Wind energy and energy potential assessment on Ambon Island

Lory Marcus Parera[1], Abhi Rizky Heluth[2], Mey Chyntia Yesaya[1], Johanis Leuwol[1]
[1]Department of Electrical Engineering, Ambon State Polytechnic, Ambon, Indonesia
[2]Department of Public Works, South Buru District Government, Ambon, Indonesia

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ABSTRACT

Ambon Island has a high dependence on fossil fuels, which causes environmental and energy security problems, even though the potential for renewable energy, especially wind, is enormous according to national energy plan data. This study aims to assess the technical and economic feasibility of wind energy development in Latuhalat Village as a case study. Wind speed and direction data for the period January-December 2024 from the Ambon Maritime Meteorological Station were analyzed, showing that the prevailing winds are from the east and southeast. Assuming an air density of 1.225 kg/m³, a turbine efficiency of 35%, and a rotor sweep area of 78.54 m², the estimated annual energy reaches 24,528 kWh. A capacity factor of 30% results in a realistic output of 7,358 kWh/year. A horizontal-axis wind turbine with inverse taper blades is recommended to suit local wind characteristics, producing 0.7-46.8 kW of power with a system efficiency of 67%. This study concludes that Latuhalat Village has viable wind energy potential for further development. Its implementation requires a holistic approach encompassing technical, economic, social, and policy aspects to support sustainable energy transition on Ambon Island.

Corresponding Author:

Lory Marcus Parera
Department of Electrical Engineering, Ambon State Polytechnic
Jl. Ir. M. Putuhena, Wailela Rumahtiga Ambon, Indonesia
Email: lorymarc8@gmail.com

1. INTRODUCTION

Ambon Island is currently still heavily dependent on fossil fuels, especially in meeting the electricity needs of the community. This dependence causes a number of problems, ranging from environmental pollution due to greenhouse gas emissions to the risk of energy supply instability due to fluctuating fuel prices and availability [1]. On the other hand, the potential for developing renewable energy such as wind energy is actually very promising. According to data from the National Energy General Plan, the potential for new and renewable energy, including wind energy in Maluku, could reach 3,188 MW, but it has not yet been optimally utilized [2]. One of the main obstacles is the limited availability of accurate and comprehensive data on wind energy potential in Ambon Island, where the available data is still scattered and not standardized. This complicates the planning and decision making process for the construction of wind power plants. In addition, the lack of comprehensive technical and economic studies on the feasibility of wind energy development in certain areas is also an obstacle to promoting sustainable energy transition on Ambon Island [3].

Based on meteorological and climatological data, the Ambon City area has relatively stable wind speeds throughout the year, especially in coastal and upland areas. The average wind speed in this region ranges from 4-7 meters per second, which is an adequate range for the operation of wind power plants. In addition, tropical climate conditions with consistently blowing sea breezes are a major supporting factor in the development of wind energy [4].

The potential of wind energy in Ambon City is also supported by central and local government policies that encourage the utilization of renewable energy. The Indonesian government has set a renewable energy mix target of 23% by 2025, and the development of wind power plants in areas wind such as Ambon can be a significant contributor to achieving this target. In addition, the utilization of wind energy is also in line with efforts to reduce greenhouse gas emissions and support sustainable development.

To develop a renewable energy project, Dore *et al.* [5] a technical and economic feasibility analysis is required. However, studies on this subject are still minimal, especially for the Ambon Island region. Nevertheless, with the support of increasingly advanced technology and the government's commitment to encourage renewable energy investment, the potential for wind power generation in Ambon City can be a promising energy solution to meet the electricity needs of the community and support regional economic growth.

Industrial growth in any country depends on creating a balance between energy production and consumption. Energy production in turn depends on the availability of renewable and non-renewable energy resources. Reliable estimation of wind potential for the location under study requires a thorough understanding of wind characteristics. This has motivated researchers around the world to conduct studies using short-term and long-term wind speed data by using appropriate mathematical functions and distributions to model the measured wind speed data. This provides reliable wind power estimation of the site for efficient wind farm planning and installation [6].

