© Universiti Tun Hussein Onn Malaysia Publisher's Office

PAAT

http://publisher.uthm.edu.my/ojs/index.php/paat

e-ISSN : 2821-2924

Progress in Aerospace and Aviation Technology

Conceptual Design and Analysis of Small-Scale Wind Turbine for Household Usage in Malaysia

Nor Afifah Ruzi[1], Nur Hayati Rosly[2*]

[1]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA

[2]Aircraft System and Design Research (ASDR), Department of Aeronautics Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400, MALAYSIA

*Corrseponding Author

DOI: https://doi.org/10.30880/paat.2023.03.02.004
Received 5 September 2023; Accepted 19 November 2023; Available online 14 December 2023

Abstract: Wind energy is a valuable renewable resource that holds great potential for generating electrical power through wind turbines. However, there is a lack of practical and cost-effective small-scale wind turbines designed specifically for household usage. This study aims to address this need by focusing on the design and performance analysis of a small-scale vertical Darrieus wind turbine tailored for household applications in Malaysia. The objective is to propose an optimized turbine design that maximizes energy conversion efficiency. Computational fluid dynamics (CFD) simulations using ANSYS Fluent software are conducted to evaluate the turbine's performance, with the power coefficient (Cp) calculated at various tip speed ratios (TSR). Two 3D designs with different blade configurations are developed using SolidWorks for the CFD simulations. The findings from this study contribute to the design optimization and performance evaluation of vertical Darrieus wind turbines, providing a sustainable and viable alternative for residential energy needs. This research addresses the pressing demand for clean and affordable energy solutions in Malaysia and supports the transition towards renewable sources.

Keywords: Small-scale wind turbine, vertical axis wind turbine, tip speed ratio, power coefficient, household usage

1. Introduction

Malaysia is a country committed to reducing greenhouse gas emissions and achieving sustainability goals, has a growing demand for electricity. To address this, there is a need to explore and utilize renewable energy sources. While solar energy has gained significant attention, wind energy remains an underutilized resource, particularly at the household level. Small-scale wind turbines designed specifically for household usage have the potential to contribute to the renewable energy landscape in Malaysia. These turbines can be installed in various locations, including urban and rural areas, and are well-suited for areas with low wind speeds. Incorporating wind turbines into residential properties can reduce dependency on the grid, lower electricity costs, and promote energy self-sufficiency [1].

Wind turbines operate based on the principle of converting the kinetic energy from the wind into mechanical energy, which is then transformed into electrical energy. Wind turbines consist of several key components, including rotor blades, a rotor hub, a nacelle, and a tower. The design and functionality of wind turbines can vary, with different types available for different applications. It is crucial to understand the underlying mechanisms of small-scale wind turbines to ensure their effective design and successful deployment. Different types of wind turbines are available, each with its own design and functionality suited for specific applications [2].

In this study, the focus is on the conceptual design and analysis of vertical axis wind turbines (VAWTs), specifically the vertical axis Darrieus wind turbine. The vertical axis Darrieus wind turbine is characterized by its

*Corresponding author: nurhayati@uthm.edu.my

vertical orientation and curved blades. Unlike the more commonly seen horizontal axis wind turbines (HAWTs), VAWTs have the advantage of being able to capture wind energy from various directions, making them well-suited for locations with turbulent or changing wind patterns. The Darrieus design is one of the most popular types of VAWTs due to its compact size, reduced noise levels, and ability to operate in low wind speeds.

2. Methodology

In this study, the performance evaluation of the two designed of small-scale wind turbine is conducted through a simulation process using ANSYS Fluent software. The aim is to determine the highest power coefficient, Cp, achieved by the Darrieus wind turbine with varying numbers of blades and different tip speed ratios, TSR. To accomplish this, several steps are undertaken in the simulation process to compare the performance of two designs which is leading to the selection of the optimal wind turbine design. To accomplish this, several steps are undertaken in the simulation process.

2.1 Design of Darrieus Wind Turbine

The design of the small-scale wind turbine was developed using SolidWorks software 2022. The design process involved extensive research and thorough examination of relevant literature to gain valuable insights and knowledge. This comprehensive review of research literature played a crucial role in informing the design decisions and ensuring that the wind turbine design aligns with established principles and best practices.

