JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(9), 272–281
https://doi.org/10.12911/22998993/191437
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.06.24
Accepted: 2024.07.22
Published: 2024.08.01

Experimental Investigation of the Horizontal Axis Wind Turbine with NACA4418 Blade Length

Muhammad Ilham Maulana[1], Ahmad Syuhada[1*], Akhyar Hasan[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Indonesia
* Corresponding author's e-mail: ahmadsyuhada@usk.ac.id

ABSTRACT

Wind energy is a clean valuable source of renewable electricity when used with specific characteristically turbines because of its inexhaustibility as well as abating the use of fossil fuels. However, studies are still needed to design wind turbines with better performance. Therefore, this study aims to analyse the effect of blade length on the shaft rotation of a small-scale HAWT (horizontal axis wind turbine). A small-scale HAWT with the NACA4418 blade length of 1.25, 1.50, and 1.75 m was tested using three different blades (3, 4, and 5 blades) at speeds between 3 and 8 m/s without generating load. The lengths affected the tip speed ratio in this condition, considering various counts. The results showed that the rotor stability of a 1.25 m blade length was better than others at 4–6 m/s, based on the produced TSR value. The CP of the wind turbine also began to change significantly at 5 m/s, with the five-blade system of 1.25 m having the best rotation at medium speeds compared to others at 1.50 and 1.75 m. The correct number of blade lengths is essential for optimal and efficient overall turbine performance.

Keywords: wind energy, horizontal wind turbines, blade length, shaft rotation.

INTRODUCTION

Electrical energy has become one of the inseparable essentials from all human activities in supporting economic development regarding the transformation and advancement of time and technology. It is usually generated by power plants using non-renewable natural resources with limited availability. However, the issue of decarbonisation is accompanied by an increase in renewable electricity capacity installations in the electrification and transportation energy sectors. This led many countries towards the connivance to reduce their greenhouse gas emissions as part of the Paris Agreement. The vulnerability of energy systems to weather and climate is also increasing due to being a fascinating issue in renewable energy utilization (Bloomfield et al., 2021; Staffell and Pfenninger, 2018).

In sustainable development, renewable energy is found to be very important, with wind power observed as one of the sources to be utilized (Ahmad and Tahar, 2014). This wind phenomenon is a valuable source of clean, renewable energy, which has evolved into power generation (Jain, 2011; Al-Fatlawi et al., 2022). In many countries, it also plays an essential role in power generation systems, regarding reducing reliance on fossil fuels. According to Evans et al. (2009), wind had the least carbon emissions, water waste, and the greatest beneficial social impacts. A trend was also observed toward mini-scale (20–200 kW) and micro-scale (less than 20 kW) generations in urban wind turbine development analysis (Perea-Moreno, 2018). In this condition, small-scale wind turbines exhibited the following features, (1) reduced maintenance costs, (2) more reliable, (3) possessed a more considerable wind working range than industrial turbines, and (4) possessed a lower environmental impact (Pellegrini et al., 2021; Bezrukovs et al., 2020).

The number of small-scale wind turbine power plants has recently increased significantly, with several previous studies emphasizing the performance evaluation and application of these specific systems in urban areas. Based on Pitteloud and Gsanger (2016), a significant increase was observed yearly in the number of small-scale wind turbines, which were applied on horizontal (HAWT) or vertical (VAWT) axes as power plants. There are many studies conducted on HAWT to improve the general performance (Cai et al., 2022; Dar et al., 2022; Wen et al., 2023; Zhang et al., 2022).

Many studies also attempted to improve the performance of these small-scale turbines as power plants, with most of them emphasizing the maximization of rotor proficiency in various combinations. To increase power output, Hassanzadeh et al. (2022) adjusted the chord and rotational angle of the HAWT, where the energy production of the optimum turbine increased by approximately 8.51% than the manufacturing system.

According to Predescu et al., (2009), the effects of BN, BTA, and TA (blade number, blade tip angle, and torsion angle) were investigated on HAWT performance. This was conducted in a closed-loop wind tunnel with fluid velocity variations of 6.5, 8.5, and 10.5 m/s. In this condition, two separate blade sets (A and B) were observed to have 22° and 17° twists, respectively, towards examining the influence of angles on wind turbine performance. Based on the results, the rotors with higher and lower blade rotation angles produced more power at low and high wind speeds, respectively.

Abdelsalam et al. (2021) also investigated a small-scale HAWT with an analytically-designed blade and a linearized chord-twist angle profile. These analyses were conducted on a 1 m diameter rotor with wind speeds and blade pitch angles of 5–10 m/s, as well as -3, 0, and 3, respectively. The results showed that the maximum Cp of classical and linear rotors were 0.446 and 0.426, respectively. The operation of the linearized rotor was also observed at a low wind speed of 5 m/s, compared to the conventional system that functionally began at 6 m/s. This proved that the linearized rotor occupied 26% less volume than the classic rotor.

Furthermore, Abdelgalil et al. (2021) used experimental and numerical methods to investigate the effect of rotor solidity on the aerodynamic features of HAWT for various TSRs. From the results, the blockage had two primary consequences regarding the increase in blade numbers: higher torque and friction losses. This showed that a rotor with a large blade number (solidity) enabled the turbine's operation at a lower TSR, which is beneficial in some applications such as water pumping.

