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Small-Scale Wind Turbine Selection Based on Wind Energy Potential Analysis Using Windographer

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ABSTRACT — Wind energy is a renewable resource with significant potential for generating electricity, particularly in small islands not connected to the State Electricity Company (Perusahaan Listrik Negara, PLN) grid. This study estimated the electrical energy production of small-scale wind turbines using Windographer software, based on an analysis of wind energy potential utilizing the Weibull distribution. The research focused on selecting small-scale wind turbines tailored to the wind energy potential and electricity needs of Miangas Island, North Sulawesi. The estimation of electrical energy production was conducted using the frequency distribution of wind speeds recorded hourly at a height of 50 m over the 2011–2020 period. The analysis encompasses average wind speed, wind direction distribution, Weibull distribution, average wind power density, and the annual estimation of electrical energy production. The results indicated that Miangas Island had an average annual wind speed of 5.5 m/s, with a wind speed frequency distribution of 15% and an average wind power density of 160.9 W/m². Simulations based on the analyzed wind potential demonstrated that small-scale wind turbines with capacities of 50 kW, 35 kW, and 10 kW could generate 98,434.49 kWh/year, 75,738.78 kWh/year, and 15,875.48 kWh/year, respectively. Considering the energy supply-demand balance, a 35-kW wind turbine is identified as the optimal choice to meet the annual electrical energy demand of Miangas Island, which is approximately 25,550 kWh.

KEYWORDS — Wind Energy, Wind Speed, Miangas Island, Wind Turbine, Windographer.

I. INTRODUCTION

The adoption of the 2015 Paris Agreement on climate change has significantly intensified global efforts to mitigate the impacts of climate change driven by human activities. A critical pathway to addressing this global challenge lies in expanding the use of renewable energy sources and undertaking a fundamental transformation of the existing global energy system [1]. The worldwide adoption of renewable energy has been accelerating, reflecting a strong commitment to reducing dependence on fossil fuels, which contribute significantly to global warming and greenhouse gas emissions [2]. Among renewable energy technologies, wind energy has emerged as one of the most prominent solutions for minimizing the environmental impact of energy production, particularly in reducing anthropogenic pollutants in the atmosphere [3], [4]. Additionally, case studies focusing on remote islands isolated from primary power grids demonstrate that wind energy is a highly competitive alternative to fossil fuels for electricity generation [5].

There are over 85,000 islands worldwide, with approximately 13% inhabited by about 740 million people [6]. In recent decades, remote islands have gained prominence as critical sites for designing systems powered entirely by renewable energy sources. The adverse effects of climate change, coupled with the economic challenges posed by fossil fuel-based electricity generation, are particularly pronounced in small island communities. As a result, these islands are increasingly utilized as models for evaluating renewable energy penetration rates and as pilot sites for implementing smart energy systems. Several islands have successfully transitioned to 100% renewable energy systems, setting benchmarks for global adoption. The Sams and Faroe Islands in Finland exemplify the use of entirely renewable energy sources [7]. In the Pacific, Ta'u Island and Hawaii are leading the United States in achieving 100% renewable energy targets [8]. The Galapagos Islands have established a benchmark for Latin America in achieving 100% renewable energy systems (RES) [9], while Jeju Island in South Korea serves as a testing ground for 100% RES integrated with smart grid technologies [10]. This success serves as a catalyst for Indonesia to actively advance the development of renewable energy power plants in its remote areas and small islands.

This study focused on a case study of Miangas Island, a small outermost island with an area of 3.15 km² situated near the border with the Philippines. Miangas Island is geographically located at 05° 33' 20.8'' N and 127° 09' 6.8'' E, approximately 521 km from the capital city of North Sulawesi Province, positioned between the Sulawesi Sea and the Philippine Sea. The island experiences consistently strong wind potential throughout the day, making it a promising candidate for renewable energy solutions. Currently, the island's electricity supply is generated by a diesel power plant (*pembangkit Listrik tenaga diesel*, PLTD) with a capacity of 2 × 40 kW, serving 234 household customers. The total electrical energy consumption on the island is approximately 70 kWh per day, equivalent to 25,550 kWh annually. However, extreme weather conditions and high sea waves during the rainy season (November to April) frequently disrupt the transportation of fuel to Miangas Island's dock. These disruptions often result in delays in the supply of diesel fuel (*bahan bakar mesin*, BBM) to the PLTD, causing disruption in the electricity supply for the island's community.

