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A Machine Learning–Based Adaptive Framework for Wind Energy Potential Assessment across Nigeria's Climatic Zones

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ABSTRACT
The current focus on transitioning of energy to cleaner and more sustainable energy systems has led to global increase in the search for effective methods to assess renewable energy potential. In this study, a machine learning-based adaptive framework is proposed for the assessment of wind energy potential across he different climatic zones in Nigeria. The framework proposed the modelling of a complex temporal and spatial dependencies in wind patterns by training a Long Short-Term Memory (LSTM) algorithm, enhanced with the attention-based mechanism on the Nigerian Meteorological Agency (NiMet) long-term data with attributes such as elevation, wind speed, wind direction, maximum temperature (T_{max}), and minimum temperature (T_{min}). The proposed framework incorporates the comparism of the enhanced deep learning model with the baseline statistical approach (Weibull distribution), to evaluate the robustness of the proposed model. Additionally, the proposed framework is designed to integrate the output of the deep learning model into the Geographic Information System (GIS) for spatial analysis and wind farm site suitability mapping. The proposed framework in this study addresses some limitations in previous studies, including the utilization of conventional statistical models, and the focus on single locations. The expected result from the proposed framework is a higher accuracy and precision, with improved spatial adaptability when compared with the Weibull-based models, enabling more reliable wind energy assessment across Nigeria's climatic zones. This study provides a data-driven approach that can be utilized for forecasting wind energy with higher accuracy and precision, aiding decision-makers in renewable energy planning and national grid optimization.

Keywords:
Machine Learning,
Wind Energy Assessment,
LSTM,
Attention Mechanism,
NiMet,
Renewable Energy,
Nigeria,
GIS.

INTRODUCTION

Wind power is a major component of renewable power development due to the global focus on sustainable and low-carbon energy sources. The environmental benefit and economic potential of wind energy has made it increasingly recognised worldwide (Summerfield-Ryan & Park, 2023). The recent advancement in Artificial Intelligence (AI) has enhanced wind resource forecasting in terms of precision and accuracy, offering innovative approaches to renewable energy assessment (Moshtaghi et al., 2025). Developing countries like Nigeria are yet to fully explore the potential of wind energy, as they face challenges like inadequate meteorological coverage, sparse long-term data, and the limited use of advanced predictive techniques (Nkalo, 2025). The different climatic zones in Nigeria, ranging from the arid Sahelian region in the north to the humid coastal region in the south, has complex dynamics wind, which are affected due to different topography, surface roughness, and atmospheric stability (Ukoba et al., 2020). In Nigeria, statistical methods like Weibull and Rayleigh distributions are majorly utilized to characterize wind speed distributions, but they often fails to understand nonlinear spatio-temporal variations inherent in wind behaviour (Nymphas, & Teliat, 2024). The recent advancement in AI, machine learning, and deep learning techniques particularly the deep learning based Long Short-Term Memory (LSTM) networks, has improve wind energy assessments (Khan et al., 2023). Different researchers have applied the LSTM algorithms in the analysis of in modelling sequential meteorological data, and this algorithm have presented promising results.

Enhancing the LSTM with attention mechanism can improve the performance of the model by helping it to identify critical temporal dependencies and improve interpretability (Al-Selwi et al., 2024).

To build on this advancement, this paper presents a framework that integrate machine learning techniques and spatial analysis for nationwide wind energy assessment in Nigeria. The proposed framework in this study utilized the Nigerian Meteorological Agency (NiMet) meteorological datasets, and passes through a pipeline which include data collection, data preprocessing, feature engineering and model building (LSTM–Attention temporal modelling), linked with GIS-based visualization for wind farm site suitability analysis. The proposed framework form a foundation for future implementation and validation, making contribution to the broader goal of Nigeria's renewable energy transition.

