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# Development of a Mathematical Model to Predict Wind Energy Potential and Vertical Axis Wind Turbine Efficiency

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## Abstract

The world's energy supply remains highly dependent on fossil fuels, such as petroleum, coal, and natural gas, which are non-renewable. Due to their limited availability, the development of alternative energy sources is crucial. Renewable energy options include biomass, solar energy, wind energy, and small-scale hydropower. Among these, wind energy is considered relatively clean, environmentally friendly, and free from carbon dioxide emissions. The design of wind turbines must be adapted to local wind profiles to achieve optimal efficiency. This study focuses on the performance of vertical axis wind turbines (VAWTs) using linear regression analysis to examine the relationship between wind speed and corrected power output. The results indicate a significant effect of wind speed on turbine performance, showing that potential wind power in an area is a key factor in determining the energy output of VAWTs. These findings highlight the importance of designing turbines effectively and selecting suitable sites to optimize renewable energy utilization.

**Keywords:** Renewable Energy, Power, Potency, Wind Turbine.

## 1. Introduction

Today, global energy is heavily dependent on fossil fuels such as petroleum, coal, and natural gas, which are non-renewable energy sources [1-2]. This situation is exacerbated by almost all industries in the world using oil-fueled engines and transport vehicles as their source of driving energy [3-5]. Due to the limited supply of fossil fuels, it is necessary to develop alternative energy sources, such as new and renewable energy, such as wind energy [6], micro hydro power plants, biomass, and solar energy, where wind energy has long been an important energy source in several countries [7-8].

Renewable energies such as solar energy and wind energy are unlimited sources of energy compared to fossil fuels [9-10]. The high demand for electricity in modern society, combined with the significant gap between generated energy and consumer needs, poses a challenge. Meeting this demand solely through conventional sources would be tough [5-6]. Therefore, the use of renewable energy sources, such as solar, wind, and biomass, is necessary to meet the increasing electricity demand [13-15]. There are problems associated with the use of wind and solar energy due to their intermittent nature, which not only affects the generation but also impacts the voltage and frequency of the system. Therefore, solar and wind power plants are integrated with diesel systems to supply reliable, safe, and economical power for isolated loads [16-17].

Wind power sources are a solution for harnessing new and renewable energy that is relatively clean and environmentally friendly, as they do not produce carbon dioxide. [18-20]. The design of wind turbines has specific characteristics, so the design must be adjusted to the wind profile, where the turbine will be installed, to obtain an optimal power coefficient or efficiency[21-22]. This is a challenge in itself in the development of wind energy, especially in areas in Indonesia that have relatively low wind speeds, but have the potential for wind energy that is feasible to be developed [23-24].

Wind energy does not rely on fossil fuels to produce energy[25-27]. Wind energy conversion systems generally consist of three main devices that make up a wind turbine, which converts wind energy into electrical energy [28-30]. The first device is a rotor consisting of two or three fiberglass blades connected to a hub that contains a hydraulic motor, which transforms each blade according to the prevailing wind conditions, allowing the turbine to operate efficiently at varying wind speeds. The Nacelle is a large house behind the rotor that houses the drive shaft, gearbox, transformer, and generator [31-32].

Wind turbine generators can have a vertical or horizontal axis of rotation. Vertical axis wind power plants are advantageous to be installed in urban centers because they are less affected by wind direction compared to horizontal axis wind power plants [33-34]. It is easy to maintain because it does not require a complicated structure, such as yawing tools. In the case of horizontal-axis wind turbines, the angle of attack due to the rotation of the wind turbine is constant. A significant amount of research has been conducted on predicting the aerodynamic characteristics of blades, and numerous proprietary technologies have been developed. However, in the case of vertical-axis wind turbines, the angle of attack due to the rotation of the wind turbine changes continuously. Therefore, it is essential to develop a vertical-axis wind turbine to undergo the verification process[35-36]. The most apparent method of verification is experimentation. However, due to space limitations, this method is limited to tiny wind turbines. Mathematical models have been studied for various output predictions used in the design of horizontal-axis wind turbines, but they do not take into account vertical blade pitch angles or buffer locations, and only partial studies have been carried out [37-38].

