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Wind Energy Integration in North-West Nigeria: A Weibull and Levelised Cost of Energy Assessment of Urban and Rural Prospects in Katsina State

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ABSTRACT
Electricity supply in Katsina State is inadequate: urban areas suffer persistent outages and load shedding, while many rural communities have no grid connection. This study assessed whether wind energy can serve as a reliable secondary (complementary) source of power in both settings. A concurrent mixed-methods design combined a questionnaire survey of 400 valid respondents in Katsina Metropolis, Dutsin-Ma, Charanchi and Rimi with Weibull analysis of Nigerian Meteorological Agency (NIMET) wind data and a levelized cost of energy (LCOE) assessment. The state-average wind power density at 50 m was 158.5 W/m² (Fair-to-Good), peaking at 201.5 W/m² in Rimi. LCOE for a 100 kW installation ranged from ₦26.3/kWh (Rimi) to ₦43.9/kWh (Charanchi), well below the cost of diesel generation. Rural respondents reported significantly greater electricity unreliability and greater willingness to adopt wind energy than urban respondents ($p < 0.001$ for both). Wind energy is technically and economically viable as a secondary source, most strongly in rural, high-wind communities. Policy recommendations and priorities for further research are presented.
Keywords: wind energy; feasibility; Weibull distribution; levelized cost of energy; rural electrification; Katsina State

1. INTRODUCTION

1.1 Background

Reliable electricity underpins industry, health care, education, small business and household life. Despite Nigeria's abundant energy resources, the country suffers from an unstable and unreliable supply. National access stood at 55.4% in 2020, but the urban–rural gap is stark: 83.9% in urban areas against 24.6% in rural areas. The average grid-connected household receives only about 6.6 hours of supply a day (PeopleSuN Project, 2023).

Katsina State shares this problem acutely. It lies far from the southern gas-fired stations that generate most of the nation's power, so it depends on an over-stretched and unstable national grid. Rural communities are frequently not connected at all, while connected urban centres still experience outages, voltage fluctuations and load shedding. Households, small and medium enterprises, schools and health centres consequently rely on expensive and polluting petrol and diesel generators or, in many villages, on kerosene lanterns and firewood.

Wind has emerged globally as one of the cleanest and most cost-effective renewable sources for complementing grid electricity. Earlier meteorological work places Katsina's mean wind speed at 3.5–5.5

m/s at 50 m, with an average power density of about 160.6 W/m² (Balarabe et al., 2014), and other studies report speeds above 6 m/s at greater heights. This potential informed the 10 MW Lambar Rimi Wind Farm, one of the earliest utility-scale wind projects in West Africa. Yet beyond that pilot, the resource remains largely unexploited.

1.2 Problem statement, aim and objectives

Despite federal and state interventions such as solar mini-grids and distribution upgrades, supply across the state remains grossly inadequate. There is little localised, comparative research on whether wind can practically serve as a secondary electricity solution for both urban and rural settlements, taking account of differences in resource, infrastructure readiness, cost and community needs. Without such evidence, policymakers, investors and communities cannot plan or justify adoption.

The aim of this study is therefore to assess the feasibility of wind energy as a reliable secondary source of electricity across urban and rural Katsina State. Its objectives are to:

(a) examine the existing state of electricity supply and its challenges in urban and rural areas;
(b) assess the state's wind energy potential using wind speed and wind power density data;
(c) evaluate the technical and economic feasibility of wind as a secondary power source;
(d) compare the prospects and challenges of adoption between urban and rural areas; and
(e) recommend strategies for integrating wind energy into the state's electricity mix.

The remainder of the paper is organised as follows. Section 2 reviews the related literature and identifies the research gap; Section 3 describes the methodology; Section 4 presents the results; Section 5 discusses the findings, limitations and implications; and Section 6 concludes with recommendations.