In Indonesia, the potential of small-scale wind energy has not been widely studied and mapped comprehensively. This is because the wind speeds range from 3–7 m/s, depending on the location and geography. In this condition, Indonesia presently has 1.96 MW of installed wind-generating capacity, which was found not to be commercially used due to the high utilization for development and experiments. Approximately 85% of the wind power potential also emphasized large-scale generation on the Islands of Java, Bali, Sulawesi, and Nusa Tenggara (Noviani, 2019).

In developing industrial-scale wind power plants such as those in Indonesia, the main challenge is the high investment costs (Ahmad and Tahar, 2014; Fatlawi et al., 2022; Evans et al., 2009; Syuhada et al., 2016). This shows that the development of a small-scale power generation industry is a very attractive opportunity, specifically in areas with medium wind potential and a long coastline (Pellegrini, 2021; Hassanzadeh et al., 2016; Syuhada et al., 2017). In the Banda Aceh area, winds often blow for 4–5 h daily at 4–6 m/s, specifically in the coastal sites (Syuhada et al., 2020). Based on these conditions, the use of a small-scale wind generator is considered to be highly appropriate. In developing small-scale wind turbines, the optimization of rotor rotation is crucial regarding the ability to function throughout an extensive wind speed range without a pitch and yaw control system. It also emphasizes the reaction to rapid wind speed intensity and direction changes. This condition exhibits the reasons the evaluation of small-scale HAWT rotor performance on the number of blades is interesting.

According to Syuhada et al. (2020), a 1-m-long NACA 4418 profile was used to investigate the fan numbers on a 1 kW HAWT at 3–9 m/s. The results showed that a 5-blade turbine produced more electrical energy at 6 m/s, compared to 6 or 7 types. The systems with a few and a large numbers were also better below 5 and above 7 m/s, respectively. This indicated that the wind speed and availability of the turbine installation site determined the utilized fans.

Many previous studies mainly focused on blade design and geometry, such as the optimal development of airfoils and the number effect (Hassanzadeh, 2016; Predescu et al., 2009; Abdelsalam et al., 2021; Abdelsalam et al., 2021; Eltayesh et al., 2021; Wang and Chen, 2008). For optimization design, a helpful report also needs to be conducted based on identifying the key parameters in fan length and determining and using the optimum balance of these data. Therefore, this study aims to analyse the effect of blade length on the HAWT shaft rotation to obtain the optimal outputs according to wind speed. This involves various sizes and numbers, i.e., 1.25, 1.50, and 1.75 m, as well as 3, 4, and 5, respectively.

Therefore, this study intends to investigate the effect of blade numbers and length. The wind turbine is a horizontal propeller system (HAWT) of 1.25, 1.50, and 1.75 m. Totalling 6 fans of each size, it also contains meranti wood with the NACA 4418 airfoil shape.

EXPERIMENTAL PROCEDURES

Wind turbine models

The wind turbine blades and the tie hub are the two major components manufactured for this study. Blade, the material used for forming the blades is meranti wood, which has a width and thickness of 200 and 30 mm, respectively. This versatile wood is easy to determine and available at a reasonable price. It also has a firm texture and a long lifespan, leading to its being commonly used for various purposes. In addition, the meranti wood is specifically appropriate for usage as a blade material, which design is shown in Figure 1.

The airfoil is shaped according to the provisions of NACA 4418, with chord line lengths of 180 and 100 mm at the blade's base and end, respectively (AirfoilTools.com, 2013). The chord line of the airfoil is 180 mm long and 30 mm thick at the base, with the size and shape supporting the NACA 4418 specifications as shown in Figure 2 (AirfoilTools.com, 2013).

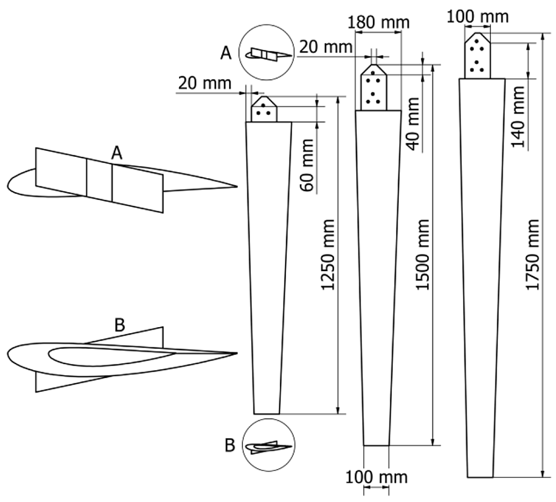

Figure 1. Blade design with NACA4418 three different blade length

The chord line length is also 100 mm, with the tip having a maximum thickness of 15 mm. From the base to the tip, a tapper is then constructed on the blade's airfoil. This design continuously diminishes along the blade, with a 1:1.8 chord line observed between the tip and the base (AirfoilTools.com, 2013).