Using the calculated scale and shape parameters, the most likely most frequent wind speed for a given wind probability distribution, and the wind speed that carries the maximum energy (VMaxE) can be calculated (1) and (2) [7]:

$$V_{MP} = C\left(\frac{K-1}{K}\right) \quad (1)$$

$$V_{MaxE} = C\left(\frac{K+1}{K}\right) \quad (2)$$

As the objective of this study was to investigate the wind energy potential of the coastal and offshore sites in Latuhalat Village, Ambon City, it was important to calculate the wind power per unit area, known as wind power density (WPD). This determines the capacity of the wind resource at a particular location [4], [8]. This is calculated as (3):

$$\frac{P}{A} = \frac{1}{2}\rho C^3 T\left(1 + \frac{3}{K}\right) \quad (3)$$

where ρ is the density of air (1,225 kg/m^3) [4].

The wind energy potential of a location can be assessed based on wind speed and wind power density (WPD). Based on these parameters, wind potential is classified into several classes, ranging from low to very high. Table 1 shows the classification of wind energy potential based on WPD values (W/m²) and wind speed ranges (m/s).

Table 1. Wind energy scale

Wind power class	WPD (W/m^2)	Wind speed (m/s)
Poor	0-200	0.0-5.6
Marginal	200-300	5.6-6.4
Fair	300-400	6.4-7.0
Good	400-500	7.0-7.5
Excellent	500-600	7.5-8.0
Outstanding	600-800	8.0-8.8
Superb	>800	8.8-11.9

Wind power is available from the kinetic energy of moving air masses. Wind power generation systems convert wind energy into electricity using wind turbines. Only at the beginning of this century, the development of high-speed wind turbines to generate electric power has been undertaken. The amount of energy carried by the wind increases by a factor of increasing speed and is proportional to the mass of air passing through the area swept by the rotor [9], [10].

2. RESEARCH METHOD

This study was conducted in Latuhalat Village, Nusaniwe District, Ambon City, Maluku, at an altitude of ±150 meters above sea level. The main data on wind direction and speed were obtained from the Ambon Maritime Meteorological Station using an anemometer installed in the official observation area. The data covers the period from January 1, 2024, to December 31, 2024.

Selecting the right location is a determining factor in the success of a wind energy project. A poor location, even with good turbines, will produce minimal electricity. The following is the methodology for selecting a location. Topographical data [11] is the most important starting point for hilly areas such as Latuhalat. The basic principle is to take advantage of the speed-up effect. Moving air is forced upward by hills, narrows, and consequently accelerates.

The Table 2 presents the research stages used in the wind energy potential study. Each step includes the main activities, data sources or tools used, as well as the outputs and their contribution to the research objectives. These stages aim to ensure that the analysis process is carried out systematically and in an integrated manner, from site identification to the technical and energy feasibility evaluation of the planned wind turbine system.

Table 2. Structured overview of research methodology steps and their objectives

Step	Activity	Tools/data source	Output/result	Purpose/contribution
1	Site identification and characterization	Topographical survey (Latuhalat Village)	Mapping of ridges, slopes, and open fields	To determine the most promising geographical zones for wind acceleration (speed-up effect).
2	Primary data collection	Anemometer data (Ambon Maritime Meteorological Station, Jan–Dec 2024)	Wind speed (m/s) and wind direction (°) dataset	To obtain reliable meteorological records as the baseline for energy potential assessment.
3	Secondary data collection	Climatic records, land-use maps, and spatial coordinates	Complementary datasets on slope, vegetation, and settlement areas	To support contextual analysis and identify constraints for turbine installation.
4	Wind rose analysis	Wind rose plot for meteorological data (WRPLOT) view software	Monthly wind rose diagrams (Jan–Dec 2024)	To visualize wind speed distribution and prevailing wind direction trends.
5	Wind energy potential estimation	Mathematical models (wind power density, (3)–(6)	Average WPD (W/m²), expected energy yield (kWh/year)	To quantify the theoretical and realistic wind energy potential.
6	Site suitability mapping	Overlay analysis of topography and prevailing winds	Optimal sites (MS-1 hilltop, RS-2 open field)	To select the most favorable turbine installation sites based on wind exposure.
7	System performance calculation	Turbine efficiency models (Cp=0.35, Betz limit, (8), (9))	Mechanical vs. electrical output power, overall efficiency ≈67%	To evaluate the technical feasibility of wind turbine deployment.
8	Validation and feasibility assessment	Comparison with international wind classification standards (table of wind power class)	Realistic capacity factor (30%), annual energy yield ≈7,358 kWh/year	To verify results against standard benchmarks and assess economic viability.

