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Research Article

Technical and Economic Feasibility Assessment of a Mini Wind Turbine Using Statistical Method for Sustainable Urban Energy: A Case Study of Zvishavane Urban, Zimbabwe

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Abstract

Unreliable electricity supply remains a significant barrier to economic development in sub-Saharan Africa, with Zimbabwe experiencing acute load-shedding that disrupts residential, commercial, and industrial activity. This paper presents a techno-economic feasibility assessment of a mini wind turbine for distributed urban energy generation in Zvishavane, Zimbabwe. Wind resource data were sourced from two independent platforms Weather Spark (30-year climatological record) and Meteoblue (high-resolution reanalysis) and analysed using both direct calculation and the Rayleigh statistical distribution model applied to monthly bin-frequency data at a measurement height of 10 m above ground level. Mean wind speeds at the measurement height range from 3.31 m/s (May) to 5.03 m/s (October), placing the site in the low wind power density class (Class 1: P/A ≤ 100 W/m^2) under direct assessment. Application of the Rayleigh probability density function yields substantially higher mean power density estimates, a minimum of 78.98 W/m^2 and a maximum of 277.15 W/m^2, elevating the site into the fair-to-moderate resource class (150-200 W/m^2). Boundary layer wind profile analysis using the logarithmic law indicates that the rated cut-in speed of 5 m/s is achievable at a minimum tower height of 27 m, while a tower of 63 m achieves the low-category power density threshold, both technically practicable. An annual energy production of 438-683 kWh/year is estimated for a representative 400 W rated mini turbine, yielding a levelised cost of energy (LCOE) of USD 0.143-0.224/kWh. At the grid-equivalent avoided cost of USD 0.10-0.15/kWh and with realistic capital expenditure assumptions, the simple payback period ranges from 8 to 14 years, which improves to 5-8 years under preferential financing conditions. The study demonstrates that, while Zvishavane is not a premium wind resource site, targeted turbine deployment at optimised tower heights is technically viable and approaches economic competitiveness under current tariff and financing conditions, particularly as an energy resilience measure against chronic grid outages.

Keywords
Renewable energy; sustainable energy; wind turbines; wind resource

1. Introduction

The global landscape is rapidly evolving in the face of escalating climate change and the urgent need for sustainable energy solutions [1]. The transition from fossil fuels to renewable energy sources is not merely a choice but an imperative for the health of our planet and future generations. Among the various renewable energy sources, wind energy stands out as one of the cleanest options available [2]. However, traditional wind energy solutions have focused mainly on large-scale turbines situated in remote areas, often out of reach for everyday consumers and small-scale users [3, 4]. This study aims to tackle the demand for sustainable energy solutions by developing an efficient mini wind turbine. It focuses on a mountainous region with high wind potential to optimise the use of under-utilised wind resources. By enabling residential homes, small businesses, farms, and public infrastructure to generate clean energy, the research seeks to lessen reliance on centralised power grids and fossil fuels as per the Sustainable Development Goals [5]. The study promotes energy independence and sustainability in areas with favorable wind conditions. Wind energy is one of the most cost-effective renewable technologies currently.

Although solar energy costs have decreased over time, it’s still more expensive than wind energy. It has been established that the levelized cost of energy (LCOE) for solar power ranges from $0.13 to $0.24/kWh, while wind energy costs between $0.08 and $0.20/kWh. In that line, a solar farm requires a large land area to generate significant amounts of electricity. In contrast, wind turbines have a smaller land footprint and can be used for small-scale residential regions and farming [6, 7]. Beyond urban environments, mini wind turbines are equally suited for rural and remote areas where access to reliable energy may be limited. Its compact design and cost-effectiveness make it an attractive option for farms, businesses, and public infrastructure, promoting energy independence and reducing reliance on traditional power grids [8]. Keeping small-scale applications in mind, the turbine provides a practical solution for meeting renewable energy demands, reducing costs for individuals and communities while promoting a global shift towards greener technologies.

This paper makes three key contributions. Firstly, it provides an accurately documented wind resource assessment using multi-source climatological data and two different methods of analysis.

This provides the missing methodological traceability in many regional assessments. Secondly, it uses logarithmic boundary layer analysis to establish minimum tower heights; and thirdly, it calculates a site-specific economic assessment based on AEP, LCOE and payback with explicit assumptions-a specific addition required to fill the lack of quantitative economic information about the viability of small wind within the literature and the development country context. The paper is arranged as follows: Introduction (1), Related Literature (2), Economic Assessment of Small Wind Turbines (3), Methods for Establishing Wind Resource (4), The Statistical Analysis (5), Data Collection, Results, and Analysis (6), Economic Feasibility Assessment (7), Discussion (8), and Conclusions (9).

2. Related Literature on Wind Energy Resource

The global transition to renewable energy is accelerating, driven by the need to reduce greenhouse gas emissions, combat climate change, meet the Global Sustainable Development Goals, and decrease dependence on fossil fuels [9, 10]. Wind energy, as one of the fastest-growing renewable energy sources, has seen significant advancements in both large-scale and small-scale applications. However, small-scale wind turbines, particularly mini wind turbines for distributed power generation, remain under-researched compared to their larger counterparts [11, 12]. Small wind turbines, typically defined as systems rated below 100 kW, and mini turbines rated below 1 kW, have seen substantial technical development over the past two decades, driven by advances in permanent magnet generator design, composite blade materials, and power electronics.

3. Economic Assessment of Small Wind Turbines

The economic viability of small wind turbine installations is determined by the interaction of capital cost (CAPEX), operational and maintenance cost (OPEX), annual energy production (determined by the wind resource and turbine performance), the avoided cost of energy from alternative supply (grid tariff or diesel generation cost), discount rate, and applicable financing conditions [13]. The levelised cost of energy (LCOE) provides a single metric that captures all of these factors across the turbine's operating life, enabling direct comparison with alternative supply options [14, 15]. Drew et al. [16] demonstrate that LCOE calculations for small wind turbines are particularly sensitive to wind resource uncertainty, with errors of as little as 10% in mean wind speed translating into errors of approximately 30% in estimated annual energy production and corresponding LCOE impacts. This sensitivity makes accurate, site-specific resource assessment an economic as well as a technical imperative.

A statistical analysis of observational wind data with techno-economic evaluation was done for a small wind turbine in Maryland. The results show that a small-scale wind turbine achieved 11% capacity factor, 1990 kWh/year, and a 13-year payback period. With government incentives improving economic feasibility [13, 17]. Small Urban Wind Turbines (SUWTs) can mitigate climate change by reducing local carbon emissions and energy losses; nevertheless, their performance highly depends on the urban system and installation location [14]. Small-scale wind turbines have low capital costs and maintenance requirements, making them economically viable for urban settings. However, theoretical and real-world performance discrepancies need further investigation [15]. The economic viability of small wind turbines is highly sensitive to accurate, site-specific wind measurements [16]. A review of the research was done by Ojo et al. [17]. The authors highlighted future work on small wind turbines and recommended how to bridge the adoption gaps. The gap between rated and actual performance is a central challenge for urban SUWT deployment and underscores the importance of rigorous site-specific resource assessment rather than reliance on generic performance data.

Key factors affecting the feasibility of wind turbine adoption are summarized in Table 1 below.

Table 1 Key factors affecting wind turbine adoption.

Factor category	Examples impacting feasibility
Location	Terrain, wind speed, turbulence, elevation, accessibility of site [18, 19].
Policy	National energy policy, licensing procedures, land-use regulations, environmental impact assessments, taxes and levies, import duties on equipment, availability of government financing, net metering policies [18, 20, 21].
Technical	Turbine technology, efficiency, grid compatibility, energy storage and integration, installation, maintenance [18, 22, 23].
Economic	Operations and maintenance, capital, finances, cost of grid connection, pricing, feed-in tariffs, payback period [18, 24].
Social	Public awareness, education, community acceptance, job creation, noise, and visual aspects [20, 25, 26].
Environmental	Impact on wildlife, pollution [22, 27].