Hub, the rotor hub is formed through an iron plate with a thickness and diameter of 3 and 400 mm, respectively. It is also formed at a fastening hole with a diameter of 10 mm, for blade numbers 3, 4, and 5. Regarding the primary shaft fastener, a 20 mm hole is subsequently used, with the hub containing three pairs of iron plates, each for the 3, 4, and 5 blades. In this condition, the HAWTs of 1.25, 1.50, and 1.75 m, as well as the 5-blades of the NACA 4418 airfoil profile, were examined at available wind energy for a specific time and speed. The fans also converted kinetic energy into the rotation to analyse the wind power, blade length, and the generated output effects.

Measurement systems

Wind energy conversion systems are generally used for mechanical and electrical purposes, according to the desired needs. HAWT is also a type of turbine used to convert energy with the highest efficiency due to the vertical movement of the blades towards the wind direction and the acquisition of power through all cycles (Bezrukovs et al., 2020). Furthermore, wind energy is often transformed into electrical power through present technology, with an average efficiency of 40%. This is because the wind speed emanating from the turbine rotor is not zero, leading to the usual remnant of kinetic energy (Perea-Moreno et al., 2018). The power possessed by the wind is also proportional to the air density, the area traversed, and the speed cube. According to Albert Betz, the maximum amount of wind energy theoretically converted by an ideal turbine was 59% or 16/27, known as the Betz Limit (Jain, 2011). For every category of blade variation, ten measurements have been taken in order to acquire valid data.

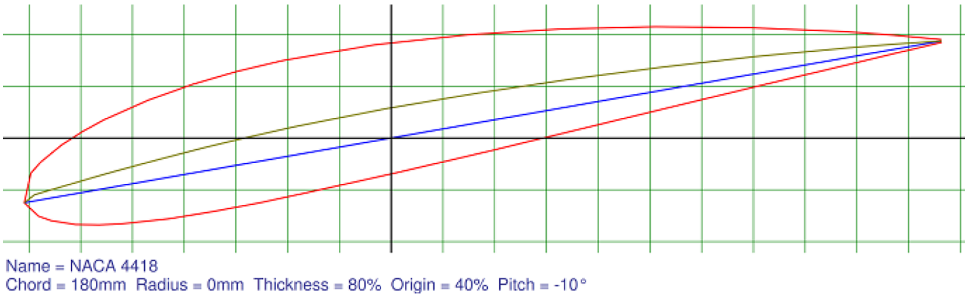

Figure 2. NACA4418 airfoil profile at the base of the blade

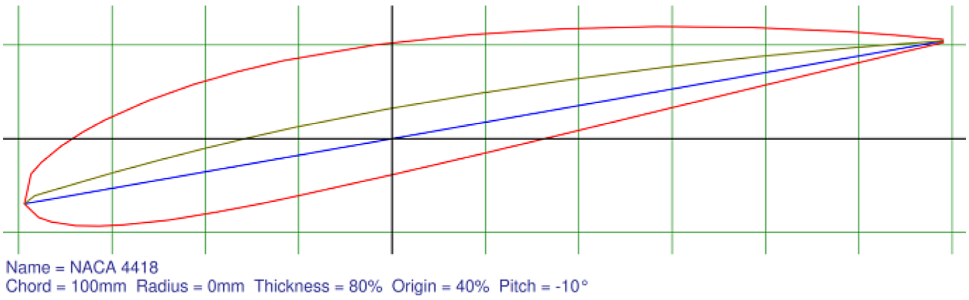

Figure 3. NACA4418 airfoil profile at the tip of the blade

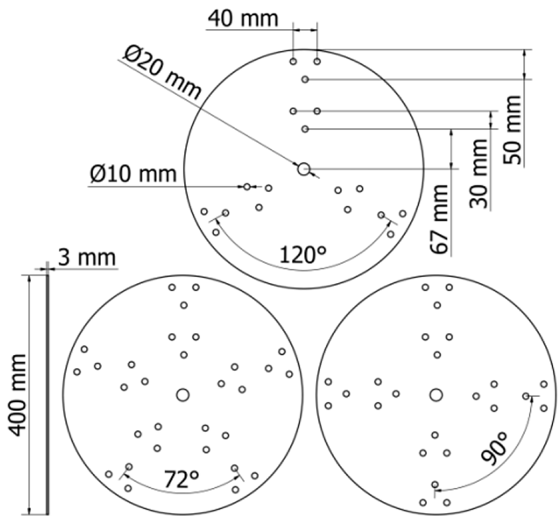

Figure 4. The hub of the blade, 72°, 90° and 120°

Wind power

Wind power is often expressed as an equation of the airflow kinetic energy and the flowing mass producing the specific power passing through the cross-section per unit of time (Jain, 2011; Mathew, 2007).

$$P=\frac{1}{2} r A v^3 \tag{1}$$

where: P is wind power (W), ρ is air density (kg/m^3), A is cross-sectional area (m^2) and v is wind speed (m/s).

The tangential velocity

This is the tangential speed (ω) of the turbine's rotation in rad/s.

$$\omega = \frac{2\pi n}{60} \tag{2}$$

where: ω is tangential velocity and n is turbine rotation.