Mathematically, the wind energy is potentially calculated by:

$$P_w = \frac{1}{2}\rho_{air}.Alpt.v^3 \tag{1}$$

Turbine coefficient calculated by:

$$Cp = \frac{{}^{8}/_{27}\rho_{udara}.Alpt.v^3}{{}^{1}/_{2}\rho_{udara}.Alpt.v^3} \tag{2}$$

Generator Efficiency calculated by:

$$\eta = Pg\ /\ Pw \times 100\% \tag{3}$$

Power Output calculated by:

$$Pout, adj. = \frac{1}{2}\rho_{air}.Alpt.v^3.Cp.Efficiency\ system \tag{4}$$

## 2. Methods

In the case of this data collection, the author goes directly into the object to be researched to obtain valid data, and then the researcher uses the following method:

1. Observation Method
   Conducting direct observation of the use of vertical-axis wind turbines.
2. Regresi Linier Testing

Linear regression is a data analysis technique that predicts the value of unknown data using other related and known data values. Mathematically modeling unknown or dependent variables and known or independent variables as linear equations.

## 3. Results and Discussion

It is noted that the maximum wind speed data is collected daily, with the highest speed measurement recorded from January to December 2021 (Fig. 1). From the results of the data, meeting the requirements for wind speed and conditions that can be used to produce electrical energy, explaining that class 3 wind speed is the minimum limit and class 8 is the maximum limit that can be used to produce electrical energy. The wind speed level is given at 10 meters above the ground. In September, the maximum speed is 6.9 m/s, which falls within class 5, spanning a speed range of 5.5 m/s to 7.9 m/s under natural conditions, including road dust, flying paper, and swaying tree branches. Then, calculations are made to get the corrected output power as follows.

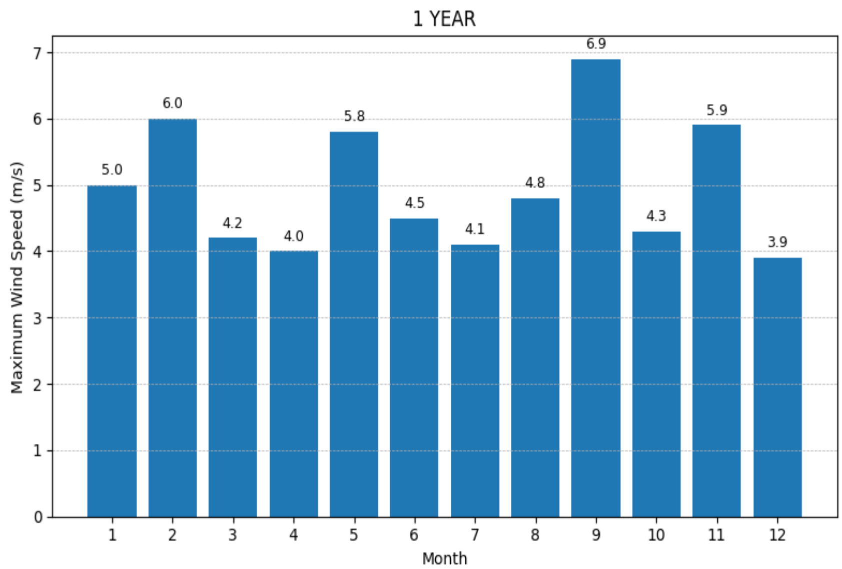


**Figure 1.** Max wind speed by month

### 3.1. Cross-sectional area of the blade

Formula: Finding the width of the spoon
Circle into a semicircle

| | | | |
|---|---|---|---|
| = | π x r x r | = | 182,32 / 2 |
| = | 3,14 x 7,62 x 7,62 | = | 91,16 cm |
| = | 182,32 | | |