After careful consideration and evaluation of various wind turbine configurations, the helical type Darrieus wind turbine was chosen as the focal point of this research. This design was selected due to its unique helical shape, which offers several advantages in terms of aerodynamic performance and energy capture. The helical configuration enables the wind turbine to efficiently harness wind energy from various directions, making it suitable for diverse wind patterns commonly encountered in different locations.

Fig. 1 and Fig. 2 below depict two different designs of small-scale wind turbines, each with a different number of blades. These designs were developed using SolidWorks software, a powerful tool for 3D modeling and design. These two designs showcase the versatility of small-scale wind turbines and the different options available for optimizing energy generation. The choice between a three-bladed or two-bladed design depends on various factors, including the wind conditions, power requirements, and desired performance characteristics for the specific application.

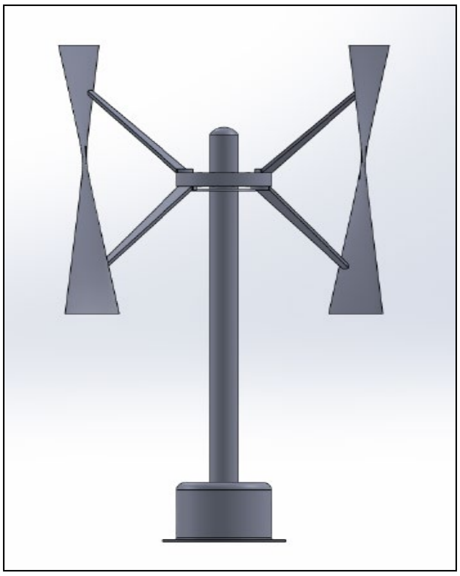

Fig. 1 - Darrieus wind turbine with two-bladed model designed in SolidWork software

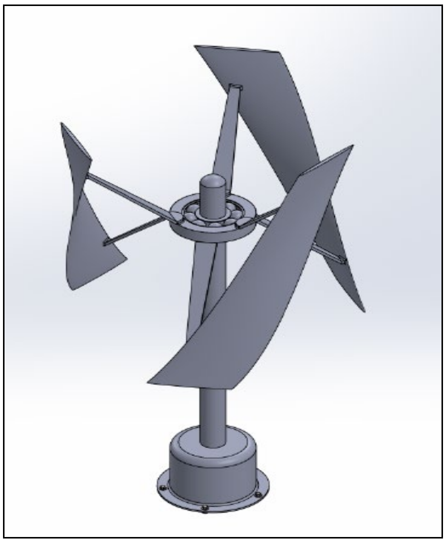

Fig. 2 - Darrieus wind turbine with three-bladed model designed in SolidWork software

2.2 Flow Simulation

The wind turbine blade design is created using SolidWorks software as the initial step of the computational fluid dynamics (CFD) simulation. The blade drawing is saved in STEP format. Afterward, the surface is meshed, and boundary conditions are defined. Any errors encountered during this process are displayed in the transcript. Once the simulation model is developed and the mesh is created, the next step is to specify the physics and numerical solution methods. Flow parameters are set, and the appropriate numerical scheme is selected. ANSYS FLUENT, specialized software within ANSYS WORKBENCH is used as the flow solver for simulating fluid flow in complex designs. Generating a suitable mesh is crucial for accurate results. Mesh generation has traditionally been a challenging aspect of the analysis process due to the lack of fully automated techniques. Dedicated software programs are available for mesh and grid generation, and proficiency in using these tools is essential. It is important to optimize the mesh size to ensure ANSYS Fluent can successfully simulate the analysis. An example of meshing a wind turbine with three blades is shown in Fig.3.

