International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 22, Issue 2 (February 2026), PP 111-117

Load Estimation and Renewable Energy Resource Assessment for Solar–Wind Deployment in Koluama Communities, Bayelsa State, Nigeria

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Abstract
This study presents a comprehensive load estimation and renewable energy resource assessment to evaluate the feasibility of deploying a solar–wind hybrid power system for electrification of Koluama 1 and Koluama 2 communities in Bayelsa State, Nigeria. A bottom-up approach was adopted to estimate electricity demand by aggregating residential, educational, healthcare, and commercial loads. Solar and wind resources were assessed using Global Horizontal Irradiance (GHI) modelling and Weibull probability distribution analysis, respectively. Results indicate an average daily energy demand of 1,722.13 kWh/day with a peak load of 260.32 kW after incorporating a design margin for future expansion. The study area exhibits strong solar potential with a mean daily GHI of 5.14 kWh/m²/day and an average annual PV yield of 6,676.60 kWh/kWp, confirming solar energy as the primary generation source. Wind assessment shows a mean speed of 4.07 m/s, indicating moderate but complementary potential suitable for small-scale turbines. The combined resource profile supports the technical viability of a solar–wind–battery hybrid microgrid capable of delivering reliable and sustainable electricity while reducing dependence on diesel generators. The findings provide critical baseline data for subsequent techno-economic optimization and informed rural electrification planning.

***Keywords**: Load estimation, Weibull distribution, solar irradiation, wind energy, rural electrification, Nigeria*

Date of Submission: 11-02-2026 Date of acceptance: 22-02-2026

I. Introduction

Access to reliable and affordable electricity remains a fundamental enabler of socioeconomic development, yet many rural communities around the world continue to be underserved by conventional grid infrastructure. In developing countries such as Nigeria, grid extension is often hampered by high capital costs, challenging geography, and low population densities, leading to persistent energy poverty in rural settlements [1].

In response, decentralized renewable energy systems have emerged as viable alternatives for delivering electricity access to off-grid communities, particularly through solar photovoltaic (PV) and wind energy technologies, with diesel generator integrated in hybrid configurations. Such hybrid renewable energy systems (HRES) offer the potential for reliable and sustainable power generation while minimizing environmental impacts associated with fossil fuel dependence [2].

Solar PV technology has been widely recognized as the most cost-effective and rapidly deployable renewable energy solution in Nigeria due to the country's high solar insolation, which ranges between approximately 3.5 and 7.0 kWh/m²/day [3]. Despite this strong solar resource base, reliance on solar alone can be limited by diurnal and seasonal variability. Wind energy, while exhibiting moderate average speeds in many regions of Nigeria, has the potential to complement solar generation, particularly during periods of low solar irradiance [4].

Integrating solar and wind resources in a hybrid system with energy storage enhances system reliability and ensures continuous electricity supply for rural and riverine communities.

Accurate estimation of community electricity demand is a foundational step in the design of hybrid renewable energy systems because it directly influences system sizing, reliability, and cost-effectiveness. Traditional rural load estimation methods often rely on top-down approaches, which can oversimplify localized patterns of energy consumption [5].

Bottom-up load estimation approaches, which aggregate energy use from individual appliances and sectors, have been widely used in rural energy planning to produce realistic community load profiles. In addition, statistical modelling techniques such as the Weibull probability distribution are commonly applied in wind resource assessment to characterize wind speed frequency and derive energy potential [6]. Similarly, solar resource assessment frequently employs clearness index and extraterrestrial radiation models to estimate global solar irradiation for PV system design [7].

Furthermore, optimization of hybrid systems including solar PV, wind turbines, batteries, and diesel backup has been shown to reduce generator run-time and cost of energy in rural electrification studies across different Nigerian states [5]. In the specific case of Koluama communities in Bayelsa State, limited empirical research exists on electricity load estimation and renewable energy resource viability. Understanding local energy demand and renewable resource characteristics is critical to inform appropriate system design and policy interventions that align with national electrification targets and sustainable development goals. This study therefore seeks to fill this gap by estimating the electricity load profile of Koluama communities and assessing the viability of solar PV and wind energy deployment through rigorous technical analysis. The findings are intended to inform subsequent techno-economic optimization and contribute to evidence-based energy planning for rural electrification.

II. Literature Review

Rural Electrification and Hybrid Renewable Energy Systems

Rural electrification remains a critical challenge in many developing countries due to the high cost and logistical difficulties of extending centralised grids to isolated communities. Hybrid renewable energy systems (HRES), which combine two or more renewable sources such as solar photovoltaic (PV) and wind with or without storage and backup generation, have gained prominence as viable alternatives for rural electrification [6]. In Nigeria, grid extension is often impractical in riverine and remote locations, leading to continued reliance on diesel generators that are expensive to run and harmful to the environment. Hybrid systems mitigate these issues by integrating intermittent renewable sources with storage systems, enhancing both reliability and sustainability.