Therefore, there is a need for alternative electrical energy generation sourced from renewable energy, such as wind energy, to ensure the continuity of electricity supply for the residents of Miangas Island. Miangas Island, a small and remote area far from the Sulawesi PLN electricity network, faces significant challenges in accessing centralized energy infrastructure. Building an electricity network from Sulawesi is impractical, making independent energy generation on the Miangas island a necessity. Utilizing the island's renewable energy potential, particularly wind energy, offers a decentralized solution that enables local electricity production near the load centers, effectively meeting energy demands on a relatively small scale [11].

However, the significant fluctuations inherent to intermittent wind energy sources present challenges in maintaining a stable supply-demand balance [12]. Numerous studies have explored potential solutions, including interconnection, demand management, and electrical energy storage, to mitigate these instabilities [13], [14]. Power instability caused by fluctuating wind energy can lead to voltage fluctuations or voltage dips within the power grid. Even minor disruptions lasting only a few wave cycles can result in damage to critical components, such as the rotor-side converter in wind turbines [15]. Addressing the intermittent nature of wind energy requires a thorough assessment of wind potential at hourly or higher temporal resolutions. Such assessments are essential for gaining a comprehensive understanding of wind energy characteristics, including their reliability and variability across different seasons.

Wind patterns in a given location can vary significantly, with fluctuations ranging from 10% to 30% depending on changes in time of day or season [16]. To accurately calculate and analyze wind energy potential, data on wind speed, wind direction, and the magnitude of annual average wind power are essential. According to [17], a minimum of ten years of wind speed data is required to determine the average wind speed with precision. Studies on wind energy potential have been conducted extensively in various countries, including Pakistan [18], Singapore [19], Malaysia [20], China [21], Turkey [22], India [23], South Korea [24], and Iran [25]. In Indonesia, similar research has been performed at several locations [26]-[28]. However, there remains a limited body of research specifically analyzing the wind energy potential for electricity generation on small islands such as Miangas.

A wind speed range of 3–25 m/s is generally considered optimal for converting wind into electrical energy [29]. Alongside wind speed distribution [30], wind direction plays a crucial role in determining the efficiency of wind energy generation [31]. As such, a comprehensive assessment of wind characteristics is vital for estimating wind energy potential and selecting the most suitable wind energy conversion system [32], [33]. Accurate analysis of wind energy potential is particularly critical for the effective implementation of wind power plants (WPPs), as it informs the design and selection of appropriate wind turbines [34].

This study aimed to evaluate the wind energy potential in Miangas Island and estimated the electrical energy output of small-scale wind turbines using Windographer software. The turbines considered in this research have capacities of 50 kW, 35 kW, and 10 kW. These capacity variations were selected based on the availability of small-scale wind turbines in the market and the energy consumption patterns in Miangas Island. The findings on the estimated energy production of these turbines are expected to facilitate the selection of appropriate wind turbines, aligning with the energy supply-demand balance. Furthermore, the results can serve as supporting data for wind power development policies n Miangas Island.

II. MATERIALS AND METHODOLOGY

A. WIND ENERGY POTENTIAL ANALYSIS

This study evaluated wind energy potential using wind measurement data spanning ten years (2011–2020) at a height of 50 m above ground level, with a time interval of 60 minutes. The wind data were derived from remote sensing satellite observations, utilizing atmospheric models and the assimilation of meteorological data represented on a global grid with a spatial resolution of 0.5° latitude by 0.5° longitude. The data, obtained from the NASA Langley Research Center (LaRC), were processed using Windographer software to analyze key parameters, including wind direction, average wind speed, the frequency distribution of wind speeds per year, and wind power density, employing statistical analysis methods.

