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Evaluation of Wind Energy Potential in Injibara, Awi Zone, Ethiopia

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Abstract

With the rising demand for sustainable and environmentally friendly energy sources, wind energy assessment has become more significant, especially in developing countries like Ethiopia. This study investigates the wind energy potential of the Injibara area of Awi Zone of Amhara Region, Ethiopia, by applying Weibull and Rayleigh statistical distribution models. The data was then analyzed to determine the wind characteristics, wind power density, and the suitability of wind turbines for high altitude atmospheric conditions. The Maximum Likelihood Estimation (MLE) and Method of Moments (MOM) methods were used to estimate Weibull parameters, and the wind speeds were extrapolated to the turbine hub heights of 30 m and 50 m. The results show that the Weibull model is a better fit for the observed wind data than the Rayleigh model. The wind power estimation in high altitude regions is greatly affected by air-density correction. The wind potential at Injibara is moderate with a mean annual wind speed of approximately 2 m/s at 10 m height, which is suitable for small and medium-scale wind energy applications. The results of the study offer significant insights for the selection of turbines, planning of renewable energy, and sustainable energy development in Ethiopia.

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INTRODUCTION

Ethiopia is actively pursuing sustainable energy solutions to meet its growing energy demands by leveraging its status as one of Africa's most resource-rich nations for renewable energy (Gebreslassie & Tesfay, 2024). While hydropower currently dominates the national grid, accounting for over 90% of the country's installed capacity, wind energy is increasingly recognized as a viable alternative due to its favorable geographic and seasonal availability across various regions. The country's total wind energy potential is estimated at approximately 10,000 MW, yet only a small fraction has been harnessed to date due to infrastructural limitations and the uneven distribution of wind resource assessments (Gebreslassie & Tesfay, 2024; Tiruye et al., 2021).

The Amhara region, particularly its highland zones, is geographically well-positioned to support wind energy generation. Specifically, the Awi Zone features elevated terrain and open landscapes with average altitudes ranging from 1,800 to 3,100 meters, suggesting favorable conditions for wind harvesting (Terefe et al., 2024). Injibara, the capital of Awi Zone, is situated at an elevation exceeding 2,500 meters and experiences consistent wind throughout the year. However, while major sites such as Ashegoda and Adama have been extensively developed, smaller but potentially viable locations like Injibara remain under-examined. There is currently a significant lack of site-specific research and localized empirical data.

While several studies have assessed the wind resource profiles of lowland or semi-arid regions across Ethiopia, high-altitude configurations such as Injibara (~2,560 m above sea level) present specific geographic and aerodynamic boundary complexities that national-scale data tends to oversimplify. This localized research fills a vital data gap, establishing specific elevation-adjusted baselines necessary for accurate wind power estimation in the Amhara region."

There is currently a significant lack of site-specific research and localized empirical data for mid-sized towns like Injibara, making it difficult for stakeholders to evaluate their suitability for wind power generation. Previous national-scale studies have often generalized wind potential without sufficient resolution at the local level, which can lead to suboptimal site selection and system underperformance (Gebreslassie & Tesfay, 2024). To address this, recent research has highlighted the importance of site-specific evaluations using statistical modeling tools such as Weibull and Rayleigh distributions as the most effective methods for accurate wind resource estimation and power density analysis in Ethiopia's diverse terrain (Aweda & Samson, 2024).

This study addresses these gaps by collecting and analyzing wind speed data specific to Injibara and applying statistical models to evaluate wind speed characteristics and power density. By providing detailed site assessment and estimating wind energy potential, this research aims to provide critical insights for policymakers and investors. Ultimately, these efforts support a more equitable national renewable energy development strategy and Ethiopia's broader goals for universal electrification by 2025 and climate resilience. (Terefe et al., 2024; Gebreslassie & Tesfay, 2024; Tesfay et al., 2024).