In a recent study by [8] fuzzy logic controller was used to optimise a solar–wind–battery hybrid system designed for rural electrification, showing improvements in reliability and reductions in power supply failures. This reinforces the broader view that hybrid renewable energy systems can provide dependable and sustainable electricity to off-grid communities when properly designed and controlled.

Load Estimation and Demand Forecasting

The design of effective hybrid renewable energy systems for rural electrification necessitates accurate estimation of electricity demand, as under-estimation can compromise system reliability and oversizing leads to unnecessary capital cost increases. Bottom-up load estimation method, which aggregate energy use from individual appliances and sectors, have been widely used in rural energy planning to produce realistic community load profiles [9]

Bottom-up load estimation methods, which sums up energy consumption of individual appliances, provide a more accurate profile of actual electricity demand [10]. While most research in Nigeria has focused on simulated technical performance, recent approaches have begun to incorporate data-driven forecasting methods that improve the accuracy of load models used in system design.

Machine learning models was employed in the research carried out by [10] to forecast hybrid microgrid energy demand, illustrating that combining statistical and computational techniques enhances load prediction over traditional methods. Their work underscores the importance of reliable demand projections in hybrid system design, particularly when renewable energy penetration increases and system balance becomes more sensitive to demand variability. Accurate load forecasting not only supports system sizing but also influences economics, reliability, and environmental performance in rural electrification projects.

Solar and Wind Energy Resource Assessments

Solar and wind resources are the primary drivers for renewable energy generation in off-grid systems. Resource assessment is thus a critical step in the design of any hybrid system. Solar radiation modelling typically relies on clearness index and extraterrestrial radiation models to estimate global solar irradiation available at a location. High solar irradiation levels make solar PV systems particularly attractive in tropical regions like Nigeria. According to [11] consistent solar energy availability in Port Harcourt, Nigeria, using solar resource and techno-economic analysis, showing that solar PV could be economically justified in regions with adequate irradiation data [12]. Hence, the approach is applicable to other coastal regions such as Koluama.

Wind energy resource assessments often use statistical distributions to characterise wind speed frequency and energy potential. The Weibull probability distribution, in particular, has been widely applied for this purpose. In studies of hybrid microgrids, wind speed analysis using Weibull models has provided critical insights into the viability of wind turbines as part of renewable portfolios. While wind speeds in many parts of Nigeria are moderate, adequate average speeds (around 4–5 m/s at 10 m height) have been reported, supporting small and medium-scale turbine integration when combined with solar PV [13]. Such hybrid resource profiles enhance overall energy reliability and complement solar variability.

Techno-Economic and Simulation Studies

Numerous studies have employed simulation tools such as HOMER Pro to evaluate the techno-economic feasibility of hybrid renewable energy systems in rural contexts. In Kwara State, [13] designed and optimised hybrid systems incorporating solar PV, wind, and biomass for multiple off-grid communities, demonstrating significant reductions in greenhouse gas emissions and high internal rates of return, with payback periods between 3.2 and 3.5 years.

Their sensitivity analyses confirmed the robustness of hybrid configurations under variable cost and resource conditions. Their findings are relevant to understanding how solar and wind can contribute significantly to reducing reliance on diesel and other fossil fuels.

In the feasibility study by [14] in north-central Nigeria, different hybrid configurations were evaluated using HOMER Pro software, comparing grid-tied and off-grid scenarios and establishing benchmarks for net present cost (NPC) and cost of energy (COE). They found out that PV-battery systems performed well as standalone configurations, emphasizing the importance of economic analysis in identifying optimal system designs under local conditions. While the optimal configuration varied by context, these studies collectively highlight the importance of rigorous techno-economic analysis when planning renewable energy solutions in hybrid system configuration for rural electrification.

III. Methodology

Study Area Description

Koluama communities are made up of Koluama 1and Koluama 2 community. They are located in Southern Ijaw Local Government Area of Bayelsa State, Nigeria. The community lies between latitude $4.7101°N$ and longitude 5.58°E.

The area is characterized by riverine terrain, dispersed settlements, and limited infrastructure development. Economic activities are predominantly fishing, petty trading, and subsistence livelihoods. The communities are not connected to the national electricity grid and rely mainly on small diesel and petrol generators, which are costly to operate and environmentally polluting.

Load Estimation Approach

A bottom-up load estimation method was employed to determine the electricity demand of the communities. Energy consumption data were estimated based on typical appliance ownership and usage patterns in rural Nigerian households, as well as public and commercial facilities such as schools, health centers, religious buildings, and small businesses.

