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Wind energy potential assessment, estimation, and modelling in the Vhembe district, Limpopo Province

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Abstract

This study addresses the global challenge of assessing renewable wind resources by evaluating wind energy potential, spatial availability, and localised applications—such as household electricity, irrigation, and small-scale community projects—within South Africa's Vhembe District, Limpopo Province. The research integrates meteorological data from local weather stations with Geographic Information Systems (GIS) and Remote Sensing (RS) techniques. This approach maps spatial wind distribution while accounting for environmental constraints, weather conditions, and regional land suitability. The empirical results reveal highly variable wind energy prospects across the Vhembe District and broader Limpopo locations. Furthermore, the study demonstrates the efficacy of the Conceptual Framework for Identification of the Rural Energy Deployment Application Tool in optimising site selection. Utilising integrated GIS and RS methodologies provides a robust framework for identifying viable inland wind resources, confirming that Vhembe possesses strategic pockets capable of supporting decentralised rural energy projects. These findings provide community leaders and regional decision-makers with a data-driven tool to successfully plan, implement, and accelerate sustainable wind energy deployment in remote rural areas.

Keywords: Climate and geographical Data, Power curve, Remote sensing mappings, Weibull distribution, Wind energy assessment, Wind energy potential, Wind maps and characteristics.

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Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Institutional Review Board Statement: This is not applicable as the study does not involve humans or animals. The ethical review and approval were permitted and waived for this study as it exclusively used the secondary meteorological data obtained from the South African Weather Stations (SAWS) and the Agricultural Research Council of the Institute for Soil, Climate and Water (ARC-ISCW) data and geospatial data obtained through the GIS Software Analysis, which did not involve any human or animal subjects.
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1. Introduction

Various models and frameworks exist for rural energy assessment and deployment in the Vhembe District region. The conceptual framework in Figure 1 identifies rural energy deployment applications. The renewable energy framework encompasses solar, wind, hydropower, biomass/biogas, geothermal, tidal, ocean, and waves, as shown in Figure 1 [1]. Wind plays a vital role in generating electricity [2].

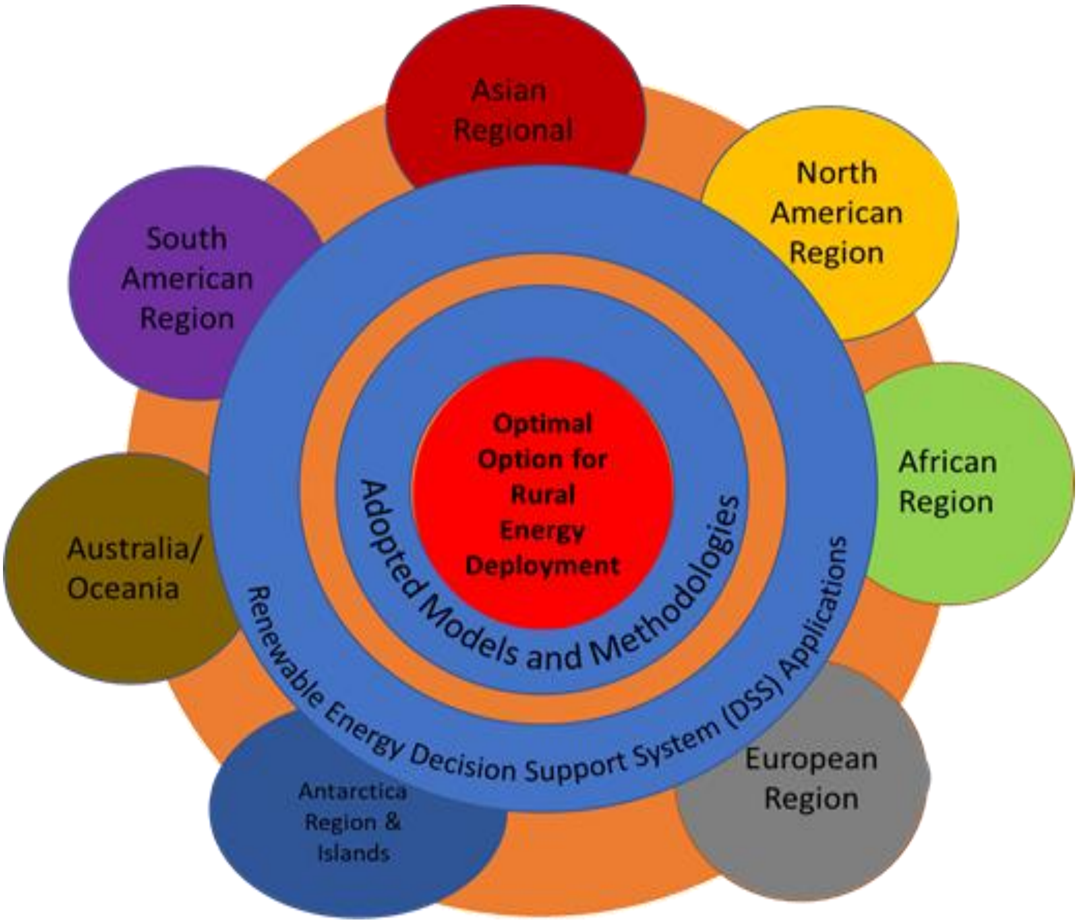

Figure 1.
Conceptual Framework for Identifying Rural Energy Deployment Applications.

Wind is a significant and promising renewable energy source due to its low adoption, utilization, and production worldwide. Its advantages include low cost and easy maintenance [2]. According to the 2020 IEA report on sustainable development from 2002 to 2030, only 27% of existing projects in 2019 indicate that renewable energy deployment remains challenging despite improvements, as shown in Figure 2. Efforts are underway across the country to address the energy mix.

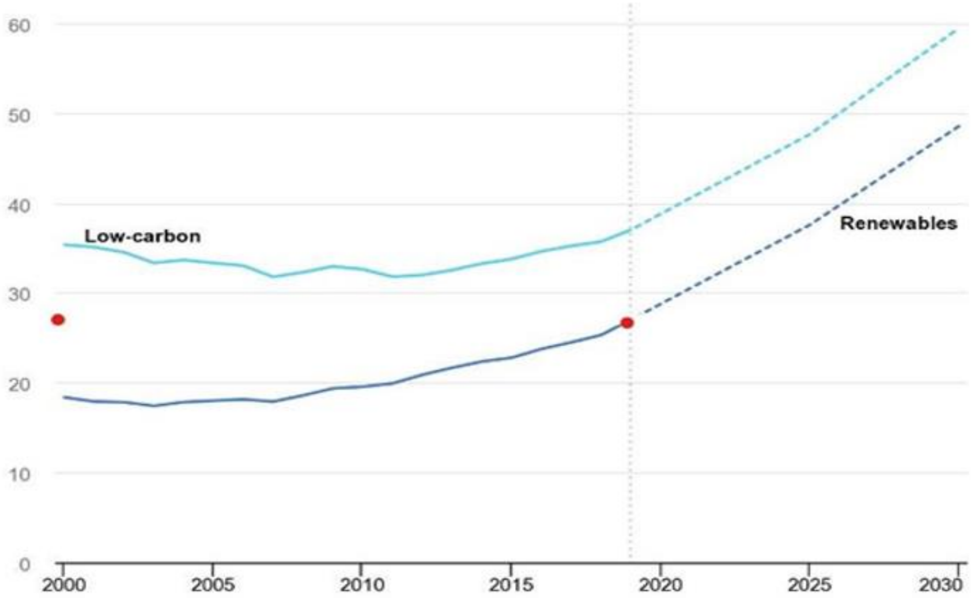

Figure 2.
The 2000 to 2030 Sustainable Development Scenario for South Africa Renewable Energy Development: © IEA, 2020.