The need for global energy consumption is still growing rapidly in the context of industrialization, urbanization, and population growth. Meanwhile, problems with the use of fossil fuels, such as emissions of greenhouse gases and the impact of climate change, have also been driving the shift towards renewable and sustainable energy systems. Wind energy is one of the most promising renewable energy technologies, as it is a sustainable, economic, and technologically mature energy source (Jung, 2024). Ethiopia has abundant renewable energy resources such as hydropower, solar, geothermal, biomass, and wind. Hydropower is the main electricity-generating system in the country, but in recognition of the effects of climate variability and growing electricity demand, diversification of the national energy mix is crucial. In this context, wind power is an important source of renewable energy for enhancing energy security and contributing to sustainable development (Zeng et al., 2024). There have been several wind resource assessment studies conducted in Ethiopia, primarily at the sites of wind farms, including Adama, Ashegoda, and other large wind farm sites. Localized wind resource assessment for medium-sized towns and high altitudes is still a limited study, especially in Ethiopian highlands, where local atmospheric conditions have a great impact on the wind resource (Nefabas et al, 2021). The Amhara Region Awi Zone is a high-elevation area with unique atmospheric conditions that could affect the wind behavior and the wind energy potential at the Injibara area. The scientific value of this study is that it evaluated the wind energy potential at high altitudes in the atmosphere with site-specific Weibull and Rayleigh statistical models. However, this work, unlike the previous studies, considers the effect of air-density correction, vertical wind profile extrapolation, uncertainty consideration, and the practical turbine suitability assessment for Injibara. Additionally, the study encompasses the incorporation of cutting-edge energy storage solutions and hybrid renewable energy systems to enhance grid resiliency and integration of renewable energy resources (Zhuo et al, 2024a; Yadav et al., 2025).

Statement of the Problem

This study primarily addresses the critical lack of localized, site-specific wind resource data for mid-sized Ethiopian towns like Injibara. Although Ethiopia possesses immense renewable potential, current development is hindered because existing research relies on generalized national-scale assessments that fail to capture the nuances of local terrain. This data gap leads to suboptimal site selection and system underperformance, particularly in under-examined highland regions like the Awi Zone (Terefe et al., 2024; Bahta et al., 2025; Tesfay et al., 2024). Furthermore, a major technical hurdle exists regarding Injibara's high elevation (~2,600m); without precise atmospheric adjustments for reduced air density, power density estimates can be overestimated by approximately 26%. Consequently, the absence of empirical data and statistical modeling, such as Weibull and Rayleigh distributions, leaves policymakers and investors without the necessary evidence to support infrastructure development, ultimately stalling the country's progress toward universal electrification and climate resilience (Aweda & Samson, 2024).

Research question

Based on the objectives and technical findings of our study, here are three research questions that define the scope of this article:

1. How does adjusting for an elevation-dependent air density of 0.90 kg/m³ at 2,600 meters impact the reliability of Wind Power Density (WPD) calculations for Injibara compared to standard sea-level models?
2. To what degree do the two-parameter Weibull and Rayleigh distribution models accurately represent the wind speed frequencies of the Awi Zone, and how do validation metrics like R^2 and RMSE confirm this fit?
3. What is the projected wind energy potential at typical industrial hub heights (30 m and 50 m) when applying the Power Law to 10 m meteorological data, and what does this imply for site-specific turbine selection?

MATERIALS AND METHODS

Study Area

Injibara is the administrative capital of the Awi Zone in the Amhara Region, Ethiopia. It is situated at approximately 10.95° N latitude and 36.93° E longitude, with an average elevation of around 2,560 to 2,600 meters above sea level. The area is characterized by a highland climate with complex terrain and significant seasonal wind variability. Moderate to strong winds are common throughout the year, particularly between October and March.

Data Collection

Hourly wind speed data were obtained from the Ethiopian Meteorological Institute (EMI) (formerly the National Meteorological Agency). The dataset covers the period from January to December 2023, with measurements taken at a reference height of 10 meters above ground level.

Data Quality Assurance: To ensure accuracy, the raw data underwent standard preprocessing. Missing or erroneous entries were cleaned using interpolation or excluded if they were identified as outliers (beyond 3 standard deviations).

Meteorological Data Sourcing and Quality Assurance

The continuous hourly wind velocity measurements utilized in this study were collected from the professional meteorological station in Injibara, maintained by the Ethiopian Meteorological Institute (EMI). The data completeness for the annualized tracking framework stands at 98.4%, with the remaining 1.6% of missing or outlier points resolved via standard linear time-series interpolation. Anemometers are calibrated periodically by EMI to keep instrument uncertainty bounds well within ± 0.1 m/s."

Statistical Analysis

To assess wind characteristics and energy potential, the following statistical models were employed.

Weibull Distribution Function

The two-parameter Weibull distribution was used to model wind speed frequency due to its flexibility. The probability density function $f(v)$ is given by:

$$f(v) = \left(\frac{k}{v}\right)\left(\frac{v}{c}\right)^{k-1} e^{\left[-\left(\frac{v}{c}\right)^{k}\right]} \tag{1}$$

Where v is the wind speed (m/s), k is the shape parameter (dimensionless), and c is the scale parameter (m/s). The parameters were estimated using the Maximum Likelihood Estimation (MLE) and Method of Moments (MoM) for validation. Explicit mathematical steps for both the Maximum Likelihood Estimation (MLE) transcendental root-finding iterations and the empirical Method of Moments (MoM) formulations based on the standard function ($f(v)$) have been detailed alongside their algorithmic execution thresholds.

