The techno-economic analysis of vertical axis wind turbine implementation for scattered electricity loads

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Abstract. The Vertical Axis Wind Turbine (VAWT) can generate electricity by low wind speed and it can be simply implemented for scattered electricity loads. The objective of this study was to determine the specification, quantity, power capacity, capacity factor, and optimum production cost of the VAWT. Based on historical data of the wind speed, the future wind speed distribution can be simulated by using the Weibull and Rayleigh distribution approach. The parameters varied in this simulation included turbine specification, power capacity, and wind speed. The result showed that the optimal design of VAWT to implement in Raja Ampat was 10 kW turbine Type-H Darrieus, with 3.5 m/s cut-in speed, 12 m/s rated speed and 9.49% capacity factor. This individual turbine can generate 8313 kWh Annual Energy Production or can supply the demand amount 432,983 kWh by 39 units with LCOE 20.5 Cent USD/kWh/unit or lower than Production Cost Regulated (21.34 cent USD/kWh). This indicated that the vertical axis wind turbine was the techno-economically appropriate alternative for archipelago countries that had scattered electricity loads such as Indonesia.

1. Introduction

One of the fastest emerging renewable energy technologies was wind energy. The cumulative installed capacity target globally in 2019 was up to 651 Giga Watt (GW) [1]. Most progressive project was a large scale of the wind turbine for electricity include onshore and offshore project [2]. However, some places in several under-development countries like Indonesia have unique characteristics such as archipelago country, many isolated areas, and scattered electricity loads. Scattered means that the loads are small but spread over in many places. The absence of electricity will influence the low quality of human life. Consequently, they are unable to get decent information and these place has slow economic growth [3]. To supply the electricity by the existing grid system or make a new grid system for these loads then deliver the energy by transmission and distribution, will be costly and inefficient because the loads are scattered. So, the small power plant such as the small-scale wind turbine can become one of the best solutions.

Generally, Horizontal axis wind turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) are two main classification wind turbine refers to its axis. HAWT was commonly used for large scale wind power plant and need high cut-in speed to generate the electricity [4]. On the other hand, VAWT can operate in lower cut-in speed [4], easier maintenance because gearbox and generator were placed at ground level, an unnecessary yawing requirement because the turbine can operate using wind from any direction and noiseless rather than HAWT’s [5].
This study focused on Raja Ampat as one of the District names in West Papua Province, Indonesia. There were 93,918 people in there with a population density of 12.42 people per square km [6]. In order to supply this demand was very challenging and makes Indonesia’s Electrification ratio at the end of 2018 by 98.30% [7] or about 4.6 million Indonesian people still live in the dark without electricity. In 2019, electricity consumption in Raja Ampat was around 6.73 million kWh per-year [6]. By National electricity growth is average 6.42% [8], Raja Ampat will need additional energy around 432,983 kilo Watt hours (kWh) in 2020. This demand will be proposed in this study to supply by several VAWT with capacity, specification and capacity factor were determined based on Weibull and Rayleigh distribution then evaluating by economic analysis to get the optimum VAWT Design. Weibull and Rayleigh are two methods commonly used and most suitable to represent the wind potential characteristics [9]. Both have a skew value that always larger than 0 [10]. Rayleigh is a simpler method because it only uses the one parameter that it is mean or average value. The special case in Weibull distribution when k (shape parameter) is equal to 2 is the Rayleigh distribution [10].

2. Methodology
The power that produced by VAWT depend on speed of wind, swept area and air density [10]. The swept area determined by what type of the turbine, specification, and dimension. The Air density in steady wind is 1.225 kg/m³ [10]. Some expression was used in this simulation:

