International Journal of Basic Science and Technology
October, Volume 10, Number 3, Pages 238 - 246 http://www.ijbst.fuotuoke.edu.ng/238
https://doi.org/ 10.5281/zenodo.13429763 **ISSN 2488-8648**

Exploring the Impact of Building Roofs on Vertical Axis Wind Turbines

[2]Buhari, M· [1]Ahmad, A., [3]Abubakar, N., [3]Namaiwa, B.M. and [2]Zakari, M.S.

[1]Mechanical Engineering Technology, Federal Polytechnic, Kaura Namoda, Zamfara State, Nigeria.
[2]Science Laboratory Technology, Federal Polytechnic, Kaura Namoda, Zamfara State, Nigeria.
[3]Building Technology, Federal Polytechnic, Kaura Namoda, Zamfara State, Nigeria

Article Information

Article # 10036
Received: 4th April. 2024
Revision: 8th Sept. 2024
2nd Revision: 3rd Sept. 2024
Acceptance:27th Sept. 2024
Available online:
24th October, 2024.

Key Words
Vertical Axis Wind Turbine
Power Coefficient
Tip Speed Ratio
Gable Roof, Flat Roof

Abstract

Urban wind energy harvesting, a promising departure from the traditional approaches favoring open terrains and large wind power plants, is gaining public interest. Despite the challenges of urban areas, such as lower wind speeds and higher turbulence levels, this shift presents significant opportunities. Specific locations, such as zones around high-rise buildings, offer the potential for high wind speeds, highlighting the innovative and hopeful nature of urban wind energy. Turbines were incorporated in two types of building roofs (Gable and flat roofs) in the design. Also, turbine systems were fabricated using locally available materials and tested with different wind speeds by use of fans as blowers. The results show that the Gable roofed Vertical Axis Wind Turbine has achieved a maximum coefficient of power (C_p) value of 0.142 when compared with the maximum coefficient of power (C_p) of the flat Vertical Axis Wind Turbine at the same wind speeds and subjected to the same experimental conditions is 0.033 at a wind speed of 3 m/s, this indicates that the maximum C_p of the Gable roof Vertical Axis Wind Turbine has increased by 33.3% compared to the flat Vertical Axis Wind Turbine. Additionally, the Gable roof Vertical Axis Wind Turbine has achieved a maximum tip speed ratio value of 10.832 at a wind speed of 1 m/s, showcasing an 84% increase compared to the flat roof Vertical Axis Wind Turbine. Moreover, the Gable roof Vertical Axis Wind Turbine has reached a maximum mechanical power value of 0.172 at a tip speed ratio of 3.063, which is a 338.3% improvement compared to the flat Vertical Axis Wind Turbine on the prototype experiment. These results illustrate the potential and benefits of integrating wind turbines on building rooftops, such as the Gable roof Vertical Axis Wind Turbine, in enhancing urban wind energy studies

***Corresponding Author:** Buhari M.; mamudabuhari@gmail.com

Introduction

The global need for energy is expected to increase, and renewable sources are becoming more important in fulfilling this demand (Adelekan *et al.*, 2024). Urban wind power is crucial in distributed energy and has been integrated into numerous engineering projects (Zhang *et al.*, 2022). Growing urban populations present unique sustainability challenges. Innovative renewable energy strategies are needed to address the increasing electricity demand (Fan *et al.*, 2021). Rooftop wind turbines are a common form of urban wind power utilization and have demonstrated potential for generating electricity in the built environment (Kwok & Hu, 2023). Typically, these turbines are called mini- or micro-turbines, featuring small rotor diameters of less than 5–10m and rated capacities of less than 50kW (Surve *et al.*, 2023).

Vadhyar *et al*. (2024) highlighted the potential for generating local wind power through small-scale rooftop turbines due to increased urbanization and high-rise buildings. However, the feasibility of this technology is being questioned due to various factors that need to be considered during its design and implementation. This review, which comprehensively examines the present technology landscape, is crucial in understanding the essential elements, including wind resource assessments, urban architecture, turbine design, and methods to enhance power output.