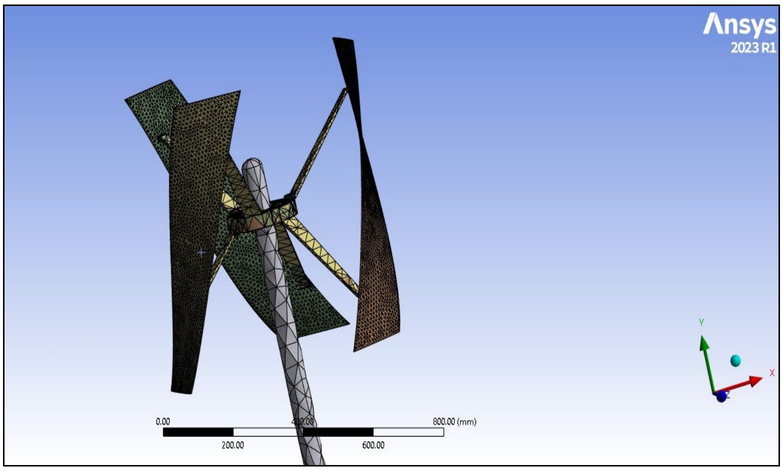

Fig. 3 - Mesh generation for a wind turbine with three blades

3. Result

In the result part, the focus will be on the results obtained from the Ansys Fluent simulation, specifically examining the performance of two different configurations of Derrius wind turbines with varying numbers of blades. The simulation results will be thoroughly discussed and analyzed. The performance evaluation of these wind turbines will primarily be based on the key parameters of tip speed ratio and rotor power coefficient. The inlet enclosure experiences a typical wind speed of 5 km/h, while the outlet maintains a normal static pressure of 1.01325 Bars. The rotational speed of the blades (RPM) is adjusted to achieve specific values of tip speed ratio ranging from 1 to 10.

3.1 Simulation Torque Result

To calculate the wind turbine power in this simulation, the torques generated during the simulation need to be recorded. By doing so, the torques obtained for each TSR (Tip Speed Ratio) result can be organized into a Table 1 for a clearer visualization and analysis.

Table 1 - Torque generated in ANSYS and calculated rotor power

Tip Speed Ratio	Torque (Nm)	Rotor Power (W)
1	0.06	0.023
2	0.14	0.120
3	0.18	0.317
4	0.26	0.273
5	0.40	0.767
6	0.45	1.230
7	0.51	1.330
8	0.49	2.471
9	0.46	2.490
10	0.39	1.773

The power output can be calculated using the formula:

$$Power\ Output\ (\mathrm{W}) = \mathrm{Torque\ (Nm)} \times \mathrm{Angular\ Velocity\ (rad/s)} \quad (1)$$

Angular velocity (ω) is related to The Tip Speed Ration (TSR) and wind speed as follows:

$$\omega = TSR \times wind\ speed\ (m/s) \quad (2)$$

In particular, the wind velocity in this simulation remains constant at 5 km/h, acting as the controlled variable. This wind speed generates highest power output of 5.767 watt/hour over an area of 24.627 m². It is noteworthy that the area considered for wind power generation corresponds to the inlet area, which measures 9 m². Furthermore, it is essential to consider the air density, which is maintained at 1.225 kg/m³. Thus, as part of the second objective, which involves analysing the performance of the proposed wind turbine under specific wind conditions in Malaysia, the rotor power coefficients of both the three-blade and two-blade wind turbines are recorded.

3.2 Simulation for Two-Bladed Darrieus Wind Turbine

Table 2 - Data for two-bladed of Darrieus wind turbine

Tip Speed Ratio	Rotor Power (W)	Rotor Power Coefficient
1	0.28	0.008
2	1.28	0.035
3	2.51	0.070
4	4.86	0.135
5	9.35	0.260
6	12.56	0.349
7	16.38	0.455
8	18.31	0.508
9	19.04	0.529
10	17.89	0.497

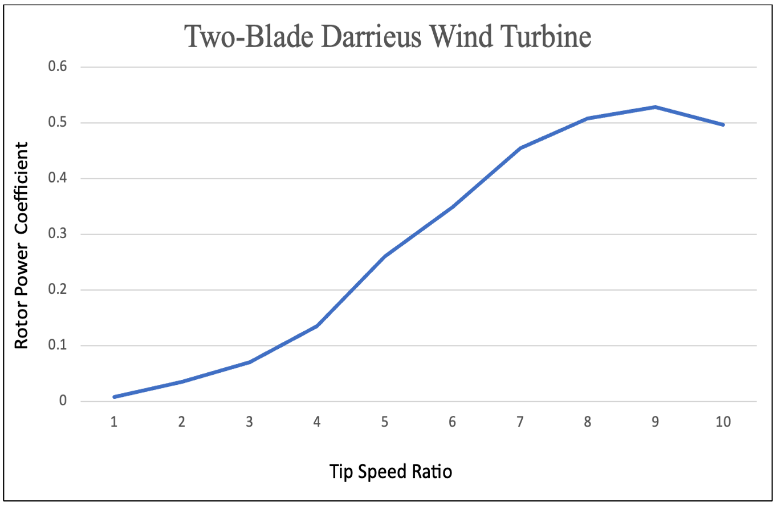

Fig. 4 - Graph of rotor power coefficient against tip speed ration for two-bladed wind turbine

