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Analysis of Wind Energy Potential as a Vertical Axis Wind Turbine Drive (VAWT)

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Abstract

The use of wind energy in rural areas of Indonesia is still limited. This study assesses the potential of wind energy in Sigara Gara Village as a driver of vertical-axis wind turbines. The data used was in the form of secondary wind speed data in 2021 from the Graha Garuda Mas housing complex weather monitoring station at an altitude of ±13 m. Data per second is averaged daily, then compiled into monthly and annual averages. The results show a yearly average of 0.70 m/s with a monthly range of 0.70–0.80 m/s. The value is below the initial operating speed range prevalent for small wind turbines. The power per unit area calculated from this average is very low, making it unfeasible for a VAWT drive. The study suggests higher micro-mapping, or diverting to other sources of NRE that are more suitable to local conditions.

Keywords: Wind energy, Sigara Gara Village, VAWT, Resource evaluation.

1. Introduction

The national electricity demand continues to increase, but the supply in rural areas is still vulnerable during peak hours [1-3]. The government encourages the Adoption of a New Renewable Energy mix to reduce emissions and strengthen local energy security [4-7]. Wind energy is attractive because it is modular, has a relatively low initial cost, and is community-friendly [8-10]. Wind potential is greatly influenced by the location, sensor height, surface roughness, and building barriers [11-13]. The near-ground flow profile tends to weaken and fluctuate, making it difficult for small turbines to operate stably [14-16]. Many turbine installations occur without adequate resource audits and end up unproductive [17-18]. This condition necessitates a data-driven pre-feasibility study before making investment decisions. Sigara Gara Village was chosen as a case study because of the plan to utilize small-scale vertical-axis wind turbines [19].

The main problem is that there is no statistical summary of wind speed that is representative of local altitudes. Anemometer secondary data at an altitude of ±13 m is available, but has not been analyzed for design needs. Without average, maximum, minimum, and monthly spread information, testing the cut-in requirements is impossible. This study asked about the daily, monthly, and annual speed profiles in Sigara Gara Village and the amount of power density. This study also assessed whether the profile met the initial operating range of VAWT at the measurement height.

The purpose of this study is to analyze the potential of wind energy in low-speed areas in Sigagaragar Village. The study summarized speed statistics, ranging from resolution per second to daily, monthly, and yearly averages, to capture low-wind regimes. The study assessed the frequency and duration of events v < 2 m/s so that the availability of energy was realistically reflected. The study calculated the power density using equation (1) as an initial feasibility indicator. Results were compared with the cut-in range of VAWT small turbines and estimated decent operating hours at sensor height. The study evaluated tower elevation scenarios and micro-siting options to increase effective speeds. The study closes with technical recommendations and alternatives to NRE if the feasibility is not met.

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

2. Methods

The research method employs a descriptive-analytical approach to map the character of the wind in Sigara Gara Village, Patumbak District, Deli Serdang Regency. Researchers used secondary wind speed data from the Graha Garuda Mas housing complex Station at an altitude of about 13 m. The work procedure includes a brief literature study, data acquisition, quality control, aggregation, and statistical summarization. Quality control includes physical range checks, momentary spike detection, duplicate handling, and exclusion of days with significant data gaps. The data is summarized per second into daily averages, then compiled into monthly and annual averages. The statistics calculated include the average, maximum, minimum, standard deviation, as well as the frequency and duration of low wind events v < 2 (m/s).

The researcher calculated the wind power density as a feasibility indicator using a compressibility factor (1) and employed a reference value of $\rho \approx 1{,}225$ kg/m³. The results are then compared to the cut-in range of small turbines prevalent for VAWT and estimated feasible operating hours based on the proportion of time when v exceeds that threshold. As visual support, monthly profiles are presented in line graphs and concise tables to facilitate technical interpretation and pre-eligibility decisions.

3. Results and Discussion

The wind profile of Sigara Gara Village shows a consistent low-speed regime throughout the year (Table 1). The annual average is 0.73 m/s, with a standard deviation of approximately 0.047 m/s and a coefficient of variation of ±6.4%. The dual-axis graph confirms this fact because there are only two speed levels, namely 0.70 m/s and 0.80 m/s. The annual average line remains below the typical small turbine cut-in threshold, so the chances of reliable operation at sensor heights are minimal. The four peak months—March, April, May, and July—form an "island" that is not long enough to restore annual energy production.