2. Review of Related Literature

2.1 Concepts

Electricity supply refers to the generation, transmission and distribution of power through the national grid. Nigeria's grid is dominated by thermal (gas-fired) and hydroelectric generation in the south, so power reaching distant northern states suffers transmission losses and instability. Installed capacity of about 13 GW falls short of a forecast peak demand near 20 GW, and actual generation rarely exceeds 6 GW, which explains the chronic outages nationwide.

Wind energy is the conversion of the kinetic energy of moving air into mechanical and then electrical power by turbines. Viability at a site depends mainly on wind speed, wind power density and measurement height, since both speed and the energy carried increase markedly with height. A secondary or complementary solution is a supporting source used alongside the grid to fill gaps, improve reliability and reduce dependence on diesel back-up. Solar mini-grids have so far been the most widely deployed complement in Nigeria, whereas wind remains comparatively underexploited despite favourable conditions in several northern states.

2.2 Empirical evidence and research gap

Balarabe et al. (2014) analysed six years (2008–2013) of surface wind data and found considerable potential in Katsina, although their data came from a single monitoring location and ignored economics and urban–rural contrasts. A nationwide NIMET-based assessment using Weibull and geographic information system (GIS) techniques found moderate-to-good, relatively steady winds across the North-West and recommended wind–solar integration where wind alone is not consistent enough. Adizua and Anele (2026) modelled LCOE for northern states, including Katsina, at roughly US$0.07–0.12 per kWh, judging wind economically competitive but constrained by weak grid integration and policy gaps. The PeopleSuN survey of 3,599 households and 1,122 enterprises (PeopleSuN Project, 2023) documented about 6.6 hours of supply daily, roughly 32.8 outages a month and an 11% loss in sales for affected businesses, but did not sample Katsina or unconnected communities.

Taken together, the literature confirms that Katsina has one of Nigeria's most favourable wind profiles. However, existing studies are either narrowly technical, relying on single stations, or national in scope. No reviewed study combines wind-resource assessment, economic analysis and a direct urban–rural comparison for Katsina State. This study fills that gap.

3. METHODOLOGY

3.1 Research design and sampling

The study used a concurrent mixed-methods design, pairing a descriptive household and enterprise survey with an analytical assessment of meteorological data. The pairing suits a two-dimensional problem that requires both physical resource data and community-level demand and acceptance data. The population comprised households and small enterprises in Katsina State, projected at about 10.9 million people in 2024.

Multi-stage sampling was used. Katsina Metropolis was purposively selected to represent urban areas, and Dutsin-Ma, Charanchi and Rimi to represent rural areas, based on proximity to existing or proposed wind installations and documented supply gaps. Two wards were then randomly selected in each area, and households and small enterprises were drawn from them by simple random sampling. The Taro Yamane formula (Yamane, 1967), $n = N/(1 + Ne^2)$, with a 5% margin of error ($e = 0.05$), gave about 400 respondents, which was raised to 420 to allow for non-response.

3.2 Instruments and data sources

Primary data came from a structured questionnaire with demographic items and a four-point Likert scale on supply quality, wind awareness, feasibility, urban–rural differences and integration strategies, supported by interviews with officials of the state energy ministry, the Rural Electrification Agency and NIMET. Item means of 2.50 or above were interpreted as agreement and means below 2.50 as disagreement. Experts reviewed the instrument for content and face validity, and a pilot of 30 respondents returned a Cronbach's alpha above 0.70. Secondary data were NIMET wind speed and wind power density records for 2020–2026.

3.3 Wind resource analysis

Wind speeds were fitted with the two-parameter Weibull distribution in Microsoft Excel. The shape (k) and scale (c) parameters were estimated from the mean and standard deviation of wind speed, and wind power density (WPD) was computed with an air density of 1.225 kg/m³.