The frequency distribution of wind speed was represented using the Weibull distribution for both monthly and annual periods, calculated using (1), (2), dan (3) [35].

$$\bar{V} = c\Gamma(1+\frac{1}{k}) \quad (1)$$

where $\bar{V}$ is the mean wind speed (m/s), Γ represents the gamma function (x), c is the scale parameter (m/s), and k is the dimensionless shape parameter.

The Weibull distribution was calculated using the probability density function (2) and the cumulative distribution function (3).

$$f(v) = \frac{k}{c}(\frac{v}{c})^{(k-1)}\exp[-(\frac{v}{c})^{k}] \quad (2)$$

$$F(v) = 1 - \exp[-\left(-\frac{v}{c}\right)] \quad (3)$$

where $f(v)$ is the probability density function, $F(v)$ is the cumulative distribution function, c is the scale parameter (m/s), k is the dimensionless shape parameter, and v is the wind speed (m/s).

Furthermore, the wind power density was calculated based on the Weibull distribution using (4) [36].

$$P = \int_0^\infty \frac{\mathrm{p(v)}}{A} f(v) = \frac{1}{2}\rho c^3 \Gamma(1+\frac{3}{k}) \quad (4)$$

where P is the wind density power unit swept area of the wind turbine rotor blade, with the wind direction assumed to be perpendicular to the swept area (W/m^2), ρ denotes the air mass density (1.225 kg/m^3), c is the parameter scale (m/s), and k is the dimensionless shape parameter.

B. ESTIMATION OF ELECTRICAL ENERGY GENERATED BY SMALL-SCALE WIND TURBINES

The electrical energy generated by wind turbines is derived from the conversion of wind kinetic energy into mechanical energy, which drives the rotation of the generator to produce electricity. Consequently, the amount of electrical energy produced by a wind turbine is determined by two primary factors: wind speed and the power capacity of the wind turbine. The electrical power capacity produced by the wind turbine was calculated using (5) [37].

$$P_{WT_e}(v) = \frac{1}{2}\,\rho\, A\, V^3\, C_P\, \eta_m\, \eta_G \quad (5)$$

where $P_{WT_e}(v)$ represents the electric power generated by the wind turbine at a specific wind speed (W), ρ is the air mass density (1.225 kg/m^3), A is the swept area of the wind turbine blades (m^2), V is the wind speed (m/s), C_P is the wind turbine power coefficient, η_m is the mechanical system efficiency, and η_G is the generator efficiency.

The electric power capacity of a wind turbine is defined as the optimal electric power produced at the rated wind speed (V_{rated}). As a result, the electric power output is influenced by the wind turbine's performance characteristics, represented by its power curve, which is specified by the manufacturer. The wind turbine power curve is bounded by three key parameters: the cut-in wind speed, the rated wind speed, and the cut-out wind speed, as expressed in (6).

$$P_{WT_e} = \begin{cases} 0 & v < v_{cut\ in} \\ \frac{1}{2}\,\rho A V^3 C_P\, \eta_m\, \eta_G & v_{cut\ in} \leq v \leq v_{rated} \\ 0 & v > v_{cut\ out} \end{cases} \quad (6)$$

given $V_{cut\ in}$ is the minimum wind speed at which the wind turbine begins generating electrical power (m/s), V_{rated} denotes the optimum wind speed at which the wind turbine produces maximum electrical power (m/s), and $V_{cut\ out}$ refers to the maximum wind speed at which the wind turbine ceases generating electrical power (m/s).

Once the power capacity of the wind turbine and the wind speed distribution are determined, the annual electrical energy generated by the wind turbine can be calculated using (7).

$$E_{WT} = \sum_i^0 P(V_i)\ x\ f(V_i)\Delta V \quad (7)$$

where E_{WT} represents the electrical energy produced by the wind turbine (kWh), $P(V_i)$ denotes the electrical power curve of the wind turbine at a specific wind speed (W), and $f(V_i)\Delta V$ is the probability distribution frequency of a particular wind speed per year over 8,760 hours (%).