The total community load was obtained by aggregating individual sectoral demands to generate daily energy consumption and peak power requirements. koluama 1 and Koluama 2 communities load estimation comprises of 291 households, 2 state primary school,2 health centers and 55 small businesses.

Table 1: Household Electrical Load Profile

Appliances	Power Rating (W)	Quantity	Daily Usage (h)	Daily Energy (Wh)
LED bulb	10	6	6	360
Ceiling fan	75	2	8	1200
Television set	120	1	6	720
Decoder	30	1	6	180
Phone charging	15	3	4	180
Refrigerator	150	1	10	1500
Total per Household				**4,140 Wh (4.14 kWh)**

The daily energy consumption was computed using:

$$Ed = \sum_{i=1}^{n} P_i + ti \quad (1)$$

Where:

Ed:is the daily energy demand(kWh/day)

Pi: is the rated power of appliances i (kW)

t_i:is the average daily operation time(hours)

Table 2: Daily Energy Demand for Koluama 1 & 2 Communities

Load Category	Quantity	Daily Energy per Unit (kWh)	Total Daily Energy (kWh)
Households	291	4.14	1,204.74
Primary School	2	20	40
Health Center	2	35	70

Small Businesses	55	5	275
Total Load			1,589.74

Source: Authors' survey & Calculations

In order to give room for future expansion for energy demand, 8.3 % design margin applied. The average energy is 1.722.13kWh/day

Peak load estimation was done by using equations (2) (and 3). Applying a load factor 0.275 which commonly used in literature for rural and riverine communities.

$$\text{Average Power (kW)} = \frac{\text{Average Energy(kWh/day)}}{24} \quad (2)$$

$$Peak\ Power\ (kW) = \frac{Average\ Power(kW)}{Load\ Factor} \quad (3)$$

The aggregated load resulted in an average daily energy demand of 1.722.13kWh/day with a peak demand of 260.32kW

Koluama Communities Solar Irradiation Viability Assessment

Global Horizontal Irradiance is the total amount of shortwave solar radiation received per unit area by a surface horizontal to the ground**.** It provides a baseline measurement of the total solar radiation received per square meter on a horizontal surface, offering insight into the solar resource availability in the region. The global horizontal irradiance level is given by:

$$GHI = DNI * \cos(\theta_z) + DHI \quad (4)$$

Where:

DNI: direct normal irradiance (W/m²)

θ_z: solar zenith angle (degrees)

DHI: diffuse horizontal irradiance (W/m²)

Annual Solar Energy Yield

The Annual Solar Energy Yield estimates the total electrical energy that a photovoltaic (PV) system can produce over a year under local irradiance conditions. This yield depends on several factors, including the surface area of PV modules, their conversion efficiency, and the system's orientation and tilt. The annual energy yield is given by

$$Daily\ Energy\ per\ panel = GHI_{avg}\ x\ PV_{area}\ x\ \eta \quad (5)$$

$$Annual\ Energy\ Yeild(AEY) = Daily\ Energy\ per\ panel\ x\ 365 \quad (6)$$

$$Annual\ Energy\ Yeild(AEY) = GHI_{avg}\ x\ PR\ x\ 365 \quad (7)$$

Where:

GHI_{avg}: Average daily global horizontal irradiance (kWh/m²/day)

PR: Performance ratio (typically between 0.75 and 0.85)

η: System efficiency

PV_{area}: PV area for one panel

365: days in a year

Koluama Communities Wind Speed Assessment

Wind speed characteristics were evaluated using the two-parameter Weibull distribution, widely adopted for wind energy analysis due to its statistical accuracy. It is implemented in MATLAB.

The Weibull Probability distribution function (PDF) is expressed as

$$F(V) = \frac{k}{c}\frac{v}{c}.^{k-1}\ e^{-\frac{vk}{c}} \quad (8)$$

Where:

F = weibull probability distribution function

V = wind speed (m/s)

K = shape constant

C = scale parameter (m/s)

The corresponding cumulative distribution function (CDF) is given by:

$$1 - e^{-\frac{vk}{c}} \quad (9)$$

The weibull parameters were determined using mean wind speed method:

$$K = \frac{\delta^{-1.086}}{v_m} \quad (10)$$

$$C = \frac{v_m}{\gamma 1 + \frac{1}{k}} \quad (11)$$

Where:

v_m = Mean wind speed (m/s)
δ = Standard deviation of wind speed (m/s)
γ = Gamma function
Using a mean wind speed of 4.07 m/s at 10 m height, the derived Weibull parameters indicate moderate but exploitable wind energy potential suitable for medium-scale wind turbines, especially in hybrid configurations
Wind Power density is computed as

$$P_d = \frac{1}{2} p v^3$$

Where:
P_d = wind power density (W/m^3)
p = Air density (kg/m^3), taken as 1.22kg/m^3)
V = wind speed (m/s)

IV. Results and Discussion

Community Electricity Load Assessment
The estimated electricity demand for Koluama 1 and Koluama 2 communities is summarized in Table 3.

