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Design and Numerical Study of Low-Speed Propeller Wind Turbine for Frontier Regions in Indonesia

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ABSTRACT

Wind power is one of the fastest-growing renewable energy sources in the world because of its many advantages. Wind power also presents fundamental challenges in some regions of the world, which are being addressed through research and development projects. This study aims to design and analyze propeller wind turbine for low-speed regions especially in those frontier, outermost and least developed regions often referred to as 3T (terdepan, terluar, tertinggal) in Indonesia. An open-source numerical software tool for aerodynamic and structural analysis of wind turbines is used to design airfoils. Four different airfoil types are selected based on literature study which produced four turbine blades: S826 (Antasena 1.1), NACA 4412 (Antasena 1.2), NACA 4415 (Antasena 1.3), and SG6043 (Antasena 1.4). Through simulations and analysis, it is found that Antasena 1.4 (SG6043) is the most suitable airfoil for low wind speed conditions (3-5 m/s). The power output predictions for various wind speed classes indicate that Antasena 1.4 has the highest potential power output, meeting and even surpassing the target values in certain months. Numerical simulation of Antasena 1.4 shows best power coefficient (C_p) 0.5747. The results demonstrate the promising applicability of Antasena 1.4 as an airfoil profile for turbines operating under low wind speed conditions.

Keywords: renewable energy, wind power, numerical simulation, turbine blade, frontier region, low speed.

NONMENCLATURE

Symbols	
C_D	Coefficient of drag
C_L	Coefficient of lift
C_p	Coefficient of power
C_L/C_D	Lift to drag ratio

1. INTRODUCTION

Wind turbines can be categorized into two types based on the orientation of their rotational axis: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). HAWTs have their axis aligned parallel to the wind direction, while VAWTs have their axis perpendicular to the wind direction. HAWTs are more commonly used due to their higher efficiency in harnessing wind energy from a specific wind direction compared to VAWTs [1]. Wind turbine blades continue to be the target of technological improvements by the use of better designs, materials, manufacturing, analysis and testing [2]. The effectiveness and functioning of wind turbines rely on the specific design and configuration of their rotor blades. These blades serve as aerodynamic components responsible for generating lift and thrust forces by capitalizing on the pressure disparity between their upper and lower surfaces when subjected to wind currents [3]. When designing wind turbine blades, several factors need to be considered, including blade length, airfoil shape, number of blades, pitch angle, twist angle, and chord distribution. A detailed review of wind turbine blade design is presented, including theoretical maximum efficiency, propulsion, practical efficiency, HAWT blade design, and blade loads [4]. One approach to blade design is the Betz method, which is a straightforward method based on Betz's elementary momentum theory. This theory explains how wind energy is converted into wind turbines. The Betz method assumes a two-dimensional, stable, and non-

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compressible wind flow. It also assumes no friction or turbulence losses in the wind flow before and after passing through the turbine rotor. By using the Betz method, it is possible to calculate the maximum power coefficient that an ideal wind turbine can achieve, which is 0.593 or 59.3% of the total kinetic energy in the wind flow. The structural design process of the wind turbine blade is constrained mainly by the aerodynamic outer surface of the blade and required stiffness criteria [5]. In designing wind turbine blade models, this study utilizes the Qblade application as a simulation tool with the Blade Element Momentum (BEM) method embedded in Qblade, as done by [6]. The software already covers a broad spectrum of lower order analysis techniques that are specific for wind turbine blade design and aerodynamic or aeroelastic analysis [7]. They utilized the Qblade application to identify suitable airfoils for small-sized horizontal-axis wind turbine (HAWT) designs under various Reynolds number variations. Through their study using the Qblade application, it was found that at Re = 50000, the SG6043 airfoil exhibited the highest coefficient of lift compared to other airfoils. Similar results were also observed at higher Reynolds numbers such as Re = 400000. To validate the results obtained from Qblade, they compared them with experimental data conducted by [8][9][10]. It can be observed that the data generated from the Qblade analysis closely approximated and corresponded well with the experimental data for the SG6043 airfoil at most points. Based on the obtained results and the validity of accurate outcomes, it can be concluded that the SG6043 airfoil is suitable for low wind speed conditions. Wind speed conditions at frontier regions in Indonesia are obtained from secondary data provided by HOMER software.

