Comparative Modelling and Simulation of Small Wind Turbine System Using MATLAB/Simulink Based on Various Power Coefficient Models in Kupang-Indonesia

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***Abstract*— With the rapid depletion of fossil fuels that cause environmental impact such as climate change while the need for energy, especially electricity, is increasing in demand, the use of renewable energy must be immediately executed. One of the types available in most parts of the world is wind energy. In Indonesia, this energy can be implemented in Kupang, Nusa Tenggara Timur due to its high potential in which in contrast, has faced electricity crisis and frequent blackouts. Thus, this research aims to models and compares small wind turbines based on existing power coefficient mathematical approaches which are polynomial, sinusoidal, and exponential using MATLAB/Simulink. The result of this study is based on the selected model, which is the Ovando et al. model with a coefficient of 0.4513. This model produced power in the range of 9000–16000 W under the assumption of periodic wind speeds of 50–60 km/h. The calculations were based on pre-determined parameters, including a blade radius of 2 m, a tip speed ratio (λ) of 7, a pitch angle (β) of 0 degree, and an air density of 1.225 kg/m³. The output may help in solving Kupang's electricity issues and reach 23% of renewable energy target by 2025.**

Keywords—renewable energy, small wind turbine system, Kupang, MATLAB/Simulink, Power coefficient mathematical model

I. Introduction

Renewable energy is essential for generating electricity and meeting energy demands, largely due to its environmental benefits and reduced dependence on fossil fuels [1], [2]. Yet, challenges such as weather impacts, low efficiency, high investment costs, and transportation issues are undeniable [2], [3], [4], [5]. These address the implementation of energy modelling through simulation in its early phase before decision making [6], [7]. Simulation software like Matrix Laboratory or generally MATLAB, particularly its Simulink toolbox, allows for effective modeling of energy systems, including solar and wind energy. Wind energy has garnered global attention, with many countries establishing wind farms to produce clean energy in line with the Kyoto Protocol. [8]. In the case of Indonesia, as stated in *Peraturan Pemerintah No. 79 Tahun 2014* for the national energy regulation, the usage of wind energy has become significant to meet the target of 23% of renewable energy in the energy mix by 2025, currently 14%, which also fulfils *Rencana Umum Ketenagalistrikan Nasional* 2019-2038 (RUKN) and Net Zero emissions [9]. The Ministry of Mineral and Energy Resources estimates Indonesia's wind energy potential at 154.88 GW, consisting of 60.65 GW onshore and 94.2 GW offshore [9], with optimal locations primarily in eastern regions like South Sulawesi and Nusa Tenggara Timur (NTT) [10].

Aside from potential and location, one of the important parameters that have been studied and simulated is the power coefficient (Cp) of turbine which shows the relationship between the actual power to the available potential (the ambient wind turning the turbine). Cp mathematical model has been developed throughout the years, giving many approaches, generally expressed in polynomial, sinusoidal, and exponential functions [8], [11], [12]. However, these studies either only review the existing models or invent a new model.

Several other studies determine how to model the wind turbine in Indonesia using MATLAB/Simulink. The study in Manado used data collection, model creation, testing and simulation on one year wind speed data with maximum power 8000 W (in nighttime) and 3322 W in average based on the wind speed [13]. The study in Tegal uses similar methods, however without accounting for certain period of wind speed, which fixes the speed of 3 m/s and determines the blade radius by 6 m, and rotor angular speed by 4 rad/s, resulting in 768.55 W and torque of 192.1 Nm [14]. Then, the study in Cilacap with the same method is done to produce mechanical power output of 221.9 W and a torque of 6.448 Nm [15]. These previous studies implement one power coefficient approach which lack the comparison for another coefficient. Thus, innovatively, this research will emphasize the use of various power coefficients to provide broader analysis and results which also serve as the initial feasibility study through MATLAB/Simulink energy modelling for a selected location as the case study.

Corresponding to the necessity of energy supply and potential, a study can be conducted specifically in Kupang, Nusa Tenggara Timur, Indonesia, as electricity crisis and regular blackout occur often due to natural disruption [16], [17], [18]. Moreover, *Perusahaan Listrik Negara* (PLN) data shows 94.04% or 1.190.641 family in NTT having access to electricity, leaving 215 villages unsupplied [18]. Knowing the highest potential in this area lies on wind energy by 10.188 MW [18], [19], this study is conducted to provide comparative analysis on small wind turbines models based on MATLAB/Simulink simulation, specifically for horizontal axis type with three blades for various selected power coefficients from existing literatures to find the potential power to solve Kupang's electricity issues.