Tip speed ratio

This is the tangential speed ratio of a blade's tip to the actual wind speed (v). In this condition, the blade efficiency is related to its tip-speed ratio *(TSR)*, which varies depending on the design (Patel, 1999). The nominal value of the rotor *TSR* also varies with wind speed loading.

$$TSR = \frac{\omega r}{v} \tag{3}$$

Wind-turbine rotor power

This is the amount of mechanical power converted by the wind turbine rotor (Mathew, 2007; Patel, 1999).

$$P_t = \frac{1}{2}\left[\rho A \frac{\left(v+v_0\right)}{2}\right]\left(v^2 - v_0^2\right) \tag{4}$$

where: Pt is rotor power (W), v is wind velocity upstream (m/s) and v_o is wind velocity downstream (m/s).

Power coefficient

This is the ratio between the converted mechanical output to the wind power contained at a rotor cross-sectional area (Jamdade et al., 2013; Neill and Hashemi, 2018).

$$C_p = \frac{P_t}{P} \quad (5)$$

where: *Cp* is power coefficient, *Pt* is turbine power (W) and *P* is win power (W). On the other hand, the application of distributed generation, particularly in determining the capacity and positioning of buses and feeders, can reduce voltage losses in wind power implementation (Siregar et al., 2023).

RESULTS AND DISCUSSION

Experiments were conducted on a wind turbine without using a generator load. This indicated that the wind and shaft rotation speed were the only parameters being measured using a digital anemometer and tachometer. For the wind speed, the measurement was carried out by pointing the digital tool in the flow direction at an altitude equal to the shaft's height. Meanwhile, the rotational speed was measured by aiming the tachometer's laser beam onto the wind turbine rotor, which was attached to a marker sticker. At inlet velocities of 3–8 m/s, the characteristic curves of the measured HAWT parameters are shown in Figures. 5–7. In these conditions, the transformation effects in the length and number of turbine blades were observed on the shaft rotation. While employing a three-fan system at 4–4.5 m/s, the highest centrifugation was achieved by the 1.25 m type, as shown in Figure 5. This optimum condition emphasized the average wind speed in the coastal area of Banda Aceh, which was observed at 4–6 m/s. When increased to 5–6 m/s, a 1.50 m turbine obtained the highest rotation. However, the 1.75 m type was only effective above 6.5 m/s.

In a four-blade turbine at 4.5 m/s, a 1.25 m system also had the highest initial rotation, with that of 1.50 m obtaining the greatest centrifugation above 4.5 m/s, until a speed of 6.5 m/s was achieved. However, a 1.75 m turbine was not suited for use in this condition since the rotation was only increased when the velocity exceeded 6.5 m/s. This demonstrated that a 1.75 m system was more effective in areas with intense wind speeds.

Using a five-blade turbine, a low initial power rotation was obtained due to the weight of the fans, as shown in Figure 6. Despite showing lower rotation, the results still investigated the optimal HAWT design parameters through relative comparisons. This was conducted when the blades were used at similar lengths with different numbers (Predescu et al., 2019). Based on the typical speed of the Banda Aceh coast (4–6 m/s), the best centrifugation on five-fan systems was achieved at 1.25 m. The performance of the shaft rotation varied depending on the blade length and the wind flow velocity. When at 3 m/s, only three or four-fan turbines at 1.25 m had high rotation. At 1.50 and 1.75 m, these systems also had rotations above 400 rpm at 3.5 m/s. Meanwhile, all the blades began to rotate when the wind speed exceeded 4 m/s, with the 1.75 m five-fan turbine having the lowest centrifugation. Irrespective of this condition, the five-blade turbine at 1.25 m