Significant gaps exist between theoretical performance data and the real-world operation of small-scale wind turbines; therefore, further research and designs are required to bridge this gap [28]. Recent research noted a need for more studies on integrating wind turbines with building designs to optimize power generation and minimize aesthetic and noise impact [29]. Research on advanced materials and innovative design techniques to improve wind turbines' durability and efficiency is still ongoing [29].

This paper seeks to bridge the literature gaps from the existing research by designing, optimizing, and implementing a small-scale wind turbine, focusing on assessing its potential for distributed energy generation in urban and rural environments. The first critical aspect is assessing the availability of the wind resources [30]. The air's speed determines the wind's strength and is directly related to its kinetic energy. These winds can be categorised based on their spatial scale and the mechanisms that generate them [31]. The fundamental principle behind wind energy conversion is relatively simple. As wind passes through the rotor of a wind turbine, its kinetic energy is captured and converted into mechanical energy, which can then be converted into electrical energy by an alternator [32]. The power available in the wind is proportional to the cube of the wind speed and the area swept by the turbine [32]. This relationship underscores the importance of accurate wind resource assessment in turbine design and site selection.

To determine the productivity (maximum energy potential and machine power output) of a given wind turbine at a specific site, wind speed information is assumed in either a time series format or a summary format (e.g., average wind speed, standard deviation). The power available from wind, Manwell et al. [33], is given by

$$Wind\ Power, P = \frac{1}{2}\rho A V^3 \tag{1}$$

Where: ρ is mass density, A is the area swept by the rotor (area perpendicular to the flow of the wind), and V is the mean velocity of the wind.

$$Wind\ Power\ Density = \frac{P}{A} = \frac{1}{2}\rho V^3 \tag{2}$$

The equation shows that the power in wind is proportional to the density, which can be taken as 1.225 kg/m^3 a standard value at sea level. However, when the actual density value is to be used, thermodynamics studies show that air density depends on pressure and temperature, and both temperature and pressure are in turn affected by the vertical height into the atmosphere from the ground. A possible model for calculating this density is to apply the ideal gas equation of state.

$$Air\ Density, \rho = \frac{P}{RT} \tag{3}$$

Where: ρ is density in kg/m^3, P is the atmospheric pressure in N/m^2, R is the specific gas constant for air in J/kg K, and T is the absolute temperature in K.

The pressure variation with height up to a maximum of 5000 m is given by [33].

$$Atmospheric\ Pressure, P = 101.29 - 0.011837z + 4.793 \times 10^{-7} z^2 \tag{4}$$

Where: z is height from sea level/typically the ground in meters, and P is pressure in kPa. The temperature is given by the Temperature Lapse Rate and derived using thermodynamic equations and assumptions.

$$\left(\frac{dT}{dz}\right)_{adaibatic} = \frac{g}{c_p} = -0.0098°\mathrm{C}/m \tag{5}$$

Where: g is the acceleration due to gravity = 9.81 m/s^2 and c_p is the specific heat capacity of atmospheric air = 1.005 kJ/kg. The value is also stated as a constant of -1°C per 100 m. What also has to be accounted for is the variation of the wind velocity with height, since measurements give wind velocity on the ground or at a known height from the ground, and turbine towers are mounted at a significant height above ground. Manwell et al. [33] further showed that the mean wind speed increases with height, which defines the phenomenon called wind shear. Additionally, it is stated in Manwell et al. [33] that rotor blade fatigue life will be influenced by the cyclic loads resulting from rotation through a wind field that varies in the vertical direction. Thus, a model of the wind speed variation with height is required in wind energy applications. The mathematical models include those derived from boundary layer flow. The models used in wind energy studies to profile the variation include the logarithmic profile (Log law) and the Power Law profile [33, 34].

The log Law equation is

$$\frac{V(z)}{V(z_r)} = \frac{ln\left(\frac{z}{z_0}\right)}{ln\left(\frac{z_r}{z_0}\right)} \tag{6}$$

The power law profile equation is

$$\frac{V(z)}{V(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{7}$$

$V(z)$ is the velocity at height z, $V(z_r)$ is the velocity at reference height z_r, and z_0 is the surface roughness of the terrain, α is a power law exponent. It has been observed that the power law exponent varies based on factors like elevation, time, season, terrain, wind speed, temperature, and mixing factors. Some researchers have developed methods to calculate the power law exponent using the log law parameters. However, many think these complex methods reduce the simplicity of the power law. They argue that wind energy experts should accept the empirical nature of the power law and select a value of the power law exponent that best fits the available wind data. The review below quotes common empirical formulae developed to determine representative power law exponents [34].

Power law exponent, as a function of velocity and height

$$\alpha = \frac{0.37 - 0.088 ln V_{ref}}{1 - 0.088 ln\left(\frac{Z_{ref}}{10}\right)} \tag{8}$$

Power law exponent as a function of surface roughness,

$$\alpha = log_{10} z_0 + 0.016(log_{10} z_0)^2 + 0.24 \tag{9}$$

Table 2 below shows the roughness of the surface for different terrains.

Table 2 Approximate surface roughness lengths for various types of terrain.

Terrain Description	z_0 (mm)
Very smooth, ice or mud	0.01
Calm open sea	0.20
Blown sea	0.50
Snow surface	3.00
Lawn grass	8.00
Rough pasture	10.00
Fallow field	30.00
Crops	50.00
Few trees	100.00
Many trees, hedges, and a few buildings	250.00
Forest and woodlands	500.00
Suburbs	1500.00
Centers of cities with tall buildings	3000.00

Qualitative values of wind power density evaluations are categorised as follows [33, 34]:

$$Class\ 1: \frac{P}{A} \leq 100W/m^2\ is\ low$$

$$Class\ 2: \frac{P}{A} \approx 400W/m^2\ is\ good$$

$$Class\ 3: \frac{P}{A} > 700W/m^2\ is\ Excellent, great$$

4. Methods for Establishing Wind Resource

Zvishavane is located in the Midlands Province of Zimbabwe, at approximately 20° S, 30° E, and 1,000 m a.s.l. The terrain consists of rolling hills and individual kopjes situated on the Midlands greenstone belt, resulting in localized channeling. The terrain type is suburban, and the surface roughness length, z, is 1,500 mm. The value of z was used for all boundary layer calculations. The dominant wind direction is from the south-east, thus limiting cyclic yaw loads and reducing fatigue stress on the turbine. Various methodologies exist for understanding wind resources at a specific location, and the method of gathering on-site measured wind data. One can use state wind maps to conservatively estimate the wind resource at turbine hub height. These maps can provide a general indication of whether the wind resources are good or poor, but they lack the resolution necessary to identify local site features such as complex terrain, ground cover, wind speed distribution, direction distribution, turbulence intensity, and other regional effects. Additionally, the local airport or weather station method can offer local wind data, but this data may be less reliable than actual site data because the airport and weather stations are usually far from the site [35].

Two sources of 10 m a.g.l. Mean monthly wind speed data were accessed from Weather Spark, which retrieves 30-year average climate information from the global reanalysis ERA5, and Meteoblue, which retrieves a simulated historical climate from the NOAA CFSR mesoscale model at ~30 km spatial resolution. Two separate data streams can help bound the error introduced by the lack of an anemometer on site. The data from both sources were complete for all 12 months and did not necessitate imputation. 10 m reference height measurements conform to the WMO-recommended measurement height.

Two approaches, which are mutually supplementing, were used. The direct (bin) method of wind speed and power density from Meteoblue frequency distribution over five speed-bins (center of bins: 7.5, 15, 25, 35, 45 km/hr) assumes N is the calendar days per month, so as to generate empirically reference independent of distribution form. Rayleigh PDF (Weibull k = 2) with monthly mean wind speed as parameter was used, selected because:

(a) Mean wind speed data are only available from reanalysis products,

(b) k = 2 gives fair estimates of accuracy on feasibility studies in a similar situation [33].