Recognizing that the lack of modern energy exacerbates poverty in rural areas, the Republic of South African (RSA) government is committed to a policy document aimed at promoting renewable energy, especially in rural regions [3]. The policy envisions integrating renewable energy into the mainstream energy economy with various measures, benefiting rural communities, small schools, clinics, and women and children who no longer need to collect firewood [4].

The Sustainable Livelihoods Approach (SLA) guides these measures, requiring the development of effective and safe technologies to ease burdens associated with cooking, water collection, and domestic tasks [5]. Short and medium-term goals should be established to improve electricity infrastructure through imaginative grid concepts and renewable technologies [6]. Adopting and promoting green energy is recognized internationally as a path to independence from fuel oils and reliance on the natural environment [7].

The global push for renewable energy is primarily driven by two factors: the urgent need to address climate change and governments' commitment to establishing secure and sustainable power sources [8]. Recognized as vital for the future, renewable energy harnesses natural phenomena such as sunlight, wind, rain, tides, waves, and geothermal heat [9].

The complexity and uncertainty surrounding these technologies and their applications require an effective distributed energy system planning tool for decision-makers [10]. Proper assessment of their potential is vital for planning and promoting renewable energy technologies [11, 12]. To manage this complexity, modern spatial planning relies closely on the integration of Artificial Intelligence and spatial optimization tools within Multi-Criteria Decision Analysis (MCDA) frameworks, notably for micro-siting energy units while mitigating surrounding environmental risks [13]. Matching technical viability with regional water, energy, and food demands requires smart innovation practices tailored specifically to the vulnerable river catchments within the Vhembe District Municipality [14].

As a result, wind energy, being clean, abundant, affordable, and environmentally preferable, has gained prominence globally and is among the fastest-growing renewable energy sources [15]. Major wind energy projects in South Africa are primarily located along the coast, especially in the Western Cape, the Eastern Cape, and the Northern Cape.

Before constructing a wind farm, a detailed verification of specific wind conditions at the site is essential. The assessment will compare wind energy generated, estimated, and potential use for power generation at selected sites.

Wind energy is a renewable energy source that has the potential to generate significant amounts of electricity [16]. However, wind energy output at any given location is highly unpredictable, fluctuating significantly by the day, hour, or even minute. This makes it challenging to accurately forecast how much energy a wind turbine can generate. Therefore, various wind energy estimation models are essential to predict the amount of energy produced by a wind turbine in a specific area [17]. Recent comprehensive literature reviews have stressed that mapping regional atmospheric behaviour requires an adaptive blend of advanced predictive tools and extreme value metrics to circumvent the limitations of traditional fixed parametric distributions across evolving micro-climates [18]. Furthermore, this is crucial when scaling down national infrastructure data to specific municipal layers where regional constraints often disrupt grid assumptions [19]. This paper presents an assessment of the district's wind energy potential using various methods. The statistical methods used include wind speed measurements from meteorological and wind data, application of the Weibull distribution and estimation using the power curve of a wind turbine, together with modelling using the Geographic Information Systems (GIS) and Remote Sensing (RS) technique to map wind potentials in area.

2. Materials and Methods

2.1. Study Side for Wind Energy Assessment

The Vhembe District, located in South Africa's Limpopo Province Figure 3 is a mountainous, subtropical region with an average altitude of 1,500 meters above sea level. It experiences hot summers and mild winters. The district's average annual wind speed of 10 m/s falls within the ideal operational range for wind turbines (8 to 12 m/s), indicating significant potential for wind energy generation. Despite this, the full extent of the Vhembe District's wind energy potential remains unassessed [20-28]. This regional gap is further pronounced when observing broader trends where deep learning models combined with generalized extreme distributions are increasingly necessary to forecast the short- and long-term wind profile stability specific to the Limpopo Province [20, 29]. Additionally, downscaled climatological projections for the province indicate rising multi-hazard weather volatility, making robust structural estimation models mandatory for any long-term sustainable infrastructure asset deployment [12, 21, 30-34].