Using computational fluid dynamics, Yin and Muhieldeen (2024) conducted a rigorous study on how vertical shadings affect the cross-ventilation performance in an office building. They compared on-site measurements with numerical results and used them as boundary conditions for the simulations. Their findings, which resulted from a meticulous process, demonstrated that adding vertical shadings to windows can improve ventilation rates when the wind blows from 45° to 90°.

Vertical Axis Wind Turbines (VAWT), with their ability to capture wind energy from any direction, are a practical and cost-effective solution for the varied flow conditions found in urban environments. In such areas, the flow around buildings contains high wind speed areas, and the blockage effect can further enhance wind velocity (Xu *et al.*, 2021). Additionally, these turbines can be installed at an elevation that does not disrupt pedestrians or vehicles, making them a feasible and reassuring option for urban energy solutions.

The study by Rafiei *et al.* (2023) focused on using shrouded VAWTs in urban areas. The research explored the potential of these turbines, particularly diffuser-shrouded VAWTs, to have a low environmental impact on urban energy supply. The study's economic assessment highlighted a significant 40% reduction in the levelized cost of energy for an optimized cluster of two diffuser-shrouded VAWTs compared to two bare VAWTs, demonstrating the promising cost-effectiveness of these findings for the future of urban energy supply. It is essential to note that a VAWT positioned at the front corner of a building's roof generates significantly more power than the same turbine in an open, uniform wind environment. Due to its significant benefits, studying the impact of this configuration on various building heights is crucial (Rezaei and Paraschivoiu, 2023).

When installed on the rooftops of high-rise buildings, straight-bladed vertical axis wind turbines (SB–VAWT) offer various advantages compared to Horizontal Axis Wind Turbines (HAWT). They are omnidirectional, have lower installation and maintenance costs, produce reduced noise emissions, and perform effectively in highly turbulent conditions (Siddiqui *et al.*, 2021).

Jooss et al.'s experimental research (2022) used a wind tunnel to determine the optimal placement for a roof-mounted wind turbine. The study involved two cube-shaped buildings and a Savonius vertical axis wind turbine. The researchers varied the turbine's position and height on one of the buildings and simulated wind from five directions. The turbine's performance was assessed using a reliable power measurement method.

Hu *et al*. (2024) conducted a study exploring wind resources on rooftops, VAWT operation, and their impact on the wind field. They experimented with wind turbines using the NACA0018 airfoil model on a building rooftop in a wind tunnel under specific wind conditions. The study revealed that the turbines caused a decrease in wind speed above the building and increased turbulence intensities due to the blunt body effect. Additionally, it emphasized the significant influence of tip-speed ratios, wind directions, and turbine installation locations on the flow field atop the building.

The study by Turhan and Saleh (2024) examines the use of (VAWT) for electricity generation and highlights the significant energy consumption of buildings. It emphasizes the urgent need for innovative systems to reduce energy usage in contemporary structures, proposing renewable energy sources.

Malge and Belvekar (2023) have introduced a groundbreaking innovation in the renewable energy sector with their wind booster, which aims to enhance the self-starting ability of vertical-axis wind turbines. The wind booster's behavior was thoroughly analyzed across different frequencies using ANSYS-SAMCEF software, and the Von Mises stress model was utilized to calculate maximum and minimum stress. The recorded maximum stress in vertical deflectors was 4.64 MPa, accompanied by a maximum deflection of 9.75×10^{-3}, providing a comprehensive understanding of the wind booster's performance.

Diaz et al. (2024) conducted a study on harnessing wind energy on the rooftop of a 29-meter-tall building. The study sought to create a process for incorporating Small Wind Turbines (SWTs) into urban buildings to encourage energy self-sustainability. Its comprehensive framework involved seven steps: site selection, urban wind energy evaluation using computational fluid dynamics (CFD) simulation and on-site measurements, SWT selection, annual energy production estimation, environmental impact assessment, resilience and economic analysis, and system installation.