Review of Related Works

The recent advancement in computational modelling and AI have significantly evolved wind energy assessment and forecasting over the past few years. The traditional statistical methods such as Weibull, Rayleigh, gamma, lognormal distributions have majorly been employed for many years (Ogunsola & Osagiede, 2018); (Audu et al., 2019); (Akpootu et al., 2022); While the Weibull and Rayleigh distributions have achieved high performance under stationary conditions, there exist a limitation in their ability to capture nonlinear and dynamic nature of wind patterns influenced by variability in climate, topographic, and tempo. Recently, different researchers have employed the machine learning and deep learning approach, which have produced promising performance, demonstrating that machine learning and deep learning approaches offers more powerful alternatives for modelling complex relationships.

Different algorithms like Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), Decision Tree (DT), Random Forests (RF), and Extreme Gradient Boosting (XGBoost), have been utilized for the prediction of wind speed and the estimation of wind energy across different geographical zones, and have produced promising results with high accuracies and precisions (Tuncar et al., 2024; Zehtabiyan-Rezaie et al., 2023). Among these algorithms are the deep learning-based algorithms, particularly LSTM networks, which has shown optimal performance when applied to handle time-dependent meteorological data. This outstanding performance is due to the model's ability to retain long-term temporal dependencies (Yassen et al., 2025).

Recent studies have tried to improve performance through the integration of attention mechanism with the LSTM algorithm, which allows the LSTM model to focus more on the relevant features within temporal sequences (Belletreche et al., 2024). The integration of attention-based mechanism with the LSTM model have achieved improved results when applied on forecasting wind speed and wind power in rich region like the United States, the United Kingdoms, and China (Mei et al., 2024; Jia et al., 2025). However, these models are developed in geographically localized area, and always depend on dense sensor networks, which are not always available in developing countries like Nigeria.

In Nigeria, research efforts on the prediction of wind speed and the estimation of wind energy have primarily focused on use of statistical or single-site analyses. For instance, researchers like Abdulkadir (2025) and, Akpaneno & Bichi (2022) used the NiMet data to estimate Weibull parameters and wind energy density in Kano, Jigawa, and Katsina, while the model dive moderate accuracy, they lacks scalability across diverse climatic regions. Similar to these studies, Audu et al. (2019) study stated that the conventional statistical approaches fail to reflect Nigeria's heterogeneous wind regimes, which are influenced by dynamics in local topography and atmosphere.

There is a growing emphasis on the development of data-driven adaptive frameworks to address these gaps which can be generalized across different climate zones. Integrating LSTM + attention mechanism with GIS-based spatial analysis can offer promising pathway toward holistic wind energy mapping in Nigeria. This frame work can both improve predictive models in terms of performance such as accuracy and precision, and also enable assessment of real-time resource and strategic planning for national renewable energy expansion.

MATERIALS AND METHODS

In this study a deep learning adaptive frame work that integrate LSTM+ attention mechanism with GIS-based spatial analysis is proposed for the prediction of wind energy potential across Nigeria's four distinct climatic zones. The proposed framework in this study introduced the meteorological data from NiMet for the training of LSTM + attention mechanism with GIS-based spatial analysis, focusing on the extraction of data-driven pattern, temporal sequence learning, and spatial visualization. Figure 1 present the conceptual workflow of the proposed framework, showing the stages involved in the proposed method.