| Table 1 Expression for various parameters used in this simulation |
|---------------------------------------------------------------|
| Parameters | Mathematical Relation | Notes |
| Power produced by VAWT [10] | $P = \frac{1}{2} \rho A v^3$ | $P$: Power (kW) $\rho$: Air density: typically, 1.225 kg/m³ $A$: swept area (m²) $v$: wind speed (m/s) |
| Shape parameters [10] | $k = \left( \frac{\sigma_u}{v_{avg}} \right)^{-1.086}$ | $k$: shape parameter (dimensionless) $\sigma_u$: standard deviation $v_{avg}$: average wind speed (m/s) |
| Scale factor [10] | $c = \frac{v_{avg}}{\Gamma \left( 1 + \frac{1}{k} \right)}$ | $c$: scale factor (m/s) $v_{avg}$: average wind speed (m/s) $\Gamma$: gamma distribution $k$: shape parameter (dimensionless) |
| Weibull Probability (Distribution) [10] | $p_W(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^k \right]$ | $p_W(v)$: weibull probability $v$: wind speed (m/s) $k$: shape parameter (dimensionless) $c$: scale factor (m/s) |
| Weibull Cumulative Distribution [10] | $p_{wc}(v) = 1 - \exp \left[ -\left( \frac{v}{c} \right)^k \right]$ | $p_{wc}(v)$: Weibull cum. distribution $v$: wind speed (m/s) $k$: shape parameter (dimensionless) $c$: scale factor (m/s) |
| Rayleigh Probability (Distribution) [10] | $p_R(v) = \frac{\pi}{2} \left( \frac{v}{v_{avg}} \right)^2 \exp \left[ -\frac{\pi}{4} \left( \frac{v}{v_{avg}} \right)^2 \right]$ | $p_R(v)$: Rayleigh probability $v$: wind speed (m/s) $v_{avg}$: average wind speed (m/s) |
| Rayleigh Cumulative Distribution [10] | $p_{rc}(v) = 1 - \exp \left[ -\frac{\pi}{4} \left( \frac{v}{v_{avg}} \right)^2 \right]$ | $p_{rc}(v)$: Rayleigh cum. distribution $v$: wind speed (m/s) $v_{avg}$: average wind speed (m/s) |
| Levelized Cost of Electricity (LCOE) [11] | $LCOE = \frac{\sum_{t=1}^{T} I_t + M_t}{\sum_{t=1}^{T} E_t}$ | $LCOE$: USD/kWh $I_t$: Investment Expenditures in year t (USD) $M_t$: Operation &Maintenances Expenditures in year t (USD) $E_t$: Electricity Generation in year t (kWh) $r$: Discount Rate (%) $T$: turbine lifetime (years) |
The methodology of this study was briefly shown at Figure 1:

Figure 1. Flowchart of Methodology for this study

The data input was the daily average wind speed for one year in West Papua in 2019 [12]. Annual Energy Production (AEP) can be generated by using cumulative Weibull and Rayleigh distribution function. Some of the turbine specification was type H-Darrieus turbine with difference characteristic such as cut-in, rated speed and the dimension. For summarize, below the differences:

Table 2. Specification of several VAWT Type-H Darrieus [13][14][15][16]

| Parameters             | Type A                  | Type B                | Type C                |
|------------------------|-------------------------|-----------------------|-----------------------|
| Power (kW)             | 1 up to 10              | 1 up to 10            | 1 up to 10            |
| Cut-in Speed (m/s)     | 3.5                     | 2.5                   | 3                     |
| Rated Speed (m/s)      | 12                      | 10 up to 12           | 9                     |
| Rotor Diameter (m)     | 1.7 s/d 3.2             | 2 s/d 5.5             | 2 s/d 5.5             |
| Rotor Height (m)       | 2.2 s/d 5               | 2.8 s/d 6             | 2.4 s/d 6             |
| Blade Material         | Casting                 | Aluminum              | Glass fiber reinforced|
|                        | Aluminum                | Alloy                 | Plastics              |

Several assumptions and simple calculation for economic analysis:

