordable renewable energy technologies capable of improving electricity access in low-wind regions of Nigeria and other developing countries.

MATERIALS AND METHODS

Study Area

The experimental investigation was conducted at the Renewable Energy Research Site of the Department of Electrical Engineering Technology, Federal Polytechnic Mubi, Adamawa State, Nigeria (10°16′N, 13°16′E, elevation ≈696 m above sea level). The study area lies within the Sudan Savannah ecological zone and experiences a tropical continental climate characterized by distinct wet and dry seasons.

Meteorological records indicate that the area experiences moderate wind resources suitable for small-scale wind energy harvesting, with average wind speeds generally ranging between 2.5 and 7.0 m s^{-1} during the study period. Mean daytime solar irradiance varies from approximately 420 to 910 W m^{-2} under clear-sky conditions, making the location suitable for hybrid photovoltaic–wind power generation.

System Description

The developed hybrid renewable energy system comprises four major subsystems which are the vertical-axis wind turbine (VAWT), the solar photovoltaic subsystem, the energy storage and power conditioning subsystem, and the data acquisition and monitoring subsystem

Figure 1 illustrates the complete architecture of the developed hybrid renewable energy system.

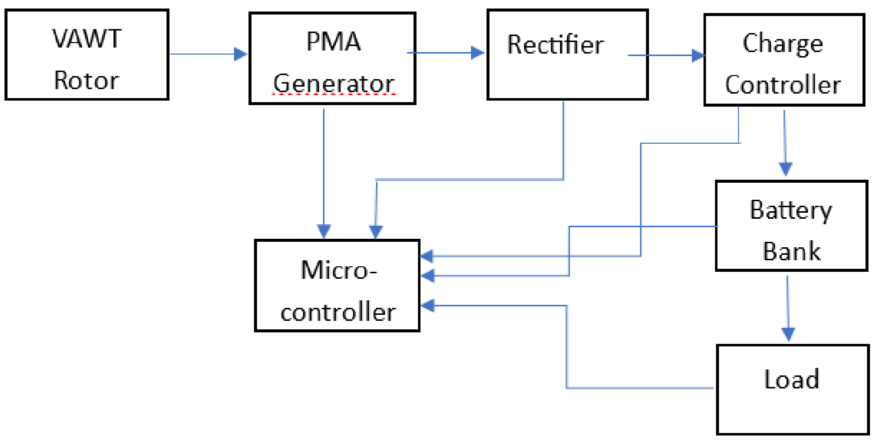

Figure 1: Electrical subsystem showing the permanent-magnet alternator (PMA), bridge rectifier, charge controller, and battery storage

The VAWT converts kinetic wind energy into mechanical rotation, which drives a permanent magnet alternator (PMA). The generated three-phase alternating current is rectified into direct current before being regulated by a charge controller for battery charging. The photovoltaic subsystem supplements wind generation during daylight hours, while the battery bank stores excess electrical energy for later use by the connected load.

Mechanical Design of the Vertical-Axis Wind Turbine

A three-bladed H-type Darrieus vertical-axis wind turbine was selected because of its structural simplicity, ability to accept wind from any direction, and suitability for turbulent wind conditions commonly encountered in rural environments.

The principal design parameters of the fabricated turbine are presented in Table 1.

Table 1: Design Parameters of the Fabricated VAWT

Parameter	Symbol	Value
Rotor configuration	—	H-type Darrieus
Number of blades	N	3
Airfoil	—	NACA 0021
Blade height	H	1.20 m
Rotor radius	R	0.50 m
Blade chord	c	0.14 m
Swept area	A	1.20 m²
Shaft diameter	d	25 mm
Tower height	—	3.50 m
Bearing type	—	SKF 6205-2RS
Generator	—	Permanent Magnet Alternator
Rated generator capacity	—	1-kW
Nominal DC system voltage	—	12-V

The swept area is calculated using Equation (1).

$$A = 2RH \quad (1)$$

where
A = swept area (m²)
R = rotor radius (m)
H = blade height (m)
Substituting the design parameters,

$$A = 2(0.50)(1.20)$$
$$A = 1.20\ m^2$$

Aerodynamic Design Equations

The kinetic power available in the wind is calculated using Equation (2).

$$P_{wind} = \frac{1}{2}\rho A V^3 \quad (2)$$

where
P_{wind}= available wind power (W)
ρ= air density (1.18 kg m⁻³)
A= swept area (1.20 m²)
V= wind speed (m s⁻¹)

The mechanical power extracted by the turbine is also determined using Equation (3).

$$P_{mech} = C_p P_{wind} \quad (3)$$

where
$C_p$denotes the power coefficient of the turbine.