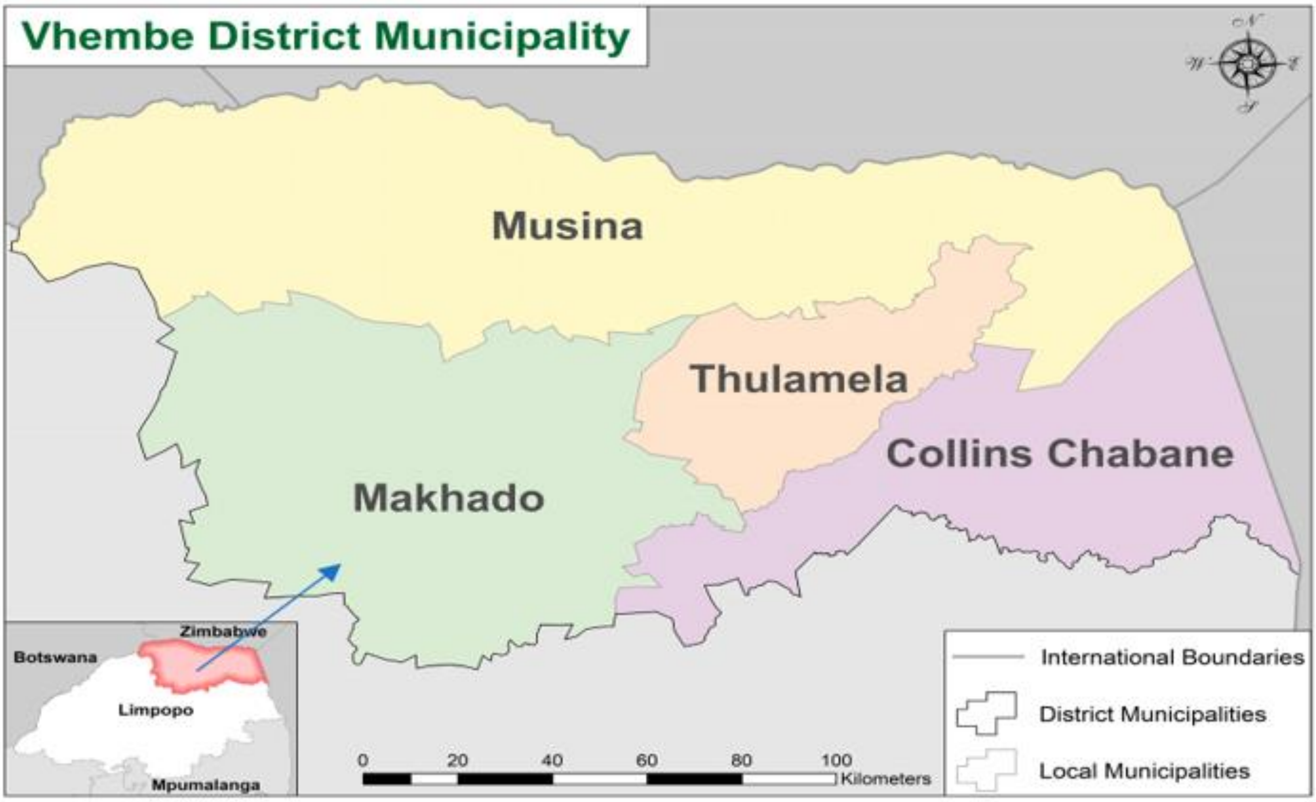

Figure 3.
The Vhembe District and its four municipalities.

The district has four municipalities with limited electricity connectivity and faces energy challenges, especially in their socio-economical balance. The area is situated at 22.7696° S Latitude, 29.9741° E, 25 Longitude of the Limpopo Province, and 250m above mean sea level [21, 22, 35].

2.2. Geographical Meteorological and Wind Data

The statistical model uses historical wind speed data to predict the future wind speed. This model estimates a location's wind energy potential by using historical weather and wind data, and it's relatively simple to create and use.

The assessment and estimation of the wind energy deployment was focused on the 10-meter height allowance for typical wind farm systems, data assessment, capacity, annual energy, and energy outputs.

The collected wind power data are typically in time series format, with each data point representing the average wind power over a year. The weather conditions and data sources were harvested from January to December 2018 (including daily, monthly, seasonal, and yearly variations during the measurements and recordings) to obtain measurements of the wind average to be used in determining wind potential. The wind speed was obtained from the installed stations at the Thohoyandou (coordinates: -23.0790, 30.3830) and the Tshivhasie Tea Venda (coordinates: -22.9700 30.3500) at an average wind direction from Degree North. These wind speed measurements were periodically extracted during 08h00, 14h00, and 20h00, as shown in Table 1.

Table 1.
The Installed Wind Speed locations and lands.

Wind Station Name	Longitude (°, E)	Latitude (°, N)	Elevation (m)	Land Cover
Thohoyandou	23.0790	30.3830	614	Urban
Tshivhasie Tea Venda	22.9700	30.3500	967	Sparse forests

2.3. Wind Speed Modelling Using the Weibull Distribution

Analysing a location's wind patterns is a crucial first step for any wind energy project. The cost of electricity generated by wind turbines relies heavily on the available wind resources, making it essential to understand both wind speed and direction at a site before making development decisions.

Predicting wind speed is difficult because it changes so much, not only from place to place but also from moment to moment. However, the way wind speed varies at a specific location can be described using a probability distribution, which shows how likely different wind speeds are to occur. The Weibull distribution, for instance, is commonly used to express this likelihood, as shown in Equation 1: -

$$\mathrm{f}(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \times \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (1)$$

In the given formula, f(v) represents the probability density function of wind speed, v is the wind speed, k is the shape parameter, and c is the scale parameter (representing the number of hours in a year).The two-parameter Weibull distribution is particularly useful for assessing wind energy because it accurately captures how wind speed data is skewed. This distribution relies on two key parameters:

1. Shape parameter (k): This dictates the shape of the distribution. A higher k value means the distribution has a longer "tail" towards higher wind speeds.
2. Scale parameter (c): This controls the overall scale of the distribution, with a higher c value indicating generally higher wind speeds.

The Weibull distribution is well-suited for modelling wind speed data since strong winds are uncommon in most regions. Consequently, it's widely adopted for predicting wind energy potential. Table 2 presents the recorded wind speed data for a year at a specific location, as collected by weather stations.

Table 2.
The wind speed data over a period of a year.

Wind speed (m/s)	Frequency (Hz)
2	10
3	20
4	30
5	40
6	50

2.4. Wind Energy Potential Using the Power Curve

The power curve is an essential tool for estimating a site's wind energy potential. For the Vhembe District assessment, this graph illustrates the relationship between wind speed and the electricity output of a specific wind turbine at varying speeds. Manufacturers typically provide these curves. To estimate the wind energy potential, historical wind data, obtained from the wind speed distribution, was used. Figure 4 displays an ideal power curve for a wind turbine.

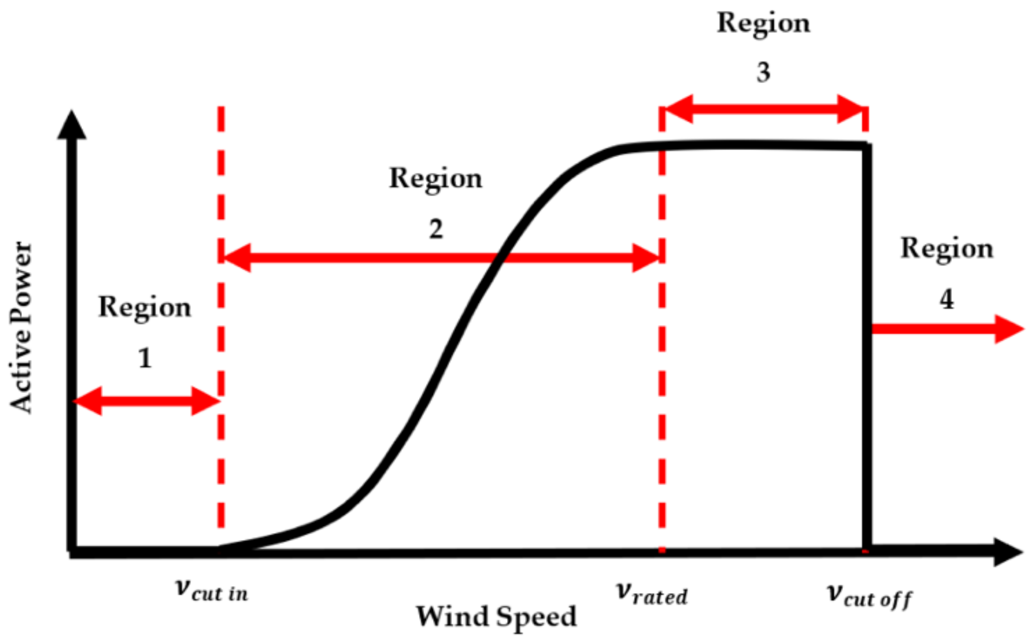

Figure 4.
The ideal power curve of a wind turbine.