The physical consequences of these findings lean on the cubic properties of wind energy potential per unit area. An increase of 0.10 m/s from 0.70 to 0.80 m/s does raise the potential by about 48 percent, but the value remains low in absolute terms. At this range, small turbines will more often be below the cut-in than above it. The capacity factor tends to be close to zero, energy production is unpredictable, and maintenance costs are not covered by output. In other words, the existence of an installed capacity has the potential to be an illusion of performance, since the real energy that reaches the load is almost non-existent.

Methodological added value arises when the assessment does not stop at the "low average". Feasibility evaluation should be conducted using the threshold over-threshold metric, which is the P(v>cut-in chance during operating hours [20-22]. In this dataset, the form of velocity distribution cannot be reliably estimated because there are only two levels. However, the evidence is strong enough to conclude that P(v>cut-in) is close to zero at sensor height. The no-go decision in the current conditions, therefore, has a clear statistical basis, while avoiding sunk costs on unproductive infrastructure.

Table 1. Annual of Wind speed and potential energy

Month	Mean wind speed (m/s)	*P*, (W/m^2)
January	0.70	0.21
February	0.70	0.21
March	0.80	0.31
April	0.80	0.31
May	0.80	0.31
June	0.70	0.21
July	0.80	0.31
August	0.70	0.21
September	0.70	0.21
October	0.70	0.21
November	0.70	0.21
December	0.70	0.21
Max	0.80	0.31
Min	0.70	0.21
Annual mean	0.73	0.24

A simple wind profile law gives a preliminary guide, e.g., $v(z)=vref(z/zref)^{\alpha,}$ with the shear exponent α representing the local roughness [23-24]. With a conservative α of 0.20, the elevation from 13 m to 30 m increases the speed by about 18 percent. The average of 0.73 m/s increased to ±0.86 m/s. Even at 80 m, the increase factor is about 1.44, so that the average only reaches ±1.05 m/s (Figure 1). The calculation of this scenario gives an important message: even if the speed increases with altitude, the speed base is too low to break through the general cut-in range.

However, micro-siting is still worth considering as a risk-controlled option. The principle is to reduce local roughness and avoid obstructions that cause wake and turbulence. The location of an open sloping hill, the edge of a rice field without a row of tall trees, or a wind corridor that is in the direction of the dominant wind can increase the effective speed. However, this approach must be based on a new disciplined measurement campaign. Using a calibrated anemometer, record data every 1–10 minutes, and install two sensor heights to separate the shear effect. Implement data quality control: range checks, surge detection, flat-line checks, and clear data recovery logs.

To maximize the value of data, implement a gated decision framework. The first stage is a three-month screening to test whether P(v>cut-in) crosses the agreed technical threshold. If it passes, continue the 12-month campaign to capture seasonal variation and construct a credible Weibull curve. The results are then used to estimate feasible operating hours, potential curtailments, and realistic capacity factors. This framework aligns the cost of measurement with the value of the information, while also providing a compelling reason for when the study should be terminated.

Technical analysis should also be complemented by straightforward economic analysis to ensure that decisions are more robust. Instead of directly calculating LCOE, which requires a lot of assumptions, use a cost-effectiveness screen: how much cost per kWh must be achieved so that the project does not lose competition with the comparative options available in the village. In the tropical context, the intensity of daytime solar tends to be high and stable. With solar panels, daily production is more guaranteed, and downtime is low. Therefore, a rational hybrid strategy is to make the sun the backbone, while the wind—if later proven adequate in other locations—acts as a top-up at a particular hour.