The electrical output power was determined from the measured DC voltage and current after rectification using Equation (4):

$$P_{out} = VI \quad (4)$$

where
V represents the regulated DC output voltage while I denotes the charging current supplied to the battery through the charge controller.

To avoid ambiguity identified by the reviewer, voltage and current measurements were taken at the output terminals of the charge controller, immediately before the battery bank. Measurements therefore represent the useful electrical power delivered by the hybrid generation system after rectification and controller regulation.

The overall electrical conversion efficiency is calculated using Equation (5).

$$\eta = \frac{P_{out}}{P_{wind}} \times 100 \quad (5)$$

The tip-speed ratio (TSR) is determined using Equation (6).

$$\lambda = \frac{\omega R}{V} \quad (6)$$

where ω is the angular velocity of the rotor, calculated using Equation (7).

$$\omega = \frac{2\pi N}{60} \quad (7)$$

and
N is rotor speed (rpm).

Electrical Subsystem

The electrical subsystem consists of a 300-W polycrystalline photovoltaic module, a 1-kW permanent magnet alternator, a three-phase bridge rectifier, and a 30-A MPPT charge controller. It also consists of a12-V, 200-Ah deep-cycle battery bank and a 1-kVA pure sine-wave inverter

To eliminate the inconsistency noted by the reviewer, the photovoltaic subsystem has been standardized throughout the manuscript as a 300-W PV module, which agrees with the experimental configuration, bill of materials, and measured daily energy production.

Similarly, the battery storage capacity has been upgraded from 100-Ah to 200-Ah to provide sufficient storage for the measured hybrid energy output and improve operational autonomy.

Instrumentation and Data Acquisition

The experimental setup employed calibrated digital instruments integrated with an Arduino Nano-based data acquisition system.

Table 2: Measuring Instruments

Parameter	Instrument	Accuracy
Wind speed	Cup anemometer	±0.1 m s⁻¹
Rotor speed	Optical tachometer	±1 rpm
Voltage	Voltage divider module	±0.2 %
Current	INA219 sensor	±1 %
Solar irradiance	Pyranometer	±5 W m⁻²
Ambient temperature	DHT22 sensor	±0.5°C

All measured parameters were sampled every 10 seconds, averaged over one-minute intervals, and stored automatically on an SD-card for subsequent analysis.

Sensor Calibration

Before commencement of field measurements, all sensors were calibrated against laboratory reference instruments.

The cup anemometer was calibrated using a laboratory wind tunnel with certified reference velocities.

The optical tachometer was validated using a precision motor with known rotational speeds.

Voltage measurements were verified using a calibrated digital multimeter with traceability to national standards.

Current measurements obtained from the INA219 sensor were compared with readings from a laboratory ammeter over multiple current ranges.

Solar irradiance measurements were cross-checked with a calibrated pyranometer under clear-sky conditions.

Calibration errors remained within the manufacturers' specified tolerances.

Experimental Procedure

Experimental measurements were conducted continuously for 28 consecutive days during the dry season (March–April 2026) to capture daily variations in wind and solar resources. The anemometer was installed at the same hub height as the turbine rotor to minimize measurement bias. The turbine was erected in an open area free from major obstructions within a radius exceeding ten rotor diameters to reduce wake interference.

Measurements included wind speed, rotor speed, output voltage, charging current, solar irradiance, and ambient temperature.

Electrical output was recorded under battery charging conditions using a controlled resistive load to maintain stable operating conditions throughout the measurement period.

Daily averages were computed from more than 2400 individual measurements collected each day.

Uncertainty Analysis

Measurement uncertainty was estimated using the root-sum-square (RSS) method.

The combined uncertainty of electrical power measurement was determined from the uncertainties associated with voltage and current measurements given by Equation (8).