This location can increase wind speed by 50% or more compared to the surrounding flat areas. Look for long, open ridges with a consistent slope between 15° and 30°. This slope is steep enough to accelerate the wind, but not so steep that it causes excessive turbulence.

Historical data from the nearest weather station can provide a general picture of the predominant wind direction (the most frequent wind direction) in the region. For Ambon Island, the prevailing winds often come from the east and southeast. Ideal hill locations are those that are perpendicular (normal) to the direction of these prevailing winds [12], [13]. This ensures that the hills receive the full force of the wind.

Figure 1 is a conceptual map of wind potential based on topography. This diagram is used to show how wind speed and turbulence levels are influenced by the shape of the land surface.

- Overlay Map 1: potential zones based on topograph. This map classifies village areas based on their predicted wind potential derived from landform.

This diagram shows that high open locations (peaks/ridges) have the best wind potential, while valleys and sheltered areas tend to have weak and turbulent winds. This map is very useful for wind turbine planning, meteorological studies, and environmental analysis.

Figure 2 is a flowchart that explains how to determine the best location for installing wind turbines based on the prevailing wind direction and hill topography.

- Overlay Map 2: predominant wind direction and optimal turbine position. This map combines wind direction data with topography to find the best location. The data includes wind direction from the northeast, north, south, wind reception location, and turbulence location.

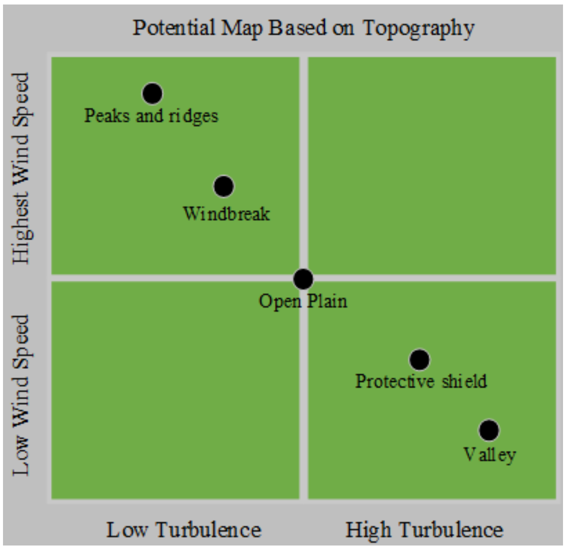

Figure 1. Overlay map of potential zones based on topography

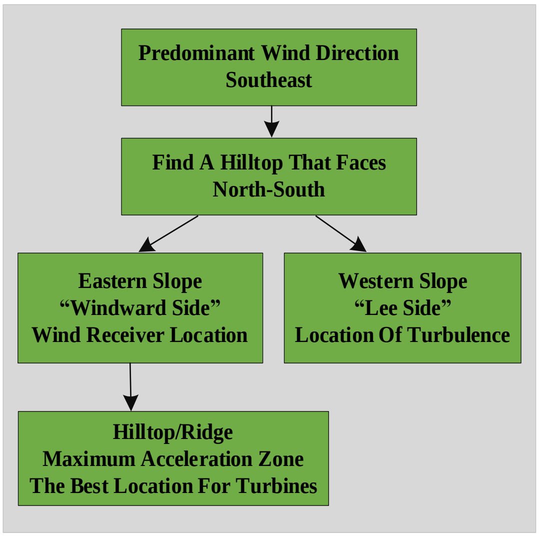

Figure 2. Overlay map of predominant wind direction and optimal turbine position

Based on map analysis, measuring stations should be placed in strategic locations to confirm predictions:

– At the Main Station (MS-1): installed at the top of the hill identified as the most promising (according to overlays 1 and 2). The minimum tower height is 30 m.
– At the Reference Station (RS-2): installed in an open field near a residential area. This data will be used as a reference to quantify the increase in wind speed at the top of the hill.

The purpose is to compare the data from MS-1 and RS-2 to provide a real speed-up ratio, which will be used as the basis for calculating energy and financial feasibility.