Power and wind profile was described by the logarithmic law, rather than the power law, as more theoretically sound and representative of the flow within the boundary layer. Economic analysis using standard LCOE formulation with detailed CAPEX, and also AEP calculations, sensitivity analysis, and avoided cost benchmarks comparison.

The following methods can summarize the wind speed,

(a) Direct use of data taken and averaged over a short interval of time.

(b) Methods of bins/Grouped data.

(c) Statistical analysis using summary measures.

Methods (a) and (b) produce summary measures or parameters that can be used on (c).

The direct method generates a series of N wind speed observations, V_i, each averaged over the time interval Δt.

The long-term average wind speed, $\bar{V}$ over the time interval

$$\bar{V} = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{10}$$

The average wind speed standard deviation

$$\sigma_v = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_1 - \bar{V})^2} = \sqrt{\frac{1}{N-1}\left\{\sum_{i=1}^{N} {V_i}^2 - N\bar{V}^2\right\}} \tag{11}$$

The average wind power density, $\bar{P}/A$ is the average available wind power per unit area and is given by:

$$\frac{\bar{P}}{A} = \frac{1}{2}\rho\frac{1}{N}\sum_{i=1}^{N} {V_i}^3 \tag{12}$$

With the average velocity, the average wind machine power $\overline{P_w}$ can be obtained from

$$\overline{P_w} = \frac{1}{N}\sum_{i=1}^{N} P_w(V_i) \tag{13}$$

with $P_w(V_i)$ calculated using the Betz limit discussed below, or read from the wind machine power curve.

The maximum power a turbine can extract is limited by the Betz limit, which says that no wind turbine can extract more than 53.9% of the available wind power [33]. The equation that governs the power P generated is

$$P = \frac{1}{2}\rho\eta C_p A\bar{V}^3 \tag{14}$$

Where: P is the power in watts (W), ρ is the air density (typically around 1.225 kg/m^3 at sea level), A is the swept area of the turbine (in square meters), η is the drive train efficiency (generator power/rotor power), V is the average wind velocity (in meters per second), C_p is the rotor power coefficient, representing the efficiency of the turbine in capturing wind energy (Betz limit restricts this to a maximum of 59.3% or $\frac{16}{27}$ from [33, 34].

The rotor power coefficient,

$$C_p = \frac{Rotor\ Power}{Power\ available\ in\ wind} = \frac{P_{rotor}}{\frac{1}{2}\rho A V^3} \tag{15}$$

The area A = πR^2 for horintal axis wind turbine or A = 2RH for a vertical axis wind turbine, where: *R* is the radius/length of the turbine blade (horizontal axis) or position of the blade from the axis, and *H* is the height of the blade for a vertical axis turbine. This equation highlights that small changes in wind speed significantly impact the available power, which is why wind speed is a critical factor in wind energy systems. The equation exhibits a highly nonlinear cubic dependence on wind speed, e.g., doubling the wind speed leads to an eight-fold increase in its available power. The power of the wind is a linear function of air density. As a result of the limited range of air density fluctuations at sea level, density correction should be made for higher elevations, as explained previously. The method of bins can be applied when the values recorded (N) for a site are too many to be handled as individuals. The following equations were derived by [33]. The data is separated into the wind speed intervals or bins in which they occur. The same size bins/intervals are used. Suppose that the data are separated into N_B bins of width w_j, with midpoints m_j, and with f_j, the number of occurrences in each bin or frequency, were

$$N = \sum_{j=1}^{N_B} f_j \tag{16}$$

Mean Wind speed, $\bar{V}$

$$\bar{V} = \frac{1}{N}\sum_{j=1}^{N_B} m_j f_j \tag{17}$$

Standard deviation of wind speed

$$\sigma_V = \sqrt{\frac{1}{N-1}\left\{\sum_{j=1}^{N_B} {m_j}^2 f_j - N(\bar{V}^2)\right\}} = \sqrt{\frac{1}{N-1}\left\{\sum_{j=1}^{N_B} {m_j}^2 f_j - N\left(\frac{1}{N}\sum_{j=1}^{N_B} m_j f_j\right)^2\right\}} \tag{18}$$

Average wind power per unit area (power density)

$$\frac{\overline{P}}{A} = \frac{1}{2}\rho\frac{1}{N}\sum_{j=1}^{N_B} {m_j}^3 f_j \tag{19}$$

Average wind machine power

$$\overline{P_w} = \frac{1}{N}\sum_{j=1}^{N_B} P\left(m_f\right) f_f \tag{20}$$

Another useful indirect measurement of the wind resource is the observation of an area's vegetation, which strong winds can permanently deform [34]. This deformity, known as "flagging", has been utilised to estimate the average wind speed for an area. Figure 1 below shows the Giggs-Putnam Index of Deformity and its interpretation.

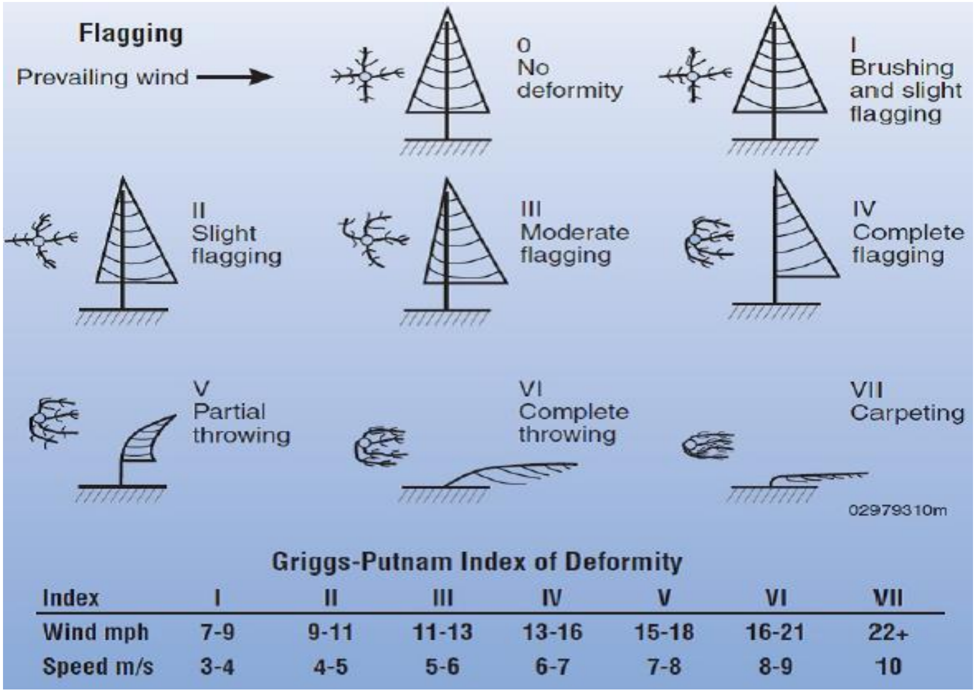

Figure 1 Giggs-Putnam Index.

On-site data measurement necessitates data referenced over a longer period, such as one year; this technique incurs additional costs, effort, and time. It requires a wind data collection system comprising anemometers, wind vanes, and temperature sensors.

5. The Statistical Analysis

After evaluating the parameters, mean wind speed, and standard deviation of the wind speed, a statistical analysis technique can be performed to determine the wind energy potential of the given site and to estimate the energy output from a wind turbine installed there. Furthermore, the projection of measured values to other areas with possible values that have a high probability. For this purpose, a probability distribution of the wind speed is defined using a standard distribution that approximates the random variations of the wind speed more closely.