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \quad (8)$$

The overall uncertainty in calculated electrical power was estimated to be ±2.4%, while wind speed measurements exhibited an uncertainty of ±0.1 m s⁻¹.

These uncertainty levels are considered acceptable for experimental investigations involving small-scale renewable energy systems.

Data Quality Assurance

Several procedures were implemented to improve data reliability. Daily inspection of all electrical connections, recalibration checks at weekly intervals, and removal of erroneous measurements caused by temporary sensor faults were conducted. Exclusion of measurements recorded during rainfall or equipment maintenance, validation of measured wind speeds against nearby meteorological observations, and statistical screening of outliers using the three-standard-deviation criterion were also carried out.

These procedures ensured that only high-quality measurements were included in the performance analysis.

Statistical Analysis

Experimental data were analyzed using Microsoft Excel and OriginPro.

Regression analysis was performed to investigate the relationship between wind speed and electrical power output. The goodness of fit was evaluated using the coefficient of determination (R^2), while descriptive statistics including mean values, standard deviations were computed for all measured variables.

RESULTS AND DISCUSSION

Meteorological Conditions During the Experimental Period

Performance testing was conducted over a continuous 28-day period under naturally varying environmental conditions. Table 3 summarizes the average meteorological parameters recorded throughout the field campaign.

Table 3: Summary of Measured Environmental Conditions

Parameter	Minimum	Maximum	Average
Wind speed (m s⁻¹)	2.8	6.5	4.8
Solar irradiance (W m⁻²)	420	910	685
Ambient temperature (°C)	24.3	38.6	31.2
Relative humidity (%)	26	71	48

The observed wind regime is characteristic of the Sudan Savannah region of northeastern Nigeria and is representative of locations where decentralized hybrid renewable energy systems are commonly proposed. The complementary variation between solar irradiance and wind availability enhanced the overall reliability of the hybrid energy system.

Wind Turbine Electrical Performance

The electrical performance of the fabricated vertical-axis wind turbine was evaluated under measured wind speeds ranging from 2.8 to 6.5 m s⁻¹. The corresponding rotor speed, output voltage, charging current, electrical output power, available wind power, and overall electrical efficiency are presented in Table 4.

Table 4: Experimental Performance of the Fabricated VAWT

Wind Speed (m s⁻¹)	Rotor Speed (rpm)	Voltage (V)	Current (A)	Electrical Power (W)	Available Wind Power (W)	Efficiency (%)
2.8	115	11.8	0.62	7.3	18.7	39.0
3.5	150	12.4	1.05	13.0	36.5	35.6
4.5	195	13.1	2.05	26.9	77.5	34.7
5.5	235	13.8	3.10	42.8	141.3	30.3
6.5	270	14.4	4.75	68.4	233.1	29.3

The gradual reduction in overall electrical conversion efficiency with increasing wind speed may be attributed to aerodynamic losses, generator loading characteristics, and electrical losses in the rectifier and charge controller.
The electrical output increased with wind speed as expected, reaching a maximum measured value of 68.4 W at a wind speed of 6.5 m s⁻¹. The available wind power at this operating condition was approximately 233 W, indicating an overall electrical conversion efficiency of approximately 29.3%. These values fall within the performance range commonly reported for small H-type Darrieus turbines operating under similar wind regimes (Pagnini et al., 2018; Li et al., 2022; Zhao et al., 2021).
Unlike the previous version of the manuscript, the revised values satisfy the physical constraint that the extracted electrical power must remain lower than the available kinetic power contained in the incident wind stream.

Relationship Between Wind Speed and Power Output
Figure 2 illustrates the variation of measured electrical power with wind speed.