This study considered the use of three small-scale horizontal-axis wind turbines available on the market. The first was the 50 kW Seaforth Energy AOC15/50 turbine, which has a hub height of 30 m, a rotor diameter of 15 m, a cut-in wind speed of 4.6 m/s, a rated wind speed of 11 m/s, and a cut-out wind speed of 22.4 m/s. The second was the 35 kW Endurance G-3120 turbine, with a hub height of 30 m, a rotor diameter of 19 m, a cut-in wind speed of 3.5 m/s, a rated wind speed of 11 m/s, and a cut-out wind speed of 25 m/s. Lastly, the 10 kW Bergey Excel S turbine was included, featuring a hub height of 18 m, a rotor diameter of 7 m, a cut-in wind speed of 2.5 m/s, a rated wind speed of 11 m/s, and a cut-out wind speed of 20 m/s. In addition to market availability, the selection of these small-scale wind turbines was based on their ability to meet the current electrical energy consumption needs of Miangas Island. The calculation of the electrical energy generated by the wind turbines was conducted using (5) through (7) and Windographer software.

III. RESULTS AND DISCUSSION

A. AVERAGE WIND SPEED

The results of the hourly wind speed data analysis at a height of 50 m above ground level for the period 2011–2020, along with the corresponding monthly average values, are presented in Table I and Figure 1. Over the ten-year period, the average wind speed was calculated to be 5.5 m/s, classifying the wind conditions in Miangas Island within the moderate wind speed category. The lowest annual average wind speed, 4.9 m/s, was observed in 2017, while the highest, 5.9 m/s, was recorded in both 2015 and 2019. Analysis of the ten-year dataset reveals that only three years had annual average wind

TABLE I
MONTHLY AVERAGE OF THE WIND SPEED

Month	Average Wind Speed per Year (2011-2020) (m/s)
January	6.79
February	7.43
March	6.71
April	5.06
May	3.57
June	4.23
July	5.24
August	6.03
September	5.5
October	4.91
November	4.85
December	5.73
Average	5.5

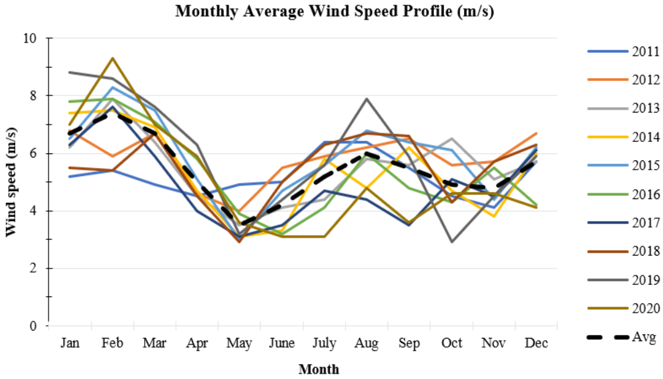

Figure 1. Monthly average of wind speed over ten years.

speeds exceeding 5.5 m/s, whereas the remaining years recorded averages at or below this threshold. These findings suggest that the wind energy potential in Miangas Island is more suited for small-scale applications, such as household-level energy generation. This conclusion was a key consideration in determining the appropriate capacity for the wind turbines evaluated in this study.

The monthly wind characteristics over the ten-year observation period are detailed in Figure 1. The data indicate that the highest average wind speeds typically occurred in January or February, except in 2011 and 2018, when the peak was observed in August. February recorded the highest monthly average wind speed, reaching 7.43 m/s, whereas May had the lowest, at 3.57 m/s. Over the entire period, the maximum wind speed recorded was 9.4 m/s in February 2020, while the minimum wind speed was 2.9 m/s in May 2018. The years 2019 and 2020 exhibited the largest wind speed variations, with standard deviation values of 2.0 and 1.9, respectively.

Table I reveals that the wind speed potential exceeds the average speed of 5.5 m/s during January through March, as well as in August and December. Conversely, from April to July and September to November, the wind speed potential is equal to or below the average. The distribution of monthly average wind speeds exhibits a standard deviation of 1.1, indicating a relatively high degree of fluctuation.