Upon careful analysis of the graph representing the performance of the Two-blade Darrieus Wind Turbine, several key observations can be made. The graph illustrates the relationship between the rotor power coefficient and the tip speed ratio, providing valuable insights into the efficiency and effectiveness of the wind turbine. One observation is that the Two-blade Darrieus Wind Turbine demonstrates a peak rotor power coefficient of 0.529. This coefficient represents the maximum level of power conversion achieved by the turbine within the tested operating conditions. With an efficiency of 52.9%, the wind turbine effectively converts a significant portion of the kinetic energy from the wind into mechanical power.

3.3 Simulation for Three-Bladed Darrieus Wind Turbine

The simulation of the three-blade wind turbine utilized the exact same settings and preparations as the two-blade turbine. After conducting simulations for 10 different TSR values in ANSYS, the torque outputs were recorded in the result component. The torque data for the three-blade design has been compiled and presented in the Table 3 below.

Table 3 - Data for three-bladed darrieus wind turbine

Tip Speed Ratio	Rotor Power Coefficient
1	0.016
2	0.069
3	0.149
4	0.345
5	0.478
6	0.549
7	0.510
8	0.437
9	0.355
10	0.205

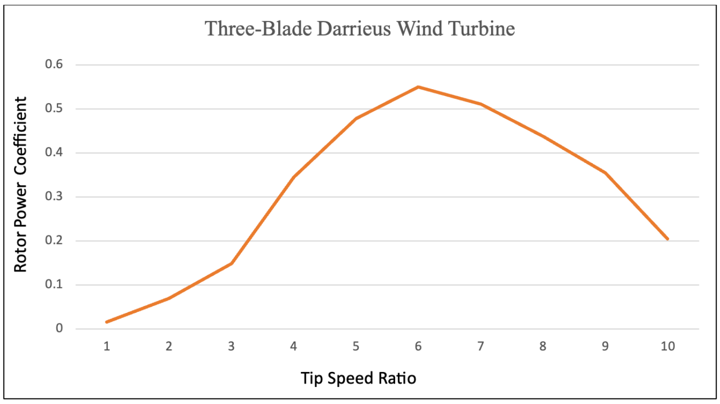

Fig. 5 - Graph of rotor power coefficient against tip speed ration for three-bladed wind turbine

The simulation results of the three-bladed Darrieus wind turbine provide valuable insights. The line graph shows a consistent trend that aligns closely with findings reported by previous researchers. Notably, the turbine achieves a peak rotor power coefficient of 0.549, indicating an impressive efficiency of 54.9%. One significant improvement is the positioning of the peak and the overall gradient of the line, which has shifted towards lower Tip Speed Ratios (TSR). This shift suggests enhanced performance at lower TSR values, highlighting the turbine's ability to generate power efficiently under varying wind conditions. Furthermore, the observed trends in the graph closely resemble the findings of previous studies discussed extensively in Literature Review. This consistency lends credibility to the accuracy and reliability of the simulation results obtained in this study.

3.4 Comparing Result

To determine the optimal wind turbine for household use in Malaysia, a thorough comparison of simulation results is essential. The performance of both the two-blade and three-blade Darrieus wind turbines is graphically presented below for easy evaluation. Factors such as peak rotor power coefficient, efficiency, and other relevant parameters are considered to identify the superior option. This analysis enables an informed decision regarding the wind turbine that offers the highest performance and suitability for household applications in Malaysia.