II. Power Coefficient Theorem

Power coefficient is one of the parameters used to obtain the power of wind turbines. Tracing back, the wind turbine is based on kinetic energy which depends on mass airflow to express the following power equation (1).

$$P_w = \frac{1}{2}\rho A v_w^3 \quad (1)$$

P_w stands for wind power (W), ρ for density (kg/m^3), A for area (m^2) and v_w for wind speed (m/s). However, the kinetic energy cannot be directly converted to mechanical energy. Ideally, the amount that can be converted is 59.25% (Betz's Limit). Through this limit which has been developed by various scholars, the power turbine is now expressed as in equation (2):

$$P_m = \frac{1}{2}\rho \pi R^2 v_w^3 C_p(\lambda,\beta) \quad (2)$$

In which P_m represents mechanical power (W), R as blade radius of the turbine (m), v_w as wind speed (m/s), Cp as power coefficient, λ as tip speed ratio, and β as pitch angle (°). The power coefficient (Cp) is a vital aspect in wind energy conversion system [12]. It can be defined as the ratio of wind energy extracted to real potential when the air kinetic energy reaches the turbine. It can be obtained through several methods such as numerical analysis to make mathematical functions, algorithms approaches or wind turbines testing in which data will be collected and processed to make $Cp(\lambda,\beta)$ variation graph. Several of the approaches in polynomials, sinusoidal, and exponential representations for three blade models can be further described as follows [8], [12]:

a) Polynomials models is a common model to represent Cp in which the curve can be generated based on the equation (3) which is detailed in Table I.

$$C_p(\lambda) = \sum_{i=0}^{i=n} a_i \lambda^i \quad (3)$$

TABLE I. Constants of Power Coefficient in Polynomial Functions Related Studies

Constants	Polynomial Order Functions for Power Coefficient			
	Third [20]	**Fourth** [21]	**Fifth** [22]	**Seventh** [23]
a_0	-0.02086	0.11	0.0344	0
a_1	0.1063	-0.2	-0.0864	0.0051
a_2	-0.004834	0.097	0.1168	-0.0022
a_3	-0.000037	-0.012	-0.0484	0.0052
a_4	0	0.00044	0.00832	-0.00051425
a_5	0	0	-0.00048	-0.00002795
a_6	0	0	0	0.0000046313
a_7	0	0	0	-0.0000001331

b) Sinusoidal models in the general equation based on the existing functions are expressed in equation (4) and Table II.

$$C_p(\lambda,\beta) = [b_0 + b_1(\beta + b_2)] \sin\left[\frac{\pi(\lambda+b_3)}{b_4+b_5(\beta+b_6)}\right] + b_7(\lambda + b_8)(\beta + b_9) \quad (4)$$

TABLE II. Constants of Power Coefficient in Sinusoidal Related Studies

Constants	Sinusoidal Order Functions for Power Coefficient				
	Moussa [20]	**Coto** [24]	**Xin** [25]	**Merahi** [26]	**Nouira** [27]
b_0	0.5	0.44	0.44	0.5	0.5
b_1	-0.00167	0	-0.0167	-0.0167	0.0167
b_2	-2	0	0	-2	-2
b_3	0.1	-1.6	-3	0.1	0.1
b_4	18.5	15	15	10	18.5
b_5	-0.3	0	-0.3	-0.3	-0.3
b_6	-2	0	0	0	-2
b_7	0.00184	0	0.00184	-0.00184	-0.00184
b_8	-3	0	-3	-3	-3
b_9	-2	0	0	-2	-2

c) Exponential models have several studies regarding the function that can be generalized as the following equation (5) and (6) in which the constant values are shown in Table III.

$$C_p(\lambda,\beta) = c_0\left(\frac{c_1}{\lambda_i} - c_2\beta - c_3\beta\lambda_i - c_4\lambda_i^{c_5} - c_6\right)e^{-\left(\frac{c_7}{\lambda_i}\right)} + c_8\lambda \quad (5)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_9\beta + c_{10}} - \frac{c_{11}}{1+\beta^3} \quad (6)$$