The monthly variation in wind speed is influenced by the monsoon wind cycle. From November to March, the northeast monsoon season occurs, characterized by strong winds. In May, there is a transition in the monsoon winds, shifting from the northeast monsoon to the southwest monsoon, with opposing wind directions. This transition contributes to May having the lowest average wind speed. The northeast monsoon occurs when the sun is positioned in the southern hemisphere, causing the southern hemisphere to be warmer than the northern hemisphere. In line with the nature of wind, which flows from high-pressure to low-pressure areas, the northeast monsoon carries winds from the north, predominantly passing over vast water bodies. Conversely, the southwest monsoon brings winds from the Australian mainland, which are warm and generally associated with lower pressure. The southwest monsoon occurs when the sun is positioned in the northern hemisphere, from June to October. During this period, winds blow from the southern hemisphere. The monthly wind speed characteristics are essential for optimizing the utilization and allocation of power plants to ensure a continuous supply of electrical energy.

Table II summarizes the average annual wind speeds recorded from 2011 to 2020. Over this ten-year period, the mean annual wind speed was 5.5 m/s. Annual wind speeds exceeding this average were observed in 2012, 2015, and 2019. The lowest annual wind speed was recorded in 2017, while the highest wind speeds were noted in 2015 and 2019.

The hourly average wind speed characteristics, derived from ten years of daily average data (2011–2020), are presented in Figure 2. The profile indicates that the average wind speed over 24 hours remains relatively stable at approximately 5.5 m/s. During daytime hours, wind speeds are higher and more consistent, particularly from 8:00 AM to 9:00 PM. Conversely, wind speeds tend to decrease at night, with the lowest speeds observed around 3:00 AM.

The difference in pressure and temperature between the sea surface and land is one of the primary factors influencing increased wind speed during the daytime. As the sun heats the surface, the land warms more quickly than the sea, resulting in a breeze blowing from the sea toward the land. Conversely, at night, the land cools more rapidly than the sea, causing the wind direction to reverse. In Miangas, the land area is significantly smaller than the surrounding sea, leading to stronger sea breezes compared to land breezes. This daily wind speed pattern is useful for estimating the duration of operational wind conditions, defined as the period during which wind speeds remain above the cut-in speed and below the cut-out speed. Under these conditions, wind turbines operate within their optimal rotational range, producing continuous electrical energy. Understanding diurnal pattern is essential for optimizing energy storage methods and load management strategies.

When analyzed from the perspective of the supply-demand balance for electrical energy, the diurnal profile depicted in Figure 2 is quite advantageous. Household energy consumption typically occurs from morning to evening, between 7:00 AM and 9:00 PM. During this period, wind speeds tend to be higher and more stable on average. However, it is important to note that peak loads occur for a duration of 2 to 3 hours within this timeframe. In theory, wind power plants (WPPs) are less suitable for supplying peak loads due to the variability of wind energy. Therefore, a backup system, such as diesel generators or an alternative energy source, is necessary to serve as a peak load generation system.

B. WIND DIRECTION DISTRIBUTION

The analysis results indicate that the predominant and strongest wind directions throughout the year are from the northeast (30° to 60°) and the southwest (210° to 240°), as shown in Figure 3. These wind patterns are influenced by the monsoon seasons, including both the eastern and western monsoons. From November to April, the dominant wind direction originates from the northeast, corresponding to the western monsoon season, while from May to October, the dominant wind direction shifts to the southwest, aligning with the eastern monsoon season. A wind distribution map is crucial for determining the orientation system of wind turbines. This ensures that the turbine blades remain perpendicular to the prevailing wind direction, allowing the turbines to capture wind energy efficiently. Additionally, identifying the dominant wind direction plays a vital role in evaluating wind energy potential and selecting optimal locations for wind turbine tower installation [33], [38]. Overall, the most frequently occurring wind speeds throughout the year range between 4 m/s and 7 m/s. However, there is a period of strong winds observed in February, with wind speeds ranging from 8 m/s to 10 m/s, as shown in Figure 3.