Formula Blade Cross-Section Area
Length x Width
= 50 cm x 91,16 cm
= 0,5 m x 0,9116 m
= 0,455 m$^2$

### 3.2. Wind energy potential

The wind speed influences this, and determining the wind energy potential can be carried out by calculating the air density, which, in general, has a density of 1,225 kg/m$^3$. The potential power of the wind at a speed of 6.9 m/s can be calculated using the following formula:

$$Pw = \frac{1}{2}\rho_{air}.Alpt.v^3$$

Pw = 0,5 x 1,2 kg/m$^3$ x 0,455 m$^2$ x (6,9)$^3$

Pw = 91,55 Watt.

### 3.3. Turbine power coefficient

$$Cp = \frac{8/27\,\rho_{udara}.\,Alpt.\,v^3}{1/2\,\rho_{udara}.\,Alpt.\,v^3}$$

Cp = 0,296/0,5 = 0,59.

### 3.4. Generator efficiency

After getting power, the efficiency of the system in the wind turbine can be calculated using the formula:

η = Pg / Pw x 100%

= 68,7 / 91,55 x 100%

= 0,75.

### 3.5. Power output

To determine the corrected output power, calculations are carried out using the following formula:

$P_{out,\,adj.} = \frac{1}{2}\rho_{air}.\,Alpt.\,v^3$.Cp. Efficiency system

$P_{out,adj}$ = 0,5 x 1,225 x 0,455 x $(6.9)^3$ x 0,59 x 0,75

$P_{out,adj}$ = 40,51 Watt

$P_{out,adj}$ = 0,04 kW.

**Table 1.** Corrected output power calculation results table

| No. | Density (kg/m³) | Velocity (m/s) | Area (m²) | *Cp* | *η* | Pout (kW) |
|---|---|---|---|---|---|---|
| 1 | 1.225 | 125 | 0.455 | 0.59 | 0.75 | 0.02 |
| 2 | 1.225 | 216 | 0.455 | 0.59 | 0.75 | 0.03 |
| 3 | 1.225 | 74.1 | 0.455 | 0.59 | 0.75 | 0.01 |
| 4 | 1.225 | 64 | 0.455 | 0.59 | 0.75 | 0.01 |
| 5 | 1.225 | 195.1 | 0.455 | 0.59 | 0.75 | 0.02 |
| 6 | 1.225 | 91.1 | 0.455 | 0.59 | 0.75 | 0.01 |
| 7 | 1.225 | 68.9 | 0.455 | 0.59 | 0.75 | 0.01 |
| 8 | 1.225 | 110.6 | 0.455 | 0.59 | 0.75 | 0.01 |
| 9 | 1.225 | 328.5 | 0.455 | 0.59 | 0.75 | 0.04 |
| 10 | 1.225 | 79.5 | 0.455 | 0.59 | 0.75 | 0.01 |
| 11 | 1.225 | 205.4 | 0.455 | 0.59 | 0.75 | 0.03 |
| 12 | 1.225 | 59.3 | 0.455 | 0.59 | 0.75 | 0.01 |

After calculating Power (Watt) and conducting a linear regression analysis to demonstrate the influence of wind speed on the corrected output power, the linear regression is used to develop a mathematical model that predicts wind energy potential and the efficiency of vertical-axis wind turbines (Table 2). In this context, linear regression models the relationship between one or more independent variables (predictors) and one or more dependent variables (responses) using linear equations.