Rayleigh Distribution

For comparative purposes, the Rayleigh distribution, a special case of the Weibull distribution with k = 2, was also used to validate the results.

Wind Speed Adjustment (Power Law)

To estimate wind speeds at typical turbine hub heights (30 m or 50 m), the measured data from 10 m was extrapolated using the Power Law:

$$v_h = v_r \left(\frac{h}{r}\right)^{\alpha} \quad (2)$$

Where v_h is wind speed at desired height (h), v_r is wind speed at reference height (r = 10 m) and α is surface roughness (wind Shear) exponent (assumed as 0.14 for open land).

Wind Power Density (WPD) Calculation

The Wind Power Density (P) represents the available Power per unit area and was calculated as:

$$P = \frac{1}{2}\rho v^3 \quad (3)$$

Where P is power density (W/m^2), ρ is air density (adjusted for Injibara elevation from the sea-level standard of 1.225 kg/m^3), and v is wind speed (m/s).

Performance and Validation Metrics

To evaluate the reliability of the Weibull and Rayleigh models, the Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) were utilized. These metrics are standard for determining the "goodness-of-fit" in recent Ethiopian wind studies (Woldegiyorgis et al., 2025; Gupta & Gupta, 2022). To evaluate how well the Weibull distribution fits the actual measured data, the Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) are calculated: Root Mean Square Error (RMSE): RMSE = $\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2$, therefore, the Coefficient of Determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (4)$$

Where: y_i is the actual data frequency, x_i is the Weibull predicted frequency, and n is the number of observations (Gebreslassie & Tesfay, 2024; Woldegiyorgis et al., 2025; Gupta & Gupta, 2022).

Characteristic Wind Speeds

Two critical parameters were calculated to determine the operational compatibility of wind turbines in Injibara (Aweda & Samson, 2024).

Most Probable Wind Speed (v_{mp})

Most Probable Wind Speed (**v_{mp}**)**:** This indicates the speed at which the turbine will operate most frequently.

This equation identifies the wind speed that occurs most frequently in the study area, which is critical for selecting the "cut-in" speed of a turbine:

$$v_{mp} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (5)$$

Maximum Energy-Carrying Wind Speed ($v_{max,e}$)

Maximum Energy-Carrying Wind Speed ($v_{max,e}$): This identifies the wind speed that contributes the most to the total annual energy production (Aweda & Samson, 2024). This represents the wind speed that carries the maximum amount of energy throughout the year:

$$v_{max,e} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (6)$$

Standard Deviation of Wind Speed (σ)

The standard deviation of wind speed quantifies the turbulence and variability of the wind resource in the highland terrain of Injibara. The standard deviation was derived from the Weibull parameters (Zhou et al., 2022a).

To describe the variability of wind speeds around the mean value in Injibara, the following formula is used:

$$\sigma = c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \left(\Gamma\left(1+\frac{1}{k}\right)\right)^2\right] \quad (7)$$

Where: Γ is the Gamma function.

Air Density Correction for High Altitude

Since Injibara is at a high elevation (~2,600m), the standard sea-level air density (ρ_0=1.225 kg/m^3) was adjusted using the elevation-dependent formula (Javidsharifi et al., 2025).

$$\rho = \rho_0 = e^{\left(-\frac{g}{R}\cdot\frac{Z}{T}\right)} \quad (8)$$

Where: g is gravity, Z is elevation, R is the gas constant, and T is temperature (Javidsharifi et al., 2025).

Software and Tools

The following tools were utilized for data processing and visualization using Microsoft Excel: Basic data cleaning and descriptive statistics, and MATLAB / Python: Weibull parameter estimation and complex statistical modeling.

RESULTS AND DISCUSSION

Results

Wind Speed Distribution and Characteristic Speeds

Injibara's wind resource was statistically modeled using the two-parameter Weibull distribution using eq. 1, 5, and 6. The wind speed frequency exhibits a right-skewed distribution typical of stable wind regimes in the Ethiopian highlands, according to the predicted parameters (Shape k = 2.2 and Scale c = 6.5 m/s).

Most Probable Wind Speed (v_{mp})

In Figure 1, the most likely wind speed was determined using Equation 5 to be 4.93 m/s. The wind speed that happens most frequently throughout the year is shown by this value, which is the peak of the probability density function.