The direction summary algorithm needs to take the reported 10° width of the wind direction sector and give it a direction summary array (usually 22.5° wide) [14]. The STAR program, and other codes that exhibit the same directional bias, adds a value of 1 to an entry location in the summary table based on the wind direction range, wind speed range, and stability class [15], [16].

Wind direction and speed data were obtained from anemometers installed in the tool park of Ambon Meteorological Station. The software used to process and analyze wind direction and speed data is a display application WRPLOT. Wind energy, both direction and speed are calculated using the windows based WRPLOT View software that presents wind rose calculations and graphical displays that show weather variables by time and date range, according to user needs. Wind rose can also be used to show a diagram of the direction of wind movement in an area [17]. Due to local slope effects, coastal effects, tool range, and temporal variability of the wind, the calculations from wind rose do not always represent the actual wind movement in the area.

Wind conditions and speed determine rotor type and size [18]. Average wind speed starts from 3 m/s which is sufficient for small size propeller turbines, more than 5 m/s for medium wind turbines and more than 6 m/s for large wind turbines [19]. Thus, wind power systems use wind energy through turbines to generate electricity [20]. To use wind energy for electricity, the first step is to calculate wind energy using:

$$E = \frac{1}{2} m . v^2 \tag{4}$$

To get the air mass, a block of air has a cross-section with an area of A (m^2), and moves with a speed of (m⁄s) [21] then the mass of air passing through the place is (5):

$$m = A . v . \rho \tag{5}$$

with (3) and (4), the amount of power generated from wind energy can be calculated, namely:

$$P = \frac{1}{2} A . v^3 . \rho . Cp \tag{6}$$

Mechanical energy in wind turbines is obtained by converting wind energy [22]. Wind energy itself is energy generated from the movement of air masses moving from areas of maximum pressure to areas of minimum pressure, the amount of power can be written mathematically as (7):

$$Ptot = m\frac{vi^2}{2\,gc} \tag{7}$$

Various factors related to wind turbine manufacturing are affected by wind turbine efficiency [23], even the value is below Betz, which is between 0.35-0.45 (35%-45%). So mathematically the actual power and real power produced by wind turbines are as (8):

$$Pm = \varphi t\ \frac{1}{2gc}\ \rho.A.V^3 \tag{8}$$

The power that the gearbox has is also in the form of rotation, it's just that the rotation frequency is higher than the rotation of the turbine. The output side is then connected to the generator shaft. The generator has not been fully able to produce output power according to its specifications [23], [24]. There are loss factors in the form of heat dissipation and winding losses that give rise to an efficiency called generator efficiency (φgen). Therefore, the electrical power generated from wind power plants can be calculated based on (9) [25]:

$$Pe = \varphi gen.Pg \tag{9}$$

Figure 3 shows the research location in Latuhalat Village, Nusaniwe District, Ambon City, Maluku. This map illustrates the spatial structure of the village, which consists not only of settlements but also includes tourist attractions, education and training infrastructure, and science and technology infrastructure, namely the Meteorological Center, which plays an important role in collecting weather and climate data.