3.4 Levelised cost of energy model

LCOE was computed for a representative 100 kW turbine with a capital cost of ₦45 million, annual operation and maintenance (O&M) cost of 2% of capital, a 20-year life and a 12% discount rate. Annual energy output was the product of rated capacity, 8,760 hours and the site capacity factor. The capital recovery factor (CRF) and LCOE were calculated as:

$$\mathrm{CRF} = r(1 + r)^{*n*} / [(1 + r)^{*n*} - 1] \quad (1)$$

$$\mathrm{LCOE} = (I \times \mathrm{CRF} + C_{\mathrm{O\&M}}) / E_{\mathrm{annual}} \quad (2)$$

where r is the discount rate, n the project life in years, I the capital cost, $C_{\mathrm{O\&M}}$ the annual O&M cost and E_{annual} the annual energy output. With $r = 0.12$ and $n = 20$, the CRF is 0.134.

3.5 Survey data analysis

Survey data were analysed in SPSS version 26 using frequencies, percentages, means and standard deviations. An independent-samples t-test compared urban and rural respondents. The null hypothesis (H_0) was that there is no significant difference between urban and rural mean scores; it was tested at the 0.05 significance level.

4. RESULTS

4.1 Response rate and respondents

Table 1. Questionnaire distribution and valid responses

Local Government Area	Category	Distributed	Valid responses
Katsina Metropolis	Urban	150	145
Dutsin-Ma	Rural	90	85
Charanchi	Rural	90	85
Rimi	Rural	90	85
Total		**420**	**400**

Of 420 questionnaires distributed, 410 were returned and 400 were valid, a valid response rate of 95.2%. Male respondents made up 59.5% of the sample, and the largest age group (35.5%) was 26–35 years, showing a young, economically active sample. Most respondents were married (63.5%). Business owners (32.0%) and farmers (23.0%) were the largest occupational groups, and rural respondents (63.8%) outnumbered urban ones (36.3%), as the sampling design intended.

4.2 Electricity supply and perceptions of wind

Respondents overwhelmingly rated supply as unreliable (mean = 3.37 on the four-point scale), reported frequent outages (3.33) that disrupt daily activities (3.44), and said they depend on alternative sources (3.30). They disagreed that available electricity meets their needs (1.83). Inadequate supply is therefore a problem in both urban and rural Katsina.

Perceptions of wind were generally favourable. Respondents agreed that Katsina has good wind resources (2.74), that they knew of the Lambar Rimi farm (2.81), that wind can complement supply (3.23) and that the resource is underutilised (3.17). The only disagreement was on whether their own community has enough wind for generation (2.44), which suggests an awareness gap rather than a resource gap, as the meteorological data below show.

4.3 Wind resource

Table 2. Weibull parameters and wind power density (WPD) at 50 m height

Location	Mean speed (m/s)	Std. dev. (m/s)	Weibull *k*	Weibull *c* (m/s)	WPD (W/m²)	Class
Katsina Metropolis	4.6	1.8	2.71	5.16	142.3	Fair
Dutsin-Ma	5.1	1.9	2.85	5.72	168.7	Good
Charanchi	4.3	1.7	2.68	4.83	121.4	Fair
Rimi	5.8	2.0	3.02	6.49	201.5	Good
State average	**4.95**	**1.85**	**2.82**	**5.55**	**158.5**	**Fair–Good**

Note. k = Weibull shape parameter; c = Weibull scale parameter. *Source:* NIMET records (2020–2026); author's calculations.

All four locations fall within the Fair-to-Good bands used to judge small- and utility-scale viability. The state average of 158.5 W/m² closely matches the 160.6 W/m² reported earlier. Rimi, host of the Lambar Rimi Wind Farm, recorded both the highest mean speed (5.8 m/s) and the highest density (201.5 W/m²), confirming the technical rationale for the farm's siting. Dutsin-Ma is also rated Good, while Katsina Metropolis and Charanchi are Fair but still sufficient for small turbines supplying household- and enterprise-level supplementary power.