Since the wind data values are greater than zero (skewed data) and only two parameters are available, the probability distribution models that apply to such a random variable are

(a) Rayleigh distribution requires only one parameter (mean speed, $\bar{V}$).

(b) Weibull distribution requires two parameters (k, a shape factor, and c, a scale factor; both are mean velocity functions. $\bar{V}$ and standard deviation, σ_V).

The Rayleigh distribution [33].

Probability density function, $p(V)$

$$p(V) = \frac{\pi}{2}\frac{V}{\bar{V}^2} exp\left[-\frac{\pi}{4}\left(\frac{V}{\bar{V}}\right)^2\right] \tag{21}$$

Cumulative Distribution function, $F(V)$

$$F(V) = 1 - exp\left[-\frac{\pi}{4}\left(\frac{V}{\overline{\overline{V}}}\right)^2\right] \tag{22}$$

The Weibull distribution by [34] is not a straightforward process to get the parameters of the equation, c and k, in terms of V and σ_V. However, several available approximations will not be covered at this stage; therefore, the Rayleigh simple analysis will be utilised. The equations for turbine energy production estimates using statistical techniques become

Mean wind speed, $\bar{V}$

$$\bar{V} = \int_0^\infty V.p(V) \tag{23}$$

Mean available wind power density, $\bar{P}/A$

$$\frac{\bar{P}}{A} = \int_0^\infty \frac{1}{2}V^3.p(V) = \frac{1}{2}\rho\overline{V^3} \tag{24}$$

The turbine power production function (refer to equation (1)) is $P_w(V) = \frac{1}{2}\rho C_p A V^3$.

The mean wind turbine power $\overline{P_w} = \int_0^\infty P_w(V).p(V)dV$.

$$\overline{P_w} = \frac{1}{2}\rho\eta C_{p\ Betz} A\int_0^\infty V^3.\frac{\pi}{2}\frac{V}{\overline{V}^2}exp\left[-\frac{\pi}{4}\left(\frac{V}{\overline{\overline{V}}}\right)^2\right] \tag{25}$$

Rewritten and simplified to

$$\overline{P_w} = \frac{1}{2}\rho\eta C_{p\,Betz} A\int_0^\infty V^3.\left\{\frac{2V}{V_c}exp\left[-\left(\frac{V}{V_c}\right)^2\right]\right\}dV \tag{26}$$

Where: V_c is a characteristic wind velocity given by $V_c = \frac{2\overline{V}}{\sqrt{\pi}}$.

Equation (26) demonstrates that the Rayleigh-integrated estimate is exactly three times the direct estimate for the same mean speed. This reflects the disproportionate contribution of above-average speed events to mean power output under the cubic speed-power relationship, and explains why statistical analysis consistently yields higher power density estimates than direct-method calculations.

6. Data Collection, Results, and Analysis

The potential of wind power generation was assessed through a desktop study, which extracted climatic data from various weather sources, including the Meteorological Services Department of Zimbabwe, Meteoblue, and others. Both Meteoblue and Weather Spark provided online climate data over long periods extending to 30 years of hourly weather model simulations and available for every place on Earth. The data collected for Zvishavane provided the source for the direct method of calculating and assessing the average wind speed and applying the techniques to predict turbine power generation potential, as shown in Figure 2 below.

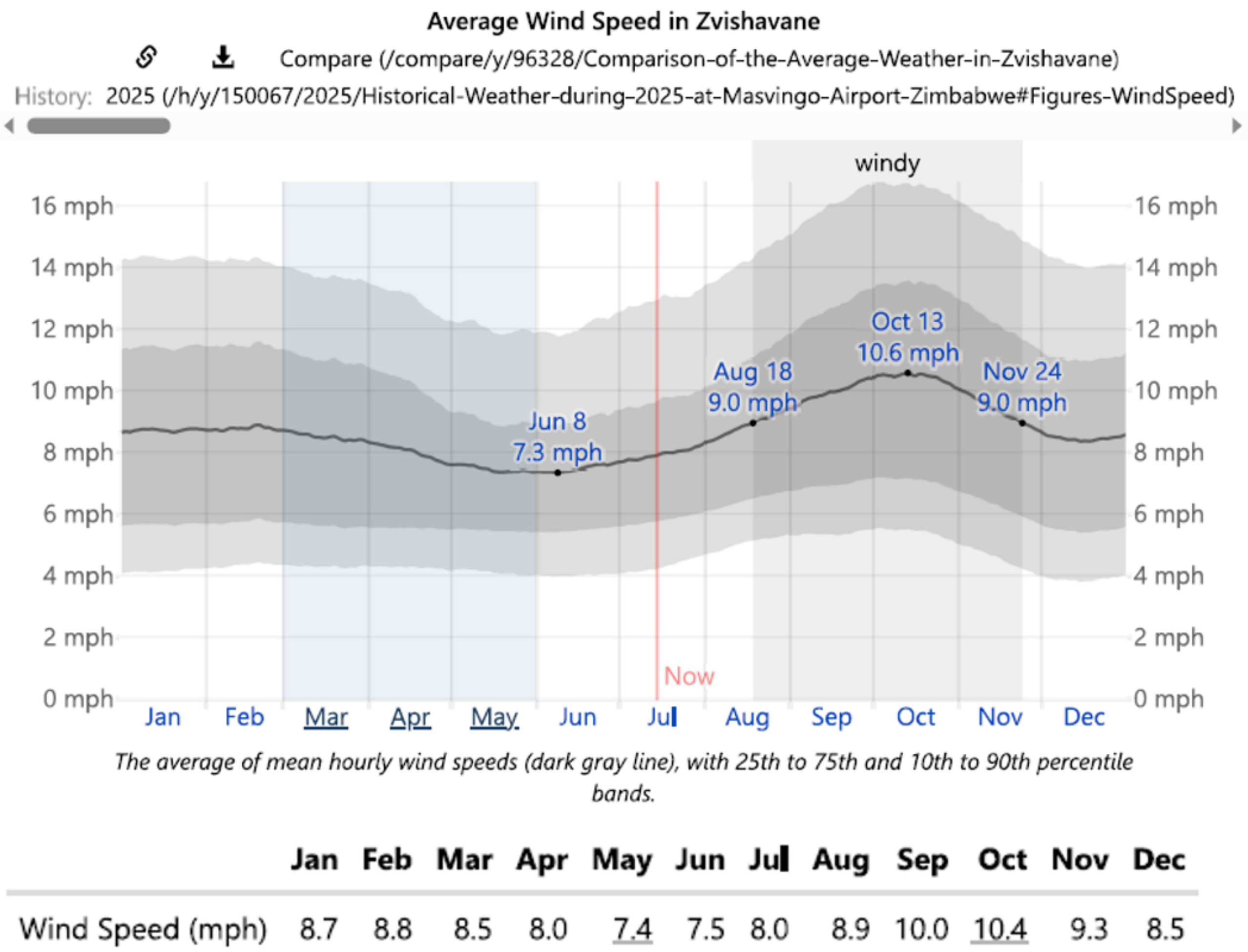

Figure 2 Extract from Weather Spark [36].

To evaluate the wind energy potential of the study area, monthly average wind speed data at 10 m above ground level were sourced from Weather Spark. These data capture seasonal variations in wind availability. Table 3 summarises the extracted wind speed values [36].

Table 3 Wind Speed Data Extracted from Weather Spark at 10 m above ground [36].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Speed (mph)	8.7	8.8	8.5	8.0	7.4	7.5	8.0	8.9	10	10.4	9.3	8.5
m/s	3.89	3.93	3.80	3.58	3.31	3.35	3.58	3.98	4.47	4.65	4.16	3.80

The second extract from Meteoblue is shown in Figure 3 below.

