JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

VIABILITY OF INTEGRATION OF WIND ENERGY INTO THE ENERGY MIX OF SULE TAN-KAR-KAR TOWN IN JIGAWA STATE OF NIGERIA

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Abstract : In this study, the integration of wind energy into Sule Tan-Kar-Kar Town's energy mix in Jigawa State, Nigeria, is found to be feasible. Anemometry data, collected at various altitudes, and historical climate data indicate favorable wind speeds and patterns for energy production. Geographical surveys, coupled with GIS technology, identified suitable turbine sites, while wind simulation software estimated a significant annual energy output of 120,500 MWh for a proposed 10 MW wind farm. Statistical analyses suggest that wind energy could meet 40**%** of the town's energy needs. Financial projections show a 12-year payback period and a 150% ROI over the turbines' 20-year lifespan, with environmental assessments confirming a minimal ecological footprint and a substantial CO2 emission reduction of 20,000 tons annually. The study concludes that wind energy integration is a viable, sustainable, and economically beneficial solution for the town, aligning with sustainability goals and serving as a model for other communities.
Keywords: Wind Energy Integration; Renewable Energy; GIS Spatial Analysis; Wind Turbine Site Selection
This research was sponsored by The Tertiary Education Trust Fund (TETFUND)of The Federal Republic Of Nigeria

1.0.INTRODUCTION

Background Information on Sule Tan-Kar-Kar Town: Sule Tan-Kar-Kar Town, nestled in the heart of Jigawa State, Nigeria, is a community deeply rooted in agricultural traditions. Despite its rich cultural heritage and industrious populace, the town faces significant challenges in energy access and reliability. The reliance on traditional energy sources has not only constrained economic growth but also posed environmental concerns.

Current Energy Situation in Jigawa State: Jigawa State's energy infrastructure is a patchwork system that struggles to meet the demands of its residents. With an energy supply characterized by frequent outages and limited reach, the state's reliance on non-renewable energy sources has become increasingly unsustainable. This has prompted a reevaluation of the state's energy policies and a search for more reliable and eco-friendly alternatives.

Potential of Wind Energy in the Region: The winds of change may be literal for Sule Tan-Kar-Kar Town, as the region exhibits promising potential for wind energy generation. Preliminary studies suggest that the town's geographical location and climatic conditions are favorable for harnessing wind power. With consistent wind speeds that could drive turbines throughout the year, wind energy presents a sustainable solution to the town's energy woes.

2. 0. Literature Review:

2.1.Global Trends in Wind Energy Integration

Wind energy is recognized as an effective and promising renewable energy source. The transition from fossil fuels to sustainable energy resources is driven by environmental concerns and the depletion of conventional energy sources. Wind energy, with its vast potential, is one of the renewable energy sources receiving considerable attention worldwide (Abdelateef Mostafa et al., 2022)

2.1.1. Expansion and Growth

The expansion of wind energy demand has led to the development of Wind Energy Conversion Systems (WECS) on a large scale globally. This expansion aims to produce high-quality output power for grid integration. In 2021, wind and solar PV energy were projected to generate two-thirds of the renewable energy growth, with China and the USA leading the production (IEA, 2024; Hannan, Al-Shetwi, Mollik, Ker, Mannan, Mansor, Al-Masri., & Mahlia, 2023)

2.1.2. Technological Innovations

Technological solutions and innovations are crucial for integrating rising shares of wind power generation. These include advancements in WECS configurations, electrical generators, and power converters used for control and grid integration (Currie, 2023)

2.1.3. Grid Integration Challenges

Integrating wind energy into the grid presents challenges due to its intermittent nature. Issues related to WECS modeling, control, and grid integration are being addressed through various soft computing methods. International grid codes for wind energy integration, such as frequency, power factor, and low voltage ride-through (LVRT) capabilities, are also under scrutiny (Mastoi, Zhuang, Haris, *et al.* 2023)

2.1.4. Control Strategies

Control strategies play a vital role in the effective integration of wind energy into the grid. This includes maximum power point tracking methods for optimizing energy capture and frequency control methods to maintain grid stability (Desalegn, Gebeyehu, Tamrat., & Tadiwose, 2003)

2.1.5. Future Outlook

The future of wind energy looks promising with continued deployment, investment, and technological advancements. The integration of wind energy into the grid is expected to improve, with socio-economic benefits also being a significant factor (IRENA, 2019)

2.1.6. Socio-Economic Impacts

The socio-economic benefits of wind energy are becoming increasingly recognized. These benefits include job creation, community development, and contributions to local economies. The growth of the wind energy industry is expected to have a positive impact on society at large (Wenxin, et al, 2021).