TABLE III. Constants of Power Coefficient in Exponential Related Studies

Constants	Exponential Order Functions for Power Coefficient							
	Kotti [28]	**Khajuria** [29]	**Ovando** [30]	**Feng** [31]	**Llano** [32]	**Shi** [33]	**Bustos** [34]	**Ahmed** [35]
c_0	0.5	0.5	0.5176	0.22	0.5	0.73	0.44	1
c_1	116	116	116	116	72.5	151	124.99	110
c_2	0	0.4	0.4	0.4	0.4	0.58	0.4	0.4
c_3	0.4	0	0	0	0	0	0	0
c_4	0	0	0	0	0	0.002	0	0.002
c_5	0	0	0	0	0	2.14	0	2.2
c_6	5	5	5	5	5	13.2	6.94	9.6
c_7	21	21	21	12.5	13.125	18.4	17.05	18.4
c_8	0	0	0.0068	0	0	0	0	0
c_9	0.008	0	0.08	0.08	0.08	0.02	0.08	0.02
c_{10}	0	0.088	0	0	0	0	0	0
c_{11}	0.035	0.035	0.035	0.035	0.035	0.003	0.001	0.03

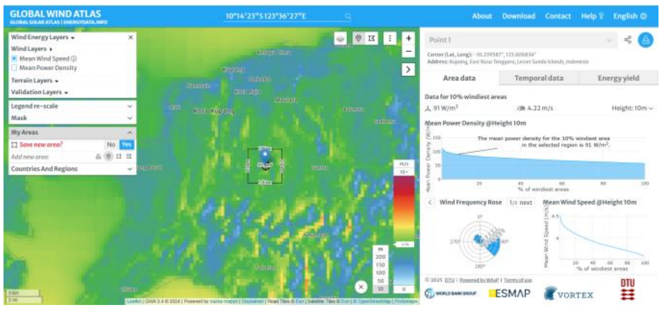
III. Method

The research method starts with problem identification, literature review, data collection, modelling and simulation as well as analysis and conclusion. However, the data collection and modelling-simulation can be discussed in this section extensively below.

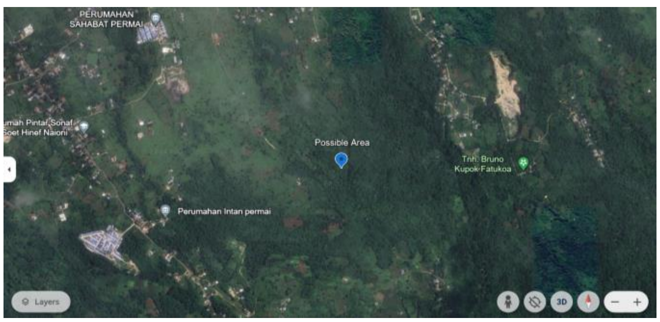
A. Data Collection

1) Wind Speed in Kupang

Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) of Indonesia data from 2020 to 2022 shows that Kupang City has an average wind speed of 2.05 m/s in Kupang District and a maximum of 7.5 m/s in Eltari District [36], with the lowest by 1 m/s [37]. While recent reports indicate wind speeds in NTT reaching 50-60 km/h (about 13.89 m/s to 16.67 m/s) [38], [39]. However, the given data is recorded for areas around the city. In consideration of the possibility of making small wind turbines farms, an open area is needed. Thus, using other sources such as Global Wind Atlas, an analysis for location selection can be made. The data shows that for open areas, in which has been identified with the help of Google Earth as well as geospatial data from Dukcapil and Landsat 8 data, possible areas in the context of relatively high wind speed and power density are within Naioni Village as shown in Fig. 1 a) which is the view and data from the Global Wind Atlas as well as b) as the view from the Google Earth.



a)



b)

Fig. 1. Naioni Village, Kupang by a) Global Wind Atlas and b) Google Earth

Global wind atlas data shows the mean wind speed of 4.22 m/s in the 10% of the windiest area for 10 m turbine hub height from the ground level, with an increase to 5.9 m/s for 50 m, 6.92 m/s for 100 m, 7.69 m/s for 150 m, and 8.19 m/s for 200 m. In comparison to BMKG data, this is more reliable since it provides better approximation based on the height's variation, showing the fulfillment to the minimum speed for small wind turbines by 4-4.5 m/s [40], [41]. Based on the scope (small wind turbine), it is assumed that the installation height will be at least 10 m from ground level. Thus, the range of wind speed from 1 m/s, 4.22 m/s, 13.89 m/s, and 16.67 m/s will be used as the basis for simulation for comparison purposes.

2). Wind Turbine Model Reference

Based on the information that the minimum wind speed in Kupang is 1 m/s, the researcher chose an existing model called AWI-E1000T as reference that backs up the idea of the wind turbine modelling in this research scope. This turbine comes in different variation based on the power specifications [42]. With the survival wind speed of 60 m/s and cut-in speed of 1 m/s, its blade radius is accounted approximately 2 m with the weight of 18.5 kg overall.

