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Savonius wind turbine blade selection based on computational fluid dynamics

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Abstract: The Savonius vertical axis wind turbine is widely used because of its simple design and efficiency at low wind speeds. The next development is the mini multi-blade Savonius helical wind turbine. At this miniature size, the performance of a mini multi-blade helical Savonius turbine due to variations in the number of blades and its impact on the energy produced has not been investigated in depth. Therefore, adjustments to the size and number of blades need to be made to optimize the performance of this turbine. The research aims to obtain the performance of the Savonius type S wind turbine with 3 blades and 4 blades using the CFD (Computational Fluid Dynamics) method. The main dimensions of the simulation model are the shaft diameter of 0.008 m, the outer diameter of 0.24 m, the height of 0.4 m, and the number of blades 3 and 4. The inner diameter of the 3-blade turbine is 0.21 m while the inner diameter of the 4-blade turbine is also 0.21 m. Both turbine models are subjected to wind speeds of 4 m/s, 5 m/s, and 6 m/s. Based on the simulation results, a turbine with 4 blades has more optimal performance compared to the 3-blade type. At a wind speed of 6 m/s, the 4-blade Savonius helical turbine produces a rotation of 498,215 rpm and a maximum power of 6,129 watts. Meanwhile, the Savonius turbine with 3 blades at a wind speed of 6 m/s produces a rotation of 545,655 rpm and a maximum power of 4,390 watts. This difference in performance shows the importance of adjusting the number of blades in wind turbine design to achieve optimal efficiency. This research provides useful insights for the further development of mini helical Savonius wind turbines in various wind conditions.

Keywords: Computational fluid dynamics; wind turbine; Savonius vertical axis wind turbine

1. INTRODUCTION

The depletion of fossil energy reserves will lead us to an energy crisis [1]. Indonesia has great potential for renewable energy sources including solar energy 4.8 KWh/m^2/day, biomass 458 GW3-6/sec wind power, and 3GW nuclear (uranium reserves) [2], [3]. Meanwhile, to date, there are more than 400 villages that do not have electricity in Indonesia [3], [4]. Indonesia has many small inhabited islands that have limited energy resources [5], [6]. This inspired researchers to develop renewable energy machines such as hydram pumps, water turbines, and wind turbines [7]. Based on this idea, it is necessary to develop wind turbines as a renewable energy source [8], [9].

There are two types of turbines when viewed from the position of the main axis, namely horizontal-axis wind turbine (HAWT), and vertical-axis wind turbine (VAWT) [10]. Horizontal axis wind turbines (HAWT) offer better performance results in terms of torque and power. Vertical axis wind turbines provide lower performance values, but lower constructive costs, easy starting possibilities, and operation at lower wind speeds [11], [12], [13], [14].

One type of vertical axis wind turbine is the Savonius wind turbine which is a solution for electricity generation systems in island areas. Savonius wind turbine. The Savonius wind turbine has various advantages, including it can rotate at low wind speeds (between 2 m/s to 5 m/s) and short wind duration. Savonius wind turbines have a performance coefficient of 0.2 to 0.3 [15],[16]. The SAVONIUS rotor type represents a simple constructive variant, with low cost, characterized by lower power coefficient (CP) values compared to the horizontal axis rotor type [5-8]. In comparison, the horizontal axis turbine rotor reaches a CP value of 45%, and the vertical axis type DARRIEUS rotor reaches a CP value of up to 35%, while the classic SAVONIUS rotor with a CP of 15% is far behind but can compensate with other features related to its simple construction, low production costs, independence of wind direction, and good starting torque at low wind speed values [9-14]. These advantages cause the Savonius wind turbine to be widely used, to drive irrigation pumps, street lighting systems, and also small power plants [17], [18].