2. METHODOLOGY

2.1 Wind Potential at Several Frontier Regions

In this study, the wind speed data at frontier regions in Indonesia were obtained from secondary data provided by HOMER software. Several villages from various provinces in Indonesia were selected to represent the wind speed conditions at frontier regions. The wind speed data obtained was classified into three categories, as shown in Table 1. The wind speed data serves as a reference for determining the type and designing the profile of the propeller. The target output power for all three wind speed classes is set at 5-10 kW. As seen in Table 1, the three classes that are considered for this study are 3 m/s, 4 m/s, and 5 m/s. Werinama Village in Maluku and Osan Village in Sulawesi were picked as the 3m/s wind speed class. These areas have an average annual wind speed of 4.65 m/s and 4/06 m/s, respectively. For the 4 m/s wind speed class, wind data is gathered from Ilmamau Village and Pasir Putih Village in Maluku, as well as Bolokut Village in Sulawesi, with average annual wind speeds of 5.31 m/s, 3.67 m/s, and 4.45 m/s, respectively. Similarly, the 5 m/s wind speed class utilizes data from Gaimar Village and Doka Barat Village in Maluku, along with Okaba Village in Papua, which have average annual wind speeds of 6.45 m/s, 6.45 m/s, and 6.43 m/s, respectively.

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Table 1 Wind speed data of several villages at frontier regions in Indonesia (wind speed units in m/s)

No	Village	Province	Class	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
1	Werinama	Maluku	3	3.92	4.13	3.36	3.18	4.66	6.46	7.29	7.15	5.62	3.96	2.72	3.22	4.64
	Osan	Sulawesi	3	3.58	3.86	3.21	3.04	4.11	5.21	5.95	6.26	5.06	3.65	2.45	2.76	4.06
2	Ilmamau	Maluku	4	5.42	5.65	4.3	4.62	6.17	7.06	7.17	6.68	5.38	4.06	3.07	4.19	5.31
	Pasir Putih	Maluku	4	3.54	3.76	2.99	2.62	3.49	4.5	5.2	5.17	4.18	3.2	2.48	2.87	3.67
	Bolokut	Sulawesi	4	3.62	4.11	3.34	3.29	4.68	6.03	6.8	6.85	5.43	3.92	2.63	2.71	4.45
3	Gaiamar	Maluku	5	6	6.44	5.09	5.21	7.28	8.63	8.94	8.56	7.26	5.58	3.94	4.47	6.45
	Doka Barat	Maluku	5	6	6.44	5.09	5.21	7.28	8.63	8.94	8.56	7.26	5.58	3.94	4.47	6.45
	Okaba	Papua	5	4.79	5.23	4.54	5.59	7.24	8.09	8.36	8.29	7.92	7.06	5.55	4.52	6.43

Table 2 Maximum C_L to maximum angle of attack for the various airfoils

Airfoil	*Maximum Lift Coefficient (C_L)*	*Angle of Attack*
S826	1.679	14.5
NACA 4412	1.661	16
NACA 4415	1.727	17.5
SG6043	1.862	16.5

2.2 Airfoil Type Selection and Blade Shape Design

Based on the wind speed data described above, four different airfoils are selected to design the turbine blades: S826, NACA 4412, NACA 4415, and SG6043. These four airfoil types are chosen based on literature studies and matched with the selected wind speed data from the locations where the wind turbines will be operated. After determining the four airfoil profiles, each airfoil is simulated using the Xfoil system integrated within the Qblade software. The obtained data from these simulations include the Maximum Lift Coefficient (C_L), Maximum Drag Coefficient (C_D), and Maximum Lift to Drag Ratio (C_L/C_D). Table 2 displays the values of the maximum lift coefficient for the four airfoil types and the corresponding angle of attack at which the lift coefficient reaches its maximum value. From Table 2, it can be observed that the maximum lift coefficient for the SG6043 airfoil is achieved at an angle of attack of 16.5° with a value of 1.862. As for the S826 airfoil, the maximum C_L is attained at an angle of attack of 14.5° with a value of 1.679, while the NACA 4415 airfoil reaches its maximum C_L at an angle of attack of 17.5° with a value of 1.727. The NACA 4412 airfoil, on the other hand, achieves its maximum C_L at an angle of attack of 16° with a value of 1.1661