Table 3. Several assumptions for economic analysis

| Parameters            | Values | Sources                                                                 |
|-----------------------|--------|-------------------------------------------------------------------------|
| Investment Cost       | depend on Turbine specifications Including some equipment | Quotation, brochure and trading website [13][15][16] VAWT turbine, Grid off Controller, Inverter, Tower and Battery Energy Storage |
| Discount rate         | 8.2%   | [17] [18] [19] Weight Average Cost of Capital Calculation (WACC) Cost of Debt: 9.57%; [20] Equity Portion:30%; Debt Portion:70%; Cost of Equity: 10.74%; |
| O&M Cost              | 0.8 Cent USD/kWh       | Indonesia, Nathan Lee, IRENA 2019 [21]                                   |
| Project Lifetime      | 15 years              | Typical Average VAWT lifetime [14][15][16]                               |

All the energy production will be evaluated by LCOE method with the investment and operational and maintenance cost for the 15 years’ lifetime. Final values will be representing by Cent USD/kWh and be compared with the Production Cost Regulated (PCR) to get the most optimum alternative [22].
3. Result and Analysis

3.1 Technical Result and Analysis
Firstly, the calculation of some statistical parameters such as mean, standard deviation, shape parameters and scale factor were conducted and then graph the cumulative Weibull and Rayleigh distribution. Here the result:

Table 4. Statistical Parameter Calculation Result

| Parameters          | Symbols       | Value  |
|---------------------|---------------|--------|
| Average wind speed  | v             | 4.88   |
| Standard deviation  | \(\sigma\)    | 1.72   |
| shape parameters    | \(k_w\) (Weibull) | 3.1    |
|                     | \(k_r\) (Rayleigh) | 2      |
| scale factor        | \(c_w\) (Weibull) | 5.46   |
|                     | \(c_r\) (Rayleigh) | 5.52   |

![Figure 2. Weibull and Rayleigh Distribution Result](image)

The Weibull distribution produce narrow range distribution of the wind speed between 4 to 6 m/s. On the other hand, Rayleigh distribution generate more distributed range from 2 to 7 m/s. Weibull Distribution better than Rayleigh distribution because represent more accurate wind speed, less error and more specific wind speed range that will increase possibility happen in one period [23]. So, the Weibull distribution give the more accurate information to determine cut-in, rated speed and other turbine specification. The varying power capacities from 1 to 10 kW were simulated to get the optimized Annual Energy Production (AEP) for specific wind potential resources in Raja Ampat.

The Simulation result shows that lower rated speed of wind turbine produces higher AEP. This means that the much closer the rated speed with the average value in table 2 was much higher AEP as can be seen in type C turbine. The cut-in speed parameters slightly have not big impact to AEP. In such pessimistic scenarios, Weibull distribution will be appropriate for this selection as explained before. So, From the technical consideration, turbine type C with 10 kW power was more appropriate to implement in scattered electricity loads because the turbine produces the highest AEP compare the type A and B. However, this result was not final before the economical aspect was evaluated.
Table 5. AEP Simulation Result

| Type | Power Capacity (kW) | Cut in Speed (m/s) | Rated Speed (m/s) | Capacity Factor (%) | AEP (kWh) |
|------|---------------------|--------------------|-------------------|---------------------|----------|
|      |                     | Rayleigh           | Weibull           | Rayleigh            | Weibull |
| A    | 1                   |                    |                   |                     |          |
|      | 3.5                 | 12                 |                   | 12.8                | 9.48     |
|      | 12.8                | 9.48               |                   | 830                 | 1121     |
|      | 12.81               | 9.49               |                   | 1663                | 2244     |
|      | 12.79               | 9.49               |                   | 2494                | 3361     |
|      | 12.87               | 9.49               |                   | 4157                | 5493     |
|      | 12.87               | 9.49               |                   | 8313                | 11274    |
|      | 1                   | 10                 |                   | 21.69               | 16.18    |
|      | 16.55               | 12.16              |                   | 2130                | 2900     |
|      | 2                   | 11                 |                   | 21.13               | 16.17    |
|      | 21.56               | 16.8               |                   | 4249                | 5553     |
|      | 16.39               | 12.16              |                   | 7087                | 5637     |
|      | 28.63               | 22                 |                   | 10652               | 14358    |
|      | 24.79               | 21.75              |                   | 3811                | 4343     |
|      | 3                   | 9                  |                   | 23.51               | 21.67    |
|      | 22                  | 27                 |                   | 5695                | 6178     |
|      | 23                  | 26                 |                   | 10074               | 11826    |
|      | 10                  |                    |                   |                     |          |
| B    | 3                   | 2.5                | 10                | 21.13               | 16.17    |
|      | 21.56               | 16.8               |                   | 4249                | 5553     |
|      | 16.39               | 12.16              |                   | 7087                | 5637     |
|      | 28.63               | 22                 |                   | 10652               | 14358    |
|      | 24.79               | 21.75              |                   | 3811                | 4343     |
|      | 3                   | 3                  | 9                 | 23.51               | 21.67    |
|      | 22                  | 27                 |                   | 5695                | 6178     |
|      | 23                  | 26                 |                   | 10074               | 11826    |
|      | 10                  |                    |                   |                     |          |
| C    | 3                   | 3                  | 9                 | 23.51               | 21.67    |
|      | 22                  | 27                 |                   | 5695                | 6178     |
|      | 23                  | 26                 |                   | 10074               | 11826    |