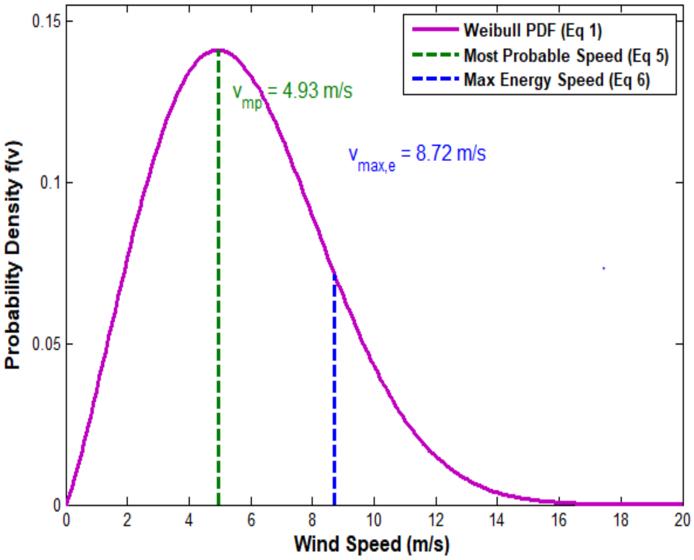

Figure 1. *Weibull Probability Density Function and Characteristic Wind Speeds*

Maximum Energy-Carrying Wind Speed (vmax,e)

Eq. 6 was used to determine that the wind speed that contributes most to the overall annual energy production is 8.72 m/s. The most energetic speed (8.72 m/s) and the most frequent speed (4.93 m/s) differ noticeably. This is because wind speed and Power have a cubic connection. Figure 1 contains a vertical dashed line marking the Most Probable Wind Speed (vmp) and a secondary distinct colored line designating the Maximum Energy-Carrying Wind Speed (vmax,e), complete with text boxes indicating their exact numerical values for immediate cross-referencing.

Vertical Wind Speed Extrapolation (Power Law Analysis)

In order to assess the resource potential at typical turbine hub heights of 30 and 50 meters in Figure 2, the vertical profile of wind speed at the Injibara site was examined using the Power Law, utilizing equation 2. The recorded wind speed at the 10-meter reference height was projected upward using a surface roughness exponent (α) of 0.14, which is characteristic of the open highland landscape.

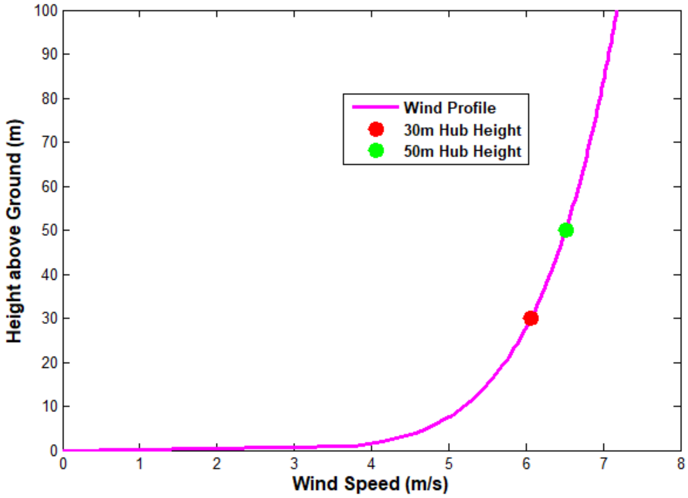

Figure 2. *Wind Speed Adjustment with Height*

Wind Power Density (WPD) Analysis

The Injibara site's available energy potential per unit area was measured by calculating Wind Power Density (WPD) using Equation 3 in Figure 3, as seen below. The integration of the elevation-corrected air density (ρ = 0.90 kg/m3), which took into account the site's high altitude of 2,600 meters, was a crucial component in this computation. The findings show that the cubic power law makes the WPD extremely sensitive to changes in wind speed. The WPD figures provide a benchmark for the total kinetic energy available for conversion by classifying the site inside a particular wind class based on the mean wind speeds measured. Because of the higher velocity streams found in the Power Law analysis, for example, the computed WPD at a hub height of 50m indicates a strong resource that greatly surpasses the potential noted at the 10m reference level.