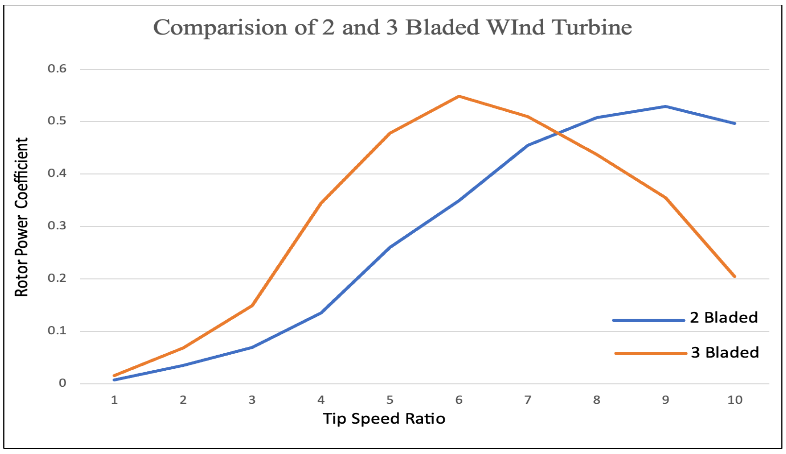

Fig. 6 - Comparison of two design wind turbines

Fig. 6 illustrates the comparison between the results obtained for the two-bladed and three-bladed Darrieus wind turbines, specifically showcasing the relationship between the rotor power coefficient and the tip speed ratio. As anticipated and supported by previous studies, notable differences are observed in both the peak values of the rotor power coefficient and the overall behavior of the lines. Upon closer examination, it is evident that the three-bladed wind turbine exhibits a slightly higher rotor power coefficient compared to the two-bladed counterpart.

However, what sets it apart is the achievement of this higher coefficient at lower tip speed ratios. This implies that the three-bladed design demonstrates improved overall performance in terms of power generation efficiency. These findings align with prior research and validate the advantages associated with utilizing a three-bladed Darrieus wind turbine configuration.

The observed higher rotor power coefficient and the ability to attain it at lower tip speed ratios highlight the enhanced performance and effectiveness of the three-bladed design. Based on these results, it can be concluded that the three-bladed Darrieus wind turbine is better suited for the intended application in this study. Its superior performance in terms of rotor power coefficient and operating range make it the optimal choice for household wind energy generation in Malaysia.

4. Discussion

The third objective of this study is to optimize the design of the wind turbine by determining the most efficiency number of blades for household applications in Malaysia, with a specific focus on comparing the performance of a two-blade and a three-blade Darrieus wind turbine under specific wind conditions. The wind velocity was maintained at a constant 5 km/h, serving as the controlled variable. The power output of each turbine was analyzed using ANSYS, and the rotor power coefficients were recorded as the key parameters.

The simulation results provided valuable insights into the performance of both wind turbine configurations. It was observed that the wind velocity of 5 km/h generated a power output of 5.767 watts per hour (W/h) over an area of 24.627 m², as discussed previously. The wind turbine's daily power output of 138.408 Wh can be of significant value to various household applications in Malaysia. The table below provided acts as a reference for evaluating the total power consumption of various household devices. By analysing the data from the table, the average daily energy requirement of 19.973 Wh was calculated. This computation allows for an assessment of whether the wind turbine's power output is adequate to meet the energy needs of the household devices listed in the Table 4 below.

Table 4 – kWh residential consumptions for a typical malaysian household [24]

Electrical Load	No. of Appliances	Power (W)	Daily Average Usage (h)		Total Hours per Week	Energy Demand (kWh)
			Weekdays	Weekends		
Air Conditioner	1	750	5.05	4.75	34.75	26.06
Tv	1	150	5.7	8.15	44.8	6.72
Iron	1	1000	0.53	0.46	3.57	3.57
Refrigerator	1	1200	8.11	8.11	56.77	68.12
Washing Machine	1	850	1.04	1.04	7.28	6.18
Lighting	5	180	5.67	5.45	39.25	7.06
Standing Fan	1	75	11.55	12.04	81.83	6.14
Rice Cooker	1	730	0.72	0.73	5.06	3.69
Kettle	1	850	0.48	0.44	3.28	2.79
Toaster	1	800	0.16	0.14	1.08	0.86
Blender	1	300	0.26	0.19	1.68	0.50
Hair Dryer	1	1125	0.09	0.05	0.55	0.62
Other Devices		300	3	5	25	7.5
Total Power Required		8310				
Total Weekly Energy Required						139.81
Average Daily Energy Required						19.973

The wind turbine generates 138.408 Wh of power per day, which is enough to power various household applications in Malaysia. In comparison, the total energy needed to operate household devices, as shown in the table, is only 19.973 Wh per day. This significant difference between the wind turbine's output and the energy required by household devices means that the wind turbine can efficiently provide electricity for these devices. With a surplus of 118.435 Wh, the wind turbine can meet the daily energy needs of essential household activities.