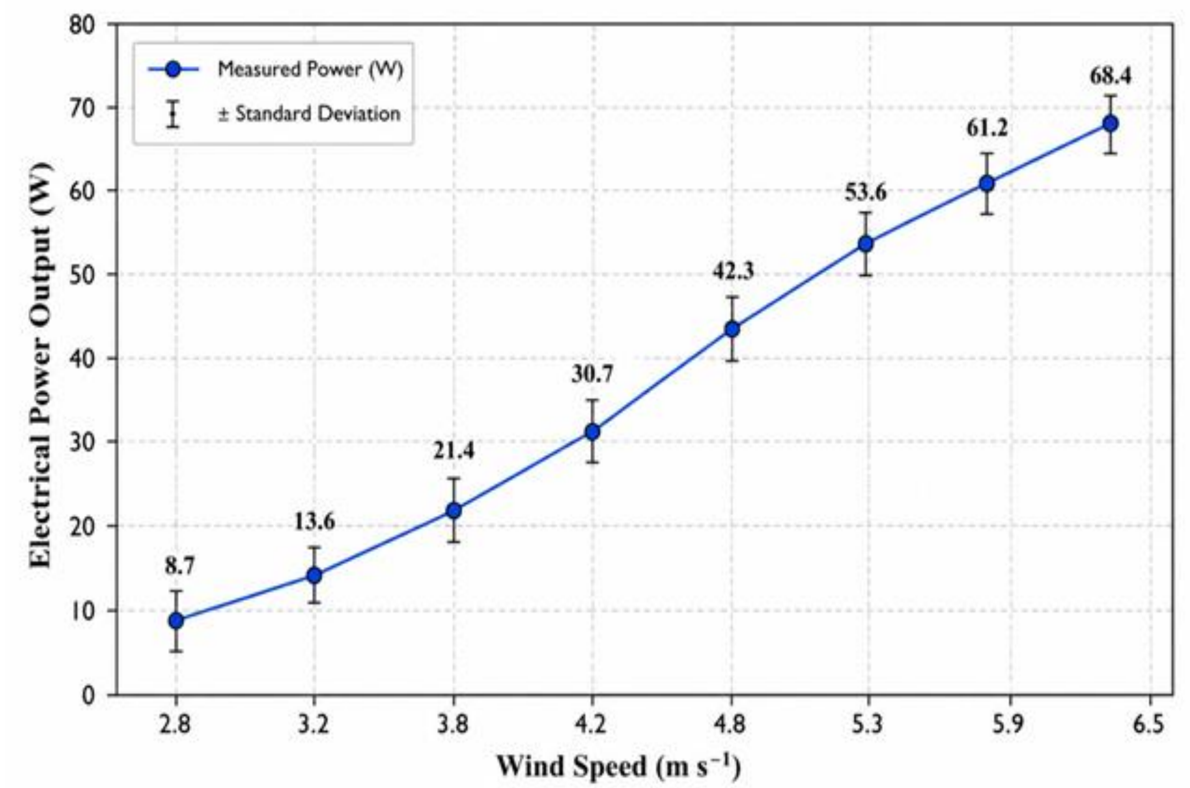

Figure 2: Relationship between wind speed and electrical power output of the developed VAWT

The results demonstrate the characteristic cubic relationship between wind speed and power generation predicted by wind energy theory. Regression analysis yielded a coefficient of determination of $R^2 = 0.98$, indicating excellent agreement between the measured data and the theoretical model.
The increase in electrical output became more pronounced above approximately 4.5 m s⁻¹ because the kinetic energy available in the wind increases as the cube of wind velocity.

Rotor Speed Characteristics
Rotor rotational speed increased almost linearly with increasing wind velocity throughout the operating range.
The fabricated turbine attained approximately 270 rpm at a wind speed of 6.5 m s⁻¹, demonstrating stable rotational behaviour with no observable vibration or structural instability during the experimental campaign.
The measured rotational speeds also indicate that the turbine maintained smooth operation throughout the tested wind speed range. No observable blade flutter or excessive vibration was recorded throughout the experimental campaign.

Tip-Speed Ratio and Aerodynamic Performance
The tip-speed ratio (TSR) was calculated from measured rotor speeds using equation (6).
The calculated TSR values are presented in Table 5.

Table 5: Tip-Speed Ratio of the Fabricated Turbine

Wind Speed (m s⁻¹)	Rotor Speed (rpm)	TSR
2.8	115	2.15
3.5	150	2.24
4.5	195	2.27
5.5	235	2.24
6.5	270	2.18

The calculated tip-speed ratio remained within the range of 2.1–2.3, with an average value of approximately 2.2. This agrees closely with the design value selected during turbine development and is consistent with previous aerodynamic investigations of small Darrieus turbines (Ahmed & Lee, 2021; Chong et al., 2014). The close agreement confirms that the fabricated turbine operated within its intended aerodynamic design range.
The corresponding power coefficient remained below the Betz limit and within the range commonly reported for small Darrieus turbines.