Various studies and research activities have been carried out where researchers used numerical methods [19], [20], [21] and experimental [20]–[22] to determine and improve the performance of rotor construction variants directed at optimizing blade shape or determining the optimal number of rotor blades [22], [23], [24], [25]. It is necessary to adjust the size and suitability of the number of blades,

Vertical axis wind turbines operating on the SAVONIUS principle are currently used for agricultural water transport applications, ventilation, low-power facilities, and other rural agricultural applications. This constructive rotor solution is also used in hydrokinetic turbine assemblies to obtain energy by changing the mechanical movement of the rotor shaft [56-59].

Analysis methods using simulation application software have been developed and are used in many fields such as electrical [26], heat transfer [27], frame structure analysis [28], and fluids (CFD). Computational Fluid Dynamics (CFD) is known as a method for predicting fluid flow characteristics and related factors. This method involves numerical calculations, Reynolds numbers, and solving the average Naviere Stokes equations (URANS) [29], [30]. CFD studies are often used to identify the character and dynamic behavior of vertical-axis wind turbines. In this research, the applications used are inventor software and also ANSYS CFD [31], [32].

Indonesia's archipelagic region where there are limited skilled human resources, welding workshop/production workshop resources, waterfall resources, and water potential energy resources, causes the need to develop a wind turbine, low technology mini, and appropriate to overcome the shortage of electrical energy in the region. the. A suitable wind turbine is a wind turbine that can be produced in one industry, easy to transport, easy to repair, easy to install, and easy to maintain. The solution: The idea is a small wind turbine, which can be folded, or easy to dismantle and assemble. Small wind turbines produce a small amount of electrical power, but when combined they produce a large amount of electrical power too. Based on the explanation above, in this research, the Savonius turbine was developed into a helix type.

Created a simulation model of the Savonius helix turbine, and analyzed the helix turbine using software. changing the blade or blade into a helix to study the aerodynamic characteristics of the Savonius turbine which is modified with helical blades so that the performance provided produces optimal and efficient power.

The research as explained in this manuscript aims to find out which of the 3-blade Savonius spiral/helical turbine and the 4-blade turbine is more recommended for producing higher rotation, torque, or power.

2. METHOD

The design stage and design calculations are based on wind potential data, as well as the general size of the turbine. The Swept Area is calculated with the equation:

$$A = D \times h \tag{1}$$

Where: A = Turbine Swept Area (m); D = Diameter/width (m); H = Height/length (m);

To utilize wind energy to become electrical energy, the first step that must be taken is to calculate the stored wind energy using a formula [33]:

$$E_k = \frac{1}{2} . m . v^2 \tag{2}$$

Where E_k = Kinetic energy (joules); m = Air mass (kg); v^2 = Wind velocity (m/s)

In the tests carried out it was discovered that the air density (ρ) was 1.225 kg/m^3. A mass of air that moves in unit time with density (ρ) :

$$m' = \rho . A . v \tag{3}$$

Where: m' = Air mass (kg/s); ρ = Air density (ρ = 1,225 kg/m^3);A = Turbine cross-sectional area (m^2); v = Wind velocity (m/s)

The kinetic energy of the wind that blows in unit time (wind power) is calculated by:

$$\text{Pin} = \frac{1}{2}\,.\rho.A.v^3 \tag{4}$$

Where: P = Wind power (Watt); ρ = Air density (kg/m^3); A = Cross-sectional area (m^2); v^3 = Wind velocity (m/s);

Each rotor of a wind turbine has different characteristics. By entering the power coefficient (Cp), the actual mechanical power (P) obtained from the kinetic energy of the wind becomes [34].

$$\text{Pact} = \frac{1}{2}\,.\rho.A.v^3.Cp \tag{5}$$

Where: Pact = Actual mechanical power (Watt), C_p= Power coefficient.