3). Tip Speed Ratio (λ), Pitch Angle (β), and air density.

Several reports and studies have suggested that the optimum tip speed ratio (λ) for three blade wind turbines is 7 which can range from 6-8 [43], [44], [45]. Whilst the same goes with the pitch angle (β) in which to obtain the maximum power point (correlated to Cp), the angle should be 0 degree [46], [47], [48]. Finally, the air density is also assumed to be 1.225 kg/m^3. Therefore, in this research, the λ is predetermined to be 7, β to be 0, and air density of 1.225 kg/m^3.

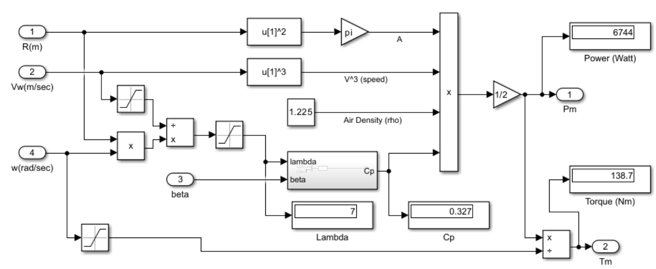
B. Modelling-Simulation

The power equation for wind turbines in (2) is used with additional equations (7) shown below.

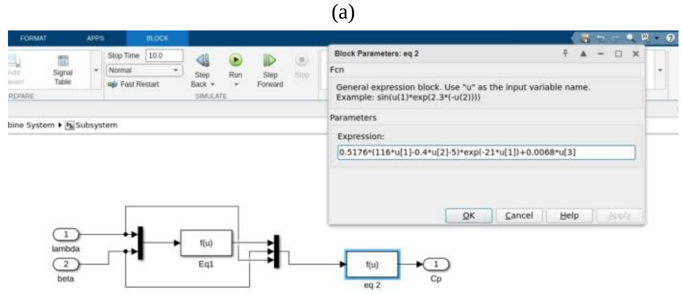
$$\omega = \frac{\lambda v_w}{R} \tag{7}$$

In which tip speed ratio (λ) means the ratio of wind turbine blade tip speed to wind speed, which can determine the angular speed or (ω).The angular speed used in the calculation are 3.5 rad/s, 14.77 rad/s, 48.615 rad/s, and 58.345 rad/s for the selected wind speed.

The power equation is then highly dependent on the power coefficients mathematical model. For the polynomial functions, modeling only focuses on the tip speed ratio as the input based on angular speed equation. Whereas for the sinusoidal and exponential function, the only difference with polynomial modelling lies on the additional input of pitch angle (β) shown in Fig. 2. Fig. 2 a) and b) are the breakdown of the function and the subsystem adjustment based on the Cp input.



(a)



(b)

Fig. 2. System for exponential and sinusoidal model a) Breakdown for Exponential and Sinusoidal Model for Small Wind Turbine and b) The Subsystem Adjustment According to the Input for Cp

Furthermore, torque or T (Nm) is also calculated alongside in which is obtained by dividing the power as P (W) to the angular speed as ω (rad/s), shown on the equation (8).

$$T = \frac{P}{\omega} \tag{8}$$

Then, for validation purposes to the modelled system, comparison between the designed model by researchers with exisiting literatures are shown in Table IV.