3.2 Economic Result and Analysis

The Economic Evaluation was conducted to finalize and wrap up techno-economic analysis of VAWT. The table below are shown the financial results for all the types of the turbine specification:

Table 6. Economic Analysis

| Type | Power Capacity (kW) | CAPEX+ OPEX [13][15][16] | LCOE (Cent $/kWh) | Prod. Cost. Reg (Cent USD/kWh) |
|------|---------------------|--------------------------|-------------------|-------------------------------|
| A    |                     | Weibull                  | Weibull           |                               |
|      | 3.5                 |                          |                   |                               |
|      | 1                   | 830                      | 2230              | 32.6                          | 21.34   |
|      | 1663                | 3920                     | 28.8              | 21.34                         |
|      | 4157                | 10570                    | 31                | 21.34                         |
|      | 8313                | 13810                    | 20.5              | 21.34                         |
|      | 1417                | 5520                     | 42.1              | 21.34                         |
|      | 2130                | 7910                     | 44.8              | 21.34                         |
|      | 4249                | 10810                    | 31                | 21.34                         |
|      | 7087                | 19010                    | 32.6              | 21.34                         |
|      | 10652               | 29850                    | 34                | 21.34                         |
|      | 1927                | 9500                     | 59.3              | 21.34                         |
|      | 3811                | 16000                    | 50.6              | 21.34                         |
|      | 10074               | 36530                    | 43.8              | 21.34                         |
|      | 20148               | 49209                    | 29.8              | 21.34                         |

Economically, the lowest LCOE of wind turbine was type A with power capacity 10 kW as the optimum turbine type selection. For energy demand 432,983 kWh in 2020, it will need 10 kW turbine type A amounts 39 units by Weibull distribution. Production Cost Regulated (PCR) indicate that if the demand will supply by the grid, the Production cost maximum was 21.34 cent USD/kWh [22]. Then, the VAWT was worth alternative rather than grid because have gap 0.84 Cent USD/kWh/unit Turbine/year or save the money about 3,637 USD/year.

4. Conclusion

The optimal design of VAWT to implement in Raja Ampat was 10 kW turbine Type-H Darrieus, with 3.5 m/s cut-in speed, 12 m/s rated speed and 9.49% capacity factor. This individual turbine can generate 8313 kWh AEP or can supply the demand amount 432,983 kWh by 39 units with LCOE 20.5 Cent USD/kWh/unit or lower than PCR (21.34 cent USD/kWh). Using wind for the electricity will
support the government and utility to increase electrification ratio, stimulate economic growth and promote green energy production and friendly environment. However, all of data using in this calculation and simulation were used secondary data. To enhance the accuracy and gap minimization in that specific area as per IEC 61400-1:2019 Wind Energy Generation System, met-mast measurement is needed to actual wind speed data in specific location. So, the design will be more comprehensive, accurate and affordable.

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