The torque produced when the Savonius S helical wind turbine first rotates is calculated using the equation:

$$\tau = \text{Pact} / \omega \tag{6}$$

The rotation produced by the Savonius blade S helical wind turbine at a wind speed of 4 m/s is:

$$\omega = \text{v} / \text{r} \tag{7}$$

$$\omega = 2\,\pi\,\text{n} / 60$$

$$\text{n} = 60 \text{ x } \omega \text{ x } 2\,\pi$$

The force that occurs due to wind pressure to rotate the turbine can be calculated from the equation.

$$\text{F} = \text{P x A} \tag{8}$$

The Tip Speed Ratio (TSR) value, which is the ratio of blade tip speed to wind speed, can be calculated using the formula:

$$tsr = \frac{speed\ of\ rotor\ tip}{wind\ speed} = \frac{v}{V} = \frac{\omega\,\text{r}}{V} \tag{9}$$

Power Coefficient (Cp)

$$Cp = \frac{\text{Pout}}{\text{Pin}} \text{ x } 100\% \tag{10}$$

Simulation, using Computational Fluid Dynamics Ansys software. The wind turbine design was created using Autodesk Inventor software. This process is divided into three stages, including pre-processing, processing, and post-processing. a) Pre-Processing Stages. This stage includes developing a geometric model using the CAD (Computer Aided Design) package, Autodesk Inventor, and other drawing software from which an appropriate mesh or grid will be built, and boundary conditions and fluid and solid properties will be applied. b) The solving stage is the core stage of CFD. At this stage, the solution is calculated based on conditions according to the pre-processing stage. c) Post-processing stage, which is the last stage in CFD. At this stage, interpretation of the simulation data is carried out which can be in the form of visualization of contours, vectors, histograms, curves, and so on. d) Presentation, descriptive methods are used to analyze the results of research carried out after carrying out the simulation process. This method will be used to describe the research by displaying the data obtained in the form of simulated images, tables, and graphs so that conclusions can be drawn later. Turbine Testing: Based on the simulation results, a type of turbine is selected, to be manufactured, then tested.

3. RESULTS AND DISCUSSION

There are two types of turbine designs, namely a turbine with 3 blades (Figure 1.a) and a turbine with 4 blades (Figure 1.b). The turbine is designed to be small, but if several turbines are put together as in Figure 1.c, it will produce a lot of power too.

(a) (b) (c)

Figure 1. (a) 3-blade turbine design sketch, (b) 4-blade turbine design sketch, (c) Energy tree plan design

To design a turbine, it is necessary to know the preliminary data as presented in Table 1.

Table 1. Main specifications

No.	Description	Specification
1	Turbine Type	Vertical Axis Wind Turbine
2	Rotor Type	Helix Savonius
3	Power Plan	150-watt
4	Wind velocity	4 m/s, 5m/s, 6m/s
5	Air Density	1.225 kg/m
6	Air viscosity	1,789x10 kg/m.s
7	Betz Limit	0.593

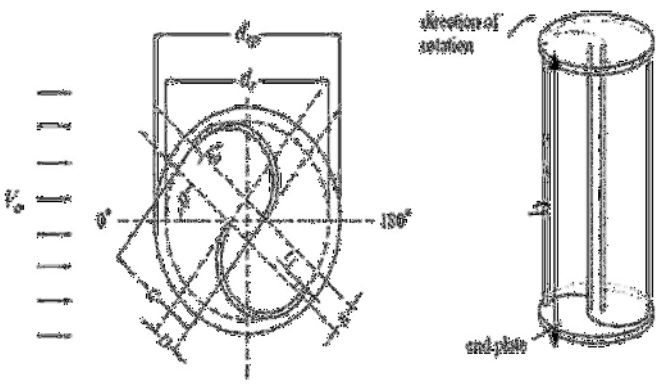


Figure 2. Part of the Savonius turbine

O = overlap; dep = outside diameter; rotor; dr = inner diameter of the rotor; s = separation gap; c= chords; ω = angular speed in rpm; v = wind speed in m/s, and h = rotor height.

The nomenclature and notation of the formulas used are presented in Figure 2. There are two turbine designs, namely the 3-blade Savonius turbine design and the 4-blade Savonius turbine design. These two designs have the same specifications except for the number of blades. Details of the Savonius 3-blade design are shown in Table 2. Information in Table 2 includes the number of blades, dimensions, and material.