TABLE IV. VALIDATION FOR POWER COEFFICIENTS MODELS BASED ON EXISTING LITERATURES

Power Coefficient Models Input Parameters	Parameters for Validation	Literatures References	Research Models Result
Third Order Polynomial for wind speed of 8.2 m/s, radius of 3.61 m, and rotational speed of 22.7 rad/s [20]	Lambda and Cp	10 and 0.500	9.9 and 0.520
Fourth Order Polynomial for wind speed of 7 m/s, radius of 2 m, and rotational speed of 21 rad/s [21]		6 and 0.400	6 and 0.380
Fifth Order Polynomial for wind speed of 4 m/s, radius of 1.525 m, and rotational speed of 15.7 rad/s [22]		6 and 0.400	5.98 and 0.393
Seventh Order Polynomial for wind speed 8 m/s, radius of 2.5 m, and rotational speed of 12.8 rad/s [23]	Lambda and Ct	4 and 0.040	4 and 0.043
Sinusoidal Model (Moussa) wind for speed of 8.2 m/s, radius of 3.61 m, and rotational speed of 18.17 rad/s [20]	Lambda and Cp	8 and 0.480	7.99 and 0.470
Sinusoidal Model (Coto) for wind speed of 16 m/s, radius of 2 m, and rotational speed of 32 rad/s [24]		4 and 0.250	4 and 0.210
Sinusoidal Model (Xin) for wind speed of 13 m/s, radius of 3 m, and rotational speed of 65 rad/s [25]		15 and 0.270	15 and 0.259
Sinusoidal Model (Merahi) for wind speed of 11 m/s, radius of 2 m, and rotational speed of 33 rad/s [26]		6 and 0.520	6 and 0.529
Sinusoidal Model (Nouira) for wind speed of 10 m/s, radius 2 m, and rotational speed of 20 rad/s [27]		4 and 0.300	4 and 0.295
Exponential Model (Kotti) for wind speed of 13 m/s, radius of 2 m, and rotational speed of 39 rad/s [28]		6 and 0.330	6 and 0.330
Exponential Model (Khajuria) speed of 10 m/s, radius of 2 m, and rotational speed of 30 rad/s [29]		6 and 0.330	6 and 0.320
Exponential Model (Ovando) for wind speed of 10 m/s, radius of 1 m, and rotational speed of 100 rad/s [30]		10 and 0.400	10 and 0.403
Exponential Model (Feng) for wind speed of 4 m/s, radius of 2 m, and rotational speed of 8 rad/s [31]		6 and 0.440	6 and 0.436
Exponential Model (Llano) for wind speed of 3 m/s, radius of 3 m, and rotational speed of 6 rad/s [32]		6 and 0.400	6 and 0.403
Exponential Model (Shi) for wind speed of 11.4 m/s, radius of 63 m, and rotational speed of 0.72 rad/s [33]		4 and 0.190	4 and 0.187
Exponential Model (Bustos) for wind speed of 12 m/s, radius of 2 m, and rotational speed of 48 rad/s [34]		8 and 0.450	8 and 0.450
Exponential Model (Ahmed) for wind speed of 12 m/s, radius of 2 m, and rotational speed of 36 rad/s [35]		6 and 0.440	6 and 0.4395

Finally, the model can be made simpler to give better visualization that can highlight important data as shown in Fig. 3. as follows:

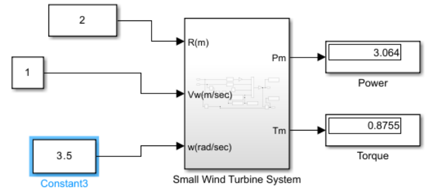


Fig. 3. Small Wind Turbine System Sample Model

IV. RESULTS AND DISCUSSION

The result of the simulation can be shown below with the given parameters in Table V. For the selected wind speed from the lowest, average, and seasonal by 1 m/s to 16.67 m/s, the power and torque for each power coefficient approaches show various results, ranging from about 3-20000 W and 1-290 Nm. It is considered that for a turbine system, a good coefficient power in relative ranges from 0.4 to 0.5 [49]. Therefore, selecting from the given range, three polynomial models satisfy the criteria (except for 5^{th} order polynomial that exceeded the range), sinusoidal functions have 3 satisfied models and exponential functions have 4 satisfied models. The highest power coefficient in terms of the range consideration lies in the third order of 0.4034 followed by [30] at 0.4513 and [26] at 0.474 from smallest to largest. For the maximum power, the [26] model reached 16900.6 W, slightly higher than [30]. The same for the torque producers, which are 289.7 Nm. Several other models do fall vaguely from the criteria such as [24], [28], [29], and others.