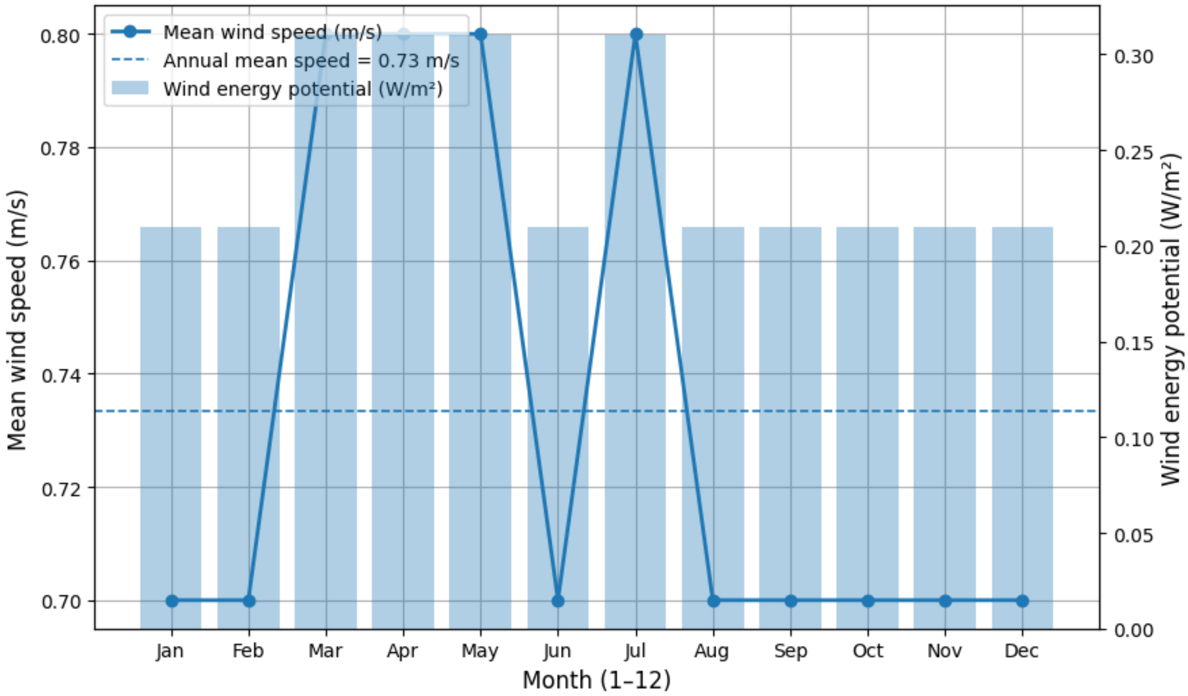

Figure 1. Monthly wind speed and wind energy potential

The scientific contribution of this study is on three sides. First, the study demonstrates how basic statistics—averages, standard deviations, and seasonal variations—can be directly translated into the relevant risk metric, i.e., the chance of breaking through the cut-in. Second, the study emphasizes the importance of explicit elevation profile scenario analysis. Such a scenario helps avoid over-optimism on tower elevation plans, especially when the speed base is very low. Third, the study offers a gated decision that links measurement campaign design, go/no-go rules, and transition options to other technologies when the data is not supportive.

Social and governance aspects also need to be clarified so that recommendations are more humanistic. The involvement of villagers from the beginning will facilitate access to land for micro-siting and test towers. A brief training program on occupational safety, data logging, and device maintenance will enhance the project's sustainability. Data transparency through village information boards is also crucial in building public trust in the scientific process. If the solar option is chosen, the same devices—such as data loggers and battery monitors—can still be used, so the initial investment is not wasted.

Finally, the study confirms a core lesson: disciplined resource audits can prevent costly and erroneous decisions. At the current sensor height, the wind regime of Sigara Gara Village does not meet the requirements for small turbine operation. Tower elevation and micro-siting can be explored, but initial projections suggest the increase is not enough to pass the cut-in. The best decision for the time being is to add wind to the watch list, resume limited measurements when there is an indication of a local wind channel, and prioritize a solar or hybrid solution with a dominant solar component. This approach maintains fiscal prudence, respects local natural conditions, and aligns with the goal of sustainable NRE-based village electrification.

4. Conclusion

This study shows that the wind resources in Sigara Gara Village are at a low-speed regime at a measurement height of ±13 m. The annual average was recorded at 0.73 m/s with a narrow monthly variation of 0.70–0.80 m/s. This pattern results in a minimal wind energy potential and falls below the cut-in range of small-scale turbines. The visualization of the tables and graphs confirms the absence of strong windy seasons as well as the capacity factor that is practically close to zero. As such, this location is not feasible for a VAWT drive at the current sensor conditions and heights.

Research recommends a risk-based phased approach. The first step involves a follow-up measurement campaign using calibrated anemometers, with measurements taken at 1–10 minute intervals and at two sensor heights, accompanied by strict data quality control. Analysis should include the estimation of the Weibull curve and the P(v>cut-in opportunity metric) as the basis for the go/no-go decision. Improvement efforts can be made through micro-siting in open locations and tower elevations to evaluate realistic speed gains. The project is only resumed when the opportunity to exceed the cut-in meets the agreed technical threshold. If meaningful improvements are not achieved, the village's energy focus will shift to solar photovoltaics or hybrid schemes with a dominant solar component, ensuring that investment remains efficient and benefits for the community are maintained.

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