Table 2. 3-blade turbine specifications

No	Description	Specification
1	Blade type	Type S
2	Number of blades	3
3	Shaft diameter	0.008 m
4	Inside diameter	0.21 m
5	Outer diameter	0.23 m
6	Blade plate thickness	0.002 m

7	high	0.4 m
8	Turbine cover diameter	0.23 m
9	Turbine cover thickness	0.0025 m
10	Curvature of helical blades	0.085 Ul
11	Turbine materials	Flat PVC-Piping

Details of the 4-blade Savonius turbine design are presented in Table 3. Information in Table 3 includes the number of blades, dimensions, and materials.

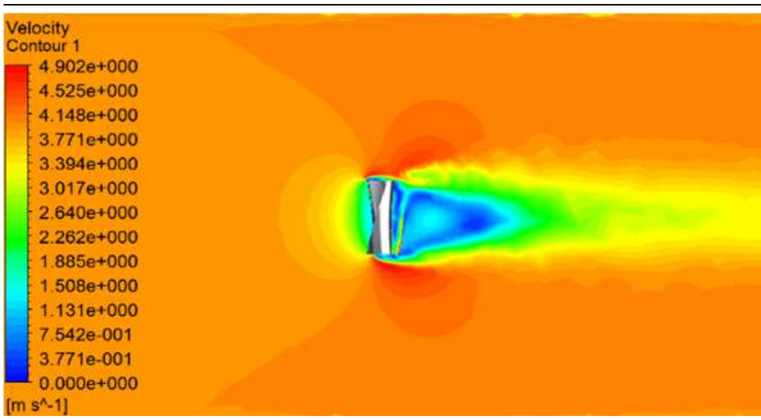
Table 3. 4 blade turbine specifications

No	Description	Specification
1	Blade Type	Type S
2	4	3
3		0.008 m
4		0.23 m
5		0.24 m
6		0.002 m
7		0.4 m
8		0.24 m
9		0.0025 m
10	Curvature of helical blades	0.085 Ul
11	Turbine materials	Flat PVC-Piping

Based on the experimental results of secondary data validation testing. In the ANSYS simulation results based on theoretical calculations and real (absolute) data from prototype experimental tests, data was obtained regarding the values of Vin, Vout, Force, Pressure, Rotation, Cp, and TSR. This data can be plotted into graphs and visualization of flow characteristics so that analysis can be carried out on 3-blade and 4-blade Savonius helix-rotor turbine models. After the simulation of the wind turbine drawing Savonius helix-rotor blades 3 and 4 is complete, using the planned test procedures the following test data is obtained: Based on the calculation formula that has been mentioned, and combined with the simulation, the results are presented in Table 4.

Table 4. Calculation results

Blade type	V (m/s)	P (Pa)	F (N)	Ps (watt)	τ (Nm)	ω (rad/s)	n (rpm)	TSR	CP
S	4	9.415	0.791	0.948	0.0249	38.095	363.780	0.999	0.2881
turbine	5	14.650	1.230	2.135	0.0448	47.619	454.727	0.999	0.3320
3 blades	6	21.000	1.764	4.390	0.0768	57.142	545.665	0.999	0.3951
S	4	9.650	0.884	1.663	0.0478	34.782	332.143	0.999	0.4614
turbine	5	15.500	1.426	2.888	0.0664	43.478	415.184	0.999	0.4101
4 blades	6	21.100	1.941	6.129	0.1174	52.173	498.215	0.999	0.5036



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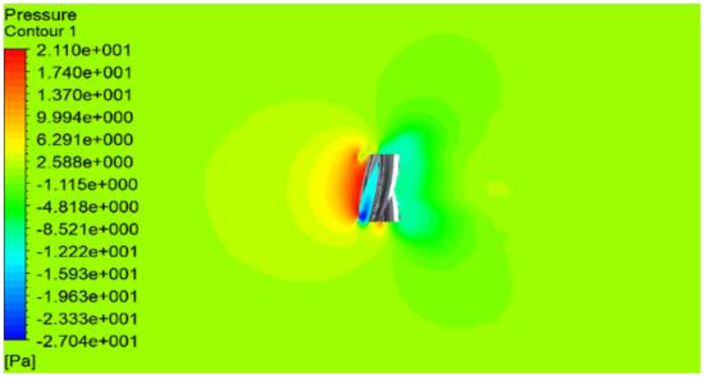