TABLE II
YEARLY AVERAGE WIND SPEED

Year	Average Wind Speed per Year (2011-2020) (m/s)
2011	5.2
2012	5.8
2013	5.5
2014	5.3
2015	5.9
2016	5.4
2017	4.9
2018	5.5
2019	5.9
2020	5.1

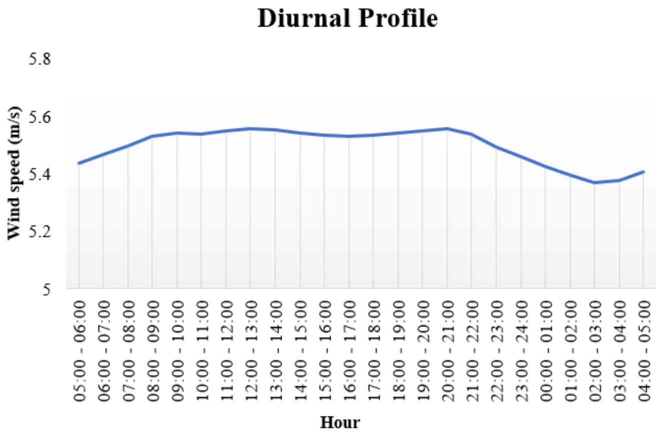

Figure 2. Daily wind speed variation (2011-2020 data).

C. WIND SPEED DISTRIBUTION AND WIND POWER DENSITY

Table III presents the Weibull parameters, where the minimum k value occurs in May and October at 1.95, and the maximum k value occurs in March and August at 3.19. The k value serves as an indicator of the stability of wind distribution at the location, suggesting a relatively uniform wind pattern due to its narrow range, which is close to 2. Additionally, Table III shows that the k values range between 2 and 3, indicating that the Weibull distribution curve skews toward higher wind speeds. This suggests that higher wind speeds are more likely to occur [39]. The c parameter represents wind speed, where higher c values correspond to higher average wind speeds. As

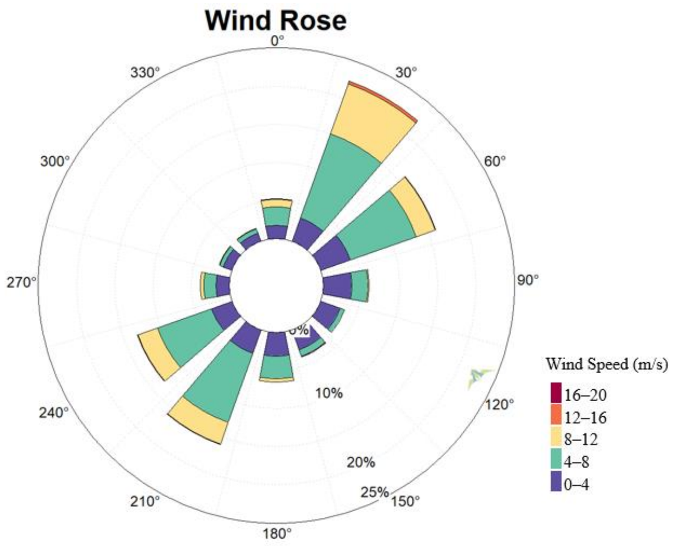

Figure 3. Average of wind direction distribution per year (2011-2020 data).

TABLE III
WEIBULL PARAMETER AND WIND POWER DENSITY (2011-2020 DATA)

Month	Weibull Parameter		Wind Power Density (W/m^2)
	k	*c (m/s)*	
January	2.56	7.64	296.82
February	2.89	8.31	357.24
March	3.19	7.48	249.78
April	2.69	5.68	117.99
May	1.99	4.03	45.25
June	2.04	4.77	86.58
July	2.23	5.92	152.14
August	2.95	6.77	190.96
September	2.41	6.21	165.66
October	1.95	5.54	142.42
November	2.39	5.47	113.69
December	2.38	6.46	187.56
Average	2.47	6.19	160.97

shown in Table III, the highest *c* value is observed in February, reaching 8.31 m/s. This indicates that February has the highest wind energy potential compared to other months within the year. Conversely, the lowest *c* value occurs in May, at 4.03 m/s, reflecting lower average wind speeds during this month. Consequently, the lower wind speeds in May are expected to result in reduced electrical energy generation in the said month.