Table 3 shows the values of the maximum drag coefficient (C_D) for the four airfoil types and the corresponding angle of attack at which the drag coefficient reaches its maximum value. From Table 3, it can be observed that the maximum drag coefficient for all four airfoils is achieved at an angle of attack of 20°. For the SG6043 airfoil, the maximum C_D value is 0.1104, while the S826 airfoil has a maximum C_D of 0.1709, and the NACA 4415 airfoil has a maximum C_D of 0.0906. The NACA 4412 airfoil, on the other hand, has a maximum C_D value of 0.1131.

Table 3 Maximum C_D to maximum angle of attack for the various airfoils

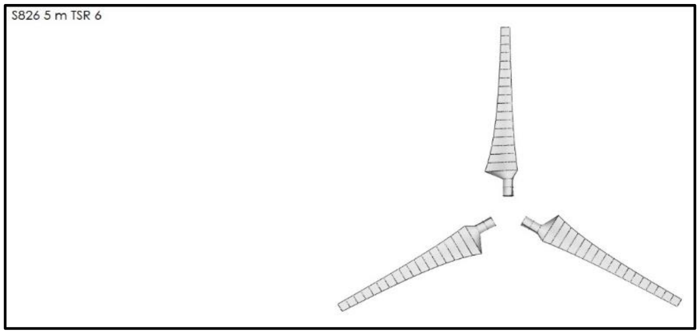
Airfoil	*Maximum Drag Coefficient (C_D)*	*Angle of Attack*
S826	0.1709	20
NACA 4412	0.1131	20
NACA 4415	0.0906	20
SG6043	0.1104	20

Table 4 shows the maximum lift-to-drag ratio (C_L/C_D) values for the four airfoil types and the corresponding angle of attack at which the C_L/C_D ratio reaches its maximum value. From Table 4, it can be observed that the maximum C_L/C_D ratio for the SG6043 airfoil is achieved at an angle of attack of 2° with a value of 18.59. As for the S826 airfoil, the maximum C_L/CD is attained at an angle of attack of 5° with a value of 14.63, while the NACA 4415 airfoil reaches its maximum C_L/C_D at an angle of attack of 6° with a value of 14.689. The NACA 4412 airfoil, on the other hand, achieves its maximum C_L/C_D ratio at an angle of attack of 5.5° with a value of 13.81.

Table 4 Maximum C_L/C_D to maximum angle of attack

Airfoil	*Maximum Glide Ratio (C_L/C_D)*	*Angle of Attack*
S826	14.63	5
NACA 4412	13.81	5.5
NACA 4415	14.68	6
SG6043	18.59	2

Subsequently, the propeller profile design process is conducted by optimizing with the Qblade [11][12][13] software using the Betz method. The optimization process involves segmenting the propeller into 33 segments and assigning an appropriate airfoil design to each segment. The goal of the optimization is to determine the optimal chord length and twist angle. The optimization is performed within a target range of tip speed ratio (TSR) values between 4 and 6. Once the propeller profiles are finalized, the turbine rotor is formed as a complete unit, excluding the hub. This process results in the creation of four turbine rotors named Antasena 1.1 (S826), Antasena 1.2 (NACA 4412), Antasena 1.3 (NACA 4415), and Antasena 1.4 (SG6043) as can be seen in Figure 1.



