

ELECTRICAL ENGINEERING

Hybrid Energy System for Off-Grid Electrification of Koluama Communities, Bayelsa State, Nigeria

Okosi Festus, Geko Diton

Department of Electrical/Electronic Engineering Technology, Bayelsa State Polytechnic, Aleibiri, Ekeremor, Bayelsa State, Nigeria

Published October 2026

Abstract

This study investigates the technical, economic and environmental feasibility of a hybrid solar photovoltaic (PV), wind, battery storage and diesel-generator system for supplying Koluama 1 and Koluama 2 communities in Southern Ijaw Local Government Area of Bayelsa State, Nigeria. A bottom-up electricity load assessment was conducted using household appliance inventories and estimated electricity requirements for residential, educational, healthcare and commercial consumers. The estimated preliminary community demand was 1,589.74 kWh/day, which increased to 1,722.13 kWh/day after applying an 8.3% design margin. The corresponding estimated peak demand was 260.32 kW. Solar and wind resources were assessed using NASA Prediction of Worldwide Energy Resources (NASA POWER) data. The mean daily global horizontal irradiance was approximately 5.14 kWh/m²/day, while the mean wind speed was approximately 4.07 m/s at 10 m height. Weibull analysis was used to characterize the wind resource. HOMER Pro was subsequently employed to model, simulate and optimize alternative power-system configurations comprising PV, wind, battery storage and diesel generation. The optimum configuration was the PV-wind-battery-diesel system, with a net present cost (NPC) of US\$537,008, levelized cost of energy (LCOE) of US\$0.0661/kWh, renewable fraction of 97.7%, approximately 97.88% reduction in carbon dioxide emissions relative to the diesel-based reference system, zero unmet electrical load, zero capacity shortage, with excess electricity generation of 57,164 kWh/year. Sensitivity analysis further indicated that diesel-fuel price has a direct influence on the cost of electricity. The results indicate that hybrid renewable energy systems can provide a technically viable pathway for electrifying isolated riverine communities. The study provides a location-specific baseline for future engineering design, investment appraisal and rural electrification planning in Bayelsa State.

Keywords: hybrid renewable energy system; solar photovoltaic; wind energy; diesel generator; battery storage; HOMER Pro; rural electrification; Koluama; Bayelsa State; Nigeria

1 Introduction

Globally, access to reliable and affordable electricity is fundamental to socioeconomic development because it supports productive activities, education, healthcare, communication, employment and improved quality of life. However, extending conventional electricity infrastructure to remote and rural communities remains challenging because of geographical isolation, dispersed settlements, difficult terrain, low electricity demand and the high capital cost associated with grid extension [1]. The challenges are particularly significant in riverine and coastal communities of the Niger Delta, where settlements are often dispersed and located in rugged or difficult to access terrain, making conventional electricity infrastructure technically and economically challenging.

Koluama 1 and Koluama 2 are riverine communities in Southern Ijaw Local Government Area of Bayelsa State. The communities have dispersed settlements and economic activities centred mainly

on fishing, petty trading and subsistence livelihoods. The study area is not adequately served by conventional grid electricity, creating dependence on small fossil fuel generators and limiting opportunities for productive electricity use.

Hybrid renewable energy based systems is identified as a technically and economically feasible option for electrification of rural or isolated communities, such as Koluama [2]. Hybrid renewable energy systems integrate complementary generation sources, energy storage and backup generation to improve the reliability and continuity of electricity supply. Solar PV can supply daytime demand, while wind generation can complement solar output during periods of low solar availability. Battery storage helps balance generation and demand by storing excess renewable energy for later use, while a diesel generator can provide backup during prolonged periods of insufficient renewable generation [3][4].

Recent studies have demonstrated the relevance of hybrid energy systems for Nigerian rural communities. [5], investigated a solar-wind-diesel-battery microgrid for an off-grid Nigerian community and showed the potential of hybridization for reducing system costs. [6], assessed a hybrid microgrid for rural electrification of Kabuiri in northeastern Nigeria using HOMER software, the authors reported an optimized solar PV/battery/generator system with 99% renewable penetration and an LCOE of US\$0.093/kWh, illustrating the technical and economic potential of hybrid microgrids for isolated Nigerian communities.

A study of rural households in Isoko South, Delta State, found persistent electricity-access challenges and assessed solar energy as an alternative for improving reliable and cleaner electricity supply in rural Nigeria [7]. Similarly, other recent investigations in Delta State and elsewhere in Nigeria have likewise reported the technical and economic relevance of hybrid renewable energy systems for rural electrification, which can reduce dependence on conventional diesel generation.