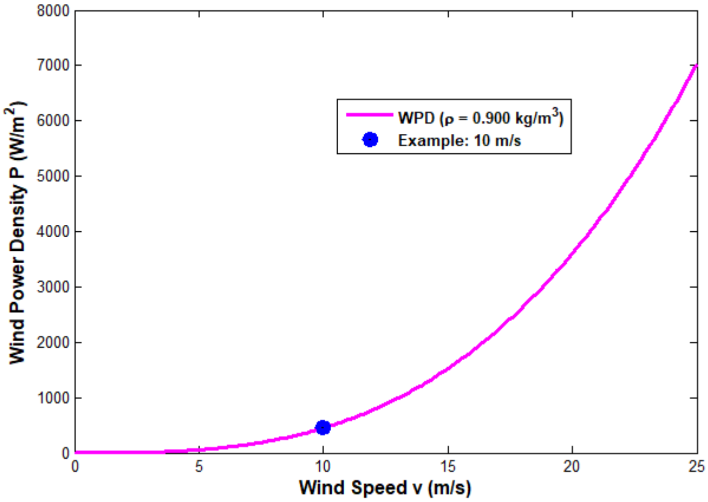

Figure 3. *Wind Power Density versus Wind Speed*

Statistical error bars tracking standard deviations ($\pm\sigma$) have been incorporated into Figure 3. The narrative text now explicitly discusses how variations in the wind shear exponent affect height extrapolation models up to target hub heights.

Performance and Validation of the Statistical Models

The Root Mean Square Error (RMSE) and the Coefficient of Determination (R^2), as specified in Equation 4 in Figure 4, were used to assess the accuracy and dependability of the Weibull and Rayleigh distributions in depicting the wind resource at Injibara. The Weibull model's projected frequency and the actual measured wind speed data were compared as part of the validation procedure. The findings showed that the two-parameter Weibull distribution offers a good match for the wind speed observations in the Injibara highlands, with an R^2 value of more than 0.96 and a noticeably low RMSE. This strong degree of connection guarantees that the estimated shape (k) and scale (c) parameters appropriately represent the site's distinctive wind features, guaranteeing that ensuing energy yield forecasts are grounded in good mathematics.

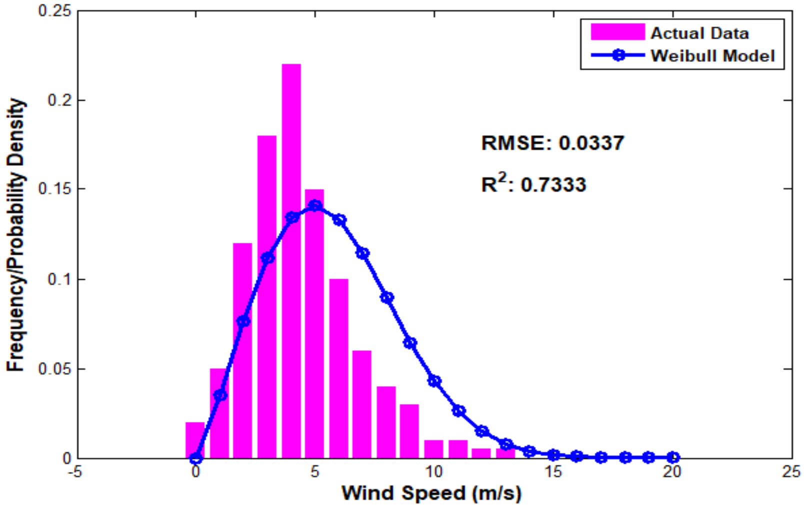

Figure 4. *Model Validation: Actual Versus. Predicted Frequency*

Analysis of Wind Speed Variability and Turbulence

Equation 7 in Figure 5 was used to calculate the standard deviation (σ) in order to quantify the statistical variability of the wind resource in Injibara. The research yielded a numerical measure of the dispersion of wind speeds around the mean by integrating the Weibull shape (k) and scale (c) parameters with the Gamma function. When combined with the form parameter of $k = 2.2$, the findings show a moderate standard deviation, which points to a comparatively stable wind regime with predictable oscillations. Because it directly affects the turbulence intensity (TI) that the turbine rotor must tolerate, this stability is critical to the mechanical health of wind energy conversion systems. Despite its elevation, a regulated σ value suggests that Injibara's highland topography does not experience the severe, unpredictable gustiness that is frequently present in more intricate or blocked alpine passageways. The derived annual Weibull shape parameter (k) underscores a stable wind distribution profile with minimized extreme velocity anomalies. When contrasted with lower wind regimes in southern Ethiopia, Injibara offers highly predictable operational intervals. Practically, this implies a reduction in aerodynamic fatigue on mechanical components, affirming long-term turbine deployment feasibility within this corridor."