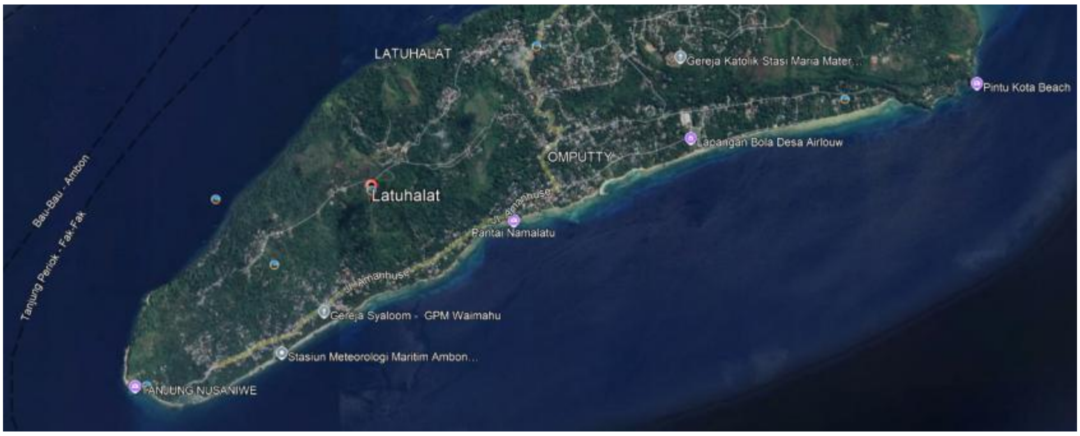

Figure 3. Geographical location of Ambon City

The existence of the meteorological station serves as a bridge connecting this map with wind energy potential analysis, as data from this station is used to calculate average wind speed, predominant wind direction, and ultimately the feasibility of installing wind turbines in the area. This map shows that Latuhalat is not just an ordinary village, but has potential that can be developed in both the tourism and renewable energy sectors.

Latuhalat Village is an area that has flat, choppy and hilly areas. The elevation of Latuhalat Village from sea level is 150 MDPL and has an area coordinate location of 24 East. Latuhalat village has an area of 13, km^2 and is located about 25.4 km west of Ambon city.

A systematic and measurable research methodology to evaluate wind energy potential, starting from data preparation and collection, analysis of wind characteristics and energy potential, determination of potential locations, to the validation stage and formulation of conclusions and recommendations, as shown in Figure 4.

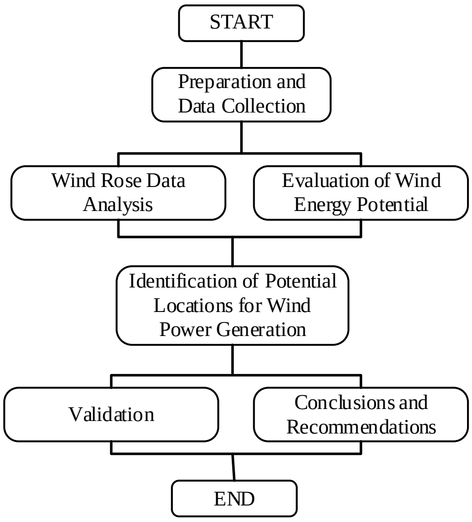

Figure 4. Research methodology

The research procedure below is designed to explain the systematic stages in analyzing wind energy potential at the study site. Each stage includes data collection, wind pattern analysis, energy potential calculation, validation, and formulation of recommendations for wind power plant development.
Research procedures:

- Data preparation and collection, including identifying the research location and its topographical characteristics, collecting wind speed and direction data from the Meteorological Station, collecting additional data on climate conditions, topography, and location coordinates.
- Wind rose analysis, which includes entering wind direction and speed data into WRPLOT software, creating wind rose diagrams to visualize wind speed and direction distribution, interpreting dominant wind patterns to determine wind energy potential.
- Wind energy potential calculation, calculating average wind speed and its distribution, calculating WPD.
- Selection of potential sites based on prevailing wind direction, topography, and accessibility.
- Data validation through simulation and comparison with wind power plant feasibility standards.
- The next step is to draw conclusions based on the results of the wind rose analysis and energy potential calculations, and provide recommendations for the development of wind power plants in the most potential locations.

3. RESULTS AND DISCUSSION

Valid wind data was obtained from the Ambon Maritime Meteorological Station. The data period used in this study starts from January 1, 2024 to December 31, 2024. The wind rose diagram created in this study is divided into monthly periods to determine the distribution of wind direction and speed each month. The following is presented the monthly windrose diagram in Latuhalat Village.

Figure 5 shows that the most wind direction that occurred in January 2024 in Latuhalat Village came from the Northwest with a percentage of 68% with an average wind speed of 5.6 m/s. The highest wind speed of 8.6% from the Northwest was on January 16 and 20, 2024. Figure 6 shows that the most wind direction that occurred in April 2024 in Latuhalat Village was still from the Northwest with a percentage of 43.7% with an average wind speed of 4 m/s. The highest wind speed of 7 m/s from the Northwest was on April 6, 2024.

Figure 7 shows that the most wind direction that occurred in August 2024 in Latuhalat Village was from the Southeast with a percentage of 48.9% with an average wind speed of 7.3 m/s. The highest wind speed of 12 m/s from the East was on August 21, 2024. Figure 8 shows that the most wind direction that occurred in December 2024 in Latuhalat village was from the Northwest direction with a percentage of 48.9% with an average wind speed of 5.3 m/s. The highest wind speed was 10 m/s from the Northwest direction on December 1, 2024.