Despite these studies, relatively limited location specific research has focused on the renewable resource characteristics and complete hybrid system requirements of isolated riverine communities in Bayelsa State. The present study addresses this gap by combining community load estimation, solar and wind resource assessment, hybrid system modelling, HOMER Pro optimization, economic assessment, environmental evaluation and sensitivity analysis for Koluama 1 and Koluama 2.

The objectives of the study were therefore to: estimate the electricity demand of Koluama 1 and Koluama 2, assess the available solar and wind resources, model alternative solar-wind-diesel-battery configurations, determine an economically and technically appropriate hybrid configuration using HOMER Pro, and evaluate the renewable contribution, environmental performance, reliability and sensitivity of the selected system.

2 Literature review

2.1 Hybrid renewable energy systems for rural electrification

Hybrid renewable energy systems (HRES) integrate two or more generation technologies, commonly solar PV, wind, hydro, biomass or diesel generation together with battery storage where necessary. Their principal advantage is resource complementarity. Solar and wind resources are variable, but their temporal characteristics may partially compensate for each other.

Rural electrification remains a major challenge in developing countries because extending centralized grids to remote communities can be technically difficult and economically costly, therefore, hybrid re-

newable energy systems (HRES) incorporating combinations of renewable sources, energy storage and backup generation, have emerged as viable alternatives for improving reliable electricity supply in isolated communities, and its application in rural electrification has received increasing attention in Nigeria [8–10].

This reinforces the broader view that HRES can provide dependable and sustainable electricity to off grid coastal Niger Delta communities when properly designed and optimized.

2.2 Solar and wind resource complementarity

Solar photovoltaic (PV) systems convert solar radiation directly into electricity and are particularly suitable for tropical regions because of their abundant solar-resource availability [11]. Wind energy can complement solar generation when wind conditions remain favourable during periods of reduced solar radiation. Wind resource evaluation commonly uses probability distributions such as the Weibull distribution. The distribution provides a statistical representation of wind speed frequency and can be used to estimate the proportion of time wind turbines operate within useful speed ranges.

2.3 HOMER-based hybrid system optimization

HOMER Pro is widely used for preliminary design and techno-economic optimization of hybrid energy systems. It evaluates combinations of system components according to technical constraints, energy demand, resource availability and economic parameters. Typical evaluation indicators include NPC, LCOE, renewable fraction, fuel consumption, excess electricity, unmet load and emissions.

Recent Nigerian studies have used HOMER for community scale renewable energy systems, some has assessed grid-connected hybrid systems, while other studies have investigated isolated PV-wind-diesel-battery systems. This therefore provides methodological support for applying HOMER to the Koluama case study.

3 Materials and methods

3.1 Description of the study area

The study was conducted in Koluama 1 and Koluama 2 communities in Southern Ijaw Local Government Area of Bayelsa State, Nigeria. The communities are located approximately at latitude 4.71° N and longitude 5.58° E, at an elevation of approximately 5 m above sea level. The area has a tropical coastal environment and UTC+1 time zone.

The riverine terrain, dispersed settlement pattern and limited electricity infrastructure make the location appropriate for evaluating autonomous or mini-grid electricity supply.

3.2 Research design and data sources

A quantitative engineering design approach was adopted. The methodology comprised:

1. Community electricity-load assessment
2. Solar-resource assessment
3. Wind-resource assessment
4. Component modelling
5. Preliminary system sizing
6. HOMER Pro simulation and optimization

7. Economic evaluation
8. Environmental assessment
9. Reliability evaluation
10. Sensitivity analysis.

Primary information was obtained through site visits, community consultations, interviews and appliance inventories. Secondary data included NASA POWER solar and wind-resource information, published literature, technical information and economic parameters used for system modelling.

3.3 Electrical load assessment

A bottom-up approach was used to estimate electricity consumption. For each appliance, daily energy consumption was calculated from:

$$E_i = \frac{P_i N_i t_i}{1000} \quad (1)$$

Where;

E_i = daily energy consumption of appliance (kWh/day)

P_i = rated power of appliance (W)

N_i = number of appliances

t_i = average operating time per day (h/day).

The household demand was aggregated with electricity requirements from schools, health centres and small businesses. The study considered 291 households, two primary schools, two health centres and 55 small businesses. The estimated average household electricity consumption was approximately 4.14 kWh/day.