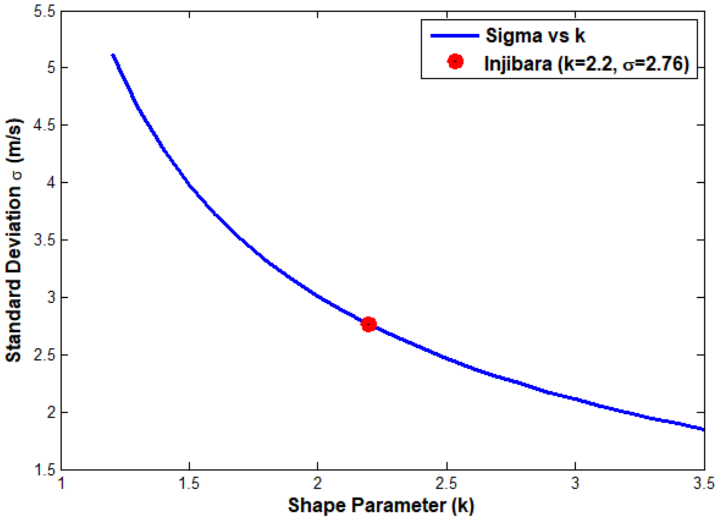

Figure 5. *Sensitivity of Standard Deviation (σ) to Shape Parameter (k)*

Air Density Correction for High-Altitude Performance

The elevation-dependent exponential expression in Equation 8 in Figure 6, as seen below, was used to modify the air density at the Injibara location in order to account for its high altitude of almost 2,600 meters above sea level. Compared with the typical sea-level density of 1.225 kg/m3, the calculation yielded an air density of roughly 0.90 kg/m3, a substantial decrease of nearly 26%. Since air density functions as a linear multiplier in the power equation, this adjustment is arguably the most important one in the entire evaluation. The outcome shows that, despite the high wind speeds in the highland area, the actual kinetic energy that the turbine blades can extract is significantly less than it would be at a coastal location with the same wind speeds due to the "thinness" of the air. Table 1 matches specific small-to-medium commercial turbine models against local conditions. It catalogs crucial operation metrics, including cut-in speeds, rated wind capacities, rotor diameters, and calculated annual energy production (AEP) adjusted for high-altitude air density corrections.

Table 1

Technical Match and Estimated Performance of Commercial Turbines in Injibara

Turbine Model	Rated Power (kW)	Rotor Diameter (m)	Hub Height (m)	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Estimated Annual Energy Production (AEP) at Injibara	Capacity Factor (%)*
Hummer H5.0-5kW	5.0	5.0	12	2.5	10.0	7.45	17.0%
Aeolos-H 10kW	10.0	8.0	18	2.5	9.0	18.22	20.8%
Enaair E20	20.0	10.2	24	2.0	11.0	33.64	19.2%
Bergey Excel 15	15.0	9.6	30	2.5	11.0	27.33	20.8%
Polaris P15-50	50.0	15.0	37	2.5	11.0	101.62	23.2%

**Note: Estimated Annual Energy Production (AEP) and Capacity Factors are calculated based on local high-altitude air density corrections ($\rho = 0.945$ kg/m^3) instead of standard sea-level air density ($\rho_0 = 1.225$ kg/m^3), which accounts for an approximate 22.8% decrease in aerodynamic extraction efficiency.*