4.4 Technical and economic feasibility

Respondents agreed that wind can serve as a reliable secondary source (3.26), that systems can operate effectively in the state (3.04), and that wind can reduce dependence on petrol and diesel generators (3.36).

They were more cautious about long-term affordability (2.67) but willing to invest if costs are manageable (3.25), which points to upfront cost as the main perceived hurdle.

Table 3. Estimated levelised cost of energy (LCOE) for a 100 kW installation

Location	Capacity factor (%)	Annual output (kWh)	LCOE (₦/kWh)
Rimi	30	262,800	26.3
Dutsin-Ma	27	236,520	29.3
Katsina Metropolis	25	219,000	31.6
Charanchi	18	157,680	43.9

Note. Annual output = 100 kW × 8,760 h × capacity factor. Annualised cost = ₦6,921,000 at all sites.

Costs of ₦26.3–43.9/kWh compare favourably with diesel-generated electricity, which recent Nigerian estimates put well above ₦150/kWh once fuel, maintenance and depreciation are counted, and are broadly competitive with grid tariff bands under the Multi-Year Tariff Order framework. Costs fall as capacity factor rises, so wind is most attractive at Rimi and Dutsin-Ma. Lower-resource sites such as Charanchi would need larger-scale deployment, cost-sharing or subsidy support to achieve comparable competitiveness.

4.5 Urban–rural comparison

Respondents saw wind as suitable for rural communities (3.26) and, less strongly, for urban ones (2.86). They agreed that rural communities need alternative power more than urban communities (3.35) and that adoption challenges differ between the two (3.31). Table 4 shows that the urban–rural differences were statistically significant.

Table 4. Independent-samples *t*-test: urban (n = 145) versus rural (n = 255)

Measure (mean score)	Urban	Rural	*t* (df = 398)	*p*	Mean difference
Electricity supply unreliability	2.85	3.19	−5.40	< 0.001	−0.34
Wind energy feasibility / willingness	2.95	3.21	−3.83	< 0.001	−0.26

Note. Scores are on a four-point scale. Critical $t = \pm 1.966$ ($\alpha = 0.05$, two-tailed).

Both differences were significant at the 0.05 level and exceeded the critical *t*-value of ±1.966, so the null hypothesis was rejected: rural respondents reported significantly greater unreliability of supply and significantly greater willingness to adopt wind energy.

4.6 Integration strategies

Table 5. Respondents' views on integration strategies (grand mean = 3.42)

Strategy	Mean	Decision
Government should invest more in wind energy projects	3.52	Agreed
Government subsidies will encourage adoption	3.46	Agreed
Public awareness campaigns will increase acceptance	3.42	Agreed
Wind should be integrated into state electricity policy	3.38	Agreed
Public–private partnerships will promote development	3.33	Agreed

This section recorded the strongest agreement of any part of the questionnaire, which signals broad public support for active government and private-sector involvement.

5. DISCUSSION

The evidence from three independent sources converges. The survey shows a severe and widely felt supply gap; the Weibull analysis shows a Fair-to-Good resource at every location studied; and the LCOE analysis shows costs far below the diesel generation on which people now depend. Wind therefore need not replace the grid. Its realistic role is to reduce reliance on costly generators and lift reliability where the grid fails, which is exactly the meaning of a secondary source.

Feasibility is not uniform. Rural communities have both the greater need and the greater willingness to adopt, and Rimi and Dutsin-Ma pair the best wind with strong demand. This matters for policy, because rural unconnected communities are where a standalone or mini-grid wind installation adds the most value. Urban areas such as Katsina Metropolis remain viable, but respondents rated them less suitable, and the case rests more on supplementing the grid and backing up commercial users than on first-time access.

The results also echo the literature. Like Balarabe et al. (2014), the study finds considerable potential, with a state average within about 1.3% of their earlier figure. Like Adizua and Anele (2026), it finds wind economically competitive but constrained by policy and finance rather than by wind speed. The recommendation of nationwide studies to combine wind with solar is also relevant, because the two resources tend to complement each other across the day and year (Ademola & Olaniyi, 2022). Respondents' doubts about whether their own community has enough wind, despite favourable data, show that communication is itself a barrier.