The regression results show a robust linear relationship between X and Y. The best model is $\hat{Y} = -34.4951 + 10.2967 \cdot X$, with $R^2 = 0.97$. This means that about 97% of Y variations can be explained by X changes in the test data range. The correlation coefficient r = 0.9849 corroborates the almost perfect positive correlation. An increase of X by one unit is estimated to raise Y by around 10.30 units on average. A negative intercept signals a threshold close to X ≈ 3.35 to initiate a meaningful response. The model error rate was relatively small, with an RMSE of 1.85 and an MAE of 1.33 on the Y scale. Significance tests showed a very significant slope (t = 17.98; p < 0.001) with a 95% interval between 9.021 and 11.572 (Table 3). This result implies the stability of the influence of X at various points in the observation range. Practically, the equation can be used for predicting Y with an average uncertainty of about ±1–2 units, as long as no extrapolation is carried out outside the data range.

**Table 1.** Regression-tested data

| No. | X | Y | $X^2$ | $Y^2$ | XY |
|---|---|---|---|---|---|
| 1 | 5 | 15.41 | 25 | 237.6 | 77.1 |
| 2 | 6 | 26.64 | 36 | 709.5 | 159.8 |
| 3 | 4.2 | 9.14 | 17.64 | 83.5 | 38.4 |
| 4 | 4 | 7.89 | 16 | 62.3 | 31.6 |
| 5 | 5.8 | 24.06 | 33.64 | 578.9 | 139.6 |
| 6 | 4.5 | 11.24 | 20.25 | 126.3 | 50.6 |
| 7 | 4.1 | 8.50 | 16.81 | 72.2 | 34.8 |
| 8 | 4.8 | 13.64 | 23.04 | 186.0 | 65.5 |
| 9 | 6.9 | 40.51 | 47.61 | 1641.2 | 279.5 |
| 10 | 4.3 | 9.80 | 18.49 | 96.1 | 42.2 |
| 11 | 5.9 | 25.33 | 34.81 | 641.5 | 149.4 |
| 12 | 3.9 | 7.32 | 15.21 | 53.5 | 28.5 |
| Σ | 59.4 | 199.48 | 304.5 | 4488.7 | 1096.9 |

**Table 3.** Linear regression coefficient (OLS) with standard error, t-statistic, p-value, and 95% confidence interval

| Term | Coef. | Std Err | t | P>\|t\| | 0.025 | 0.975 |
|---|---|---|---|---|---|---|
| const | -34.4951 | 2.884 | -11.96 | 0 | -40.922 | -28.069 |
| x1 | 10.2967 | 0.573 | 17.983 | 0 | 9.021 | 11.572 |

Linear model : $\hat{Y} = -34.4951 + 10.2967 \cdot X$
$R^2$ : 0.9700
r : 0.9849
RMSE : 1.8527
MAE : 1.3337

Figure 2 shows a consistent ascending pattern between X and Y. Linear regression lines follow this pattern well. The best equation is $\hat{Y} = -34{,}495 + 10{,}297 \cdot X$. The value of $R^2 = 0.970$ indicates 97% of the variation in Y is explained by X. A positive slope indicates a high sensitivity of Y to changes in X. Each increment of one unit of X raises Y by about 10.3 units.

The strongest visual fit appears at X ≈ 4.0–6.0. The data points are tightly knit around the line in that range. The slight deviation appears close to X ≈ 6.0, but it is still within the standard error limit. The point at X ≈ 6.9 remains close to the line and does not show a clear nonlinear pattern. A negative intercept implies a response threshold at X ≈ 3.35. Therefore, the use of the equation should ideally be limited to X = 3.9–6.9. Within this range, model accuracy is relatively high for routine estimation.

Figure 3 shows the residue scattered around the zero line. At low $\hat{Y}$ (≈ 5–10), the residue tends to be positive. In the intermediate $\hat{Y}$ (≈ 12–26), the residue shifted negatively. At high $\hat{Y}$ (≈ 28–36), the residue returned positive. The "positive–negative–positive" pattern indicates a slight curvature that the linear model has not captured. The residue range is around −2.8 to +4.0. A single dot on the large $\hat{Y}$ stands out with a high positive residue. This point has the potential to have a substantial effect on the slope of the line.