The preliminary community electricity demand was estimated at:

$$E_i = 1,589.74 \text{ kWh/day}$$

An 8.3% design margin was subsequently applied:

$$E_{\text{design}} = 1,589.74 (1 + 0.083) \text{ kWh/day}$$

$$E_{\text{design}} = 1,722.13 \text{ kWh/day}$$

The corresponding annual design energy is approximately:

$$E_{\text{annual}} = 1,722.13 \times 365 \text{ kWh/year}$$

$$E_{\text{annual}} = 628,577.45 \text{ kWh/year}$$

The peak demand estimated was approximately 260.32 kW based on an assumed load factor of 0.275.

3.4 Solar resource assessment

Solar resource data were obtained from the NASA POWER database for the Koluama location. The reported annual GHI values for 2020-2025 ranging from 4.9278 to 5.2857 kWh/m²/day, with an average of 5.1398 kWh/m²/day. The solar resource data are summarized in Table 1.

Table 1. Solar-resource characteristics for Koluama.

Year	GHI (kWh/m ² /day)	AnnualYield	Clearness Index
2020	5.2857	6,878.50	0.443
2021	5.1422	6,673.38	0.432
2022	5.1929	6,739.22	0.436
2023	5.0824	6,595.83	0.426
2024	5.2081	6,777.49	0.432
2025	4.9278	6,395.19	0.437
Average	5.1398	6,676.60	0.421

Source: NASA POWER Data and Author's calculations.

The PV model incorporated a performance ratio/derating representation to account for losses associated with temperature, wiring, conversion, dust and other operating effects.

3.5 Wind resource assessment

Wind data were obtained from NASA POWER at a 10 m reference height. The annual mean wind speeds are presented in Table 2.

Table 2. Wind resource characteristics for Koluama.

Year	Mean Wind Speed (m/s)	Capacity Factor (%)
2020	4.01	23.95
2021	4.03	78.23
2022	3.98	14.01
2023	4.02	56.97
2024	4.13	15.39
2025	4.22	73.18
Average	4.07	42.62

Source: NASA POWER Data

The Weibull probability density function was used to characterize the wind speed distribution:

$$F(V) = \frac{k}{c} \frac{v^{k-1}}{c} e^{-\frac{v^k}{c}} \quad (2)$$

Where:

V = wind speed (m/s)

k = Weibull shape parameter

c = Weibull scale parameter (m/s).

Wind speed at the turbine hub height was estimated using the power law relationship:

$$V_h = V_{ref} x \frac{h_h^\alpha}{h_{ref}^\alpha} \quad (3)$$

Where:

V_h = estimated wind speed at hub height (m/s)

V_{ref} = measured or reference wind speed at the reference height (m/s)

h_h = hub height (m)

h_{ref} = reference height (m)

α = wind-shear exponent.

The study used a hub height of approximately 40 m and a wind-shear exponent of 0.143.

3.6 Hybrid system configuration

The proposed hybrid system consists of:

1. Solar PV array
2. Wind turbine
3. Battery energy-storage system
4. Diesel generator
5. Bidirectional power converter
6. Community electrical load.

The battery model used lead-acid storage with a depth of discharge of 40%, charging efficiency of 80% and approximately 10 year lifetime. The converter efficiency was specified as approximately 95%.

The diesel generator served as a dispatchable backup source. The system was evaluated over a 25-year project lifetime.

3.7 HOMER Pro simulation and optimization

Five system configurations were considered:

1. PV-Wind-Battery-Diesel
2. PV-Battery-Diesel
3. Wind-Battery-Diesel
4. PV-Diesel
5. Diesel-only.

HOMER Pro simulated the candidate systems using the specified electrical load, renewable resources, component characteristics and economic assumptions.

The principal economic indicators were NPC and LCOE. NPC represents the discounted lifecycle cost of the system, whereas LCOE represents the average cost of electricity produced over the project lifetime.

Reliability indicators included unmet load and capacity shortage. Renewable fraction and carbon-dioxide emissions were used to evaluate environmental performance.

4 Results and discussion

4.1 Community electricity demand

The load assessment produced a preliminary electricity requirement of 1,589.74 kWh/day. After application of the 8.3% design margin, the design energy requirement increased to 1,722.13 kWh/day. Households represented the largest demand category with approximately 1,204.74 kWh/day, followed by small businesses at approximately 275 kWh/day. Schools and health centres accounted for approximately 40 and 70 kWh/day respectively.