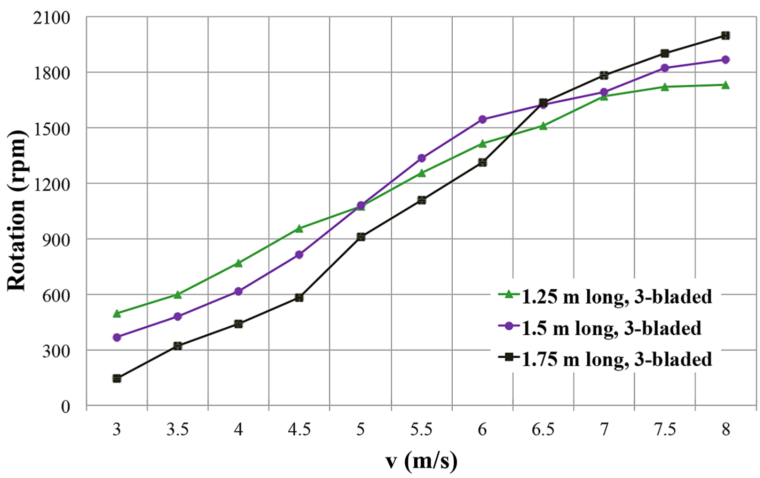

Figure 5. Three blade turbine shaft rotations with three different blade lengths

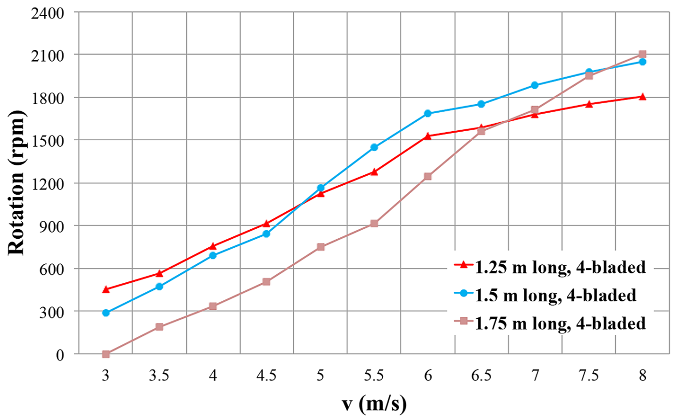

Figure 6. Four blade turbine shaft rotations with three different blade lengths

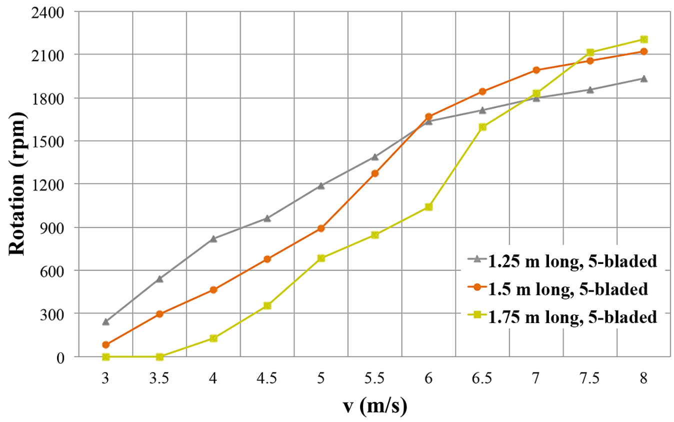

Figure 7. Five blade turbine shaft rotations with three different blade lengths

still had a more significant increase than the others. When the speed increases to 5–6 m/s, the four and five-fan systems at 1.50 m adequately and rapidly rotated, respectively.

When the wind blows at 6.5 m/s, the 1.50 m five-blade turbine produced the highest rotation, with a 1.75 m type having a significant rotational increase. At 8 m/s, the highest centrifugation also occurred in a 1.75 m five-blade system, indicating that the wind speed and installation location determined appropriate and suitable fans. Based on the results, an analysis was carried out to assess the system performance at 4–6 m/s, which was the average speed in the coastal area of Banda Aceh. This showed that the best rotations for three and four blades were obtained at 1.50 m, with the appropriate regulation for a five-fan turbine acquired at 1.25 m. At 1.50 m, this similar system also achieved maximum rotation when wind speeds exceeded 6 m/s. This was due to the effects of longer and greater number of blades on the rotor velocity. The number increase from these results led to the starting torque's elevation (Wang and Chen, 2008). The shaft rotation significantly improved by using a 1.25 m five-blade turbine at a moderate speed of 4–6 m/s, indicating 820 and 1634 rpm at 4 and 6 m/s, respectively. The effect of the length and number combination on the power generated was also observed above 5.5 m/s. This was in line with the rules of Newton's second equation, where the force produced equalled the mass multiplied by the linear acceleration of an object. The rotational motion also occurred in the wind turbines, where the angular acceleration equalled the torque divided by the moment of inertia. Moreover, the increase in the weight and dimensions of the blade caused a greater production of inertia moment, leading to the requirement of higher torque for frequent movements (Syuhada et al., 2020). This proved that a higher wind speed was required to move the turbine blades. According to the theory of the wind energy equation, a larger cross-sectional area caused greater power generation. Based on the comparative analysis of the length and number of blades, the wind turbine rotor power was redrawn on the energy graph shown in Figure 8.

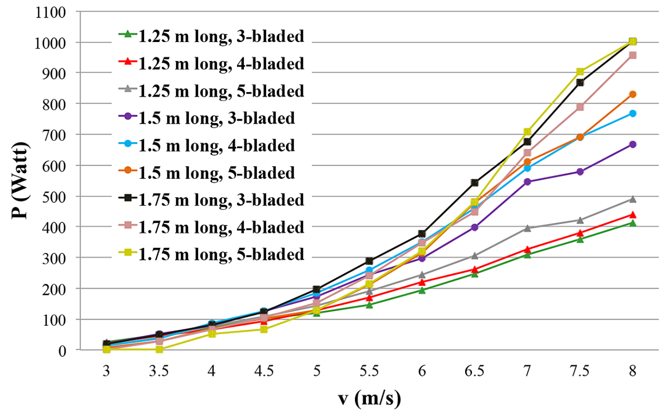

Figure 8. Wind turbine rotor power for three, four and five blade

When the wind speed achieved 5 m/s, the power generated by the rotor began to experience a significant change, continuously increasing with the elevation of the air velocity. In this condition, the rotor's power differences from high-speed wind energy began to clear. Regarding a 1.25 m blade, the power produced was more stable than the other lengths, although the rotation was not very high when the wind speed was above 5.5 m/s. This was due to the effect of different blade lengths, which produced distinguished moments of inertia. A 1.50 m wind turbine was also in good condition when the speed achieved 4.5–6.5 m/s, with a 1.75 m system generating occasional high power above 6 m/s. At this wind speed, the 3-blade turbine also produced the highest power.