The study by Peng *et al.* (2020) systematically examined wind flow characteristics and wind energy potential over the flat rooftops of tall buildings using wind tunnel testing. The team's findings on the effects of building height and width ratios for all 90° wind directions are not just significant but crucial. They set a 3 × 3 array of points on the roof plan for a given building, extending vertically to a height of z = 2H (where H is the building height). A total of 4230 points were meticulously involved in this measurement campaign, underscoring the importance and impact of this research. This study examines the effect of vertical axis wind turbines (VAWT) on the roofs of buildings. The building-integrated wind turbine (BIWT) has gained traction, tapping into the abundant wind resources in the architectural environment. It is important to carefully evaluate the potential for wind energy generation on rooftops before proceeding with feasibility studies for installing roof-mounted wind turbines. Vertical-axis wind turbines offer an exciting opportunity for generating affordable and clean energy. Imagine harnessing the power of the wind right from the rooftops of buildings, which presents several challenges. This study explores the impact of vertical axis wind turbines (VAWT) installed on building roofs.

https://doi.org/ 10.5281/zenodo.13429763 ISSN 2488-8648

Turbine Power

The power output of the wind turbine is given by

$$P_t = \rho A v^3 \eta_T \eta_G \quad (1)$$

Where: P = Power output (W), A = Sweep area (m^2), ρ = Air density (Kg/m^3), v = Wind velocity (m/s), η_T = Wind turbine efficiency, η_G= Generator efficiency (Reza *et al.*, 2015).

Electrical Power as: $P_E = \omega \times \tau \quad (2)$

Where ω is the generator speed, and τ is the electromagnetic torque, equal to the generator torque reference from the wind turbine controller (Wiens *et al.*, 2021). Also, electric power can be calculated as

$$P = IxV \quad (3)$$

The Coefficient of Power

According to the Betz limit, the Power, C_P, and max coefficient can only achieve a value of 16/27. Theoretically, this is the only maximum possible rotor power coefficient. The theoretical coefficient of power of the horizontal wind turbine, called Betz theory, is maximum at C_P = 0.593, and the actual turbine is always inferior to this value.

The coefficient of Power, Cp, which represents the efficiency of a wind turbine, can be evaluated using equation (4) (Mohammed *et. l*, 2021)

$$C_p = \frac{P_t}{0.5\rho A U^3} \quad (4).$$

Tip Speed Ratio (TSR)

The relationship between the wind speed and the rate of rotation of the rotor is characterized by a non-dimensional factor known as the Tip Speed Ratio (TSR) or Lambda (λ) (Kong *et al.*, 2020) is given by equation (5)

$$\lambda = \frac{Tip\ speed\ of\ blade}{wind\ speed} = \frac{R\omega}{V} \quad (5)$$

ω is the rotational speed, and R is the rotor radius (Ebrahimpour *et al.*, 2019).

Methodology

The analytical design parameters of the turbine were used to design the hybrid vertical wind turbine on roofs and its components using Google Sketchup 2020 model solid tools to bring out the pictorial design with dimensions. The blade was first designed using Google Sketch-up software tools, and the shaft, Savonious rotor, and radial arm, were designed after using the same software tools. Then, rotor support frames (stand) and generator were designed separately, and the assembled schematic drawing (diagram) became hybrid VAWT on the building roofs, as shown in Figure 2 and Irender diagram of the hybrid VAWT as in Figure 3