Table 3: Estimated Electricity Demand for Koluama Communities

Parameter	Value
Average daily energy demand	1.722.13kWh/day
Peak load demand	260.32kW
Load type	Residential, commercial and residential

The computed results show a total daily electricity demand of 1,589.74 kWh/day, which increased to 1,722.13 kWh/day after incorporating an 8.3% design margin to accommodate future demand growth and system uncertainties. The corresponding peak load demand was estimated at 260.32 kW using a rural load factor of 0.275.

Residential consumption dominates the load structure, accounting for approximately 75% of total daily energy use, primarily due to lighting, refrigeration, ventilation, and entertainment appliances.

The moderate peak load of 260 kW suggests that a community-scale microgrid architecture rather than individual household systems would be more technically and economically viable.

Solar Energy Resource Viability

Table 4 presents the summary of solar energy viability indicators for the Koluama community over the period 2020-2025. Solar resource assessment using Global Horizontal Irradiance (GHI) data shows that the study area possesses strong solar potential, with annual average daily GHI values ranging between 4.93 and 5.29 kWh/m²/day, and a long-term average of 5.14 kWh/m²/day. These values fall within Nigeria's high solar belt and exceed the minimum threshold (≈4.0 kWh/m²/day) typically considered adequate for photovoltaic deployment.

Furthermore, based on accepted GHI benchmark levels, average daily GHI values between 4.5 and 5.5 kWh/m²/day fall within the good solar resource category and are considered recommended for PV applications. Thus, solar PV should constitute the base generation component of the proposed hybrid configuration in Koluama communities.

The corresponding annual PV energy yield averaged 6,676.60 kWh/kWp, indicating that a 1 kWp system could generate approximately 6.7 MWh annually under local climatic conditions. This level of productivity confirms the technical suitability of solar PV as the primary energy source for the hybrid system. Inter-annual variations were relatively small, suggesting stable solar availability and low seasonal risk. Such consistency enhances system predictability and simplifies sizing procedures for PV modules and storage components.

Table 4: Summary of Solar Energy Viability Indicators

Year	Daily Avg GHI (kWh/m²/day)	Annual Yield (kWh/kWp)
2020	5.2857	6878.50
2021	5.1422	6673.38
2022	5.1929	6739.22
2023	5.0824	6595.83
2024	5.2081	6777.49
2025	4.9278	6395.19
Avg.	5.1398	6676.60

Wind Energy Resource Assessment

Table 5 shows Annual Wind Energy Performance Metrics for Koluama, from 2020 to 2025. Wind speed analysis using the Weibull probability distribution yielded a mean wind speed of 4.07 m/s at 10 m height, with derived shape and scale parameters indicating moderate but usable wind potential. Although these wind speeds are lower than typical utility-scale wind farm requirements, they are adequate for small and medium-scale turbines, particularly in hybrid configurations.

The Weibull distribution results reveal that useful wind speeds occur frequently enough to contribute supplementary generation, especially during periods of low solar irradiance such as cloudy or rainy conditions. This complementary relationship between wind and solar resources is advantageous for hybrid systems, as it reduces intermittency and enhances overall supply reliability.

Annual wind energy performance metrics demonstrate variability across years, with capacity factors ranging widely. Such fluctuations are characteristic of wind resources in coastal and riverine regions. Consequently, wind energy should not be relied upon as the primary source but rather as a supporting resource to: improve generation diversity, reduce battery cycling stress, and minimize diesel generator runtime.

The capacity factor varied significantly, from 9.39% in 2024 to 78.23% in 2021, highlighting how the turbine's operational efficiency responds to wind variability. Despite these fluctuations, the mean capacity factor of 42.62% exceeds the commonly cited benchmark range of 25–35%, indicating strong long-term performance. This demonstrates that, on average, Koluama can support reliable medium -scale energy generation

Table 5: Annual Wind Energy Performance Metrics for Koluama from 2020 to 2025

Year	Avg 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	9.39
2025	4.22	73.18

V. Conclusion

This study presented a detailed load estimation and renewable energy resource assessment for Koluama communities in Bayelsa State, Nigeria. The findings reveal an average daily electricity demand of 1.722.13kWh/day and sufficient solar and wind resources to support decentralized renewable energy deployment. Combining the load analysis with renewable resource assessment provides important insights for system design. The high solar irradiation coupled with moderate wind speeds suggests that a solar–wind– diesel generator-battery hybrid configuration is technically feasible and capable of meeting the community's demand reliably. Future work will focus on techno-economic optimization and environmental impact assessment of hybrid renewable energy systems for the study area.

Acknowledgement

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

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