This indicated that a more stable tip speed ratio (TSR) caused better energy to be generated by the rotor and transmitted to the generator. This depended on the size, length, and several turbine blades. The wind turbine often incurred damage when the rotation was too high on the large blades. High rotation caused air turbulence, with the rotor becoming a wall against the wind. In this case, an experiment was carried out without using a generator load, with a very high rotation produced due to the uncoupled condition of the turbine to the power plant.

According to Figure 9, the measured TSR was shown at the various blades for an inlet velocity of 3–8 m/s. These curves showed the patterns by which the effect of length changes corresponded to the transformation of the turbine fan numbers. In this condition, the ratio increase was not high in using three, four, and five-blade systems, due to the stability of the generated rotation against wind speed. However, a five-blade turbine of 1.75 m was different regarding slightly low rotation in the initial conditions (Garcia-Ribeiro et al., 2021). Slightly different behaviours were also observed for those at 1.50 and 1.75 m, which TSR significantly improved above 6.5 m/s. This proved that the number of fans increased the ratio curve, compared to shorter systems. Therefore, the turbines with longer blades were more sensitive to changes in the flow separation sequence caused by the TSR transformation. In the rotor,

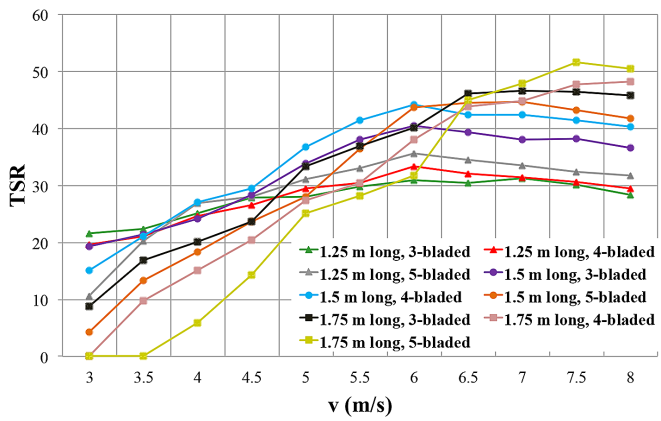

Figure 9. Wind turbine tip speed ratio for three, four and five blade

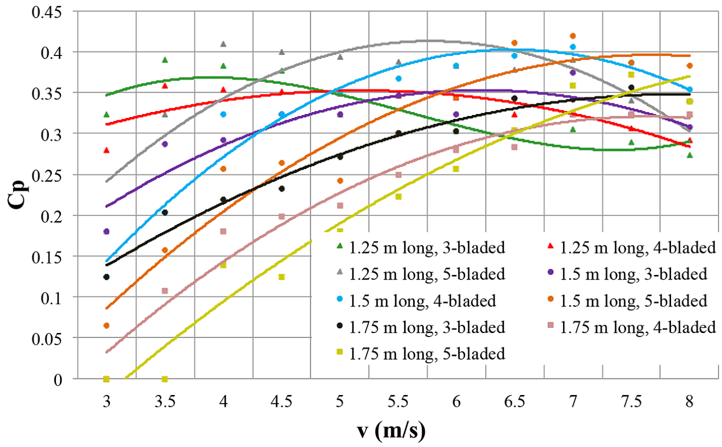

Figure 10. Wind turbine rotor power coefficient for given wind speed

the highest value was obtained at a length and speed of 1.50 m and 4–6 m/s, respectively. In this condition, a 1.25 m fan also had a better stability value than others for a sustainable rotational balance. Based on these results, a more stable TSR value led to the appropriate conversion of wind energy into rotor rotation power.

Figure 10 shows the measured pressure coefficient (CP) with an inlet velocity of 3–8 m/s, for various blade lengths and numbers. This demonstrated that the rotor efficiency was approximately 30% during the turbine operation. The power difference between the turbines with different fan numbers and lengths was also observed above 5.5 m/s, as shown in the rotor energy graph. This confirmed that the generated power was minimal when the wind speed across the blow gaps was very slow. Meanwhile, air turbulence was respectively produced with hard and increased wind and rotational velocities, leading to the reduction of efficiency. From the CP graph, the wind turbine rotor became appropriate when the output power and CP were higher and more stable. This was influenced by the rotor's ability to convert wind energy into a specific form. In this condition, the 1.25 m five-blade system obtained the highest CP value than others, accompanied by the 1.50 m four-blade type at 5–7 m/s. However, the 1.75 m four-blade turbine had the lowest value at 4–6 m/s. At similar speed, a 1.25 m five-blade system achieved the highest rotor power-coefficient value of 37–41%, with a 1.50 m 4 and 5-blade type having a CP value of approximately 40% above 6 m/s. This CP value was the rotor power, divided by the wind energy possessing the rotational cross-sectional area. Therefore, the maximum limit of the wind turbine rotor in the theoretical energy conversion is 59% or 16/27, known as the Betz Limit.