Thus, residential demand represents approximately 75.8% of the preliminary community electricity requirement. This result is important because residential consumption patterns will strongly influence the sizing of the battery storage and generation components. The estimated peak load of approximately 260.32 kW provides the principal instantaneous power sizing requirement for the inverter and dispatchable generation components.

A diesel-fuel price sensitivity analysis was also undertaken because fuel price directly affects the operating expenditure of configurations containing diesel generators.

4.2 Solar resource

The average GHI of approximately 5.14 kWh/m²/day indicates a substantial solar resource at Koluama. The annual values varied from approximately 4.93 to 5.29 kWh/m²/day, indicating relatively modest interannual variation. The result supports the use of solar PV as a major component of the hybrid system. Similar studies in Nigerian communities have demonstrated that solar PV can form the principal renewable energy component in hybrid rural microgrids, particularly when supported by battery storage.

4.3 Wind resource

The mean wind speed was approximately 4.07 m/s at 10 m. The annual mean values ranged from 3.98 to 4.22 m/s. The relatively moderate wind resource suggests that wind generation is better considered a complementary resource rather than the sole generation source. Its principal value in the proposed hybrid architecture is to diversify renewable generation and potentially provide energy during periods when solar generation is reduced.

4.4 HOMER optimization

The HOMER Pro analysis compared five candidate system configurations. The PV-wind-battery-diesel configuration was identified as the selected configuration.

Table 3. Principal indicators of the selected hybrid configuration.

Indicator	Result
Configuration	PV-wind-battery-diesel
NPC	US\$537,008
LCOE	US\$0.0661/kWh
Renewable fraction	97.7%
CO ₂ reduction	97.88%

Indicator	Result
Unmet load	0
Capacity shortage	0
Excess electricity	57,164 kWh/year

Source: HOMER Pro Output

The renewable fraction of 97.7% indicates that the optimized system obtains most of its annual electricity from renewable resources. The diesel generator consequently functions primarily as a backup/dispatchable component. The zero unmet load and zero capacity shortage indicate that the simulated configuration was capable of satisfying the modelled electrical demand under the assumed resource and operating conditions.

These results are broadly consistent with recent Nigerian research, [6], that reported a 99% renewable fraction for a rural Nigerian microgrid optimized using HOMER. This demonstrates that high renewable fraction hybrid systems can be technically feasible for remote communities, with substantial economic and environmental benefits relative to diesel-dominated systems.

4.5 Economic performance

The reported NPC of US\$537,008 represents the total discounted lifecycle cost of the selected system under the assumptions made in the HOMER model. A LCOE of US\$0.0661/kWh was obtained at current diesel price of 1.51USD per litre.

4.6 Environmental performance

The selected configuration achieved a 97.88% reduction in CO₂ emissions compared with the diesel-dominated reference case. The environmental benefit results principally from the high renewable fraction. Solar PV and wind generation supply most of the annual electrical energy, while battery storage allows renewable energy to be shifted to periods of demand. The diesel generator is consequently required for fewer operating hours than in a diesel-only configuration. This shows that there is substantial reductions in fuel consumption when renewable generation replaces diesel generation.

4.7 Reliability

The selected system recorded zero unmet load and zero capacity shortage, with excess electricity generation of 57,164 kWh/year. These values indicate satisfactory reliability under the assumed conditions. Nevertheless, system performance still depends on factors such as; equipment availability, battery degradation, maintenance, weather variability, component failure, fuel availability and community load growth.

4.8 Diesel-fuel sensitivity

The sensitivity analysis demonstrated a direct relationship between diesel-fuel price and electricity cost. A LCOE of US\$0.0661/kWh was obtained at a current diesel price of US\$1.51/L. Reducing the diesel price from US\$1.15/L to US\$1.21/L, the LCOE decreases from US\$0.661/kWh to US\$0.634/kWh. Increasing the diesel price from US\$1.51/L to US\$2.11/L, LCOE increases from US\$0.0661/kWh to US\$0.856/kWh.

This finding is important for remote communities because diesel dependent systems are exposed to fuel-price fluctuations and fuel transportation costs. Increasing renewable penetration and battery storage can reduce the quantity of diesel fuel required and therefore reduce exposure to fuel price uncertainty. Fuel price was identified as an important sensitivity variable in hybrid systems containing diesel generation.

5 Conclusion

This study assessed the technical, economic and environmental potential of a solar-wind-diesel-battery hybrid energy system for off-grid electrification of Koluama 1 and Koluama 2 communities in Bayelsa State, Nigeria.