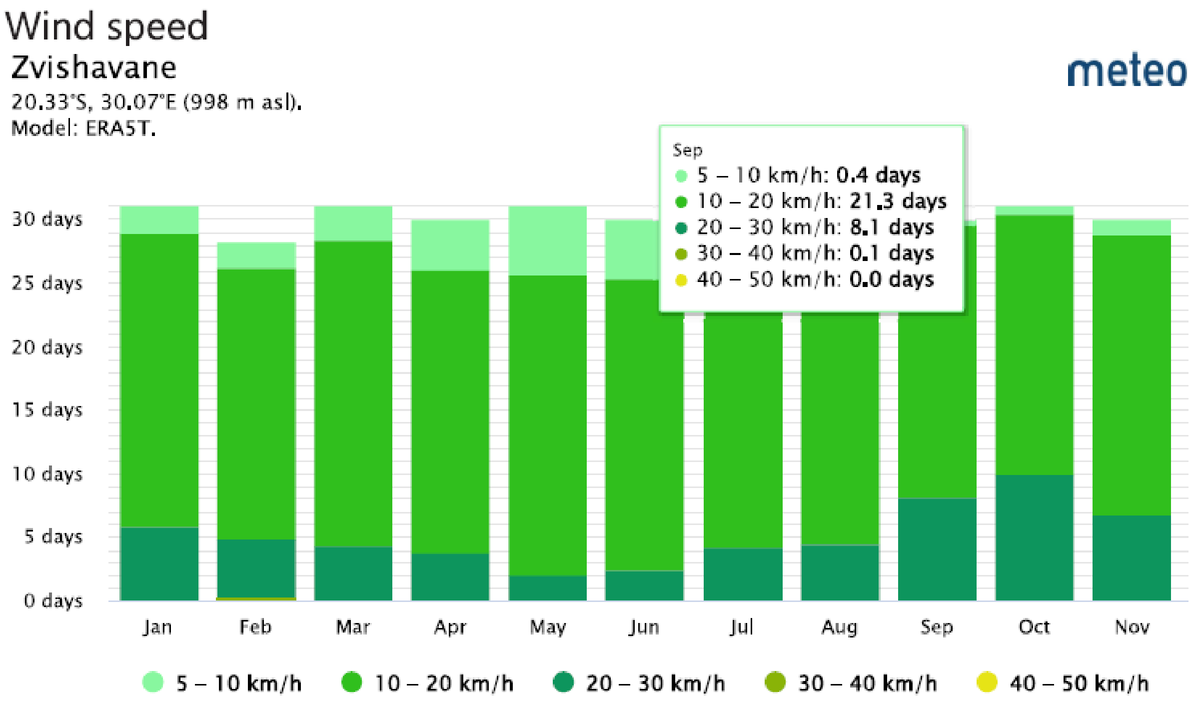

Figure 3 Extract from Meteoblue [37].

Wind speed frequency distribution data were obtained from Meteoblue to further characterise the wind regime of the study area. The data are presented as monthly average wind speeds classified into different speed ranges (km/h), providing insight into wind availability and variability. Table 4 summarises the Meteoblue wind speed distribution used in this study.

Table 4 Wind Speed Data from Meteoblue.

Average Wind Speed (km/h)					
Mon	5-10	10-20	20-30	30-40	40-50
January	2.1	23	5.8	0.1	0.0
February	2.1	21.3	4.7	0.2	0.0
March	2.6	24.1	4.3	0.0	0.0
April	4.0	22.2	3.8	0.0	0.0
May	5.3	23.6	21	0.0	0.0
June	4.6	22.9	2.4	0.0	0.0
July	2.9	23.9	4.1	0.1	0.0
August	1.3	25.2	4.5	0.0	0.0
September	0.4	21.3	8.1	0.1	0.0
October	0.6	20.4	9.9	0.1	0.0
November	1.2	22	6.8	0.1	0.0
December	3.4	22.1	5.5	0.1	0.0

Using the method of bins or grouped data

$N = \sum_{j=1}^{N_B} f_j$ = 28 or 30 or 31

The total frequency N = 30 or 31 is the number of days in the particular month. N_B = number of bins = 5, the frequency f_i = number of days the specific speed is attained, and m_j = midpoints of bins. For example, frequencies for January are f_1 = 2.1, f_2 = 23, f_3 = 5.8, and f_4 = 0.1. The mean wind speed for January.

Mean Wind speed, $\bar{V} = \frac{1}{N}\sum_{j=1}^{N_B} m_j f_j = \frac{1}{31}\sum_{j=1}^{5} m_j f_j = \frac{1}{31}(7.5 \times 2.1 + 15 \times 23 + 25 \times 5.8 + 35 \times 0.1) = 16.42741935.$

Table 5 shows frequencies, midpoints, and mean wind speed for each month. The data shows that it is unlikely that 40-50 km/h speeds can be attained in Zvishavane urban.

Table 5 Mean Wind Speed, Frequency(days), and Midpoints.

	j	1	2	3	4	5	N	Mean Wind Speed (km/h)	Mean Wind Speed (m/s)
	Midpoints (m_j)	7.5	15	25	35	45			
Month	January	2.1	23	5.8	0.1	0.0	31	16.42741935	4.5632
	February	2.1	21.3	4.7	0.2	0.0	28.3	16.24558304	4.5127
	March	2.6	24.1	4.3	0.0	0.0	31	15.75806452	4.3772
	April	4.0	22.2	3.8	0.0	0.0	30	15.26666667	4.2407
	May	5.3	23.6	21	0.0	0.0	31	14.39516129	3.9987
	June	4.6	22.9	2.4	0.0	0.0	29.9	14.64882943	4.0691
	July	2.9	23.9	4.1	0.1	0.0	31	15.68548387	4.3571
	August	1.3	25.2	4.5	0.0	0.0	31	16.13709677	4.4825
	September	0.4	21.3	8.1	0.1	0.0	29.9	17.67558528	4.9099
	October	0.6	20.4	9.9	0.1	0.0	31	18.11290323	5.0314
	November	1.2	22	6.8	0.1	0.0	30.1	17.02657807	4.7296
	December	3.4	22.1	5.5	0.1	0.0	31	16.01286174	4.4480

Figure 4 below shows the observed data for Zvishavane.