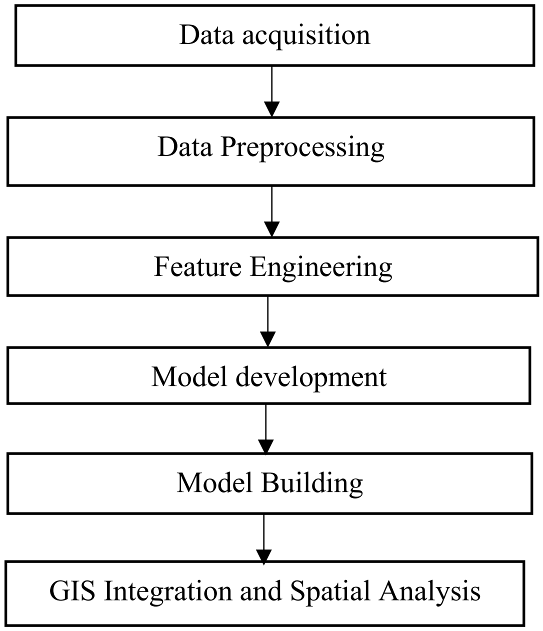

Figure 1: Proposed methodological workflow

Data Acquisition

This study proposed the utilization of the NiMet data, which contains Nigerian historical records of wind speed, wind direction, maximum temperature (T_{max}), and minimum temperature (T_{min}) across different climatic zones within the country.

Data Preprocessing

The data preprocessing phase will involve multiple stages to ensure data quality for model training. The data preprocessing stage will include the cleaning of the dataset to remove outliers, and deal with missing and incomplete values. Also normalization of temperature and wind direction data will be done, and multi-year datasets will be synchronized with the use of temporal alignment. The cleaned dataset will be divided into 70% for training, 15% for testing, and 15% for validation.

Feature Engineering

Feature engineering will be done to enhance the performance of the proposed model by computing derived features like wind components (u and v vectors), temperature range (T_{max}–T_{min}), and wind variability indices. The newly engineered features will improve the temporal learning capacity of the proposed LSTM + attention model by capturing the interactions between temperature gradients and wind flow.

Model development

The proposed model will be based on the LSTM network, enhanced with attention based mechanism. The proposed LSTM algorithm has the ability to capture long-term temporal dependencies in sequential data, and the attention layer will help the model to assigns greater weight to more influential time steps. The integration of LSTM + attention mechanism will improve interpretability and adaptability of the model to complex, and non-linear wind dynamics. The model architecture will include; Input layer (meteorological features), LSTM layers for temporal feature extraction, attention layer for feature weighting, and dense output layer for wind energy potential prediction.

Model building

After the model development, the developed LSTM + attention mechanism model will be trained on 70% of the pre-processed dataset over 20 epochs.

Model evaluation

The developed model will be evaluated to know how well the model can perform. The model will be evaluated with the use of standard evaluation matrices such as accuracy, precision, recall, and F1-scores, Additionally the model performance will be visualized with the use of confusion matrix, and accuracyand loss curves.

Baseline Comparison Using the Weibull Model

The proposed method will be compared with the two-parameter Weibull distribution, which will serve as the baseline statistical model. The Maximum Likelihood Estimation method will be utilized to estimate each of the locations for the Weibull parameters (shape and scale). The result from the LSTM–Attention model will then be used to compare that of the Weibull outputs to evaluate the expected improvement in accuracy and spatial adaptability.

GIS Integration and Spatial Analysis

The output from the proposed framework will be integrated into the Geographic Information System (GIS) environment. The Inverse Distance Weighting (IDW) which is a Spatial interpolation technique will be utilized for the visualization of the spatial distribution of wind energy potential across all the climatic zones.