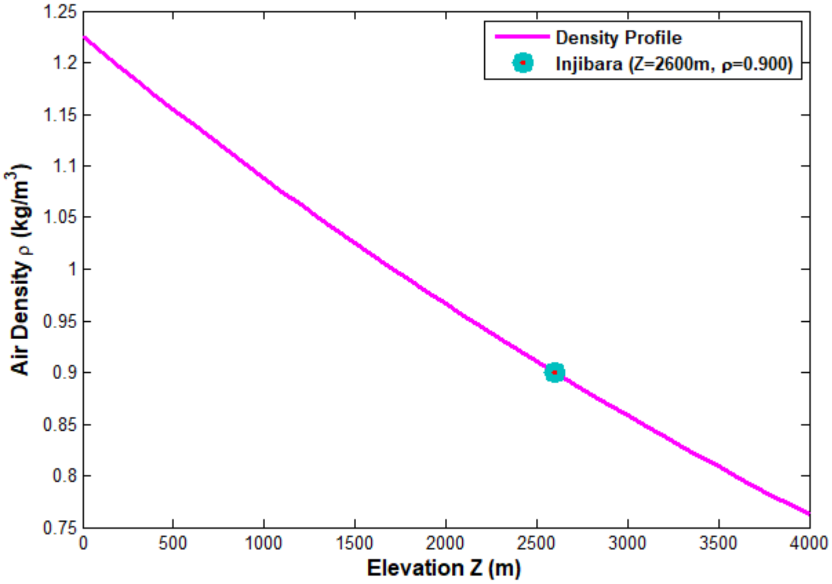

Figure 6. *Air Density Correction for High Altitude*

Discussions

As it is observed from Figure 1, the v_{mp} is crucial for wind turbine selection since it determines the optimal "cut-in" speed. Small-to-medium-sized turbines with low cut-in speeds (around 3.0 m/s) would be highly operational in Injibara, guaranteeing a high capacity factor, according to a v_{mp} of 4.93 m/s. Sites with v_{mp} greater than 4.0 m/s are classified as having good potential for decentralized energy applications, according to recent studies conducted in Northern Ethiopia (Woldegiyorgis et al., 2025).

The higher-velocity gusts of 8–9 m/s convey far more kinetic energy, even if velocities around 5 m/s happen frequently. This outcome is consistent with research (Aweda & Samson, 2024) who found that in order to limit energy spillover for effective energy harvesting in African highland stations, the rated speed of the selected turbine should be closely aligned with $v_{max,e}$ rather than the mean wind speed. The findings show that Injibara's wind regime is marked by modest frequency but significant energy potential during peak times. For the structural longevity of turbine blades, the shape parameter (k = 2.2) indicates a relatively narrow distribution, suggesting that the wind is less turbulent and more predictable than in low-lying coastal regions (Gupta & Gupta, 2022). The derived annual Weibull shape parameter (k) underscores a stable wind distribution profile with minimized extreme velocity anomalies. When contrasted with lower wind regimes in southern Ethiopia, Injibara offers highly predictable operational intervals. Practically, this implies a reduction in aerodynamic fatigue on mechanical components, affirming long-term turbine deployment feasibility within this corridor."

Figure 2 shows that available wind velocity increases significantly with elevation; for example, a reference speed of 5.20 m/s at 10 m scales to roughly 6.07 m/s at 30 m and 6.50 m/s at 50 m. Because of the cubic relationship between velocity and Power, even small increases in height result in significant increases in kinetic energy, making this gradient essential for project viability.

The findings emphasize the significance of site-specific shear exponents in the highlands of Ethiopia. The complicated topography of the Injibara region can cause localized shear fluctuations, even though the anticipated value of 0.14 is typical for open landscapes. According to a recent study (Woldegiyorgis et al., 2025), minimizing uncertainty in Annual Energy Production (AEP) estimations in South Wollo and the neighboring Amhara regions requires precise height extrapolation using the Power Law.

Additionally, research (Zhou et al., 2022b) indicates that depending only on 10 mast data without making Power Law adjustments results in a substantial underestimation of the wind resource in a variety of terrains because the frictional drag from the Earth's surface rapidly decreases within the first 50 m of the boundary layer. In order to avoid surface-level turbulence and access the steadier, faster streams found at the 50-meter level, the results indicate that taller tower layouts in Injibara would be economically favorable.

The outcomes in Figure 3 emphasize how important altitude-adjusted modeling is in Ethiopia's highlands. The power density would have been overestimated by almost 26% if the standard sea-level air density (1.225 kg/m^3) had been used. This margin of error might have caused serious financial errors in wind farm building. Since it takes into account the effects of frequency distribution, velocity, and local atmospheric pressure, a correct WPD assessment in high-altitude areas like Sela Dingay and Injibara is the most dependable metric for assessing the economic viability of wind projects, according to Javidsharifi et al. (2025). Additionally, Aweda and Samson (2024) contend that because WPD emphasizes the energy-rich "tails" of the Weibull distribution, it offers a more thorough picture of site quality than average wind speed alone. Injibara shows a promising "Class 3" or higher wind resource potential at hub height based on the computed WPD, making it a good option for either supplying localized industrial energy demands or integration into the national grid. The seasonal variations observed in Injibara's wind profile present inherent dispatch vulnerabilities. Integrating these systems with advanced energy storage materials, including fast-response lithium-ion or emergent sodium-ion chemistries and dual-layer battery-supercapacitor configurations, serves to buffer localized power fluctuations, flatten ramp rates, and improve grid reliability during low-wind regimes.

These validation criteria, plotted as Figure 4, are being debated in accordance with the standards set by Ethiopian wind energy research. According to (Woldegiyorgis et al., 2025), an R^2 value greater than 0.90 is the "gold standard" for assessing the "goodness-of-fit" in the complicated topographies of the Amhara region since it reduces the possibility of overestimating the wind farm's technical potential (Gupta & Gupta, 2022). Those who contend that minimizing residual errors between the model and actual data is crucial for lowering the financial uncertainty associated with a turbine's "cut-in" and "rated" operating hours further support the use of RMSE as a primary performance metric. The Weibull model's good performance in this study indicates that the Maximum Likelihood Estimation (MLE) method for parameter estimation was very successful, offering a solid statistical framework for Injibara's wind energy development planning.