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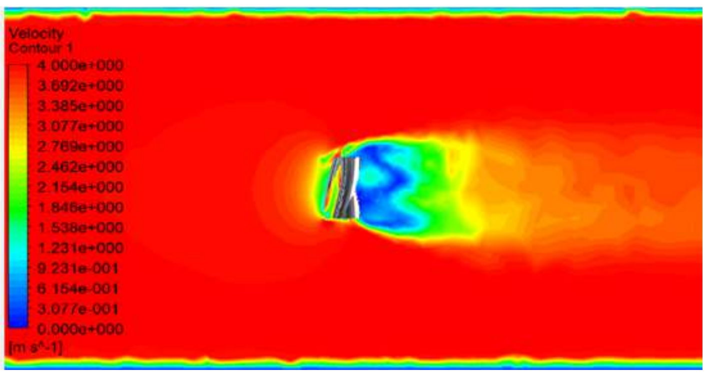
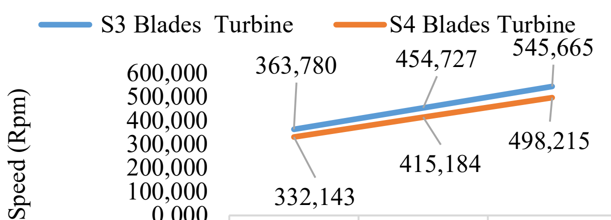


(c)

Figure 3. Simulation Results (A) Speed contour at wind speed 3.5 m/sec (b) Pressure contour. (c) Speed contour at wind speed 4 m/sec

The simulation results are presented in Figure 3, which consists of (a) Speed contour at a wind speed of 3.5 m/sec (b) Pressure contour. (c) Speed contour at wind speed 4 m/sec. On the contour, you can read areas where there is an increase or decrease in speed and areas where there is an increase or decrease in pressure. Data obtained from calculations that produce data, pressure, force, torque, speed, and power values obtained from simulation results are plotted in graphical form. From this graph, the characteristics of each turbine model can be closed to identify air speed fluctuations and blade fluctuations. The greater the wind speed, the greater the pressure on the turbine. at a wind speed of 6 m/s, the pressure value that occurs on 4 blades is greater than the pressure value on the 3-blade type, namely 21,100 Pa on blade type 4 and 21.00 Pa on blade type 3.

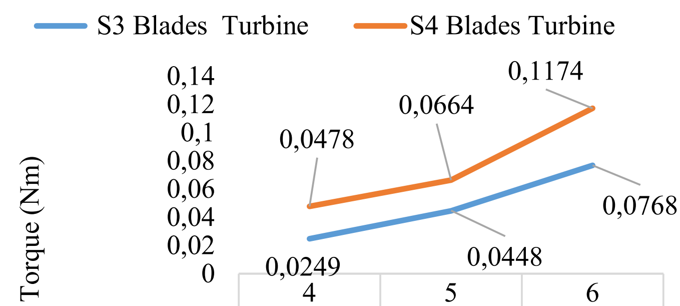


	4	5	6
S3 Blades Turbine	363,780	454,727	545,665
S4 Blades Turbine	332,143	415,184	498,215