Framework Validation and Expected Outcome

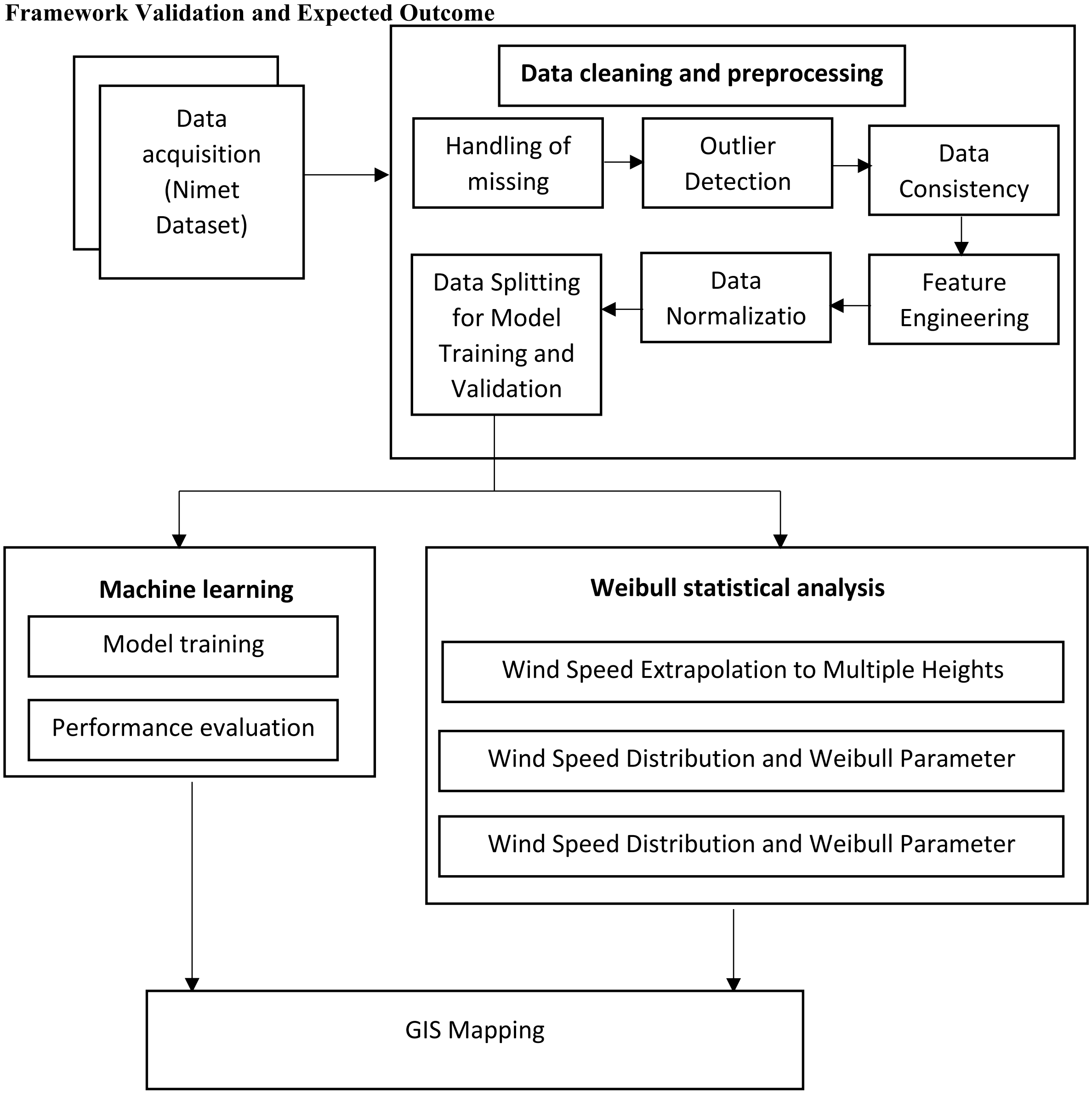

Figure 2: Proposed LSTM + attention –Based Adaptive Framework for Wind Energy Potential Assessment in Nigeria

This study proposed adaptive framework is designed to:

i. Enhance wind resource predictions accuracy as compared to the previous traditional models.
ii. Provide scalable, zone-specific insights into Nigeria's wind energy potential.
iii. Serve as a methodological guide for integrating AI-driven modelling with GIS visualization.

Once the model is implemented, model validation will be based on statistical indicators like Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) ensuring methodological rigor.