The calculation results of the average wind power density using Weibull parameter data are presented in Table III. The analysis showed that the average annual wind power density was 160.97 W/m^2, corresponding to an annual wind energy potential of 115.90 kWh/m^2. February exhibited the highest wind power density throughout the year, recorded at 357.24 W/m^2, with a wind energy potential of 257.21 kWh/m^2. This is attributed to the frequent occurrence of high wind speeds in February, ranging between 7.4 m/s and 8.3 m/s, indicating significant potential for electricity generation during this month. Conversely, May recorded the lowest wind power density of the year, at 45.25 W/m^2, with a corresponding wind energy potential of 32.58 kWh/m^2. This condition indicates that wind turbine electricity production will be minimal in May, primarily due to the lower wind speeds observed during this month, ranging from 3.5 m/s to 4.0 m/s.

The Weibull profile in Figure 4 illustrates the annual frequency distribution of average wind speeds over a ten-year period (2011–2020). As shown in Figure 4, the frequency distribution indicates that average wind speeds between 5 and 6 m/s occur 15% of the time annually. This corresponds to approximately 1,314 hours per year. This information is crucial for estimating the electrical energy production of wind turbines to be installed at the site.

D. ESTIMATION OF WIND TURBINE ELECTRICAL ENERGY PRODUCTION

Based on the annual electricity demand in Miangas Island, which amounts to 25,550 kWh, and considering the availability of wind turbines on the market as well as existing infrastructure conditions, 50 kW, 35 kW, and 10 kW wind turbines were selected for the supply-demand energy scenario analysis. Horizontal-axis wind turbines were chosen due to their higher capacity factor and greater potential for annual energy production compared to vertical-axis wind turbines [40]. The energy production calculations were performed in accordance with the power characteristics of the wind turbines as specified by the manufacturers. Given that the turbine hub heights differ from the measurement height of 50 m, extrapolation was conducted for hub heights of 18 m and 30 m. The results of the annual energy production simulation for the 50-kW, 35-kW, and 10-kW turbines, calculated using wind speed distributions and power curves as defined by (5) through (7), are presented in Table IV. Table IV shows that the average annual electricity production is 98,434.49 kWh for the 50-kW turbine, 75,738.78 kWh for the 35-kW turbine, and 15,875.48 kWh for the 10-kW turbine. Notably, the energy production from the 10-kW turbine exceeds the results of wind energy potential assessments conducted in Barangay Bagasbas, Philippines [34], a neighboring region with wind characteristics similar to Miangas Island. Previous studies in Barangay Bagasbas evaluated electricity production using 3-kW, 5-kW, 10-kW, and 20-kW wind turbines [41] with the 10-kW turbine producing 10,014.71 kWh annually.

Furthermore, Table IV shows that the 10-kW wind turbine generates less electricity than the annual energy consumption of the residents of Miangas Island, making it unsuitable for application. The 50-kW wind turbine produces 98,434.49 kWh of electricity, significantly exceeding the annual energy consumption of Miangas Island residents, which is only 25,550 kWh. From the perspective of the supply-demand balance, the 50-kW wind turbine is also not an ideal choice for installation in Miangas Island. Instead, the 35-kW wind turbine is the most suitable option, as it generates 75,738.78 kWh per year—sufficient to meet the Miangas community's energy needs of 25,550 kWh per year.

Table IV also highlights the impact of seasonal weather variations on electricity production. During the rainy season (November to April), electricity production is higher compared to the dry season. A similar trend was observed in a study conducted on Solovetsky Island, a remote island in the Arctic region of Russia, which reported increased electricity generation during the winter months (November to April) compared to summer [42]. This increase was attributed to cold polar winds and weather phenomena such as snowstorms and strong gusts. The lowest electricity production occurred in 2017, while the highest was recorded in 2019. The higher production in 2019 was due to stronger wind speeds compared to other years. According to the 2019 Annual Report on