Wind Speed m/s

Figure 4. Wind speed vs rotor rotation speed

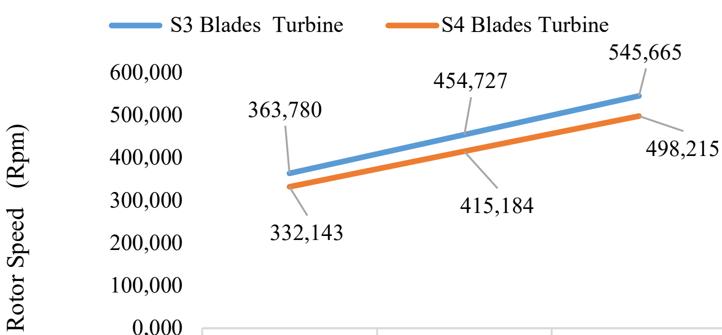
The higher the wind speed, the greater the rotation produced by the turbine, as shown in Figure 4. At a wind speed of 6 m/s, the maximum rotation speed occurs at 3 blades at 545,655 rpm and 4 blades S at 498,215 rpm and is influenced by the turbine radius.



	4	5	6
S3 Blades Turbine	0,0249	0,0448	0,0768
S4 Blades Turbine	0,0478	0,0664	0,1174

Figure 5. Wind speed vs torque on the rotor

Figure 5 shows that the greater the wind speed, the greater the torque value that occurs on the turbine. at a wind speed of 6 m/s. The highest torque value occurs on 4 blades, namely 0.1174 Nm, while on 3 blades it is 0.0768 Nm.



	0,0478	0,0664	0,1174
S3 Blades Turbine	363,780	454,727	545,665
S4 Blades Turbine	332,143	415,184	498,215

Figure 6. Relationship between torque vs rotor rotation

The highest rotation produced by 3 blades is 545,655 Rpm while with 4 blades it is 498,215 Rpm at each of the highest torque values of the two blade types, namely 0.1174 Nm on 4 blades and 0.0768 Nm on 3 blades. The greater the wind speed, the greater the power produced by the turbine. This is shown in Figure 6. The greatest power produced by a 4-blade turbine is 6,129 watts, while for 3-blade turbines it is 4,390 watts, respectively at wind speed. The highest is 6 m/s, the greater the rotation that occurs in the turbine, the greater the power produced by the turbine. The greatest power produced by 4 blades is 6,129 watts while the 3-blade type is 4,390 watts at each highest speed.

4. CONCLUSION

Based on the calculation results, several conclusions can be drawn, namely: The relationship between the amount of pressure that occurs in the turbine as a result of air speed is directly proportional, the greater the air speed that passes through the turbine, the greater the pressure that arises, the greater the power produced. The Savonius Helical Blade 4-wind turbine in this simulation is more optimal than blade 3, because it has higher efficiency and mechanical power values. In Savonius wind turbines with variations of 3 type S blades and 4 type S blades, the largest pressure value in each model is 21,000 Pa for 3 type S blades and 21,100 Pa for 4 type S blades.

REFERENCE

[1] M. Asif and T. Ã. Muneer, “Energy supply , its demand and security issues for developed and emerging economies,” vol. 11, pp. 1388–1413, 2007, doi: 10.1016/j.rser.2005.12.004.

[2] M. H. Hasan, T. M. I. Mahlia, and H. Nur, “A review on energy scenario and sustainable energy in Indonesia,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 2316–2328, 2012, doi: 10.1016/j.rser.2011.12.007.

[3] N. Reyseliani and W. W. Purwanto, “Pathway towards 100 % renewable energy in Indonesia power system by 2050 Levelized Cost of Electricity Levelized Cost of Storage,” *Renew. Energy*, vol. 176, pp. 305–321, 2021, doi: 10.1016/j.renene.2021.05.118.

[4] E. In, H. J. Van Der Windt, and G. Nhumaio, “A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries United States Agency for International Development,” vol. 144, no. March, 2021, doi: 10.1016/j.rser.2021.111036.

[5] N. U. Blum, R. S. Wakeling, and T. S. Schmidt, “Rural electrification through village grids — Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia,” *Renew. Sustain. Energy Rev.*, vol. 22, pp. 482–496, 2013, doi: 10.1016/j.rser.2013.01.049.