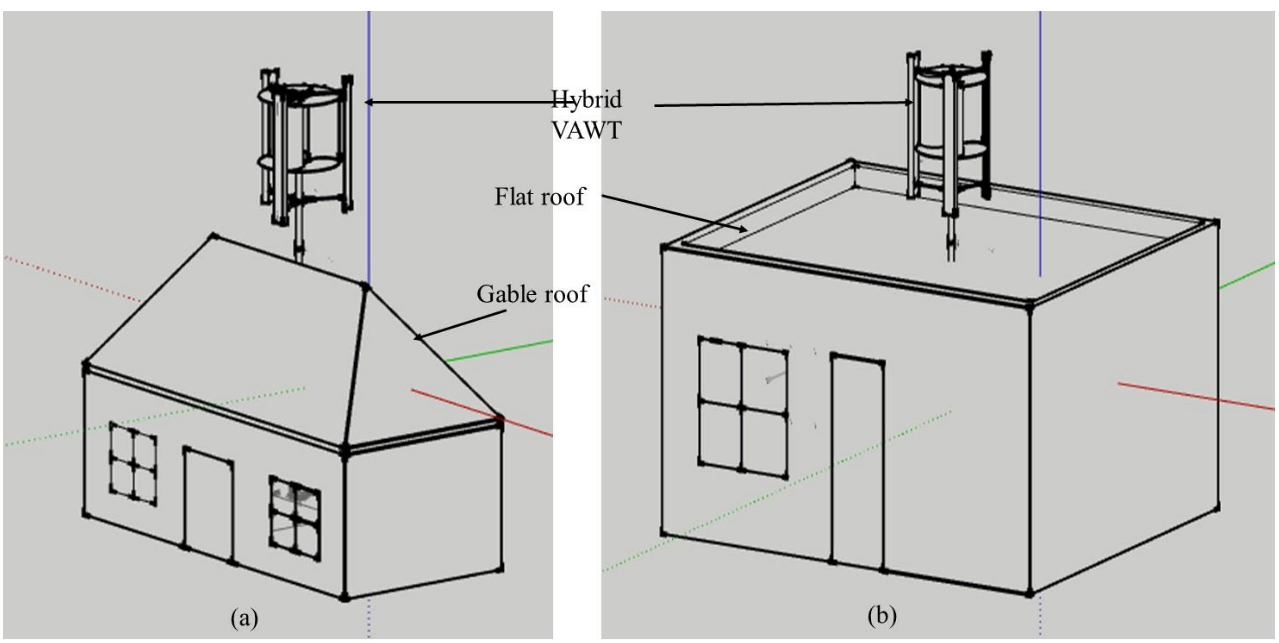

Figure 2: Schematic diagram of the (a) hybrid VAWT on Gable Roof and (b) hybrid VAWT on Flat Roof

October, Volume 10, Number 3, Pages 238 - 246 http://www.ijbst.fuotuoke.edu.ng/241
https://doi.org/ 10.5281/zenodo.13429763 ISSN 2488-8648

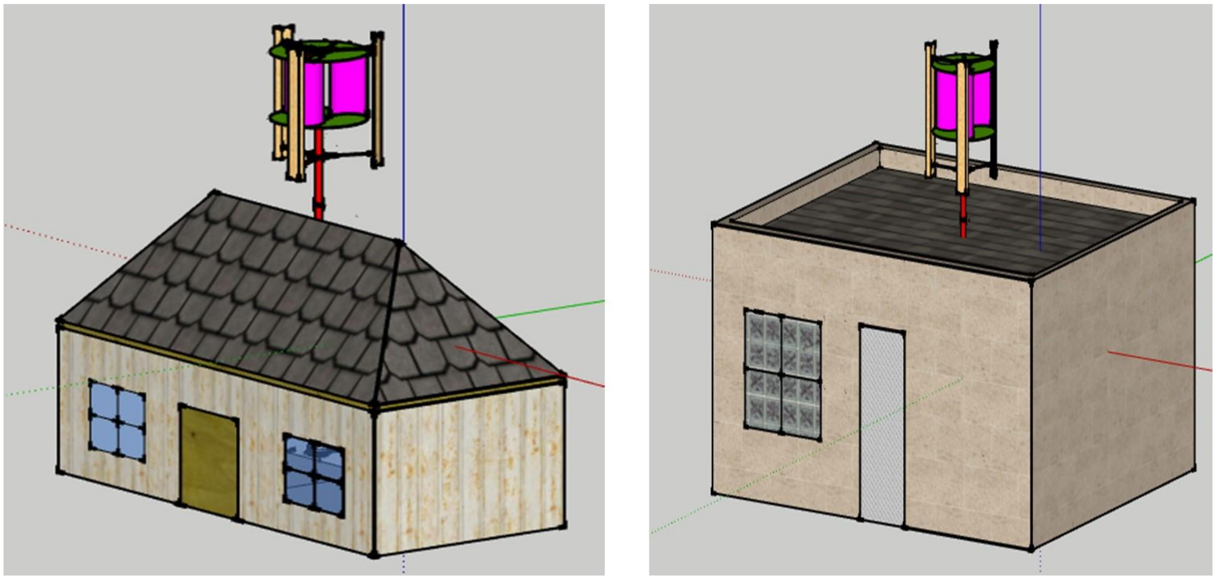

Figure 3: Diagram of the (a) hybrid VAWT on a Gable Roof and (b) hybrid VAWT on a Flat Roof