TABLE V. POWER COEFFICIENT SIMULATION RESULTS

Cp	Speed (m/s)	1		4.22		13.89		16.67	
	Output	Power (W)	Torque (Nm)	Power (W)	Torque (Nm)	Power (W)	Torque (Nm)	Power (W)	Torque (Nm)
Polynomial									
0.4737	3^{rd} [20]	3.6	1.0	274.0	18.6	9770.0	201.0	16889.3	289.5
0.4034	4^{th} [21]	3.1	0.9	233.0	15.8	8322.0	171.2	14384.7	246.5
0.5757	5^{th} [22]	4.4	1.3	333.0	22.5	11874.0	244.3	20526.0	351.8
0.4423	7^{th} [23]	3.4	1.0	256.0	17.3	9123.0	187.7	15769.7	270.3
Sinusoidal									
0.4483	Moussa [20]	3.5	1.0	259.3	17.6	9247.0	190.2	15984.3	274.0
0.3981	Coto [24]	3.1	0.9	230.3	15.6	8212.0	168.9	14195.2	243.3
0.327	Xin [25]	2.5	0.7	189.1	12.8	6744.0	138.7	11658.7	199.8
0.474	Merahi [26]	3.6	1.0	274.2	18.6	9777.0	201.1	16900.6	289.7
0.4439	Nouira [27]	3.4	1.0	256.8	17.4	9157.0	188.4	15828.9	271.3
Exponential									
0.39	Kotti [28]	3.0	0.9	225.6	15.3	8043.0	165.5	13904.0	238.3
0.39	Khajuria [29]	3.0	0.9	225.6	15.3	8043.0	165.5	13904.0	238.3
0.4513	Ovando [30]	3.5	1.0	261.0	17.7	9308.0	191.5	16090.6	275.8
0.4292	Feng [31]	3.3	0.9	248.2	16.8	8852.0	182.1	15301.9	262.3
0.3423	Llano [32]	2.6	0.8	197.9	13.4	7060.0	145.2	12203.6	209.2
0.4409	Shi [33]	3.4	1.0	255.0	17.3	9095.0	187.1	15721.1	269.5
0.4228	Bustos [34]	3.3	0.9	244.5	16.6	8720.0	179.4	15073.4	258.4
0.3528	Ahmed [35]	2.7	0.8	204.1	13.8	7277.0	149.7	12579.0	215.6

Using the highest output turbine model from [26] and assuming that the seasonal wind speed reaches 50-60 km/h periodically, the power generated reaches nearly 10000-17000 W with a torque of 200-290 Nm. However, since [26] states that the turbine was designed for 1.5 MW, this simulated research result is out of scope. Therefore, the best-selected model stands for [30] which provides power exceeding 9000-16000 W and torque range of 190-270 Nm, slightly lower than the prior. At the lowest speed of 1 m/s, the turbine produces 3 W while on the average speed of 4.22 m/s, it produces 261 W.

The outputs presented in their exact values will be different from the actual conditions, as they will vary with speed changes and direction which influence the changing of pitch angle and tip speed ratio values. The accumulated power will then be converted into electricity through a series of electrical systems transmitted for energy usage. This process could help meet the electricity demands in Kupang while addressing the urgent need to reach 23% from 14% of the current renewable energy by 2025 in RUKN and from *Rencana Usaha Penyediaan Tenaga Listrik Tahun* 2021-2030 (RUPTL) which also states the need to replace 23.231 kW of diesel capacity in this region specifically [50]. Hence, given the region's high wind energy potential and the research output, it is recommended to consider small wind turbine systems to provide local communities with electricity.

In consideration, further solutions and implementation plans are to be addressed to overcome the practical challenge including seasonal wind variations, maintenance, and integration into external systems (generators and power electronics) as well as local power grids. This includes optimization for pitch angle and tip speed ratio, the use of statistical methods to predict wind behavior over a period [51], implementation of artificial intelligence with fuzzy logics, neural networks, etc. for generators and power electronics systems performance control [52] as well as the use of financial and greenhouse gas reduction analysis to greater enhance the overall estimation results. This will give a strong basis for the next step, which is the social impact towards the local acceptance and support.

V. Conclusion

This study demonstrates small wind turbine models from MATLAB/Simulink simulation to show potential power supply to Kupang based on comparative analysis from existing power coefficient models, specifically for the horizontal-axis type with three blades. This project utilizes wind speed data of 1 m/s, 4.22 m/s and 13-17 m/s. Featuring a blade radius of 2 m, a tip speed ratio of 7, a pitch angle of 0 degree, and an air density of 1.225 kg/m³, power coefficients were analyzed based on the selected functions which are polynomial (third order, fourth order, fifth order and seventh order), sinusoidal ([20], [24], [25], [26], [27]) as well as exponential ([28], [29], [30], [31], [32], [33], [34], [35]). The best selected implementation model, Ovando et al. model yields a power coefficient of 0.4513, generating above 9000-16000 W per turbine rotation for seasonal wind. This output can meet almost of the 23.231 kW demand for diesel power replacement, may help in reaching 23% renewable energy target, provide energy to underdeveloped areas and prevent blackouts in NTT. Future research should consider optimization of pitch angle and tip speed ratio, wind prediction analysis, artificial intelligence for managing external systems, and assessments for financial viability and greenhouse gas emissions to ensure social acceptance. In addition, this may collaborate with local institutions to expedite development.

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