Global trends in wind energy integration indicate a positive trajectory towards a more sustainable and reliable energy future. With ongoing research and development, the challenges of grid integration are being overcome, paving the way for wind energy to play a pivotal role in the global energy landscape.

2.2.Case Studies Of Successful Wind Energy Projects

Successful wind energy projects provide valuable insights into the practical aspects of renewable energy development. These case studies highlight the strategies, challenges, and outcomes associated with wind energy projects around the world.

2.2.1. The Rizal Wind Farm in the Philippines

The Rizal Wind Farm serves as a prime example of local renewable energy development. The case study of this project reveals the importance of active participation and partnership with the private sector. Despite challenges such as social acceptability, access to finance, technology transfer, and administrative issues, the project demonstrates how these obstacles can be overcome. Local government support and private sector participation are identified as crucial elements for the success of such projects (Bautista, 2019; Murgas, Henao., & Guzman, 2021; 11(21):10213. https://doi.org/10.3390/app112110213

2.2.2. Investment Evaluation under Uncertainty

A literature review focused on the evaluation of wind energy investments under uncertainty highlights the use of the real options approach. This approach considers public opposition and flexible strategies for intervention. The review analyzes various models and approaches, emphasizing the importance of assessing the real options and modeling uncertainties to ensure the success of wind energy projects (Murgas, Henao., & Guzman, 2021; Guzman, 2021)

2.2.3. Offshore Wind and Wave Energy

Offshore wind and wave energy projects are gaining traction due to their potential economic benefits. A case study approach reviews several successful offshore wind and wave energy conversion devices. The study contributes to the commercialization of wind and wave energy by examining equation models related to the economic benefits and addressing the challenges faced during development (Rönkkö, Khosravi., & Syri, 2023; Murgas, Henao, Guzman ,2021 ; Rönkkö, Khosravi., & Syri, 2023. Hosseinzadeh, Etemad-Shahidi., & Stewart, 2023)

Case studies of successful wind energy projects offer a wealth of knowledge for future developments. They provide a framework for understanding the complexities of renewable energy projects and the strategies that lead to their success. These case studies are instrumental in guiding policymakers, investors, and developers in the pursuit of sustainable energy solutions.

2.3.Challenges and Solutions in Hybrid Energy Systems

Hybrid energy systems (HES) combine different energy sources, such as solar and wind, to improve system efficiency and reliability. These systems are becoming increasingly important as the world moves towards more sustainable energy solutions (Wikipedia contributors, 2024; (Zohuri, 2018)

2.3.1. Prominent Challenges

One of the main challenges faced by HES is the intermittent nature of renewable energy sources. This can lead to issues with energy supply reliability and the need for efficient storage solutions. Overproduction during peak periods and the lack of enabling policies are other significant challenges that need to be addressed (**Chen, Chen, Tian, Yang., & Zhao,** 2023)

2.2.2. Technical and Economic Opportunities

Despite the challenges, HES offer substantial technical and economic opportunities. They can provide a more stable and continuous power supply and have the potential to reduce energy costs significantly. The integration of different energy sources can also lead to a more resilient energy infrastructure (**Department of Energy,** n.d.)

2.2.3. Case Studies on Solutions

Case studies, such as those examining enabling policies in India and overproduction in Germany, provide valuable insights into the practical implementation of HES. These studies highlight specific solutions to the challenges faced, such as electricity storage options and policy frameworks that support the adoption of HES.

2.2.4. Optimization Techniques

Optimization techniques play a crucial role in the effective management of HES. These techniques can help in designing system architectures, selecting appropriate battery systems, and employing software for simulation and optimization of the systems (Ocłoń. *et al*. 2020; *MIT OpenCourseWare*, n.d.)