On the graph, the x-axis represents wind speed in meters per second (m/s), while the y-axis shows the turbine's power output in megawatts (MW). It is used to estimate the amount of energy that the turbine can produce at any x-y axis as determined at any point to the power output. Equation 2 is used to estimate the wind energy potential:

$$(E_w) = (f(v) \times \alpha) \times l \quad (2)$$

Here, f(v) represents the Weibull distribution function. α is the power curve coefficient provided by the wind turbine manufacturer, and l is the turbine size in meters (m). The resulting wind energy potential is measured in kilowatt-hours (kWh) per year.

3. Results

3.1. The Weibull Distribution of Wind Speed

We used the Weibull distribution to estimate the likelihood of various wind speeds occurring in the area. The optimal parameters for this distribution are a=2 and b=3. This indicates that the distribution features a prolonged tail of high wind speeds, and the average wind speed is 10 m/s. Figure 5 illustrates the Weibull distribution of wind speed for the Vhembe District.

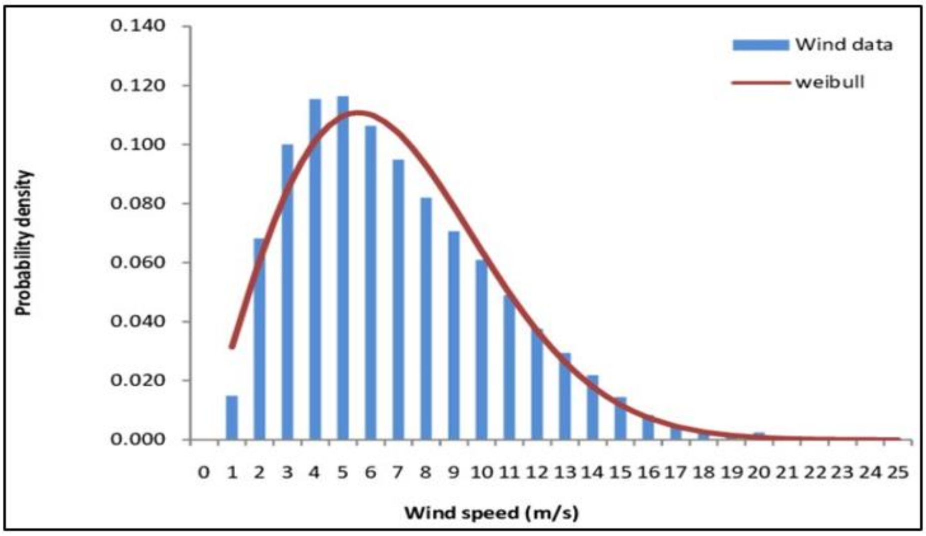

Figure 5.
Weibull distribution of wind speed for the Vhembe district

Figure 6. Displays the cumulative distribution function of wind speed for the Vhembe District.

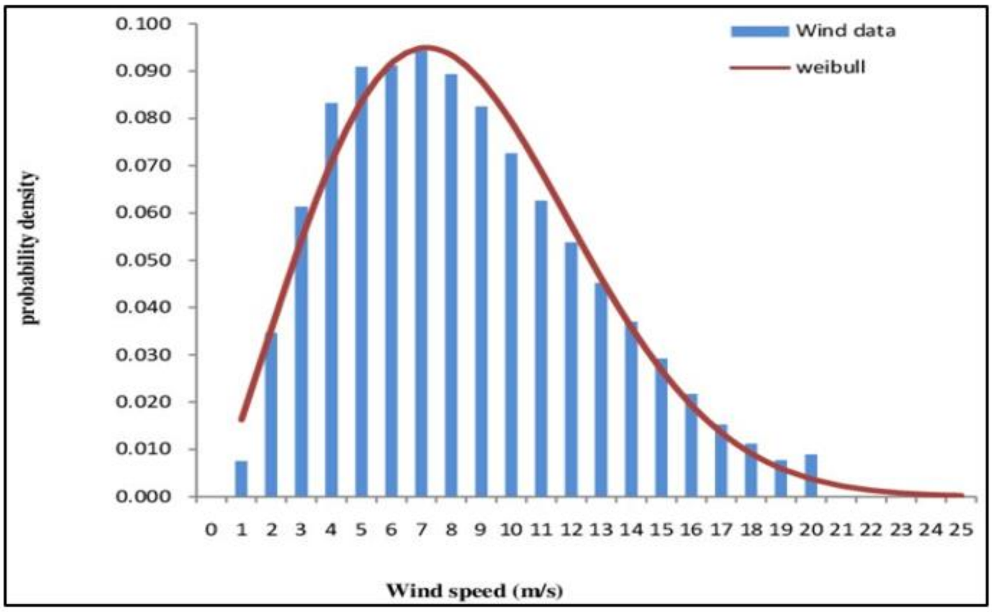

Figure 6.
The cumulative distribution function of wind speed for the Vhembe district

The Weibull distribution is a powerful tool for modelling wind speed data. It helps estimate the likelihood of various wind speeds, which is crucial for designing wind turbines and calculating the energy output of a wind farm.

3.2. Power Curve for the Wind Energy Assessment

The power curve is a valuable tool for estimating a site's wind energy potential. To get an accurate assessment, it's crucial to use the power curve alongside other factors, such as the wind speed distribution. Table 3 and Figure 7 illustrate the power curve used for the wind energy assessment in the Vhembe District.

Table 3.
The distribution of the power output against the wind speed.

Wind speed (m/s)	Power output (kW)
2	0
4	5
6	15
8	30
10	50
12	100
14	80
16	60
18	40
20	20