Experimental Setup: The experiment was set up with three electric Standing fans to save as a wind tunnel in the laboratory, and the Gable roof VAWT was placed 100 cm from the fans, facing the fans in the same line and direction, corresponding to a wind speed of 6 m/s. The distance between the blower and VAWTs was varied at some distance to vary the wind speed, and the VAWTs were tested at different wind speeds.

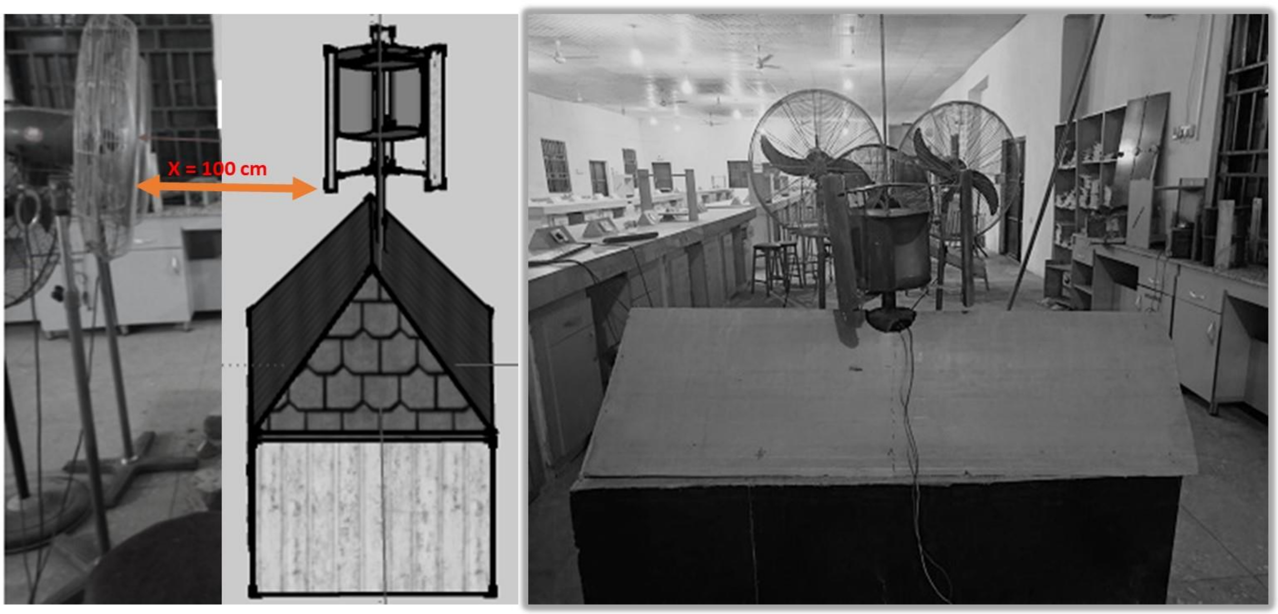

Figure 4: Symmetric diagram of the experimental setup

The setup arrangement of 3 configurations of 100cm x 180cm downstream of fans is shown in Figure 4. The average wind speed was taken using an anemometer on ten different positions in a straight line along the direction of the fan's wind when the fans were on (6 m/s). Then, a horizontal distance between the fan and the turbine position (X= 100 cm) was marked along the direction of the wind, and the gable roof with Hybrid VAWT onto the roof was placed on the position marked as shown in Figure 6. The wind speed of the position was measured using an anemometer; RPM was measured using a tachometer immediately after switching the fans against time with the use of a stopwatch on free running conditions where only the

https://doi.org/ 10.5281/zenodo.13429763 ISSN 2488-8648

inertial and bearing friction were applied until a stabilized RPM was achieved, current and voltage were measured using a multimeter, and the same procedure was repeated to obtained same parameters on each position by increasing the distance. Furthermore, flat roof VAWT was replaced, and the same experimental conditions were carried out,

Results and Discussion

Both Gable roof and Flat roof experiments were performed under the same experimental conditions, one for the Gable Roof hybrid VAWT and another for flat roof VAWT. The two turbines' horizontal distance varied for four different wind speeds: V = 6.0 m/s, 5.0 m/s, 4.0 m/s, 3.0 m/s, 2.0 m/s, and 1.0 m/s, respectively.