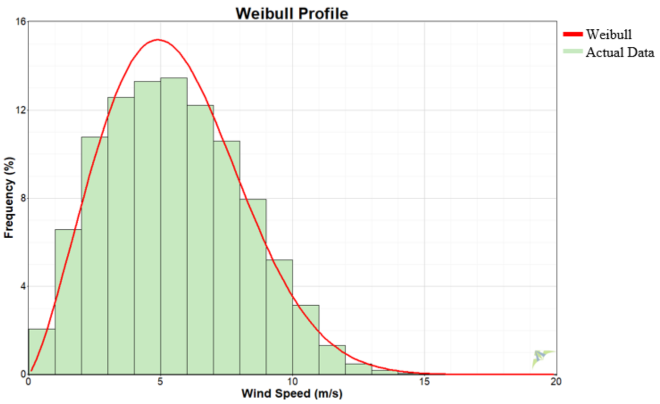

Figure 4. Frequency distribution of average wind speed per year.

TABLE IV
PRODUCTION OF SMALL-SCALE WIND TURBINE ELECTRICAL ENERGY PER YEAR

Month	Electrical Energy (kWh)		
	10-kW Wind Turbine	***35-kW Wind Turbine***	***50-kW Wind Turbine***
January	15,875.48	111,513.22	144,843.94
February	17,412.36	120,388.34	155,161.52
March	14,481.49	114,384.82	143,638.00
April	7,044.24	59,889.11	78,777.25
May	3,266.30	25,109.01	36,307.42
June	5,137.36	41,045.91	55,246.32
July	9,010.12	70,905.96	92,161.88
August	11,495.40	92,490.27	117,793.14
September	9,438.44	74,139.29	96,021.73
October	8,158.01	60,944.79	81,010.66
November	6,690,47	55,648.78	73,419.95
December	10,665.06	82,404.93	106,829.57
Total	118,674.86	908,865.44	1,181,213.88
Average per annum	15,875.48	75,738.78	98,434.49

Tropical Cyclones in the Philippines, the region experienced more frequent storm events, with many developing into typhoons. The Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) named 21 tropical cyclones in 2019. August, September, and November were the most active months during the tropical cyclone season, with November exhibiting above-average cyclone activity compared to normal climatological conditions [43].

IV. CONCLUSION

This study estimated the electrical energy generated by small-scale wind turbines with capacities of 10 kW, 35 kW, and 50 kW based on an analysis of wind energy potential in Miangas Island. The analysis utilized wind data from the NASA Langley Research Center for the 2011–2020 period. The findings revealed that Miangas Island had an annual average wind speed of 5.5 m/s, with a wind speed frequency distribution of 15% and predominant wind directions from the northeast and southwest. The highest average monthly wind speed occured in February at 7.43 m/s, while the lowest was recorded in May at 3.57 m/s. These average wind speeds fall within the moderate wind speed category, making them suitable for small-scale household electricity generation. The simulation results indicate that electricity production during the rainy season (November to April) is higher compared to the dry season. Based on wind speed distribution and power curves, the 35-kW wind turbine generated 75,738.78 kWh/year, which is sufficient to meet the electricity consumption of 234 households in Miangas Island, totaling 25,550 kWh/year. From the perspective of energy supply-demand balance, the 35-kW wind turbine is the optimal choice for application in Miangas Island. This research has successfully identified the potential of wind energy in Miangas Island as a sustainable source of electrical energy. However, the limitations of satellite data underscore the importance of further research using more detailed direct measurement data. Future research is recommended to consider factors such as topography, land use, and electrical load profile for wind energy system optimization.

CONFLICTS OF INTEREST

The authors declare that this research was conducted and written with no conflict of interest.

AUTHORS' CONTRIBUTIONS

Conceptualization, Dwi Risdianto and Nurry Widya Hesty; methodology, Dwi Risdianto; software, Nurry Widya Hesty; validation, Dwi Risdianto, Toha Zaky, and Ario Witjakso; formal analysis, Rudi Purwo Wijayanto; data curation, Agustina Putri Mayasari; writing-original draft, Dwi Risdianto and Nurry Widya Hesty; writing-reviewing and editing, Dwi Risdianto, Toha Zaky, Rudi Purwo Wijayanto, and Aryo Witjakso; visualization, Rudi Wijayanto.

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