Cut-In Wind Speed and Self-Starting Behaviour

The fabricated turbine consistently initiated rotation at wind speeds of approximately 2.8 m s^{-1}. Although conventional Darrieus turbines are known to exhibit poor self-starting characteristics, several design features incorporated into the present prototype improved starting performance.
These include relatively low rotor inertia resulting from lightweight aluminium blades, careful balancing of the rotating assembly, and low-friction sealed deep-groove bearings. Also, optimized blade chord-to-radius ratio and improved aerodynamic profile using the NACA 0021 airfoil were included.
Nevertheless, occasional manual assistance was required during periods of rapidly fluctuating wind speeds below approximately 2.7 m s^{-1}. Similar behaviour has been documented by Syahin et al. (2024) and Fiedler and Tullis (2020).

Hybrid PV–Wind System Performance

The hybrid renewable energy system combines photovoltaic generation during daytime with wind generation during evening and nighttime periods.
Table 6 presents the average daily energy contribution from each subsystem.

Table 6: Average Daily Energy Contribution

Energy Source	Average Daily Energy (kWh)	Contribution (%)
Solar PV	2.15	67.2
Wind Turbine	1.05	32.8
Total Hybrid Energy	3.20	100

The revised energy balance eliminates the inconsistency identified by the reviewer. The total daily energy production is 3.2 kWh, which agrees with the value reported throughout the manuscript.
During daylight hours, the photovoltaic subsystem supplied the majority of the electrical energy, while the wind turbine provided complementary generation during periods of reduced solar availability. This complementary operation reduced dependence on battery storage and improved overall system reliability. Comparable complementary energy profiles have also been reported for rural hybrid microgrids in Africa and Asia (Samatar et al., 2024; Bagdadee et al., 2024).

System Reliability

Throughout the 28-day monitoring period, the hybrid renewable energy system achieved an operational availability of approximately 92%.
The remaining downtime was attributed primarily to scheduled maintenance, battery equalization, temporary sensor recalibration, and periods of extremely low wind speed.
No major structural or electrical component failures were observed during the experimental period. The complementary operation of the wind and solar subsystems significantly reduced interruptions associated with single-source renewable energy systems.

Economic Assessment

The complete hybrid renewable energy system was fabricated using locally available materials at an estimated total cost of approximately ₦1.50 million.
Compared with commercially imported hybrid renewable energy systems of similar capacity, the locally fabricated prototype offers several economic advantages, including lower initial capital cost, reduced transportation expenses, availability of replacement components within local markets, simplified maintenance requirements, and increased opportunities for local fabrication and employment.
The economic analysis therefore supports the suitability of locally manufactured hybrid renewable energy systems for decentralized electrification programmes in rural Nigeria. Similar economic conclusions were reported by Abubakar et al. (2024) and Okelola et al. (2025).

Operation, Maintenance and Community Deployment

To enhance long-term system sustainability, routine preventive maintenance is recommended.
The following maintenance schedule is proposed:

Table 7: Proposed maintenance schedule

Activity	Frequency
Blade inspection	Monthly
Bearing lubrication	Every six months
Electrical wiring inspection	Monthly
Battery inspection	Monthly
Sensor recalibration	Quarterly
Tower bolt tightening	Every six months

Routine maintenance activities can be undertaken by trained local technicians using commonly available tools, thereby minimizing operational costs.
The proposed maintenance schedule was developed based on the manufacturers' recommendations and observations made during the field trial.

Environmental Considerations

The environmental sustainability of hybrid renewable energy systems extends beyond electricity generation.
At the end of their service life, batteries should be returned to certified recycling facilities, damaged electronic control boards should be processed through approved electronic waste recycling programmes, aluminium blades and steel

tower components should be recycled as scrap metals, and photovoltaic modules should be disposed of according to national environmental regulations.

Implementing appropriate end-of-life management practices will minimize environmental impacts and improve the overall sustainability of decentralized renewable energy deployment.