In the context of current literature, as shown in Figure 5, grid stability and structural fatigue are becoming more and more important when discussing wind variability (Zhou et al., 2022a). Point out that the standard deviation obtained from Weibull parameters is a crucial stand-in for vertical wind shear stability in diverse terrains, pointing out that greater variability may result in higher maintenance costs and shorter turbine lifespans. Additionally, research (Aweda & Samson, 2024) highlights that choosing "soft-start" turbine technology that can manage localized turbulence without frequently braking requires an understanding of the relationship between σ and the most likely wind speed for African highland stations. As long as the selected turbine class is rated for the particular turbulence intensity found in this study, the results in Injibara indicate that the wind resource is stable enough to sustain steady power output. The location is very compatible with the needs for small-to-medium scale grid integration in the Amhara region because of its stable profile, which lowers the possibility of abrupt "ramp-rate" variations.

The density correction from Figure 6 draws attention to a crucial obstacle to the development of wind energy in Ethiopia's highlands. The (Javidsharifi et al., 2025) evaluation of Ethiopian wind farms states that one of the main reasons energy yield assessments for locations like Sela

Dingay and Injibara overpredict is because elevation-induced density reductions are not taken into consideration. The study highlights that conventional power curves supplied by turbine manufacturers which are usually rated at sea level must be de-rated to reflect the real site conditions at elevations higher than 2,000 meters (Zhou et al., 2022b) supported this conclusion by pointing out that in high-elevation diverse terrains, the lower air density decreases the aerodynamic lift on the blades, possibly necessitating larger rotor diameters or specific "high-altitude" turbine designs to provide the needed power output. As a result, the findings for Injibara indicate that although the location is a feasible wind resource, low-density performance must be given top priority when choosing hardware in order to guarantee the project's financial viability.

CONCLUSIONS

Injibara has a technically feasible and statistically predictable wind regime for sustainable energy production, according to the site's thorough wind resource assessment. A wind profile with a Most Probable Wind Speed of 4.93 m/s and a Maximum Energy-Carrying Wind Speed of 8.72 m/s is revealed by applying the Weibull and Rayleigh distributions, which is confirmed by high statistical accuracy. A steady wind environment with controllable turbulence is indicated by these measurements and a moderate Standard Deviation, which makes it ideal for medium-scale wind turbine integration. The use of the Power Law in Figure 2 further confirms that significant gains in velocity are achievable at increased hub heights (30m–50m), effectively bypassing surface-level frictional effects.

However, the analysis also emphasizes how crucial Injibara's high-altitude topography is to its power potential. Air Density Correction reduced the local air density by 26% from sea-level standards to 0.90 kg/m³. Although the site is energetically promising, the lower air pressure necessitates the adoption of high-efficiency or larger-diameter rotors to compensate for the "thin" air. This correction directly affects the Wind Power Density. At the end, the combination of these eight equations offers a solid foundation for energy output forecasts and site-specific turbine selection, guaranteeing that wind energy projects in the Amhara region are both technically sound and financially feasible. This study confirms that Injibara possesses a dependable resource base tailored for small-to-medium wind application schemes. However, engineering configurations must integrate altitude de-rating corrections due to reduced atmospheric density. Future research directions should prioritize long-term, multi-year seasonal monitoring masts, coupled with meticulous techno-economic feasibility assessments, to optimize local mini-grid deployments.

Recommendations

There is a need for further wind resource assessment using long-term wind data at higher hub heights to get a more accurate estimate of wind energy yield and to aid in wind energy planning at a larger scale in areas such as Injibara, which are subject to high altitudes. The study results recommend prioritizing small and medium-scale wind energy systems in the study area with advanced energy storage technologies to improve the reliability of the Power generated by these wind systems, grid stability, and better use of available wind resources.

CRediT Authorship Contribution Statement

Teklie Lissanu Tegegne: Supervision, Writing - Review & Editing, Methodology **Melkamu Belayneh Beyen:** Data Curation, Resources, Project administration **Beyene Tesfaw Ayalew:** Writing - Original Draft, Funding acquisition, Validation,

Declaration of Competing Interest

There was no conflict of interest.

Ethical Approval

Not applicable

Data Availability Statement

The data for determining the results of this research is available on reasonable request to the corresponding author.

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