After looking at the monthly wind rose diagram above, the wind speed results obtained for 1 year from January to December 2024 show that there is a pattern of wind speed that goes up and down. The average maximum wind speed from January to December 2024 can be seen in Figure 9. To determine the efficiency of the wind turbine from each wind speed, the calculation of mechanical power and electrical power as calculated above for each speed from the minimum speed [5], [26] (Cut-in win speed: 3 m/s) to the maximum speed (rate power 12 m/s) can be seen in Table 3.

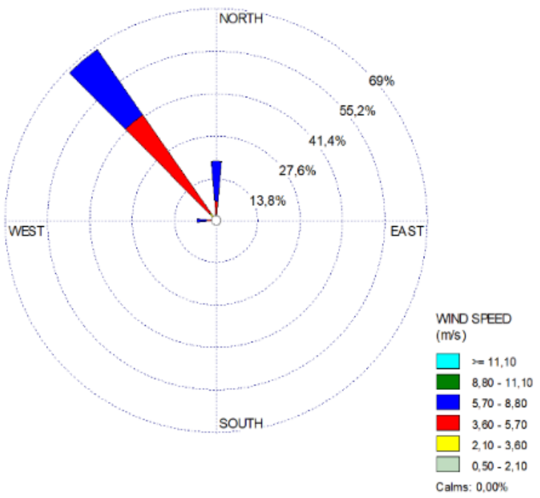

Figure 5. Wind rose diagram for January 2024

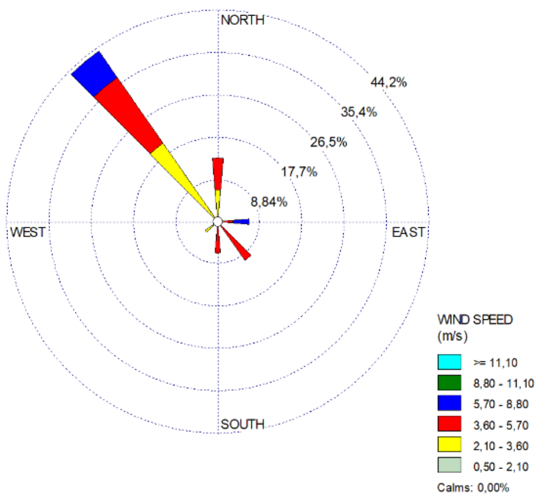

Figure 6. Wind rose diagram for April 2024

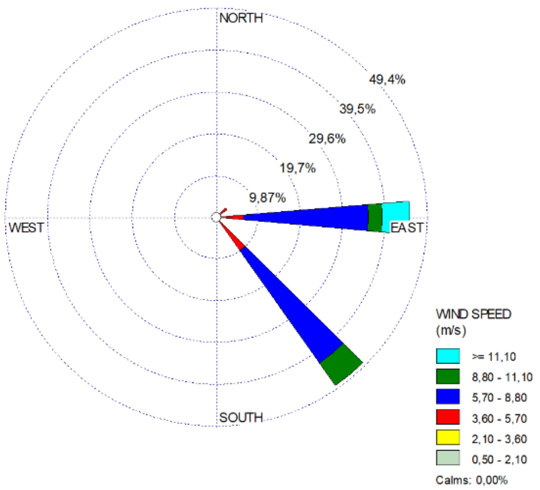

Figure 7. Wind rose diagram for August 2024

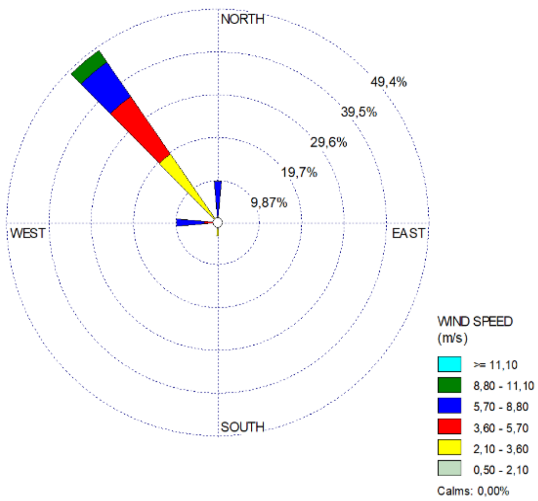

Figure 8. Wind rose diagram for December 2024

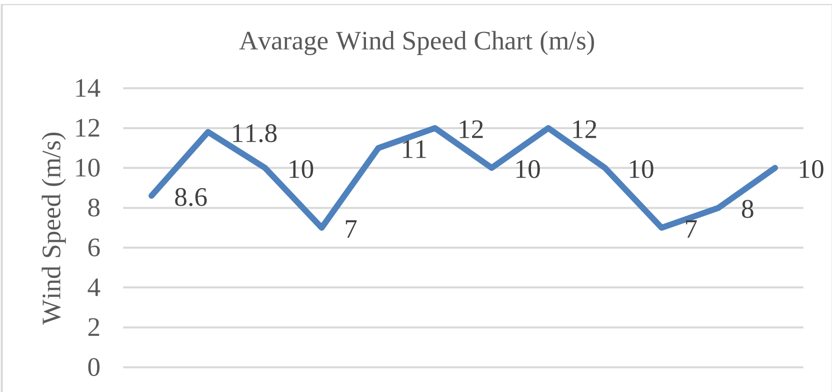

Figure 9. Monthly average wind speed graph

Table 3. Wind turbine power and efficiency at each speed

No	Wind speed (m/s)	Turbine input mechanical power (W)	Power input on the shaft (W)	Electrical power (W)	Average efficiency (%)
1	3	3094	1082	729	67
2	4	7334	2576	1738	67
3	5	14325	5013	3383	67
4	6	24753	8663	5874	67
5	7	39307	13757	9285	67
6	8	58675	20536	13861	67
7	8.6	72892	25512	17220	67
8	9	83543	29240	19737	67
9	10	114600	40110	27074	67
10	11	152532	53386	36035	67
11	11.8	188291	65902	44483	67
12	12	198028	69310	46784	67