5.1 Limitations

Several limitations apply. The wind data came from a small number of NIMET stations rather than long-term, site-specific masts, which limits the precision of turbine-siting advice. The LCOE model used one representative 100 kW turbine and fixed assumptions on cost, lifespan and discount rate, so results will shift with different equipment or financing. Perceptions were self-reported, and the study is a feasibility assessment, not an engineering design or on-site installation. These limits do not undermine the main conclusion, but they mean the figures should guide planning rather than replace detailed site studies.

5.2 Policy and practical implications

Three practical implications follow. First, siting matters: the cost gap between Rimi (₦26.3/kWh) and Charanchi (₦43.9/kWh) shows that a uniform statewide rollout would waste money, so projects should be sequenced from the strongest wind sites outward. Second, financing design matters as much as technology. Respondents were willing to invest but doubtful about long-term affordability, so concessionary loans, leasing and public–private partnerships can convert interest into installations. Third, wind should be planned together with solar. Solar mini-grids already exist in parts of the state, and a hybrid system can raise reliability, share infrastructure and lower the cost per unit of electricity.

Institutions also have clear roles. The state government can create the policy framework under the Electricity Act 2023, the Rural Electrification Agency can support off-grid and mini-grid deployment, and NIMET can supply the measurement data on which siting decisions depend. Communities themselves should be informed early, since doubt about local wind adequacy could otherwise slow acceptance of projects that the data support.

Table 6. Summary of findings by research objective

Research objective	Principal finding
Supply situation	Grossly inadequate in urban and rural areas (unreliability item mean = 3.37)
Wind potential	Fair-to-Good; state average 158.5 W/m²; Rimi highest at 201.5 W/m²
Feasibility	LCOE of ₦26.3–43.9/kWh, below diesel; strongest at Rimi and Dutsin-Ma
Urban–rural contrast	Rural need and willingness significantly higher ($p < 0.001$)
Integration strategies	Strong support for investment, subsidies, awareness and partnerships

6. CONCLUSION AND RECOMMENDATIONS

Wind energy is a technically viable and economically competitive secondary electricity source for Katsina State, able to complement an unreliable grid in both urban and rural areas. The challenge going forward is deliberate integration, financing and community-level deployment rather than resource availability. Feasibility is strongest in rural, higher-wind communities such as Rimi and Dutsin-Ma and weaker, though still viable, in lower-resource places such as Charanchi. The study recommends that:

- **Policy:** the state government use its powers under the Electricity Act 2023 to adopt a wind energy policy that designates high-potential rural areas such as Rimi and Dutsin-Ma for priority development.
- **Rural focus:** government and development partners prioritise small- and medium-scale wind installations for communities not connected to the grid, rather than concentrating on urban centres.
- **Hybrid systems:** investors explore wind–solar mini-grids at sites with a Good wind classification to improve reliability and reduce LCOE.
- **Finance:** targeted subsidies or concessionary financing be used to lower the upfront cost for households and small enterprises, especially in lower-resource areas such as Charanchi.
- **Awareness:** campaigns coordinated with the Rural Electrification Agency and NIMET close the awareness gap on local wind potential.
- **Data:** additional long-term, site-specific wind measurement stations be established across the state's 34 Local Government Areas.

6.1 Contribution and further research

The study offers a localised comparative assessment that integrates Weibull-based technical analysis, LCOE-based economic analysis and community survey data, and it provides statistical evidence of urban–rural differences in need and willingness. This can inform geographically differentiated policy in Katsina and comparable states such as Kano and Sokoto. Further work should extend measurements to more local government areas over longer periods, design and cost specific hybrid wind–solar mini-grids for rural communities, compare other northern states, and examine institutional, regulatory and financing barriers in greater depth.

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