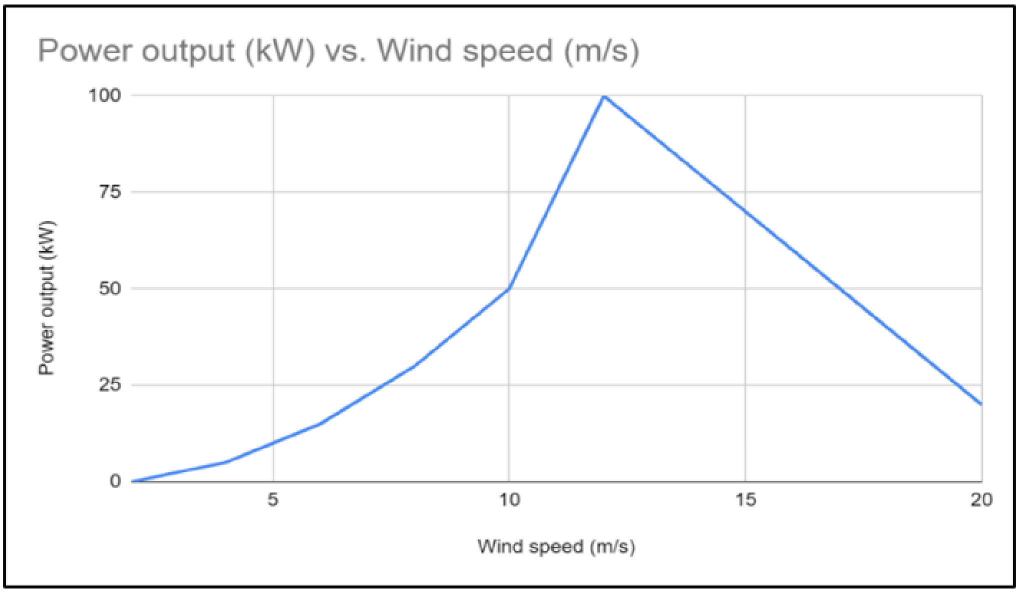

Figure 7.
The power curve for the wind energy assessment in Vhembe district area.

It's important to remember that the wind energy potential estimated for the Vhembe District relies on certain assumptions, like the average wind speed and the wind turbine's power curve. Because of this, the actual amount of wind energy that can be generated might be higher or lower than our estimate.

3.3. Geographic Information Systems (GIS) and Remote Sensing (RS) technique

As such, Figure 8 to Figure 11 show the four geological local municipalities' wind speed potentials obtained from the GIS map at the study site. Furthermore, it is recorded that the weather and climate data were obtained from the South African Weather Services and Water Research Commission (WRC) Department.

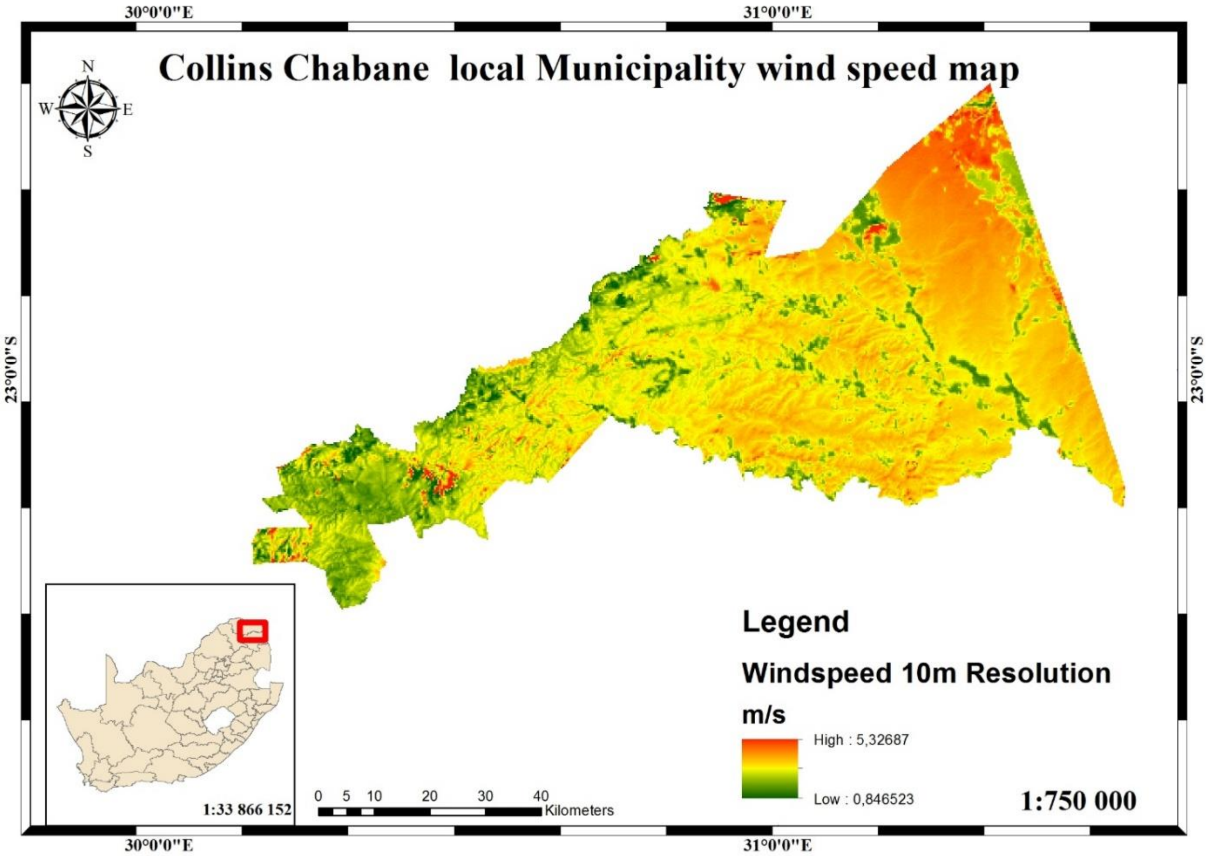

Figure 8.
The Collins Chabane wind speed map.