[6] K. Lammers, P. Bertheau, and P. Blechinger, “Exploring requirements for sustainable energy supply planning with regard to climate resilience of Southeast Asian islands,” *Energy Policy*, vol. 146, no. August 2019, p. 111770, 2020, doi: 10.1016/j.enpol.2020.111770.

[7] U. M. Sugeng, I. Y. Mukhtar, B. S. Indah, and J. Selatan, “Perancangan Pompa Hidram Pada Tabung Udara Dengan Metode VDI,” vol. 7, no. 1, pp. 36–42, 2020.

[8] O. H. Hydropower-, “Combination of solar and wind power to create cheap and eco-friendly energy,” 2020, doi: 10.1088/1757-899X/725/1/012140.

[9] R. E. PRADANA, “Pemodelan Penyediaan Energi Terbarukan Dusun Poleng Kabupaten Madiun,” *J. Sekol. Tinggi Teknol. Muhammadiyah Cileungsi*, 2021.

[10] A. D. Wibowo, S. Tinggi, T. Muhammadiyah, and J. Barat-indonesia, “Online Blade Washing Analysis on Gas Turbine Performance in Power Plants,” vol. 6, no. 3, pp. 209–220, 2021, doi: 10.22219/jemmme.v6i3.18140.

[11] S. F. Dorel, G. A. Mihai, and D. Nicusor, “Review of Specific Performance Parameters of Vertical Wind Turbine Rotors Based on the SAVONIUS Type,” 2021.

[12] A. Dewan, A. Gautam, and R. Goyal, “Materials Today : Proceedings Savonius wind turbines : A review of recent advances in design and performance enhancements,” *Mater. Today Proc.*, no. xxxx, 2021, doi: 10.1016/j.matpr.2021.05.205.

[13] J. Vicente, H. Antonio, and A. Prisco, “A review on the performance of Savonius wind turbines,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 3054–3064, 2012, doi: 10.1016/j.rser.2012.02.056.

[14] S. Roy and U. K. Saha, “Review on the numerical investigations into the design and development of Savonius wind rotors,” *Renew. Sustain. Energy Rev.*, vol. 24, pp. 73–83, 2013, doi: 10.1016/j.rser.2013.03.060.

[15] P. A. Setiawan, T. Yuwono, W. A. Widodo, K. Kludzinska, K. Tesch, and P. Doerffer, “Tests upon Savonius turbine and its usage in street lighting pole Tests upon Savonius turbine and its usage in street lighting pole,” 2020, doi: 10.1088/1757-899X/789/1/012056.

[16] D. M. Ramos and C. D. Sauceda, “CFD study of a vertical axis counter-rotating wind turbine,” vol. 5, pp. 240–244, 2017, doi: 10.1109/icrera.2017.8191273.

[17] J. L. Menet, “A double-step Savonius rotor for local production of electricity: A design study,” *Renew. Energy*, vol. 29, no. 11, pp. 1843–1862, 2004, doi: 10.1016/j.renene.2004.02.011.

[18] K. V. O. Rabah and B. M. Osawa, “Design and field testing Savonius wind pump in East Africa,” *Int. J. Ambient Energy*, vol. 17, no. 2, pp. 89–94, 1996, doi: 10.1080/01430750.1996.9675223.

[19] M. Pourhoseinian, S. Sharifian, and N. Asasian-Kolur, “Unsteady-state numerical analysis of advanced Savonius wind turbine,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–16, doi: 10.1080/15567036.2020.1859011.

[20] H. A. Hassan Saeed, A. M. Nagib Elmekawy, and S. Z. Kassab, “Numerical study of improving Savonius turbine power coefficient by various blade shapes,” *Alexandria Eng. J.*, vol. 58, no. 2, pp. 429–441, 2019, doi: https://doi.org/10.1016/j.aej.2019.03.005.

[21] S. H. Delbari, A. Nejat, M. H. Ahmadi, A. Khaleghi, and M. Goodarzi, "Numerical modeling of aeroacoustic characteristics of different savonius blade profiles," *Int. J. Numer. Methods Heat Fluid Flow*, vol. 30, no. 6, pp. 3349–3369, Jan. 2020, doi: 10.1108/HFF-12-2018-0764.