The horizontal distance between the Gable roof VAWT and flat roof VAWT was adjusted along the airflow direction to match recorded wind speeds of 6.0, 5.0, 4.0, 3.0, 2.0, and 1.0 m/s. Figure 5 compares the C_P values for the Gable roof VAWT and flat roof VAWT. The figure illustrates the coefficient of power plotted against the wind speed for the Gable roof VAWT and flat roof VAWT at wind speeds of 6.0 m/s, 5.0 m/s, 4.0 m/s, 3.0 m/s, 2.0 m/s, and 1.0 m/s respectively. Based on the data shown in Figure 5, the Gable roof VAWT achieved a maximum C_p value of 0.142 at a wind speed of 3 m/s. In contrast, the flat VAWT, under the same wind speeds and experimental conditions, reached a maximum Cp of 0.033 at a wind speed of 3 m/s. This indicates that the maximum C_p of the Gable roof VAWT is 33.3% higher than that of the flat VAWT.

Coefficient of Power (C_P) against Wind Speed (v)

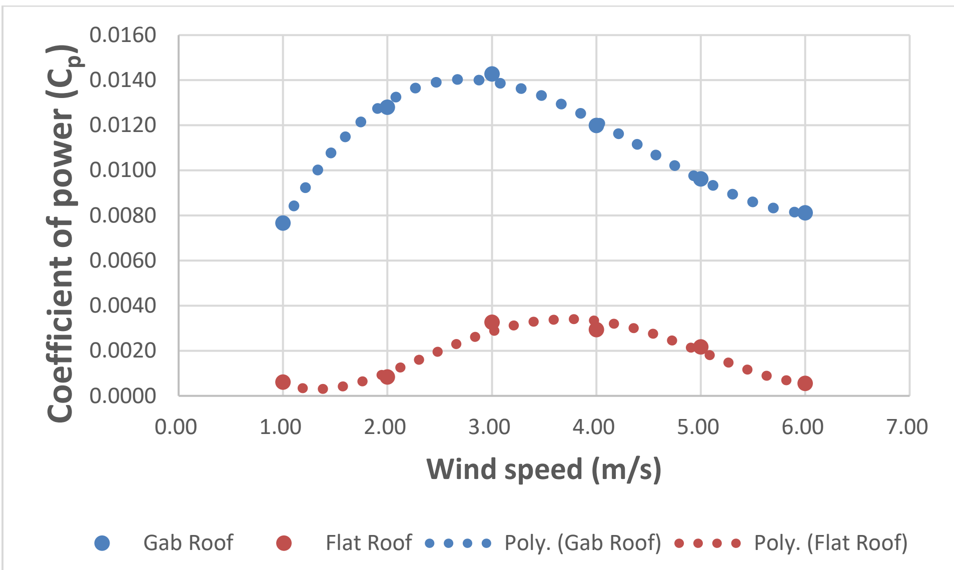

Figure 5: Coefficient of Power vs. Wind Speed for Gable roof VAWT and Flat roof VAWT

Tip Speed Ratio (λ) against Wind Speed (v)

The Gable roof and Flat roof VAWTs were tested at wind speeds ranging from 1.0 m/s to 6.0 m/s. The Gable roof VAWT achieved a maximum tip speed ratio of 10.832 at 1.0 m/s, while the Flat roof VAWT reached 6.890 at the same wind speed. This shows an 84% increase in the maximum tip speed ratio for the Gable roof VAWT compared to the Flat roof VAWT

.