System efficiency is calculated based on the electrical power generated by the generator, which is then compared to the mechanical input power at the wind turbine shaft. This efficiency can be greater or less than this value. This depends on the efficiency coefficient of each component. To facilitate the identification of the input and output power of this wind power plant can be made in the form of a graph in Figure 10.

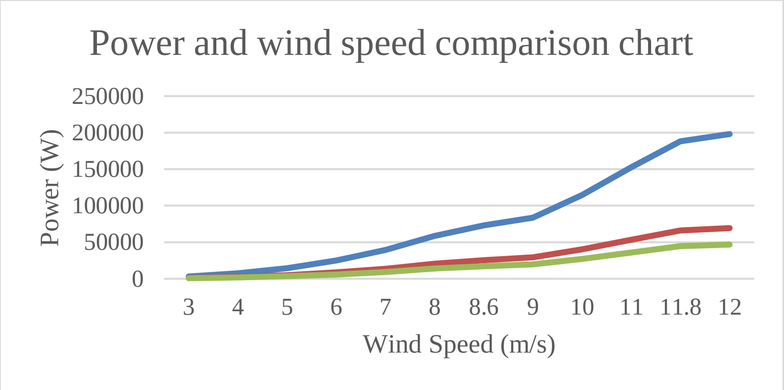

Figure 10. Power and wind speed comparison chart

From the Figure 10, it can be seen that the total power graph (blue line) has the largest value with each increase in wind speed, while the input power in the form of turbine mechanical rotation (orange line) has a lower power than the total power. This is due to the influence of wind turbine efficiency which is closely related to Betz Limits or Betz Limits which are worth a maximum value 0.53-0.6 [27]. In this turbine calculation, a Betz limit of 0.35 is used, so it is not surprising that the graph between blue and orange is quite large. The input power also decreased when converted into electrical energy [28]. This happens because there is an efficient factor in the generator and based on the calculations, the overall system efficiency is 67%. This means that the output power that can be generated is only 67% of the input power used.

To calculate the estimated annual energy yield (kWh/year) of wind turbines in Latuhalat Village, we need to know several important parameters, including average wind speed, wind speed range, and the highest wind speed that occurs several times a year.