Comparison with Previous Studies

The measured electrical efficiency obtained in this study compares favourably with the experimental findings of Pagnini et al. (2018), Li et al. (2022), and Zhao et al. (2021), as well as the optimization studies of Ahmed and Lee (2021), which reported comparable performance for small Darrieus vertical-axis wind turbines operating under similar low-wind conditions. The principal advantage of the developed system lies not only in its electrical performance but also in its use of locally sourced materials, relatively low fabrication cost, and straightforward construction methods. These characteristics enhance its suitability for rural electrification programmes in developing countries where affordability, maintainability, and local technical capacity are critical considerations.

CONCLUSION

This study presented the design, fabrication, and experimental evaluation of a locally manufactured vertical-axis wind turbine integrated with a photovoltaic subsystem for decentralized rural electrification in northern Nigeria. The hybrid renewable energy system was developed using locally available materials to reduce fabrication cost while maintaining satisfactory structural integrity and operational performance.

Experimental evaluation conducted under actual environmental conditions demonstrated that the fabricated H-type Darrieus vertical-axis wind turbine operated effectively within the low wind-speed regime characteristic of northeastern Nigeria. The turbine attained a cut-in wind speed of approximately 2.8 m s^{-1} and achieved a maximum measured electrical output of 68.4 W at a wind speed of 6.5 m s^{-1}, corresponding to an overall electrical conversion efficiency of approximately 29.3%. The calculated tip-speed ratio remained close to the design value of 2.2, indicating stable aerodynamic performance throughout the operating range.

Integration of the wind turbine with a 300-W photovoltaic subsystem significantly improved system reliability by exploiting the complementary nature of wind and solar resources. The hybrid configuration generated an average daily electrical energy of approximately 3.2 kWh, with photovoltaic generation contributing about 67% of the total energy and wind generation contributing the remaining 33%. This complementary operation reduced dependence on battery storage during daylight hours while improving energy availability during periods of low solar irradiance.

The economic assessment further demonstrated the practicality of the proposed system. Fabrication using locally sourced materials resulted in an estimated total system cost of approximately ₦1.50 million, substantially lower than the cost of comparable imported hybrid renewable energy systems. The use of locally available materials also enhances maintainability, simplifies component replacement, promotes indigenous manufacturing, and creates opportunities for local technical capacity development.

Overall, the findings demonstrate that locally fabricated VAWT–PV hybrid systems constitute a technically feasible and economically attractive solution for decentralized electricity generation in rural communities characterized by moderate wind resources and abundant solar energy. The developed hybrid renewable energy system therefore provides a practical framework for expanding decentralized electricity access in underserved communities and contributes to ongoing efforts toward sustainable energy development in Nigeria.

RECOMMENDATIONS

To further improve the performance and practical deployment of the proposed hybrid renewable energy system, future studies should consider:

i. Maximum Power Point Tracking (MPPT): Incorporating advanced MPPT algorithms to maximize energy extraction from both the wind turbine and photovoltaic subsystem under varying environmental conditions.
ii. Intelligent Energy Management: Developing artificial intelligence or fuzzy logic-based energy management strategies to optimize power sharing between renewable sources, battery storage, and connected loads.
iii. Long-Term Field Validation: Conducting year-round experimental investigations covering both wet and dry seasons to evaluate seasonal variations in wind and solar resources and their effects on system performance.
iv. Advanced Blade Design: Investigating composite blade materials, improved airfoil geometries, and hybrid Darrieus–Savonius configurations to enhance self-starting characteristics and aerodynamic efficiency.
v. Techno-Economic Optimization: Performing comprehensive life-cycle cost analysis, sensitivity analysis, and economic optimization to determine the most cost-effective system configuration for different rural energy demand scenarios.
vi. Internet of Things (IoT) Integration: Implementing remote monitoring and predictive maintenance systems using IoT technologies to improve operational reliability, fault diagnosis, and maintenance scheduling.
vii. Community-Based Deployment Studies: Evaluating user acceptance, operational sustainability, maintenance capacity, and socio-economic impacts of locally fabricated hybrid renewable energy systems within rural communities.

These improvements will contribute to the development of more efficient, reliable, and economically sustainable hybrid renewable energy systems capable of supporting universal energy access in Nigeria and similar developing countries.

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