RESULTS AND DISCUSSION

The proposed framework for wind energy resource assessment present a methodological advancement for assessment of wind energy in developing countries, particularly Nigeria. The integration of LSTM enhanced with attention mechanism in the proposed framework introduces an approach that can be utilized to capture the non-linear and temporal dependencies inherent in wind patterns. The proposed framework was compared with existing framework like Belletreche et al. (2024), and Mei et al. (2024). When compared, it was observed that the proposed framework aligns with recent advancements where LSTM and attention-based deep learning models have demonstrated superior performance in wind forecasting. For instance, a study carries out by Belletreche et al. (2024) shows that hybrid attention-based networks reduced prediction errors in desert regions significantly, while another study by Mei et al. (2024) was able to achieve an improved short-term accuracy with the use of focused attention mechanisms. These existing studies were conducted environments with rich data. However, the proposed framework in this study extends the approach to a low-data, multi-climatic region like Nigeria, addressing the limitations of single-site and purely statistical studies such as Abdulkadir (2025) and Audu et al. (2019).

This framework is relevant to Nigeria, which have varies wind behaviours across different climatic zones, with current traditional statistical models like Weibull struggling to capture spatial and temporal complexities accurately. Theoretically, the proposed framework in this study addresses the gap between data-driven modelling and spatial decision-making in renewable energy planning. The framework enables pattern recognition from noisy and small meteorological datasets, by incorporating an enhanced deep learning techniques with attention mechanism to wind resource assessment. The introduction of the GIS Is to enable spatial visualization of predicted outputs, which will help in the selection of the best wind farm site based on wind potential, elevation, and infrastructural proximity. The proposed framework present a scalable methodology that can be adopted by other countries with similar climatic challenge as Nigeria.

Although the framework is still conceptual, the expected outcome is improved prediction accuracy, reduced error margins, and better representation of spatial wind variations when compared with the traditional Weibull distribution model. Studies such as Belletreche et al. (2024) and Mei et al. (2024) have shown that attention-enhanced deep learning models typically outperform statistical approaches, and similar performance gains are anticipated in the Nigerian context.

From a policy and planning perspective, the proposed hybrid framework present valuable implications which includes:

i. It will help in guiding national and regional agencies like NiMet and the energy renewal agencies in the production of high-resolution wind potential maps.
ii. It will help investors in the identification of viable wind farm sites, thereby reducing financial risk and improving success rates of projects.
iii. It aligns with the Energy Transition Plan of Nigeria and the United Nations Sustainable Development Goals (SDG 7 and SDG 13) by promoting data-driven renewable energy expansion.
iv. Although the proposed design is still conceptual, the design provides a foundational method for future empirical validation. When the design is implemented, it will support wind prediction in real-time, adaptive forecasting, and planning of grid integration. Most importantly, the proposed framework presents machine learning as a core tool that can advance Nigeria transition to a sustainable and low-carbon energy future.

CONCLUSION

In this study, a conceptual framework that adopt a machine learning based adaptive model for the assessment wind energy potential across all climatic zones in Nigeria. The framework design focused on building of a model that can understand complex, non-linear, and temporal characteristics of wind speed and direction by integrating a meteorological data from NiMet with the LSTM algorithm, enhanced with an attention mechanism incorporated into GIS for spatial visualization. The proposed framework addresses major limitation from the existing studies on Nigerian wind energy prediction which includes narrow geographic scope, utilization of simple statistical models, and inability to generalize across diverse climatic regions. Conceptually, the proposed framework shows how machine learning and GIS approaches can be utilized to improve accuracy, interpretability, and spatial adaptability in renewable energy assessment. Generally, this study contributes to the current effort on national energy sustainability by providing a scalable and replicable model that can be utilized for policy formulation, energy mapping, and infrastructure planning. The proposed methodology can help national and regional agencies like NiMet and the energy renewal agencies in the production of high-resolution wind potential maps, aligning with the Energy Transition Plan of Nigeria and the United Nations Sustainable Development Goals (SDG 7 and SDG 13) by promoting data-driven renewable energy expansion. Future work should focus on the implementation and validation of the proposed framework with the use of multi-year NiMet datasets. Additionally, future research may also utilise hybrid method like CNN-LSTM or Transformer-based models to improve spatial-temporal performance.

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