The implications are twofold. On the one hand, global metrics remain good with RMSE ≈ 1.85 and $R^2$ high. The model is therefore suitable for daily monitoring and rapid prediction within the specified data range. On the other hand, the residue pattern opens up room for refinement. The square approach to X can capture the remaining curvature. A simple transformation on Y or X can shrink the variation of the error in the significant estimate value. Examination of the influence of extreme points through the Cook distance will aid in validation. Overall, the combination of Figure 1 and Figure 3 supports the assumption of basic linearity, but also marks opportunities for increased accuracy without extrapolating beyond the range of observations.

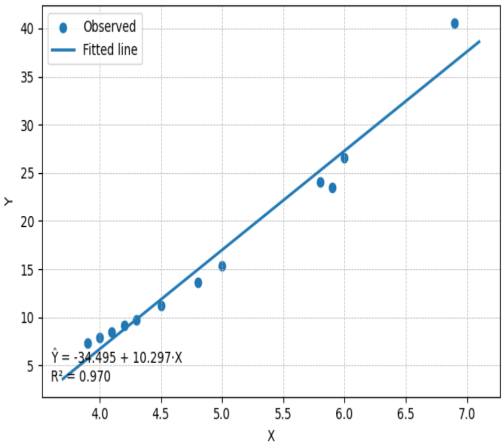


**Figure 2.** Linear regression fit

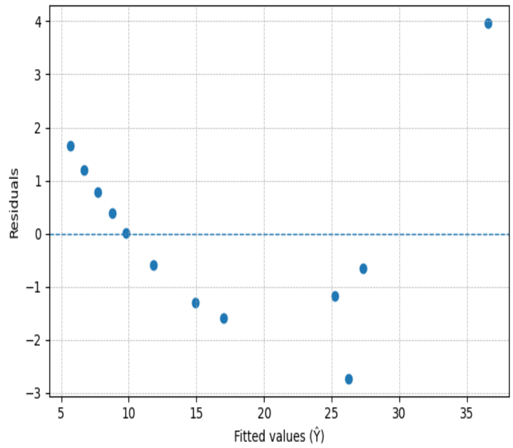


**Figure 3.** Residuals versus fitted

## 4. Conclusion

The analysis shows a very strong linear relationship between X and Y. The best model is $\hat{Y} = -34.495 + 10.297 \cdot X$ with $R^2 = 0.970$. That is, 97% of the variation Y is explained by X at the observation range. Each increase of one unit X raises Y by about 10.3 units. The model error is relatively small with RMSE ≈ 1.85 and MAE ≈ 1.33. The t-test at the slope was very significant with $p < 0.001$ and a CI of 95% = [9.021; 11.572]. Intersep negatif memberi ambang respons sekitar X ≈ 3.35. The residue plot shows a mild positive–negative–positive pattern. This symptom indicates a small curvature and a potential point of effect. Overall, the model is adequate for routine predictions in the range X = 3.9–6.9. Extrapolation outside of that range is not recommended.

Further research focuses on strengthening the usability of the model and improving the quality of predictions. The utilization of the model looks promising for quick estimation and daily monitoring. The inclusion of prediction intervals presents a clearer picture of uncertainty. Accuracy tends to increase when X-squared components or a piecewise approach are considered. The Box–Cox transform on Y or X often reduces the variation of the error and stabilizes the variance. The diagnostic suite—including standardized residues, Cook distances, and heteroscedasticity tests—provides a more comprehensive assessment of model toughness. The availability of additional observations on the tail of the X distribution enriches curvature mapping and improves global conformity. Tool calibration habits, as well as measurement replication, support consistency of data between sessions. Cross-validation or hold-out schemes add confidence before wider deployment. In heteroscedasticity conditions, the WLS or robust regression approach often results in more stable estimates. The application of the model is most relevant to the range X = 3.9–6.9, while the expansion of the range awaits updated modeling results.

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