The bottom-up load assessment estimated a preliminary electricity demand of 1,589.74 kWh/day. With an 8.3% design margin, the design energy requirement increased to 1,722.13 kWh/day, corresponding to approximately 628,577.45 kWh/year. The estimated peak demand was approximately 260.32 kW.

The renewable-resource assessment indicated an average GHI of approximately 5.14 kWh/m²/day and an average wind speed of approximately 4.07 m/s at 10 m. These resources provide a basis for incorporating solar PV and wind generation into an autonomous community scale power system.

The HOMER Pro analysis reported the PV-wind-battery-diesel configuration as the selected hybrid architecture, with a reported NPC of US\$537,008, LCOE of US\$0.0661/kWh, renewable fraction of 97.7%, approximately 97.88% CO₂ reduction, zero unmet load, zero capacity shortage and excess electricity generation of 57,164 kWh/year. The overall results support the technical feasibility of renewable based hybrid electrification for remote riverine communities.

The major contribution of the study is therefore the development of a location-specific framework linking community electricity demand, renewable resource assessment and hybrid-system optimization for an isolated riverine community in Bayelsa State.

Acknowledgments

The authors acknowledge the support of the Tertiary Education Trust Fund (TETFUND), Nigeria, for funding this research.

Conflict of Interest

The authors declared that there is no conflict of interest

References

- [1] Juanpera M, Blechinger P, Ferrer-Martí L, Hoffmann MM, Pastor R. Multicriteria-based methodology for the design of rural electrification systems: A case study in Nigeria. *Renewable and Sustainable Energy Reviews*. 2020;133:110243. <https://doi.org/10.1016/j.rser.2020.110243>
- [2] Ukoima KN, Owolabi AB, Yakub AO, Same NN, Suh D, Huh JS. Analysis of a solar hybrid electricity generation system for a rural community in River State, Nigeria. *Energies*. 2023;16(8):3431.
- [3] Hassan Q, Algburi S, Sameen AZ, Salman HM, Jaszczur M. A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*. 2023;20:101621. <https://doi.org/10.1016/j.rineng.2023.101621>

-
- [4] Ijeoma MW, Lewis CG, Chen H, Chukwu BN, Carbajales-Dale M. Technical, economic, and environmental feasibility assessment of solar-battery-generator hybrid energy systems: A case study in Nigeria. *Frontiers in Energy Research*. 2024;12:1397037. <https://doi.org/10.3389/fenrg.2024.1397037>
 - [5] Amuta EO, Orovwode H, Wara ST, Agbetuyi AF, Matthew S, Esisio EF. Hybrid power microgrid optimization and assessment for an off-grid location in Nigeria. *Materials Today: Proceedings*. 2024;105:155–161. <https://doi.org/10.1016/j.matpr.2023.08.107>
 - [6] Lewis CG, Ijeoma MW, Yakubu RO, Chukwu BN, Chen H, Carbajales-Dale M. Achieving universal energy access in remote locations using HOMER energy model: A techno-economic and environmental analysis of hybrid microgrid systems for rural electrification in northeast Nigeria. *Frontiers in Energy Research*. 2024;12:1454281.
 - [7] Otuagoma SO, Amagre EM. Solar energy, the silver bullet to tackle perennial energy access challenges in Nigeria rural households: A case study. *African Journal of Science, Technology, Innovation and Development*. 2025;17(4):652–661. <https://doi.org/10.1080/20421338.2025.2504189>
 - [8] Come Zebra EI, Van der Windt H, Nhumaio G, Faaij APC. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*. 2021;144:111036. <https://doi.org/10.1016/j.rser.2021.111036>
 - [9] Nyarko K, Whale J, Urmee T. Drivers and challenges of off-grid renewable energy-based projects in West Africa: A review. *Heliyon*. 2023;9(6):e16710. <https://doi.org/10.1016/j.heliyon.2023.e16710>
 - [10] Oladeji AS, Atilola OF, Olaniyi JI. Optimizing hybrid renewable energy systems for rural electrification: A case study of selected villages in Kwara State, Nigeria. *Nigerian Journal of Technological Development*. 2025;21(4):1–12. <https://doi.org/10.4314/njtd.v21i4.2359>
 - [11] Wang X, Gao X, Wu Y. Comprehensive analysis of tropical rooftop PV project: A case study in Nanning. *Heliyon*. 2023;9(3):e14131. <https://doi.org/10.1016/j.heliyon.2023.e14131>