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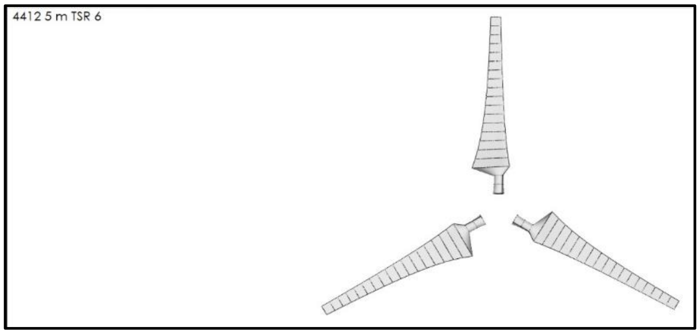

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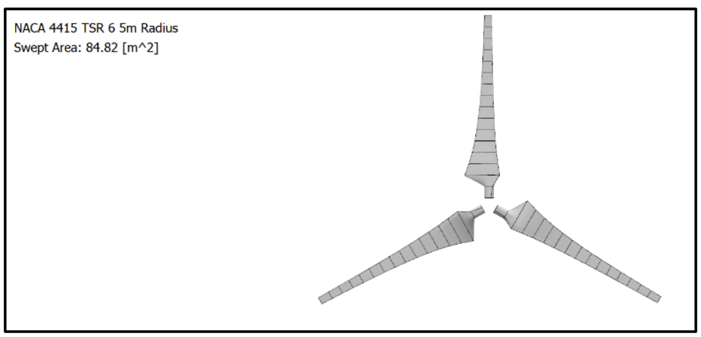

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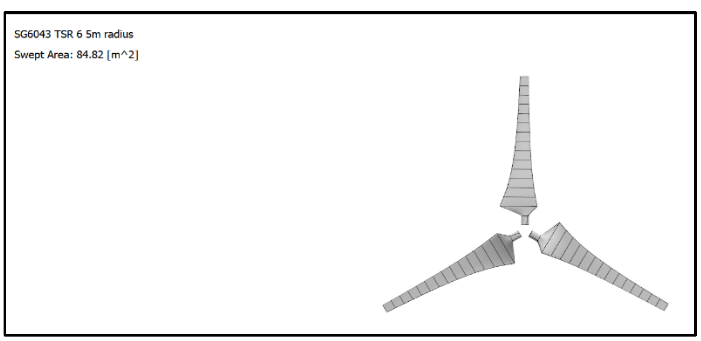


(d)

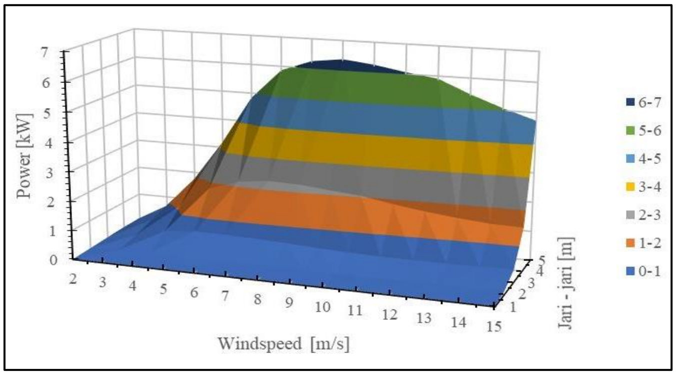
Figure 1 Turbine rotor for each of the selected airfoils; (a) Antasena 1.1 (S826), (b) Antasena 1.2 (NACA 4412), (c) Antasena 1.3 (NACA 4415), (d) Antasena 1.4 (SG6043)

3. RESULT AND DISCUSSION

Once the turbine rotor has been formed, simulations can be conducted to validate the results of the propeller profile design process. The first simulation performed is the Boundary Element Method (BEM) analysis of the rotor. The simulations are conducted within different Tip Speed Ratio (TSR) values ranging from 1 to 15 with an interval of 1. The rotor simulations are carried out within a radius range of 1m to 5m for each airfoil shape. This is done to find the most optimal radius for low wind speed conditions of 3-5 m/s. The simulations are performed with the same turbine rotation speed parameter, specifically at 40 rpm.

Numerical simulation for power to wind speed with variation of radius blade shown in figure 2. It is demonstrate that increasing radius would increase power up to 21 kW, the limitation lies in the manufacturing process.