Latuhalat Village has promising wind energy potential because its speed range covers classes with good to exceptional energy density. Its economic and technical feasibility is highly dependent on the average wind speed that can be expected throughout the year. The assumptions used are air density (ρ)=1.225 kg/m³, turbine efficiency (Cp)=35%, rotor sweep area (A)=78.54 m², and wind speed distribution can use the Weibull distribution to estimate wind speed frequency [29]. Thus, the estimated annual energy (E) can reach 24,528 kWh/year. The capacity factor of wind turbines is usually 20-40% depending on wind consistency, so E_{real}=7,358 kWh/year.

Future research on wind energy potential on Ambon Island must be holistic and applied. It is not enough to simply prove that the winds are strong; it must also address how to utilize them technically, economically, sustainably, and with the support of appropriate policies. This will ensure that this enormous potential can be converted into real clean electricity for the people of Maluku.

Wind variability in Latuhalat is quite high seasonally and topographically, but has a predictable pattern. The most suitable location for practical implementation is along open coastlines, and this location also offers a good trade-off between wind potential, accessibility, and proximity to electricity needs. In addition, dialogue with the community to begin socialization and discussion to obtain input and community support, as well as conducting feasibility studies to calculate in detail the investment costs, energy generated, and payback period.

4. CONCLUSION

The average wind speed in Latuhalat village is about 5.5 m/s and has a range of wind speeds that vary from 3 m/s to 12 m/s. The highest wind speed in Latuhalat Village from January to December 2024 was 12 m/s which occurred on June 20, 2024 and August 21, 2024 from the East.

This value was obtained after taking into account the turbine efficiency factor (35%) and capacity factor (30%), which represents the consistency of wind at that location (for example, using a Weibull distribution). These results indicate that wind energy can be a viable and sustainable renewable energy source to meet the electricity needs of Latuhalat Village.

The wind turbine used is a wind turbine with a horizontal shaft and uses blades with an inverse tapper type, in order to adjust to the wind speed in Latuhalat Village. By using the wind turbine, the capacity of the electric power generated from the generator based on the calculation results is between 0.729 kW to 46.784 kW with a wind turbine system efficiency of about 67%.

For more accurate calculations, hourly wind speed distribution data and turbine selection appropriate to local wind characteristics are required.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Lory Marcus Parera	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	
Abhi Rizky Heluth		✓				✓	✓	✓	✓	✓	✓	✓		
Mey Chintya Yesaya	✓		✓	✓			✓			✓	✓		✓	✓
Johanis Leuwol	✓		✓	✓		✓			✓	✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest, everything went smoothly and there were no obstacles that could hinder the research process.

DATA AVAILABILITY

The available data can assist the research process, and the software used, wind rose plot for meteorological data (WRPLOT), is easily accessible. However, we were previously assisted by experts working at the data collection site who provided training on how to use the software.

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BIOGRAPHIES OF AUTHORS

Lory Marcus Parera received his bachelor of engineering degree in Electrical Engineering from Atma Jaya University Makassar in 2000, and his master's degree in Electrical Engineering from Brawijaya University Malang, in 2015. He received his Professional Engineer degree from the Faculty of Engineering, Mulawarman University in 2024. He is currently a lecturer at the Department of Electrical Engineering, Ambon State Polytechnic. His research interests include new renewable energy and electric power quality. He can be contacted at email: lorymarc8@gmail.com.

Abhi Rizky Heluth received his Bachelor of Engineering degree (B.Eng.)/Bachelor of Applied Engineering (S.Tr) in Electrical Engineering (Department of Electrical Engineering) from Ambon State Polytechnic, in 2022. He can be contacted at email: abiheluth84@gmail.com.

Mey Chintya Yesaya was born in ambon, has a strong educational background in mathematics education. She earned her bachelor's degree from pattimura university majoring in mathematics education which was then continued with a master's degree in mathematics education. As an academic she have a commitment to develop my knowledge in mathematics. Currently she act as a lecturer in polytechnic who plays an active role in teaching, guiding and supporting the development of skills in mathematics. She can be contacted at email: meyyesaya@gmail.com.

Johanis Leuwol earned his bachelor's degree in Ship Mechanical Engineering at Pattimura University Ambon in 1992, and received his master's degree in Power Engineering from People Friendship University of Russia in 2013. He is currently a lecturer at the Department of Electrical Engineering, Ambon State Polytechnic. His research interests include electric power and new renewable energy. He can be contacted at email: johanesleuwol@gmail.com.