International Journal of Basic Science and Technology
October, Volume 10, Number 3, Pages 238 - 246 http://www.ijbst.fuotuoke.edu.ng/243
https://doi.org/ 10.5281/zenodo.13429763 ISSN 2488-8648

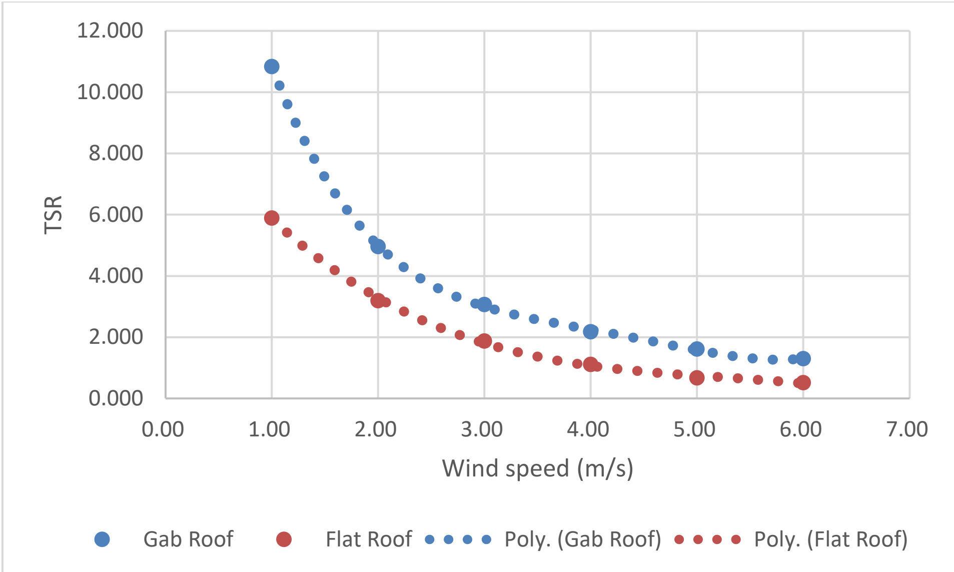

Figure 6: Tip Speed Ratio against Wind Speed for Gable roof VAWT against Flat roof VAWT

Mechanical power (w) against Tip Speed Ratio

The experiment involved varying the distance between the Gable roof VAWT and flat roof VAWT to correspond with recorded wind speeds. Mechanical power values for both VAWTs are compared in Figure 7, showing the mechanical power plotted against the Tip Speed Ratio at different wind speeds. The Gable roof VAWT achieved a maximum mechanical power value of 0.17150 at a tip speed ratio of 3.063, while the flat VAWT achieved 0.03910 at a tip speed ratio of 1.869. The Gable roof VAWT's maximum mechanical power increased by 338.3% compared to flat VAWT.

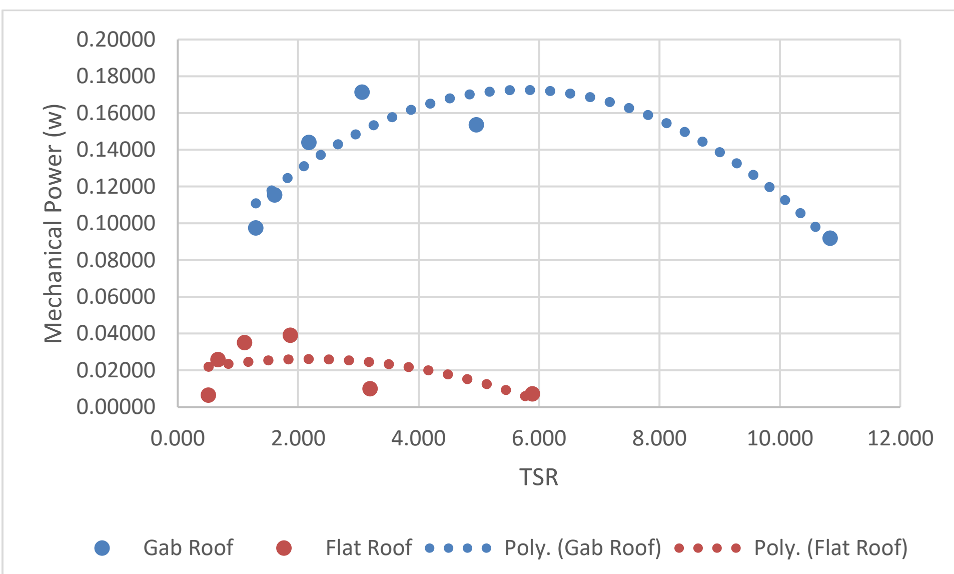

Figure 7: mechanical power plotted against the Tip Speed Ratio for Gable roof VAWT against Flat roof VAWT