The extra energy can be used to extend the operating hours of electrical devices, allowing for more extended usage without relying heavily on conventional electricity sources. Storing the surplus energy can ensure a continuous power supply even during times of low wind activity. Using wind energy for household needs promotes sustainability and cost savings. By harnessing this renewable and eco-friendly energy source, households can reduce their dependence on the traditional power grid and contribute to a greener environment.

5. Conclusion

The simulation conducted in this project to design a small-scale wind turbine for household usage has been successful. The primary objective was to propose a wind turbine design specifically tailored for household applications in Malaysia. Through extensive simulations using ANSYS Fluent, the performance of the proposed wind turbine was comprehensively analysed under specific wind conditions in Malaysia.

The analysis of the obtained data reveals that wind turbines with a greater number of blades exhibit superior performance for household applications. Specifically, the three-bladed Darrieus wind turbine demonstrated a significantly higher rotor power coefficient compared to the two-bladed configuration. This advantage was observed in achieving higher coefficients at lower tip speed ratios, highlighting the potential benefits of employing a three-bladed design for wind energy generation in household applications.

Finally, this project has been successful in achieving its objectives and providing valuable insights into the performance characteristics of two-bladed and three-bladed Darrieus wind turbines for household applications. The results clearly demonstrate the advantages of utilizing a three-bladed design, showcasing its superior performance in terms of rotor power coefficient at lower tip speed ratios. These findings contribute to the advancement of wind turbine design and optimization, enabling the development of more efficient and effective wind turbine systems for household use.

Acknowledgement

The author would like to thank the Faculty Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia for the opportunity to conduct this study.

References

[1] G. Alkawsi, Y. Baashar, A. A. Alkahtani, C. W. Lim, S. K. Tiong, and M. Khudari. (2021) "Viability assessment of small-scale on-grid wind energy generator for households in Malaysia." *Energies (Basel)*, vol. 14, no. 12, Jun. 2021, doi: 10.3390/en14123391.

[2] S. Carrara, P. Alves Dias, B. Plazzotta, C. Pavel, and European Commission. Joint Research Centre. (2021) "*Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.*"

[4] C. S. Yan, S. C. Lim, and C. K. Yoong. (2022) "Potential of Small-wind Turbine for Power Generation on Offshore Oil and Gas Platforms in Malaysia." *International Journal of Energy Economics and Policy*, vol. 12, no. 6, pp. 272–282, Nov. 2022, doi: 10.32479/ijeep.13433.

[5] W. Strielkowski, L. Civín, E. Tarkhanova, M. Tvaronavičienė, and Y. Petrenko. (2021) "Renewable energy in the sustainable development of electrical power sector: A review," *Energies*, vol. 14, no. 24. MDPI, Dec. 01, 2021. doi: 10.3390/en14248240.

[6] U. Zafar and M. S. P. Staubach. (2018) "LITERATURE REVIEW OF WIND TURBINES A Special Project By," 2018.

[7] S. Ribbing and G. Xydis. (2021) "Renewable Energy at Home: A Look into Purchasing a Wind Turbine for Home Use—The Cost of Blindly Relying on One Tool in Decision Making," *Clean Technologies*, vol. 3, no. 2, pp. 299–310, Jun. 2021, doi: 10.3390/cleantechnol3020017.

[8] H. J. Wagner. (2018) "Introduction to wind energy systems," in *EPJ Web of Conferences*, EDP Sciences, Oct. 2018. doi: 10.1051/epjconf/201818900005.

[9] O. Kiliç. (2020) "WIND TURBINE DESIGN AND ANALYSIS Yunus Emre ÖZTÜRK," 2020.

[10] R. K. Kavade and P. M. Ghanegaonkar. (2018) "Design and Analysis of Vertical Axis Wind Turbine for Household Application," *Journal of Clean Energy Technologies*, vol. 5, no. 5, pp. 353–358, Sep. 2018, doi: 10.18178/JOCET.2017.5.5.397.