As the study continues with the rotor having a 5 m radius, each airfoil then can be compared by its power output capability relative to the windspeed. The results can be observed in Figure 3. Figure 3 depicts the power output generated for each wind speed variation with different airfoil shapes. From Figure 3, it can be observed that the airfoil with the largest maximum power output is the SG6043 (Antasena 1.4) type, with a value of 20.5 kW. The second highest power output is generated by the NACA 4412 (Antasena 1.2) with a value of 12.4 kW, followed by the S826 (Antasena 1.1) with 6.36 kW, and lastly the NACA 4415 (Antasena 1.3) with 6.28 kW. Among the four airfoils, the maximum power output is achieved at a wind speed of 15 m/s, except for S826, where the maximum power output is obtained at a wind speed of 10 m/s. From Figure 3, it can also be observed that, in general, the airfoil types exhibit an increasing trend in power output as wind speed increases. However, this does not hold true for the S826 airfoil, as its power output reaches a maximum at a wind speed of 10 m/s and then decreases. Regarding the power output at the target wind speed range of 3-5 m/s in the 3T region, the SG6043 (Antasena 1.4) airfoil achieves the highest power output at a wind speed of 3 m/s with 0.709 kW. It is followed by the NACA 4412 (Antasena 1.2) with 0.686 kW, then the S826 (Antasena 1.1) with 0.6769 kW, and finally the NACA 4415 (Antasena 1.3) with a power output of 0.610 kW. As for the wind speed class of 4 m/s, once again the SG6043 (Antasena 1.4) holds the highest power output with a value of 1.826 kW.



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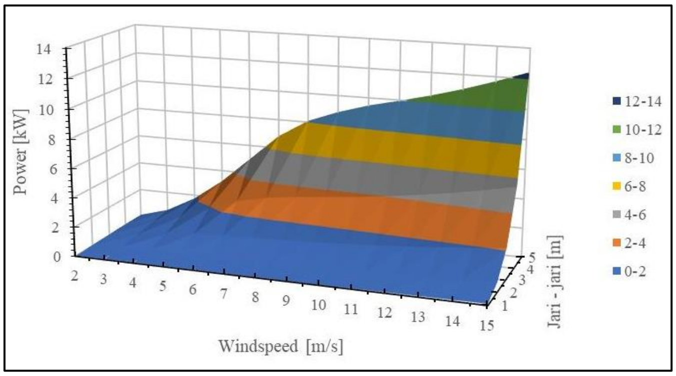

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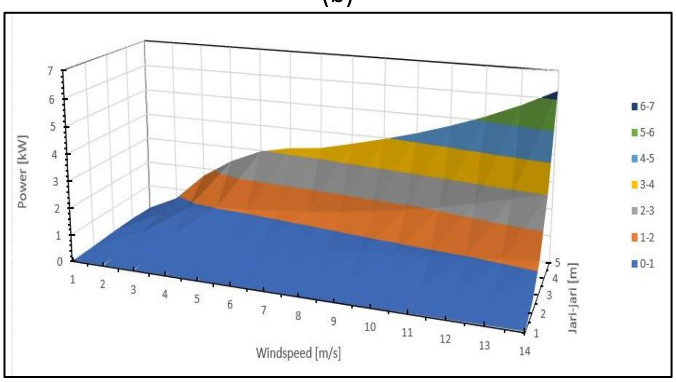

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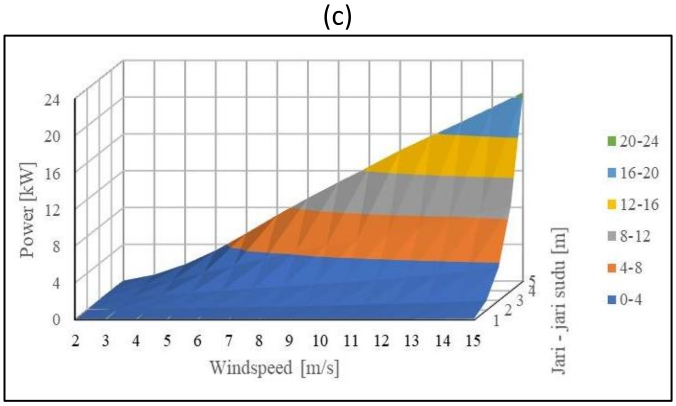

(d)

Figure 2 Power to Wind Speed graph for every radius variant of the airfoils; Antasena 1.1 (S826), Antasena 1.2 (NACA 4412), Antasena 1.3 (NACA 4415), Antasena 1.4 (SG6043)