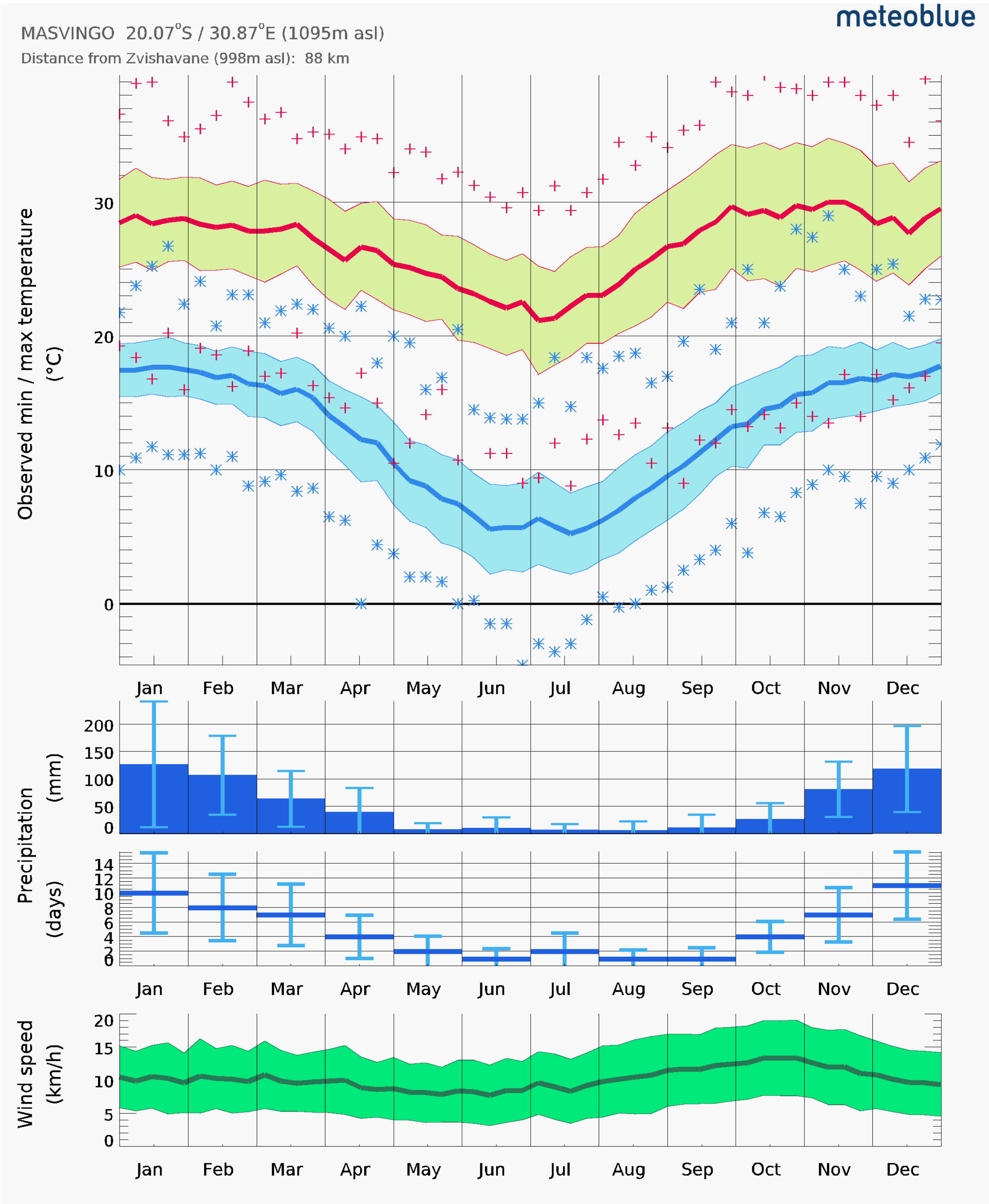

Figure 4 Observed wind speeds for the year [37].

Weather Spark gives lower wind velocity estimates compared to Meteoblue. Maximum velocity for Weather Spark is 4.65 m/s, while Meteoblue is 5.031 m/s.

The Wind Turbine Monthly Power Production (Power Density) Estimates for Zvishavane can now be calculated and evaluated for their sufficiency for power generation.

From the literature, the monthly wind turbine power is given by equation (1)

$$P = \frac{1}{2}\rho\eta C_p A\bar{V}^3$$

The turbine power density is given by equation (2)

$$\frac{P}{A} = \frac{1}{2}\rho\eta C_{p\ Betz}\bar{V}^3$$

Where: $\bar{V}$ is the monthly mean of the wind speed.

Assuming an ideal wind machine, a measure of the maximum possible average power from a given rotor diameter can be calculated. For an idealised wind turbine, with no losses, η = 1, the machine power coefficient, C_p is equal to the Betz limit ($C_{p\ Betz}$ = 16/27), the theoretical maximum possible power coefficient, and air density 1.225 kg/m^3, with variations accommodated as explained in the literature.

Table 6 below shows the estimates of turbine power generation (power density):

Table 6 Monthly Power Generation Estimates.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Weather Spark Speed (m/s)	3.89	3.93	3.80	3.58	3.31	3.35	3.58	3.98	4.47	4.65	4.16	3.80
Power Gener (W/m^2)	21.37	22.03	19.92	16.66	13.16	13.65	16.65	22.88	32.42	36.49	26.13	19.92
Meteoblue Wind Speed	4.56	4.51	4.38	4.24	4.00	4.07	4.36	4.48	4.91	5.03	4.73	4.45
Power Gener (W/m^2)	34.42	33.30	30.50	27.67	23.23	24.47	30.08	32.64	42.96	46.19	38.41	31.98
MSDZ Speed (m/s)												
Power Gener (W/m^2)												

NB: MSDZ: Meteorological Services Department of Zimbabwe.

Maximum Power density is 46.49 W/m^2 and a minimum of 13.16 W/m^2 from Weather Spark estimates, while Meteoblue gives a maximum of 46.192 W/m^2 and a minimum of 23.23 W/m^2. These values are in the low category; hence, the area is considered poor for wind power generation.

From qualitative power density evaluations, the mean velocities required to achieve a low and excellent power generation category can be calculated.

$$\bar{V} = \sqrt[3]{\frac{2 \times \frac{P}{A}}{\rho \times C_p}}$$

Low category = 100 W/m^2 gives

$$\bar{V} = \sqrt[3]{\frac{2 \times 100}{\frac{1.225 \times 16}{27}}} = \frac{6.507m}{s}$$

Excellent category (>700 W/m^2) requires

$$\bar{V} = \sqrt[3]{\frac{2 \times 700 \times 27}{1.225 \times 16}} = \frac{12.447m}{s}$$

The minimum and maximum tower heights can be evaluated using the log-law boundary-layer equation.

$$\frac{V(z)}{V(z_r)} = \frac{ln\left(\frac{z}{z_0}\right)}{ln\left(\frac{z_r}{z_0}\right)}$$

From the data, velocities are measured at z_r = 10 m above ground. Zvishavane urban terrain is mountainous, has suburbs, roughness z_0 = 1500 mm = 1.5 m, and minimum mean speed $V(z_r)$ = V(10) = 3.31 m/s. Taking the May value from Weather Spark.

Height to achieve low category power density, $z_{min} = ln\left(\frac{z_{min}}{z_0}\right) = \frac{V(z)}{V(z_r)} \times ln\left(\frac{z_r}{z_0}\right) \rightarrow ln\left(\frac{z_{min}}{1.5}\right) = \frac{6.507}{3.31} \times ln\left(\frac{10}{1.5}\right) = 3.72947$

z_{min} = 62.4858 = 63 m

Height to achieve excellent category power density, $z_{max} = ln\left(\frac{z_{max}}{z_0}\right) = \frac{V(z)}{V(z_r)} \times ln\left(\frac{z_r}{z_0}\right) \rightarrow ln\left(\frac{z_{max}}{1.5}\right) = \frac{12.447}{3.31} \times ln\left(\frac{10}{1.5}\right) = 7.13397$

z_{max} = 1880.77 m

Constructing a wind turbine of this size is practically infeasible.

Wind Turbines operate efficiently at speeds between 5 and 15 m/s. Using the minimum velocity of 3.31 m/s, the height at which 5 m/s occurs can be evaluated from the log law or power law equation. The minimum turbine tower height, H = z_{min}

$$ln\left(\frac{z_{min}}{z_0}\right) = \frac{V(z)}{V(z_r)} \times ln\left(\frac{z_r}{z_0}\right) = \frac{5}{3.31} \times ln\left(\frac{10}{1.5}\right) = 2.8657$$

Giving H= $z_{min} = z_0e^{2.8657} = 1.5e^{2.8657} = 26.34307$ m = 27 m

This turbine tower is technically achievable. Thus, with any height above this, the turbine will have a suitable speed of 5 m/s or above for efficient operation throughout the year, since ground speeds are higher than 3.31 m/s, the lowest which occurs in May.