[11] K. A. Adeyeye, N. Ijumba, and J. Colton . (2021) "The Effect of the Number of Blades on the Efficiency of A Wind Turbine," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Jul. 2021. doi: 10.1088/1755-1315/801/1/012020.

[12] X. Zhang *et al.* (2021) "Integration of small-scale compressed air energy storage with wind generation for flexible household power supply," *J Energy Storage*, vol. 37, May 2021, doi: 10.1016/j.est.2021.102430.

[13] M. K. Johari, M. A. A. Jalil, and M. F. M. Shariff. (2018) "Comparison of horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT)," *International Journal of Engineering and Technology(UAE)*, vol. 7, no. 4, pp. 74–80, 2018, doi: 10.14419/ijet.v7i4.13.21333.

[14] T. W. Wen, C. Palanichamy, and G. Ramasamy. (2019) "Small wind turbines as partial solution for energy sustainability of Malaysia," *International Journal of Energy Economics and Policy*, vol. 9, no. 2, pp. 257–266, 2019, doi: 10.32479/ijeep.7337.

[15] A. H. Rajpar, I. Ali, A. E. Eladwi, and M. B. A. Bashir, "Recent development in the design of wind deflectors for vertical axis wind turbine: A review," *Energies*, vol. 14, no. 16. MDPI AG, Aug. 02, 2021. doi: 10.3390/en14165140.

[16] S. Shukla, C. J. Ramanan, B. Jyoti Bora, A. Deo, and N. Alom, "Numerical analysis of vertical axis wind turbine blades in ANSYS Fluent," *Mater Today Proc*, vol. 59, 2022, doi: 10.1016/j.matpr.2022.04.377.

[17] by Mohamed Khaled Mohamed Mohamed Hasanin Supervisors Ahmed Farouk Abdel Gawad Assoc Hesham ElSayed Abdel Hamed Mostafa Mohamed Mohamed Ibrahim, "The Effect of Blade Geometry and Configuration on Horizontal Axis Wind Turbine Performance," 2018.

[18] N. A. Rashidi, Y. H. Chai, and S. Yusup, "Biomass Energy in Malaysia: Current Scenario, Policies, and Implementation Challenges," *Bioenergy Research*, vol. 15, no. 3. Springer, pp. 1371–1386, Sep. 01, 2022. doi: 10.1007/s12155-022-10392-7.

[19] M. Shoaib, I. Siddiqui, S. Rehman, S. Khan, and L. M. Alhems. (2019) "Assessment of wind energy potential using wind energy conversion system," *J Clean Prod*, vol. 216, pp. 346–360, Apr. 2019, doi: 10.1016/j.jclepro.2019.01.128.

[20] A. Albani, M. Z. Ibrahim, and K. H. Yong. (2018) “The feasibility study of offshore wind energy potential in Kijal, Malaysia: the new alternative energy source exploration in Malaysia.”

[21] Malaysian Meteorological Department. (2023) “Malaysia’s Climate,” *Official Website of Malaysian Meteorological Department*, Jun. 22, 2023. https://www.met.gov.my/en/pendidikan/iklim-malaysia/ (accessed Jun. 21, 2023).

[22] M. S. Hanoon *et al.*, (2022) “Wind speed prediction over Malaysia using various machine learning models: potential renewable energy source,” *Engineering Applications of Computational Fluid Mechanics*, vol. 16, no. 1, pp. 1673–1689, 2022, doi: 10.1080/19942060.2022.2103588.

[23] I. Hashem and M. H. Mohamed. (2018) “Aerodynamic performance enhancements of H-rotor Darrieus wind turbine,” *Energy*, vol. 142, pp. 531–545, Jan. 2018, doi: 10.1016/j.energy.2017.10.036.

[24] N. Mohammed, K. A. Danapalasingam, and A. Majed. (2018) “Design, control and monitoring of an offline mobile battery energy storage system for a typical malaysian household load using PLC,” *International Journal of Power Electronics and Drive Systems*, vol. 9, no. 1, pp. 180–188, Mar. 2018, doi: 10.11591/ijpeds.v9.i1.pp180-188.