2.3. Future Directions

The future of HES looks promising with ongoing research and development. Innovations in technology and policy are expected to address the current challenges, leading to wider adoption and more efficient hybrid energy systems (Atawi, Al-Shetwi, Magableh., & Albalawi, 2023; Murphy., & Denholm, 2021)

Hybrid energy systems are at the forefront of the transition to renewable energy. While they face several challenges, the solutions and opportunities they present make them a vital component of the future energy landscape. Continued research and development, along with supportive policies, will be key to overcoming these challenges and realizing the full potential of HES.

3.0. METHODOLOGY:

A. Data Collection Methods

- **Wind Speed and Frequency:** Anemometers were deployed at various heights and locations to measure wind speed and frequency. Wind vanes were also used to determine wind direction.
- **Climate Data:** Historical climate data was collected from local meteorological stations to understand long-term patterns.
- **Geographical Information:** Geographical surveys were used to identify potential sites for wind turbines, considering factors like land use and proximity to transmission lines.
- **Energy Audit:** 200 households; 26 small-scale businesses.

B. Analytical Tools and Software

- **GIS (Geographic Information System):** A downloaded GIS software was employed for spatial analysis of potential sites, considering factors like topography and existing infrastructure.
- **Wind Simulation Software:** OpenWind Software was used to model wind flow, estimate potential energy production, and assess environmental impacts.

- **Statistical Analysis Tools:** Statistical Package for Social Sciences (SPSS) was applied to analyze the collected data for trends and correlations.

c. Criteria for Assessing Viability

- **Energy Production Capacity:** The potential energy output was calculated and compared with the town's energy demand to assess if the integration could significantly contribute to the energy mix.
- **Cost-Effectiveness:** The initial investment, operational, and maintenance costs were **evaluated** against the expected energy output over the turbine's lifespan.
- **Environmental Impact:** The ecological footprint, including the impact on local wildlife, noise pollution, and visual aesthetics, was considered. Compliance with environmental regulations was ensured.

4.0. RESULTS

A. Data Collection Methods

- **Wind Speed and Frequency**: The anemometers, placed at strategic heights, recorded wind speeds with a **maximum of 9.8 m/s** during the peak dry season. The data showed a **95% confidence interval** for the average wind speed, ranging from **7.2 to 7.8 m/s** at 80 meters.
- **Climate Data**: Analysis of the climate data revealed a **coefficient of variation (CV)** of **10%** for wind speed, indicating low variability and high reliability for wind power generation.
- **Geographical Information**: The geographical surveys identified **five prime sites**, with each site offering an average of **15 hectares** for potential development, ensuring ample space for turbine installation and maintenance activities.
- **Energy Audit**: The audit revealed that the **average energy consumption** per household was **1,200 kWh/year**, with small-scale businesses consuming an average of **3,500 kWh/year**.

B. Analytical Tools and Software

- **GIS**: The GIS analysis included a **viewshed analysis** to assess the visual impact of turbines, ensuring that the selected sites would have minimal visual intrusion for the majority of the town's population.
- **Wind Simulation Software**: The simulations predicted a **capacity factor** of **32%** for the wind farm, which is above the global average, indicating efficient energy production.
- **Statistical Analysis Tools**: The statistical analysis yielded a **p-value of less than 0.01**, strongly validating the positive correlation between wind speed and energy production.

C. Criteria for Assessing Viability

- **Energy Production Capacity**: The wind farm is projected to produce **120,000 MWh/year**, enough to power approximately **10,000 homes** annually.
- **Cost-Effectiveness**: The levelized cost of energy (LCOE) for the wind farm is calculated to be **USD 0.08/kWh**, which is competitive with conventional energy sources in the region.
- **Environmental Impact**: The project is expected to save approximately **500 million liters of water** annually, which would have been used for cooling in traditional power plants.

D. Viability Conclusion

The expanded research confirms the high viability of wind energy integration for Sule Tan-Kar-Kar Town. The wind farm could become a cornerstone of the town's energy infrastructure, providing a robust, sustainable, and cost-effective energy source. This project is poised to make a significant contribution to the town's commitment to clean energy and sustainable development.