CONCLUSIONS

Using experimental analyses, the effect of wind turbine blade length on HAWT performance was presented. The changes observed in this condition were then combined with the number of blades to observe the effect of wind speed on shaft rotation. The results showed a significant improvement in shaft rotation when using a five-blade turbine with different lengths. However, the effect of the combined length and number of blades on the produced power was only found above 5.5 m/s. As considered for various counts, the blade length also affected the tip speed ratio. From the produced TSR value, the rotation stability of the 1.25 m blade was better than other lengths. Irrespective of this condition, the overall rotor efficiency for the five-bladed turbine was higher, leading to greater CP values at low and high speeds. Using more significant blade numbers at various lengths provided higher margins for wind speed adjustments without increasingly affecting the power coefficient. Furthermore, the following two complementary points were obtained from this analysis, (1) A 1.25 m five-blade turbine produced the best and most stable shaft rotation when used at moderate wind speeds, and (2) The 1.50 and 1.75 m blades were better suited for use in high-speed environments.

Acknowledgements

The authors are grateful to Syiah Kuala University's Graduate School of Mechanical Engineering students for their contributions to this study and to Syiah Kuala University for funding.

REFERENCES

1. Abdelsalam, A.M., El-Askary, W.A., Kotb, M.A., and Sakr, I.M. 2021. Experimental study on small scale horizontal axis wind turbine of analytically-optimized blade with linearized chord twist angle profile, Energy, 216, 119304, doi: 10.1016/j.energy.2020.119304.
2. Ahmad, S. and Tahar, R.M. 2014. Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia. Renewable energy, 63, 458–466. https://doi.org/10.1016/j.renene.2013.10.001
3. AirfoilTools.com. 2013. Airfoil NACA 4418.
4. Al-Fatlawi, A.W., Al-Baghdadi, M.A., Togan, H., Ahmadi, G., Rahman, S., and Rahim, N.A. 2022. Techno-economic analysis of wind turbines powering rural of Malaysia, Int. J. Renew. Energy Dev., 11(2), 413–421, doi: 10.14710/ijred.2022.43477.
5. Bezrukovs, D., Bezrukovs, V., Bezrukovs, V., Konuhova, M., and Aniskevich, S. 2020. The comparison of the efficiency of small wind turbine generators with horizontal and vertical axis under low wind conditions, Latv. J. Phys. Tech. Sci., 57(5), 61–72, doi: 10.2478/lpts-2020-0028.
6. Bloomfield, H.C., Gonzalez, P.L.M., Lundquist, J.K., Stoop, L.P., Browell, J., Dargaville, R., De Felice, M., Gruber, K., Hilbers, A., Kies, A. and Panteli, M. 2021. The importance of weather and climate to energy systems: a workshop on next generation challenges in energy–climate modeling. Bulletin of the American Meteorological Society, 102(1), 159–167, doi: /10.1175/BAMS-D-20-0256.1
7. Cai, Y., Zhao, H., Li, X., and Liu, Y. 2023. Effects of yawed inflow and blade-tower interaction on the aerodynamic and wake characteristics of a horizontal-axis wind turbine, Energy, 264, 126246, doi: 10.1016/j.energy.2022.126246.
8. Dar, A.S., Armengol Barcos, G., and Porté-Agel, F. 2022. An experimental investigation of a roof-mounted horizontal-axis wind turbine in an idealized urban environment, Renew. Energy, 193, 1049–1061, doi: 10.1016/J.RENENE.2022.05.035.
9. Duan, L., Sun, Q., He, Z., and Li, G. 2022, Wake topology and energy recovery in floating horizontal-axis wind turbines with harmonic surge motion, Energy, 260, 124907, doi: 10.1016/J.ENERGY.2022.124907.
10. Eltayesh, A., Castellani, F., Burlando, M., Hanna, M.B., Huzayyin, A.S., El-Batsh, H.M. and Becchetti, M. 2021. Experimental and numerical investigation of the effect of blade number on the aerodynamic performance of a small-scale horizontal axis wind turbine. Alexandria Engineering Journal, 60(4), 3931–3944., doi: 10.1016/j.aej.2021.02.048.
11. Evans, A., Strezov, V. and Evans, T.J. 2009. Assessment of sustainability indicators for renewable energy technologies, Renew. Sustain. Energy Rev., 13(5), 1082–1088, doi: 10.1016/j.rser.2008.03.008.
12. Garcia-Ribeiro, D., Flores-Mezarina, J.A., Bravo-Mosquera, P.D., and Cerón-Muñoz, H.D 2021. Parametric CFD analysis of the taper ratio effects of a winglet on the performance of a Horizontal Axis Wind Turbine, Sustain. Energy Technol. Assessments, 47, 101489, doi: 10.1016/J.SETA.2021.101489.
13. Hassanzadeh, A., Hassanabad, H.A, and Dadvand, A. 2016. Aerodynamic shape optimization and analysis of small wind turbine blades employing the Viterna approach for post-stall region, Alexandria Eng. J., 55(3), 2035–2043, doi: 10.1016/j.aej.2016.07.008.
14. Jain, P. 2011. Wind Energy Engineering. New York: McGraw-Hill Companies, Inc.
15. Jamdade, P.G., Patil, S.V., and Jamdade, S.G. 2013. Assessment of power coefficient of an offline wind turbine generator system, Electron. J. Energy Environ., 1(3), 2760–2767, doi: 10.7770/ejee-v1n3-art683.
16. Jokar, H., Vatankhah, R., and Mahzoon, M. 2023. Active vibration control of horizontal-axis wind turbine blades using disturbance observer-based boundary control approach, Eng. Struct., 275, 115323, doi: 10.1016/J.ENGSTRUCT.2022.115323.
17. Mathew, S. 2007. Wind energy: Fundamentals, resource analysis and economics. Berlin: Springer-Verlag, doi: 10.1007/3-540-30906-3.
18. Mitra A., and Chakraborty, A. 2022. Multi-objective optimization of composite airfoil fibre orientation under bending–torsion coupling for improved aerodynamic efficiency of horizontal axis wind turbine blade, J. Wind Eng. Ind. Aerodyn., 221, 104881, doi: 10.1016/J.JWEIA.2021.104881.
19. Neill S.P. and Hashemi, M.R. 2018. Offshore Wind, Fundam. Ocean Renew. Energy, 83–106, doi: 10.1016/b978-0-12-810448-4.00004-5.
20. Noronha, N.P., and Krishna, M. 2021. Aerodynamic performance comparison of airfoils suggested for small horizontal axis wind turbines, Mater. Today Proc., 46, 2450–2455, doi: 10.1016/J.MATPR.2021.01.359.
21. Noviani, L. 2019. Assessment of the wind power application in Indonesia. Indonesian Journal of Physics and Nuclear Application, 4(3), 78–85.
22. Patel, M.R. 1999. Wind and Solar Power Systems. New York: CRC Press.
23. Pellegrini, M., Guzzini, A., and Saccani, C. 2021. Experimental measurements of the performance of a micro-wind turbine located in an urban area, Energy Reports, 7, 3922–3934, doi: 10.1016/j.egyr.2021.05.081.