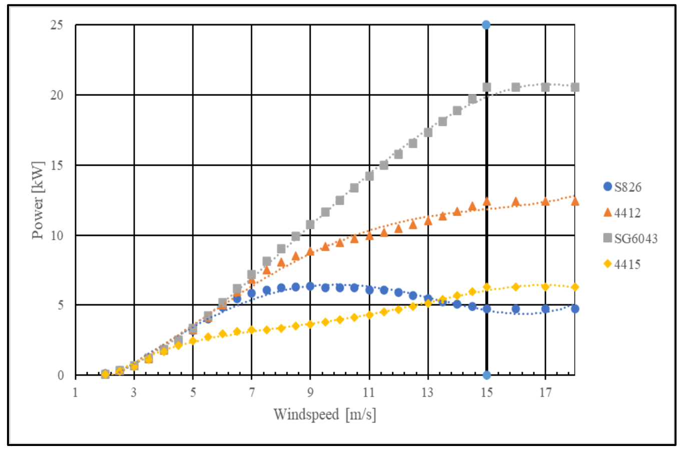

Figure 3 Power to Wind Speed graph produced by the airfoils; Antasena 1.1 (S826), Antasena 1.2 (NACA 4412), Antasena 1.3 (NACA 4415), Antasena 1.4 (SG6043)

It is followed by the S826 (Antasena 1.1) with 1.773 kW, the NACA 4412 (Antasena 1.2) with 1.763 kW, and lastly the NACA 4415 (Antasena 1.3) with a value of 1.7 kW. In the 5 m/s wind speed class, the SG6043 (Antasena 1.4) remains at the top with a value of 3.34 kW. It is followed by the NACA 4412 (Antasena 1.2) with 3.23 kW, then the S826 (Antasena 1.1) with 3.19 kW, and finally the NACA 4415 (Antasena 1.3) with a value of 2.44 kW. Among the four airfoils, none of them have reached the target power output of 5 kW in the 3-5 m/s wind speed range. The NACA 4412 (Antasena 1.2) and SG6043 (Antasena 1.4) only reach the target power output at a wind speed of 6 m/s. Meanwhile, the S826 (Antasena 1.1) reaches the target power output at a wind speed of 8 m/s. The NACA 4415 (Antasena 1.3) achieves the target power output at a wind speed of 13 m/s. Numerical simulation of Antasena 1.4 shows best power coefficient (Cp) 0.5747.

Based on the results and discussion, it was found that the designed propeller wind turbine suitable for three villages area of low-speed frontier region in Indonesia. The significance of applying designed propeller considering for high operation and construction cost will be investigated for the next continued study.

4. CONCLUSION

The frontier region selected as the study object for the 3 m/s wind speed class includes Werinama Village in Maluku and Osan Village in Sulawesi. These two regions have average annual wind speeds of 4.65 m/s and 4.06 m/s, respectively. For the 4 m/s wind speed class, wind data is obtained from Ilmamau Village and Pasir Putih Village in Maluku, as well as Bolokut Village in Sulawesi, with average annual wind speeds of 5.31 m/s, 3.67 m/s, and 4.45 m/s, respectively. As for the 5 m/s wind speed class, data is collected from Gaimar Village and Doka Barat Village in Maluku, as well as Okaba Village in Papua, with average annual wind speeds of 6.45 m/s, 6.45 m/s, and 6.43 m/s, respectively.

The design of the turbine blades is determined by four different airfoils, namely Antasena 1.1 (S826), Antasena 1.2 (NACA 4412), Antasena 1.3 (NACA 4415), and Antasena 1.4 (SG6043). These four airfoil types are selected based on literature studies and matched with the wind speed data chosen as the locations where the wind turbines will be operated.

Based on the data and discussions presented earlier, the simulation results from Qblade, and the analysis of power output data at low wind speeds, it can be concluded that the most suitable choice for the airfoil profile design is Antasena 1.4 (SG6043). Numerical simulation of Antasena 1.4 shows best power coefficient (C_p) 0.5747. The calculated results show great potential for its application as an airfoil profile in low wind speed conditions.

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