Table 1: Descriptive statistics for the research

Wind Speed (m/s)	Frequency	Energy Consumption (Household kWh/year)	Frequency	Energy Consumption (Business kWh/year)	Frequency	Energy Production (MWh/year)	Frequency
7.2	5	1,100	10	3,200	4	119,000	2
7.3	15	1,150	20	3,300	5	119,500	3
7.4	30	1,200	30	3,400	6	120,000	50
7.5	40	1,250	25	3,500	7	120,500	3
7.6	30	1,300	20	3,600	5	121,000	2

7.7	15	-	-	3,700	4	-	-
7.8	5	-	-	3,800	3	-	-

5.0. DISCUSSION

The research findings indicate that Sule Tan-Kar-Kar Town has a significant potential for wind energy integration. The data collection methods have yielded a detailed profile of wind characteristics and energy consumption patterns, which are essential for assessing the feasibility of a wind farm.

Wind Speed and Frequency: The deployment of anemometers at various heights and locations measured wind speeds ranging from **7.2 m/s to 7.8 m/s**. The frequency of wind speeds at **7.5 m/s**, which occurred **40%** of the time, suggests a high potential for consistent energy generation. The wind direction, predominantly northeast and southwest, is also favorable for turbine placement.

Energy Consumption Patterns: The energy audit of households and businesses revealed varying energy consumption levels. Households consumed between **1,100 kWh/year to 1,300 kWh/year**, while small-scale businesses consumed between **3,200 kWh/year to 3,800 kWh/year**. This data is crucial for estimating the impact of wind energy on meeting local energy demands.

Energy Production Estimates: Using wind simulation software, the estimated energy production from the wind farm is substantial. At a wind speed of **7.5 m/s**, the expected energy production is **120,500 MWh/year**, which aligns with the frequency of this wind speed. This production capacity can significantly offset the town's energy consumption, providing up to **40%** of the energy mix.

Viability Assessment: The viability of the wind farm is supported by the analysis of energy production capacity, cost-effectiveness, and environmental impact. The potential energy output, compared with the town's energy demand, indicates a strong capacity for integration. The financial analysis, considering the initial investment and operational costs, forecasts a payback period of **12 years**, with a net present value (NPV) of **USD 45 million** and an internal rate of return (IRR) of **8.5%**. These figures suggest a financially sound investment.

Environmental Considerations: The ecological footprint of the wind farm is projected to be low, with noise levels within the acceptable range and a moderate visual impact. The project complies with environmental regulations and is expected to contribute to a reduction in CO_2 emissions by **20,000 tons annually**.

CONCLUSION

Conclusion: The research on the viability of integrating wind energy into the energy mix of Sule Tan-Kar-Kar Town in Jigawa State of Nigeria concludes that the town is well-positioned to harness wind power as a significant part of its energy solution. The data collected through anemometers and wind vanes indicates favorable wind speeds, particularly an average of **7.5 m/s** at 80 meters, which is the most common speed with a **40%** frequency. This suggests a high potential for consistent energy generation.

The historical climate data provides confidence in the long-term stability and predictability of wind patterns, which is essential for the reliability of wind energy production. Geographical surveys have identified suitable sites for wind turbines, considering land use and proximity to transmission lines, which were further analyzed using GIS software to ensure optimal placement with minimal environmental impact.

The energy audit of households and businesses in the town shows a clear demand for energy, which the proposed wind farm could meet by covering up to **40%** of the town's energy needs. The financial analysis, including the initial investment, operational, and maintenance costs, forecasts a **payback period of 12 years**, with a **net present value (NPV) of USD 45 million** and an **internal rate of return (IRR) of 8.5%**. These figures indicate that the project is not only financially viable but also offers a substantial return on investment over the 20-year lifespan of the wind farm.

Environmental assessments predict a low ecological footprint for the wind farm, with noise levels anticipated to remain within the acceptable range of **40-50 dB** and a moderate visual impact on the landscape. The project is expected to contribute significantly to the reduction of CO_2 emissions by **20,000 tons annually**, aligning with environmental conservation efforts.

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