[22] Z. Lillahulhaq and V. S. Djanali, "Unsteady simulations of Savonius and Icewind turbine blade design using fluid-structure interaction method," *AIP Conf. Proc.*, vol. 2187, no. 1, p. 20009, Dec. 2019, doi: 10.1063/1.5138264.

[23] V. Dhamotharan, P. D. Jadhav, P. Ramu, and A. K. Prakash, "Optimal design of savonius wind turbines using ensemble of surrogates and CFD analysis," *Struct. Multidiscip. Optim.*, vol. 58, no. 6, pp. 2711–2726, 2018, doi: 10.1007/s00158-018-2052-x.

[24] R. Hassanzadeh, M. Mohammadnejad, and S. Mostafavi, "Comparison of Various Blade Profiles in a Two-Blade Conventional Savonius Wind Turbine," *J. Energy Resour. Technol.*, vol. 143, no. 2, Aug. 2020, doi: 10.1115/1.4047757.

[25] R. Sarath Kumar *et al.*, "Simulation studies on influence of shape and number of blades on the performance of vertical axis wind turbine," *Mater. Today Proc.*, vol. 33, pp. 3616–3620, 2020, doi: https://doi.org/10.1016/j.matpr.2020.05.665.

[26] I. Marbawi, J. Julian, and F. Wahyuni, "Pengaruh slot kumparan pada kinerja permanent magnet synchronous motor dengan metode komputasi The effect of coil slot on permanent magnet synchronous motor performance with computational method," *J. Sekol. Tinggi Teknol. Muhammadiyah Cileungsi*, vol. 10, pp. 0–10, 2023, doi: 10.37373/tekno.v10i1.323.

[27] N. A. Bahry and A. S. Nurrohkayati, "Analisis Perubahan Temperatur Mata Pahat Karbida Pada Proses Pembubutan Baja AISI 1045 Dengan FEM-Simulation di PT . X Analysis of Changes in Carbide Cutting Tool Temperature in AISI 1045 Steel Turning Process With FEM-Simulation at PT . X," vol. 9, pp. 65–73, 2022.

[28] T. J. Sains and T. Informatika, "Menghitung Tegangan Statik Pada Struktur Rangka Sepeda Bmx Menggunakan Software Catia," vol. 7, pp. 67–76, 2020.

[29] W. Tian, B. Song, J. H. Vanzwieten, and P. Pyakurel, "Computational Fluid Dynamics Prediction of a Modified Savonius Wind Turbine with Novel Blade Shapes," pp. 7915–7929, 2015, doi: 10.3390/en8087915.

[30] A. Mobin, H. Akimoto, and Y. Hara, "Comparative CFD analysis of Vertical Axis Wind Turbine in upright and tilted con fi guration," *Renew. Energy*, vol. 85, pp. 327–337, 2016, doi: 10.1016/j.renene.2015.06.037.

[31] M. Fudhail and S. Mohd, "Optimization of the Helical Wind Turbine Blade," vol. 3, no. 1, pp. 1–6, 2021.

[32] G. Ferrari, D. Federici, P. Schito, F. Inzoli, and R. Mereu, "CFD study of Savonius wind turbine: 3D model validation and parametric analysis," *Renew. Energy*, 2017, doi: 10.1016/j.renene.2016.12.077.

[33] G. Sidén, M. D. Ambrosio, and M. Medaglia, "Vertical Axis Wind Turbines : History , Technology and Applications Master thesis in Energy Engineering – May 2010 Supervisors : Jonny Hylander Authors :," no. May, p. 91, 2010.

[34] S. Brusca, R. Lanzafame, and M. Messina, "Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance," *Int. J. Energy Environ. Eng.*, vol. 5, no. 4, pp. 333–340, 2014, doi: 10.1007/s40095-014-0129-x.