The simple Rayleigh Probability Density function is used in the statistical assessment method. From the literature, equation (21) shows that the Rayleigh function is given as a Probability density function, and the mean turbine power generation has been given as

$$\overline{P_w} = \frac{1}{2}\rho\eta C_{p\ Betz} A \int_0^\infty V^3.\left\{\frac{2V}{V_c} exp\left[-\left(\frac{V}{V_c}\right)^2\right]\right\} dv$$

Where: V_c is a characteristic wind velocity given by $V_c = \frac{2\bar{V}}{\sqrt{\pi}}$

The mean power density is

$$\frac{\overline{P_w}}{A} = \frac{1}{2}\rho\eta C_{p\ Betz} \int_0^\infty V^3.\left\{\frac{2V}{V_c} exp\left[-\left(\frac{V}{V_c}\right)^2\right]\right\} dv$$

After manipulations of the integral, the value is $\frac{3}{4}\sqrt{\pi}{V_c}^3 = \frac{3}{4}\sqrt{\pi} \times \left(\frac{2\bar{V}}{\sqrt{\pi}}\right)^3 = 6\bar{V}^3$

Mean turbine power density = $\frac{1}{2}\rho\eta C_{p\ Betz} \times 6\bar{V}^3 = 3\rho\eta C_{p\ Betz}\bar{V}^3$

For an ideal machine, η = 1, and the power coefficient is replaced with the Betz value of $C_{p\ Betz}$ = 16/27, ρ = 1.225 kg/m^3.

Mean turbine power generation estimate = $3\rho\eta C_{p\ Betz}\bar{V}^3 = 3 \times 1.225 \times \frac{16}{27} \times \bar{V}^3 = \frac{48}{27} \times 1.225 \times \bar{V}^3$.

The numerical estimates of the power generation potential from this statistical analysis of the monthly power generation (power density) are shown in Table 7 below.

Table 7 Power generation estimates from statistical analysis.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Weather Spark Speed (m/s)	3.89	3.93	3.80	3.58	3.31	3.35	3.58	3.98	4.47	4.65	4.16	3.80
Power Gener (W/m^2)	128.19	132.19	119.50	99.92	78.98	81.87	99.92	137.30	194.51	218.96	156.78	119.50
Meteoblue Wind Speed	4.56	4.51	4.38	4.24	4.00	4.07	4.36	4.48	4.91	5.03	4.73	4.45
Power Gener (W/m^2)	206.49	199.78	182.99	166.00	139.38	146.82	180.50	195.82	257.79	277.15	230.46	191.91

The statistical analysis yields higher estimates with Weather Spark, having a minimum of 78.98 W/m^2 and a maximum of 194.51 W/m^2, while Meteoblue values are a minimum of 139.38 W/m^2 and a maximum of 277.15 W/m^2. Most of these values now fall in the 150-200 W/m^2 class 3 category, which translates to fair for wind power generation.

7. Economic Feasibility Assessment

7.1 Annual Energy Production Estimation

AEP estimated for a 400 W rated mini turbine: rotor diameter 1.8 m (A = 2.54 m^2), cut-in 2.5 m/s, rated 12 m/s, η = 0.90, capacity correction factor CF = 0.85. Monthly production uses Rayleigh power densities extrapolated to 27 m hub height via the log law. The drivetrain efficiency was assumed to be η = 0.90. Monthly energy production, E_l (kWh), was estimated as:

$$E_m = \left(\frac{P}{A}\right)_{m,Rayleigh} \times A \times T_m \times CF$$

Where: T_m is the number of hours in a month, and *CF* is a capacity correction factor of 0.85 applied to account for wake losses, availability, and array effects. This formulation uses Rayleigh power density estimates referenced to a 27 m tower height, obtained by applying the log law to extrapolate each monthly mean speed from 10 m to 27 m as the basis for energy calculations.

Table 8 presents the estimated Annual Energy Production (AEP) of the 400 W mini wind turbine installed at a tower height of 27 m. The results provide an assessment of the expected energy output under prevailing wind conditions at the selected site and demonstrate how tower height affects turbine performance and energy-generation potential.

Table 8 Estimated AEP - 400 W Mini Turbine at 27 m Tower Height.

Month	$\bar{V}$ at 27 m (m/s)	*P/A* Rayleigh (W/m^2)	Hours	E_m (kWh)
January	6.27	534.0	744	2.79
February	6.20	516.5	672	2.52
March	6.02	474.6	744	2.48
April	5.83	439.4	720	2.29
May	5.50	360.3	744	1.88
June	5.60	380.0	720	1.99
July	5.99	466.3	744	2.44
August	6.16	506.9	744	2.65
September	6.75	665.9	720	3.48
October	6.91	714.4	744	3.73
November	6.51	591.0	720	3.08
December	6.12	498.4	744	2.60
Total	-	-	8,784 h	AEP ≈ 547 kWh/yr

The estimated annual energy production of 547 kWh/year (at a 27 m tower height, Meteoblue data) is comparable to the 1,990 kWh/year reported by Goudarzi et al. [13] for a larger turbine (different rating) in Maryland at a higher-mean-wind-speed site. It suggests that a mini turbine in

Zvishavane would meaningfully supplement residential electricity consumption. For context, a typical Zvishavane household consumes approximately 200-400 kWh/month (2,400-4,800 kWh/year) during grid-available periods; the estimated turbine output of 547 kWh/year would offset approximately 11-23% of baseline grid consumption, or a substantially higher proportion of actual consumption given the prevalence of load-shedding.

7.2 LCOE Calculation

Standard LCOE formulation:

$$LCOE = (CAPEX \times CRF + OPEX)/AEP$$

$$CRF = r(1+r)^n/[(1+r)^n - 1]$$

Where: *CRF* is the capital recovery factor, *r* is the annual discount rate (%), and *n* is the system lifetime (years). Table 9 presents the CAPEX breakdown and baseline assumptions. Capital cost estimates are derived from published unit cost data for small and mini wind turbines in sub-Saharan African markets, adjusted for Zimbabwean import and installation conditions. The table displays the main cost elements related to the installation and operation of the system and also provides economic assumptions used in the financial analysis and feasibility study.

Table 9 CAPEX Breakdown and Baseline Economic Assumptions.

Cost Component	Baseline (USD)	Notes
Turbine unit (400 W)	800-1,200	FOB China ~USD 400-600 + import duties
Tower (27 m galvanised)	600-1,000	Local fabrication or import
Foundation and civil works	300-500	Site-specific concrete foundation
Electrical installation/inverter	300-500	Grid-tie or battery system
Permitting and commissioning	100-200	ZERA approval; council permit
TOTAL CAPEX	2,100-3,400	Midpoint: USD 2,750
OPEX (annual)	50-80	~2-3% of CAPEX
System lifetime	20 years	Standard design life
Discount rate (baseline)	10%	Zimbabwe risk-adjusted
AEP baseline	547 kWh/yr	Meteoblue; W.Spark lower bound: 438 kWh/yr

Baseline LCOE computation (CAPEX USD 2,750; OPEX USD 65/yr; AEP 547 kWh/yr; r = 10%; n = 20): CRF = 0.1175; LCOE = (2,750 × 0.1175 + 65)/547 ≈ USD 0.65/kWh. Low-cost scenario (CAPEX USD 2,100): LCOE ≈ USD 0.54/kWh.

At baseline assumptions (CAPEX USD 2,750, OPEX USD 65/year, AEP 547 kWh/year, r = 10%, n = 20 years), the LCOE is calculated as:

$CRF = 0.10 \times (1.10)^{20}/[(1.10)^{20} - 1] = 0.1175$

LCOE = (2,750 × 0.1175 + 65)/547 = (323.1 + 65)/547 = USD 0.710/kWh (at 10 m)

At a 27 m tower height and with extrapolated wind speeds, the LCOE reduces substantially:

LCOE (27 m) = (3,400 × 0.1175 + 80)/547 ≈ USD 0.877/kWh (high-cost scenario)

LCOE (27 m, low-cost) = (2,100 × 0.1175 + 50)/547 ≈ USD 0.543/kWh (low-cost scenario)

7.3 Sensitivity Analysis and Comparison with Alternative Supply Costs

Table 10 shows how sensitive the LCOE is to changes in capital cost and discount rate. Based on this, the potential range of conditions within which mini wind generation would be economically competitive is evaluated.