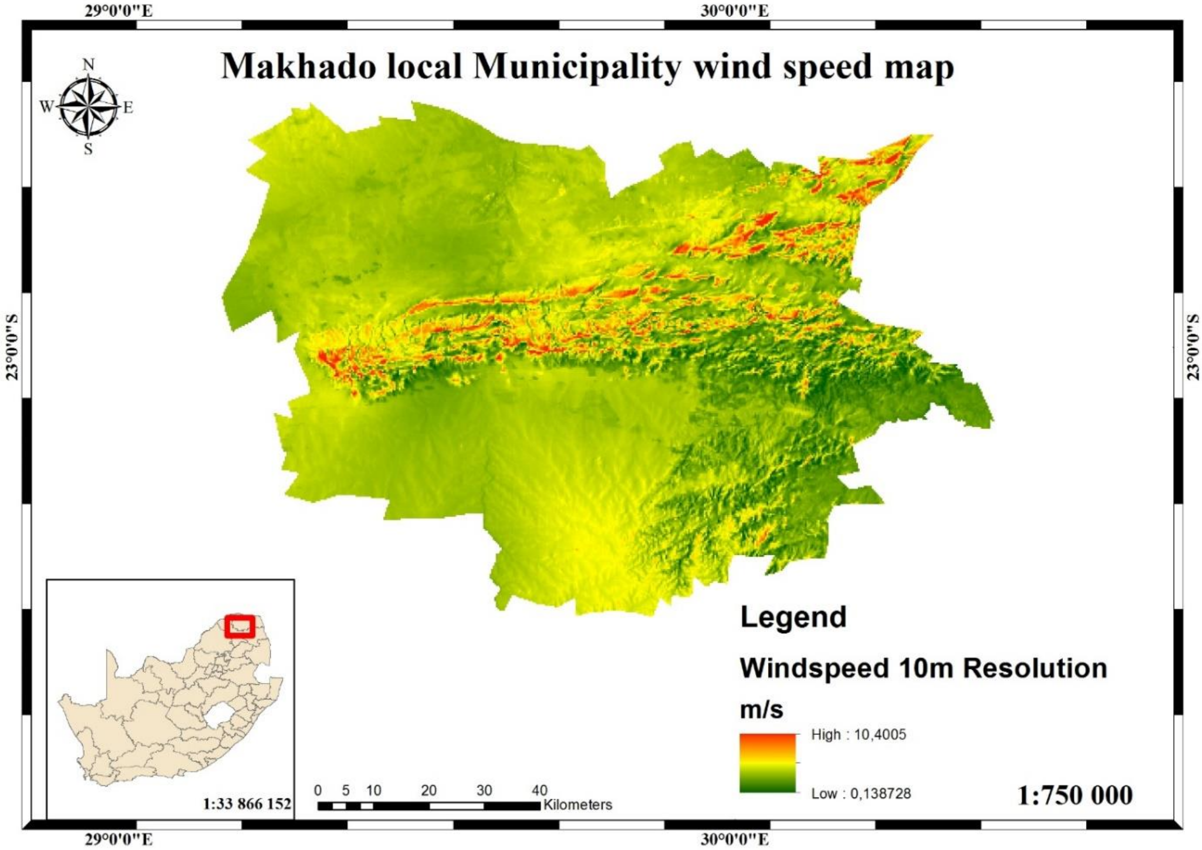

Figure 9.
The Makhado wind speed map.

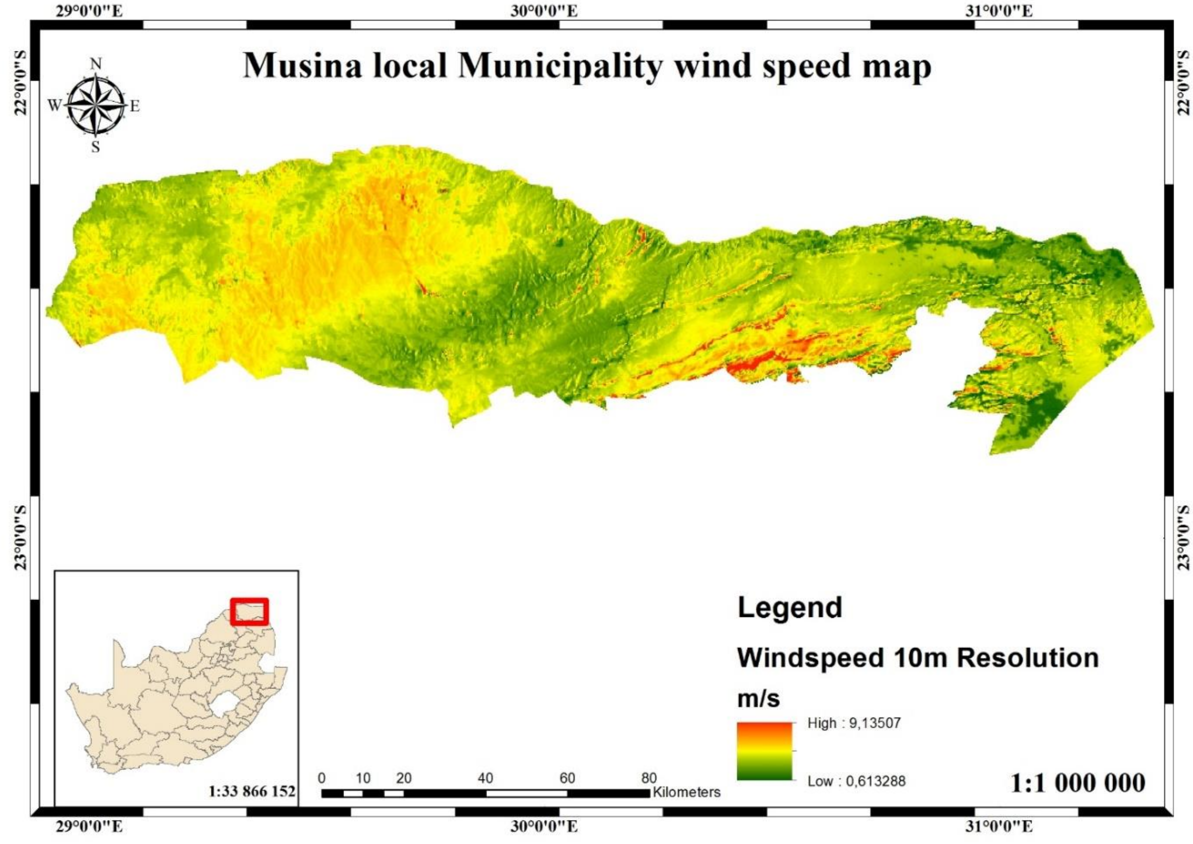

Figure 10.
The Musina wind speed map.