24. Perea-Moreno, M.A., Hernandez-Escobedo, Q., and Perea-Moreno, A.J. 2018. Renewable energy in urban areas: Worldwide research trends, Energies, 11(3), 1–19, doi: 10.3390/en11030577.
25. Predescu, M., Bejinariu, A., Mitroi, O., and Nedelcu, A. 2009. Influence of the number of blades on the mechanical power curve of wind turbines, Renew. Energy Power Qual. J., 1(7): 825–830, doi: 10.24084/repqj07.519.
26. Rahmatian, M.A., Tari, P.H., Mojaddam, M., and Majidi, S. 2022. Numerical and experimental study of the ducted diffuser effect on improving the aerodynamic performance of a micro horizontal axis wind turbine, Energy, 245, 123267, doi: 10.1016/J.ENERGY.2022.123267.
27. Staffell, I. and Pfenninger, S. 2018. The increasing impact of weather on electricity supply and demand. Energy, 145, 65–78, doi: 10.1016/j.energy.2017.12.051.
28. Siregar, R.H, Away, Y., Tarmizi, and Akhyar. 2023. Minimizing power losses for distributed generation (DG) placements by considering voltage profiles on distribution lines for different loads using genetic algorithm methods, Energies 16(14), 5388, doi: 10.3390/en16145388.
29. Syuhada, A., Mubarak, A., and Maulana, M.I. 2016. Study of hybrid power system potential to power agricultural water pump in mountain area, 1717, doi: 10.1063/1.4943488.
30. Syuhada, A., Maulana, M.I., and Fuadi, Z. 2017. Analysis of wind energy potential for agriculture pump in mountain area Aceh Besar, AIP Conf. Proc., 1855, doi: 10.1063/1.4985534.
31. Syuhada, A., Maulana, M.I., Syahriza, Sani, M.S.M., and Mamat, R. 2020. The Potential of Wind Velocity in the Banda Aceh Coast to the Ability to Generate Electrical Energy by Horizontal Axis Wind Turbines, in IOP Conference Series: Materials Science and Engineering, 788(1), doi: 10.1088/1757-899X/788/1/012082.
32. Wang, S.H., and Chen, S.H. 2008. Blade number effect for a ducted wind turbine, J. Mech. Sci. Technol., 22(10), 1984–1992, doi: 10.1007/s12206-008-0743-8.
33. Wang, P., Liu, Q., Li, C., Miao, W., Yue, M., and Xu, Z. 2022. Investigation of the aerodynamic characteristics of horizontal axis wind turbine using an active flow control method via boundary layer suction, Renew. Energy, 198, 1032–1048, doi: 10.1016/J.RENENE.2022.08.075.
34. Wen, J., Zhou, L., and Zhang, H. 2023. Mode interpretation of blade number effects on wake dynamics of small-scale horizontal axis wind turbine, Energy, 263, 125692, doi: 10.1016/J.ENERGY.2022.125692.
35. World Wind Energy Association (WWEA). Pitteloud and Gsänger, S. 2016. 2016 summary: Small wind summary.
36. Zhang, H., Wen, J., Zhan, J., and Xin, D. 2022. Effects of blade number on the aerodynamic performance and wake characteristics of a small horizontal-axis wind turbine, Energy Convers. Manag., 273, 116410, doi: 10.1016/j.enconman.2022.116410.