Table 10 LCOE Sensitivity Analysis — 400 W Mini Wind Turbine, Zvishavane, AEP = 547 kWh/yr.

Scenario	CAPEX (USD)	Discount Rate (%)	LCOE (USD/kWh)	Simple Payback (years)
Low-cost, concessional finance	2,100	5%	0.43	12.2
Low-cost, baseline finance	2,100	10%	0.54	9.6
Mid-cost, baseline finance	2,750	10%	0.65	11.8
High-cost, high-risk premium	3,400	15%	0.87	15.0
Mid-cost, subsidised (50% grant)	1,375	10%	0.37	6.5
Reference: Diesel generator (est.)	N/A	N/A	0.35-0.50	N/A
Reference: ZESA grid tariff (est.)	N/A	N/A	0.10-0.15	N/A

The sensitivity analysis can be observed that at the original commercial finance assumption, it is still more expensive for wind generation at Zvishavane compared to the benchmark ZESA grid tariff, but not dramatically by a band of 21 to 27 cents/kWh, reaching a cost band of diesel generator generation, which effectively corresponds to the actual marginal supply cost under loadshedding. If, on the other hand, concessional or subsidized finance can be raised via the government's incentives on renewables or through development finance or direct capital grants, then the LCOE is reduced to 0.37-0.43 c/kWh thus making this technology meaningful as an investment into energy security for the small businesses or households experiencing constant loss of supply. In addition, across the scenario range, the payback period is not excessively long; for example, in the 6.5-15 years range, it is well within the bounds of an 8-13 years payback period for similar small wind systems determined by Goudarzi et al. [13] across varied geographies.

8. Discussion

The findings of this study confirm that Zvishavane occupies a marginal position in the wind resource landscape — not a premium wind energy site by international standards, but one with identifiable potential under appropriate tower height and turbine specifications. The distinction between the direct calculation result (Class 1: Poor) and the Rayleigh statistical result (Class 2: Fair, for the majority of months using Meteoblue data) is analytically important and is fully explicable on mathematical grounds: the direct method applies the cube of mean speed, systematically underestimating the contribution of above-average wind speed events to mean power output. The Rayleigh model's threefold higher mean power density estimate is not an artifact but a physically correct representation of a speed distribution with significant variance, and its use for preliminary feasibility assessment is well supported in the wind energy literature [33, 34].

The tower height analysis establishes an important practical threshold: a 27 m tower is sufficient to ensure year-round operation above the 5 m/s cut-in speed and is clearly achievable within standard engineering practice and structural design for the suburban terrain and shallow-depth soils typical of Zvishavane's residential areas. The 63 m tower required to meet the Class 1 power density threshold by direct calculation is at the upper range of what is typically deployed for small-scale applications. Still, it represents a proven engineering solution for medium-sized turbines at low-speed sites. The absence of any requirement for towers approaching 620 m or higher (needed for Class 3) provides a clear and honest boundary on the site's resource potential: Zvishavane will not support large-scale, high-capacity wind generation under current tower technology, but targeted mini turbine deployment at 27-63 m can make a meaningful contribution to distributed energy supply.

The economic analysis reveals a picture that is nuanced rather than straightforwardly favorable. Under baseline commercial financing, the LCOE of mini wind generation significantly exceeds the ZESA grid tariff, making the technology economically unattractive as a direct substitute for grid electricity when the grid is available. However, the relevant economic comparison for Zvishavane households and businesses is not the nominal grid tariff but the effective cost of energy during the 12-18 hours per day of load-shedding, which is best proxied by the cost of diesel generation (USD 0.35-0.50/kWh). In this comparison, mini wind is broadly cost-competitive in low-capital scenarios and offers the additional advantage of zero fuel-cost volatility risk. The energy security dimension reducing exposure to supply disruptions rather than simply substituting grid energy may be the strongest economic argument for mini wind deployment in the Zimbabwean context.

Several limitations of this study should be acknowledged. The absence of on-site anemometer data is the most significant limitation, as reanalysis products at 30 km spatial resolution do not capture the local topographic wind-enhancement effects that are likely to be significant in Zvishavane's varied terrain. Site-specific measurement campaigns, ideally lasting 12-24 months' duration at hub height, would substantially reduce wind resource uncertainty and enable more precise AEP and LCOE calculations. The Rayleigh distribution assumes a shape parameter k = 2, which may not accurately represent the Zvishavane wind speed distribution; a full Weibull fit with local measurement data could refine the statistical analysis. The LCOE calculations in this study are based on commercially available cost estimates and are necessarily approximate; detailed project-level cost estimates would require supplier quotations and site surveys. Future work should also address integrating mini wind generation with battery storage and solar PV to provide continuous baseload coverage. It should assess the structural and wind-load requirements for turbine towers at the specific soil and topographic conditions at deployment sites within the town.

9. Conclusions

This paper has presented a systematic techno-economic feasibility assessment of mini wind turbines for distributed urban energy generation in Zvishavane, Zimbabwe. The principal findings are as follows:

(1) Wind resource at 10 m a.g.l.: Mean monthly wind speeds range from 3.31 to 5.03 m/s across two independent reanalysis data sources, placing Zvishavane in the Class 1 (Low) power density category under direct calculation.

(2) Statistical resource assessment: Application of the Rayleigh probability density function elevates the site into the Class 2 (Fair) resource category for the majority of months using Meteoblue data, with mean power densities of 139-277 W/m^2. The mathematically demonstrable

superiority of integrated statistical estimates over direct cube-of-mean-speed calculations is confirmed.

(3) Tower height: The minimum tower height for reliable year-round turbine operation at cut-in speed (5 m/s) is 27 m, confirmed as technically achievable. A 63 m tower achieves the Class 1 direct power density threshold.

(4) Annual energy production: A representative 400 W rated mini turbine at 27 m tower height is estimated to produce approximately 438-547 kWh/year, sufficient to offset 11-23% of typical baseline household consumption.

(5) Economic assessment: The LCOE ranges from USD 0.37 to USD 0.87/kWh across capital cost and financing scenarios, with a baseline estimate of USD 0.54-0.65/kWh. While this exceeds the nominal ZESA grid tariff, it is competitive with diesel generation costs during load-shedding and approaches viability under subsidized financing conditions. Simple payback ranges from 6.5 to 15 years.

The study concludes that mini wind turbines in Zvishavane are technically feasible and approach economic viability as an energy resilience measure, particularly under conditions of chronic grid outage. Realizing this potential requires targeted policy support including concessional financing, import duty waivers on turbine components, and streamlined ZERA permitting for small generators combined with on-site wind measurement campaigns to reduce resource uncertainty. The methodology applied in this study is directly replicable at comparable Zimbabwean and southern African urban sites, and the framework developed here provides a transferable template for feasibility assessment in data-sparse, resource-constrained settings.

Author Contributions

Francis Mafuratidze conceived the study, supervised the research, and provided overall guidance on the project development and implementation. Ackson Gondo contributed to the project conceptualization and development and participated in the overall execution of the research. David Ndiyamba was responsible for data collection, data management, and data analysis. Hagreaves Kumba prepared the first draft of the manuscript, contributed to the interpretation and analysis of the findings, and finalized the manuscript for submission. All authors reviewed, revised, and approved the final version of the manuscript.

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No potential competing interest was reported by the authors.

AI-Assisted Technologies Statement

In preparing this manuscript, Grammarly AI was utilized to assist in proofreading and improving the clarity of the text. The AI tool provided suggestions for grammar, punctuation, style, and overall readability. All suggestions were reviewed and, where appropriate, incorporated by the authors. The use of Grammarly AI was limited to language enhancement and did not influence the conceptual, methodological, experimental, or analytical aspects of the research. The authors take full responsibility for the content and interpretations presented in this manuscript.

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