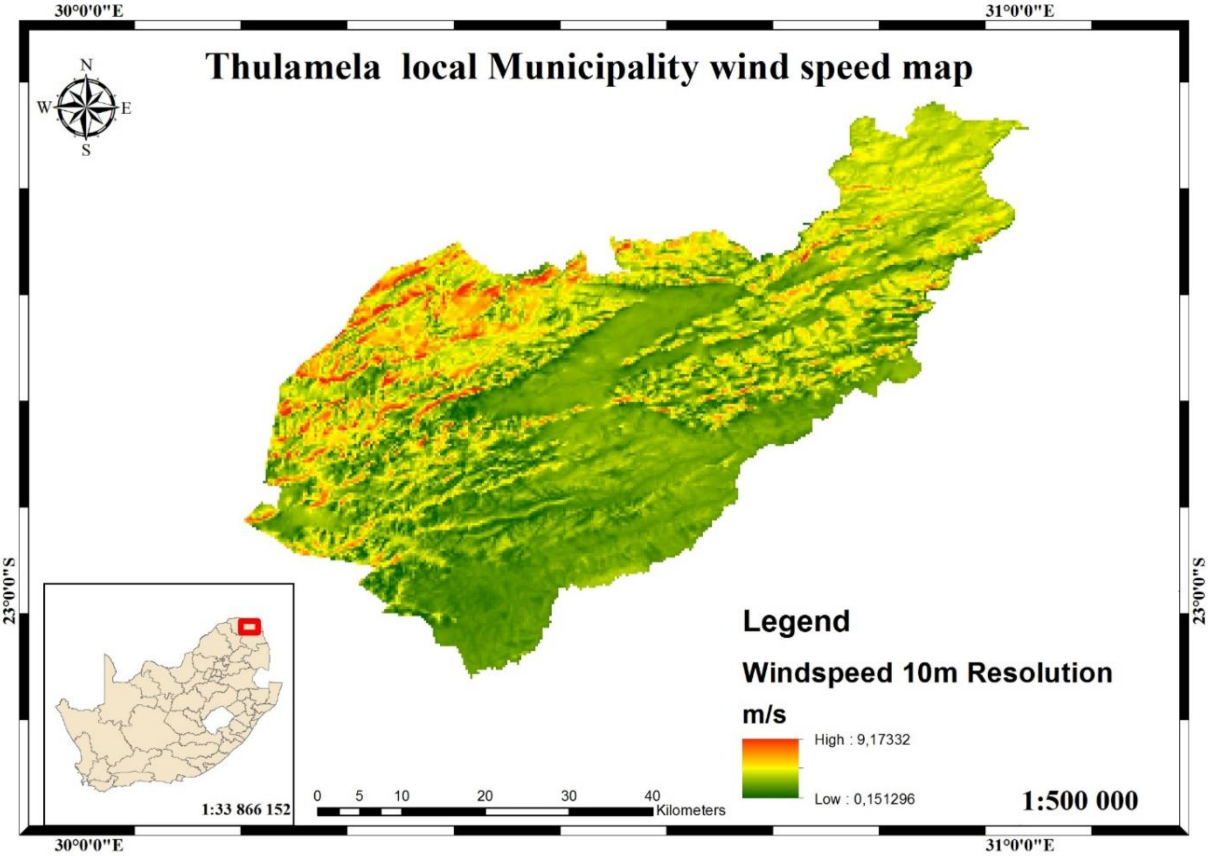

Figure 11.
The Thulamela wind speed map.

3.4. Wind Energy Mapping and its Meteorological Data Variations

In determining the wind speed potential in the Vhembe District, various measurements were conducted and recorded to estimate its energy potential. During the analysis of the data captured from the installed weather stations, it was indicated that the wind directions were from true north to clockwise with available ranges where applicable. Table 4 shows the wind direction ranges in the Vhembe district. In determining the average wind speed, the recordings were done three times during the day, morning, afternoon, and night, to obtain variations due to the humidity. These ranges were recorded during 8:00 am, 14:00 hours, and 20:00 hours. As a result, several wind analyses were obtained as indicated by the period measured. The wind measured during the early morning differs from one during the day and in the evening, as illustrated by the graphs.

Table 4.
The Wind Speed direction and coordinates.

N dir>=348.75 OR dir < 11.25	NE 33.75 to 56.24
E 78.75 to 101.24	SE 123.75 to 146.24
S 168.75 to 191.24	SW 213.75 to 236.24
W 258.75 to 281.24	NW 303.75 to 326.24

Note: Where N – North, S – South, W – West, E – East.

The daily wind measurement and analysis were obtained during the morning hours, midday, and evening monthly throughout the year. Hence, the graphs show three different sizes per location per time.

As a result, the meteorological spatial information and analysis become more critical in determining its temporal data, landscape, and coverage to obtain its evaluation for potential use. Thus, it becomes the study's primary aim in the Vhembe district to assess its wind potential. This study was carried out at a 10-meter height, and all assessments, mappings, and modeling were carried out at different locations with the installed wind speed stations for data collection.

3.5. Wind Energy Estimation and Its Potential

The wind energy potential obtained with the data produced has been taken from the north degree clockwise from 08:00 am, 14:00, and 20:00 to determine the wind speed within the area. The climate data and diagrams of the sites were taken from the data collected from the study sites over the two years, from January to December 2018. The basic formula calculates the energy potential, as Equation 3 shows. That is, the work done is multiplied by the time spent.

$$E_w = P_w \text{ x } T_w \quad (3)$$

The E_w, P_w, and T_w are the wind energy measured in watts (W), wind power density, and the total time (in hours) spent. When the average wind energy is measured throughout the year per specified area (A) at 1 meter perpendicular (or proportional) to the wind speed (U), the annual wind power estimation is obtained by Equation 4.

$$P_w(u) = \frac{1}{2}\rho A U^3 \quad (4)$$

The specified area is determined at $1m^2$ total area (A) of wind power per specified area. As a result, the average wind power density (P_w) measured per selected area through the natural air density (ρ) is assumed at 1,225 kilograms per cubic meter (1,225kg/m^3). This is a constant used for the average air density. Hence, the final wind power density will be determined by Equation 5.

$$P_w(u) = \frac{1}{2}\rho U^3 \quad (5)$$

In applying the most straightforward method on wind power density and its potential, Kishore [31] and Youm, et al. [32] mentioned that the Weibull Methodology is a suitable formula to be applied. This formula determines the average wind power density obtained in a specified area proportional to the wind speed.

In this study, as chosen for the Vhembe District, the wind speed and direction data were obtained from the South African Weather Services (SAW) and the installed Agricultural Research Council (ARC) weather station from January to December 2018, and it is illustrated in Table 5 for the wind average measurement.

An algorithmic wind estimation on hills and ridges needs to vary from theoretical analysis and logarithmic tests to determine the wind profile. Hence, measuring wind speed at height is essential for suitable wind models and estimation. As a result, the following characteristics are considered: -

1. Height above the ground (in meters).
2. Wind speed (in m/s), height above the ground (in meters).
3. Wind speed (in m/s), Roughness length of the surface zone (z0).

Table 5.
Monthly average wind speed at 10m height.

Month	Average Wind Speed at 10m Height (m/s)
January	3.0
February	3.0
March	2.8
April	2.6
May	2.4
June	2.6
July	2.8
August	3.0
September	3.0
October	3.0
November	2.9
December	2.9

The wind profile algorithmic at rough estimation, the vertical wind profile is obtained in Figure 12. The obtained wind speed profile comes from the established 10m height and the average wind severity speed of 2,8m/s through the year to get the district's average wind power density.

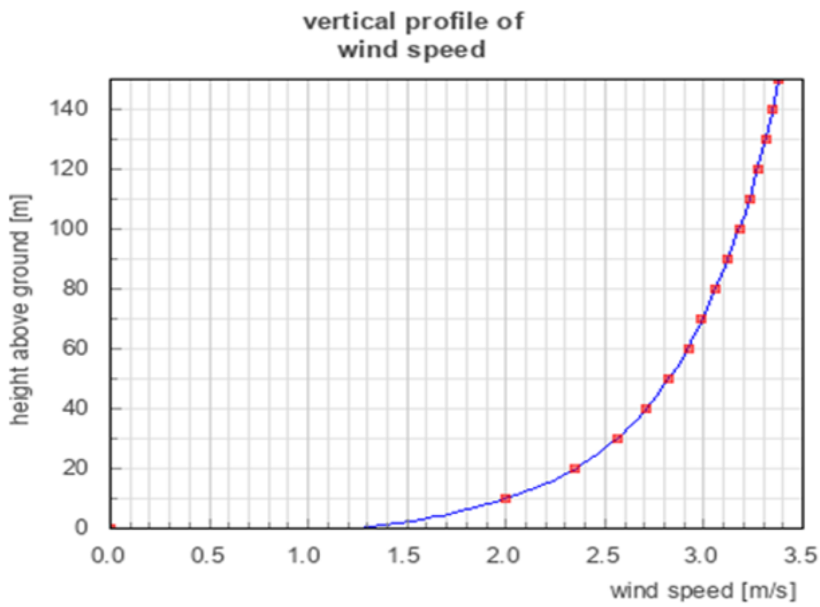

Figure 12.
The wind profile speed is under 10m in height above the ground.

These parameters are used in Table 6 to determine a specific location with specific land cover types and zones.

Table 6.
Wind profile characterization for wind turbines.

Roughness Class	Roughness Length z_0	Land cover types
0	0.0002 m	Water surfaces: seas and Lakes
0.5	0.0024 m	Open terrain with smooth surface, e.g., concrete, airport runways, mown grass, etc.
1	0.03 m	Open agricultural land without fences and hedges, maybe some far-apart buildings and very gentle hills
1.5	0.055 m	Agricultural land with a few buildings and 8 m high hedges separated by more than 1 km
2	0.1 m	Agricultural land with a few buildings and 8 m high hedges separated by approx. 500 m
2.5	0.2 m	Agricultural land with many trees, bushes, and plants, or 8 m high hedges separated by approx. 250 m
3	0.4 m	Towns, villages, agricultural land with many or high hedges, forests, and very rough and uneven terrain
3.5	0.6 m	Larger towns with high buildings
4	1.6 m	Large cities with high buildings and skyscrapers

For further investigation, it was essential to determine the area's air density (ρ) to obtain the wind power profile using the on-site measurements. Equation 6 shows this air density: -

$$\rho = a \times e^{-b.z} \quad (6)$$

The exact air density (ρ) calculation is obtained by measuring the air pressure (a) of the specified location, temperature (b), and humidity (z) from the meteorological stations installed at the sites. The material analysis, wind energy mapping, and analysis were conducted using the installed weather stations, namely, the Thohoyandou Station and the Tshivhasie Tea Venda Station.

3.6. Wind Energy Potential

At a wind speed (v), reference to Fig. 9, the available energy per unit area perpendicular to the wind stream over a given period (t) is expressed by the kinetic energy flux as shown by Equation 7 [11]:

$$E_a = 0.5 \times \rho \times v^3 \times t \quad (7)$$

Where ρ is the air density (kg/m3), and Ea is the total theoretical energy available for working with the wind turbine as a fraction of the total energy.

The maximum extractable energy of a system working at its optimum efficiency is limited by a coefficient of performance called the Betz limit (16/27 = 0.593). This capacity factor makes the extractable energy approximately 59.3 % of the theoretical energy and is given by Equation 8 [25]:

$$E_m = 0.2965 \times v^3 \times t \quad (8)$$

4. Results and Discussion

The Weibull distribution is used to estimate the probability of different wind speeds occurring in the area. The best-fit parameters for the Weibull distribution are a = 2 and b = 3. This means that the distribution has a long tail of high wind speeds and that the average wind speed is 10m/s. The Weibull distribution can be used to estimate the amount of energy that a wind farm can produce. Recent comparative evaluations of South African wind regimes confirm that while the standard two-parameter Weibull model remains highly efficient, its accuracy is significantly improved when benchmarked directly against alternative models such as Rayleigh, Gamma, or Gumbel distributions to fit complex inland geographical profiles [13, 14, 18, 19, 29, 34, 36-42]. This performance enhancement aligns with spatial mapping trends across sub-Saharan Africa, which advocate for decentralised, data-driven planning systems to optimise household-level and economic grid access within remote municipalities [17]. The amount of energy that a wind farm can produce depends on the average wind speed, the shape parameter of the Weibull distribution, and the scale parameter of the Weibull distribution.

The average wind speed in the Vhembe district area is 10 m/s. This is within the ideal range for wind turbines, which typically operate at their best between 8 and 12 m/s. The wind speed distribution in the district is also favourable, with a long tail of high wind speeds. This means that there are many hours per year when the wind is blowing at a speed that can generate electricity from wind turbines. The windiest month in the Vhembe district is October, with an average wind speed of 11.5 m/s. The calmest month is May, with an average wind speed of 8.5 m/s.

As such, in the area, an annual recording of the wind data was done throughout the year (from January to December 2018) with properties in Table 7. The wind setup and development at 10m height was considered the average and standard measurement for wind estimation and power. Data from selected stations were analyzed using the Weibull probability distribution with two parameters. The wind data obtained has been used for wind estimation, assessment, calculation, and modeling.

Table 7.
The parameters used for wind measurement.

Property	Value
Mean speed	4.115395(m/s)
Weibull parameter A	4.6(m/s)
Weibull parameter k	1.64
Air density	1.227 (kg/m^3)
Median speed	3.678749(m/s)
Max. freq.	0.1671578(%)
Speed of max. freq. (Modal speed)	2.591627(m/s)
Speed of max. power density	7.479808(m/s)
Variance	6.629131
Max. power density	13.5761(W/m^2)
Total power density	102.625(W/m^2)

As a result, wind energy in the area may be used to pump water or other mechanical applications and generate electricity. In this assessment, it has been shown that the wind turbines mounted on a tower at 10 m above the ground would capture the most wind energy in the region.

5. Conclusions

This paper provides a fundamental overview of wind as a renewable energy source for generating electricity. It also offers straightforward methods and analytical tools for rapidly estimating the amount of energy available at a specific wind site.

During the study, the statistical model was used to consider several factors, including wind speed, wind direction, air temperature, and humidity, to determine the amount of electricity that can be generated from wind turbines. This wind estimation model is a valuable tool for assessing the wind energy potential at a location and planning the development of wind farms.

In addition, the Weibull distribution is a powerful tool for modeling wind speed data and estimating the amount of energy that a wind farm can produce.

Wind energy estimation models are essential tools for wind turbine owners and operators. These models are valuable tools for planning, forecasting, and policy development in the wind energy industry. The accuracy of a wind energy estimation model depends on several factors, but it can be used to provide a reliable estimate of the amount of wind energy that can be generated at a given location.

The paper concludes with a call for further research on the wind energy potential of the Vhembe District and the development of a roadmap for the deployment of wind energy in the district. The development of wind farms in the district would help to reduce South Africa's reliance on fossil fuels and contribute to the country's carbon emission reduction goals. We recommend that wind energy assessments consider long-term variations in local wind conditions rather than focusing solely on current energy output.

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