Discussions

The results from Figure 5, which represent the relationship between The coefficient of power against wind speed for Gable roof VAWT and flat roof VAWT, show an improvement in the percentage of the Gable roof VAWT, attributed to the increased wind speed at the rooftop, translating into more power compared to flat roof VAWT (Mohammed *et al*., 2021). Figure 6 demonstrates the relationship between the tip speed ratio against wind speed for Gable roof VAWT and flat roof VAWT, indicating better performance for the tip speed ratio of Gable roof VAWT than that of flat roof VAWT for all the configurations (6, 5, 4, 2, and 1 m/s). This suggests that integrating wind turbines on building rooftops can significantly enhance their performance, thus positively affecting the performance of the hybrid Vertical Axis Wind Turbine integrated into a building roof (Rana *et al*., 2022). Furthermore, Figure 7 illustrates the relationship of mechanical power against the tip speed ratio for the Gable roof VAWT and flat roof VAWT, with a difference of 333.3%. The building rooftop serves as a device that increases wind speed due to its speed-up effect at the top of the roof. Also at rooftop the wind deflects and deflected airflow causes a skewed angle. Better performance is expected at a highly skewed angle (Mohammed *et al.*, 2021), The near rooftop positions are expected to experience higher skew angles than away positions (Zamre and Lutz, 2022). Small wind turbines are manufactured with a horizontal or vertical axis, with vertical axis wind turbines particularly interesting for building applications (ÖĞÜÇLÜ, 2020). The shape of the building, especially the roof, has a vital role in the availability of wind resources for the turbine, and appropriate roof shaping or modifications to existing buildings can be crucial in increasing the wind power potential at the specified location (Vadhyar *et a*l., 2024). The coefficient of power, torque, and coefficient of torque of the vertical axis wind turbine depends on the tip speed ratio (Aihara *et al*., 2022). Buildings obstruct and deflect the wind, increasing turbidity and decreasing wind intensity. Turbines work best in environments with strong and consistent winds, such as over an open field or off-shore (Winslow, 2019).

Conclusions

In this study, a hybrid VAWT incorporated in building roofs was designed, constructed, and tested. The results revealed that the VAWT with a Gable roof achieved a maximum C_p (coefficient of performance) value of 0.142 at a wind speed of 3 m/s. In comparison, the maximum C_p of a flat VAWT under the same wind conditions was 0.033 at 3 m/s, showing a 33.3% increase in the Cp for the Gable roof VAWT. Additionally, the maximum tip speed ratio for the flat roof VAWT was 6.890 at a wind speed of 1 m/s, while the Gable roof VAWT achieved an 84% increase in this ratio. The Gable roof VAWT reached a maximum mechanical power value of 0.17150 at a tip speed ratio of 3.063, while the flat VAWT's maximum power was 0.03910 at a tip speed ratio of 1.869. This represents a significant 338.3% increase in the mechanical power for the Gable roof VAWT compared to the flat VAWT under the same experimental conditions. The study emphasizes the important role of building shape, particularly the roof, in determining wind resources for turbines. Appropriate roof shaping or modifications to existing buildings can significantly enhance wind power potential at a specified location.

Acknowledgements

The authors thank TETFUND for the Research Grant allocated (IBR, 2024) through the Federal Polytechnic Kaura Namoda, Zamfara State, Nigeria.

REFERENCE

Adelekan, O. A., Ilugbusi, B. S., Adisa, O., Obi, O. C., Awonuga, K. F., Asuzu, O. F., and Ndubuisi, N. L. (2024). Energy transition policies: a global review of shifts towards renewable sources. *Engineering Science and Technology Journal*, 5(2), 272-287. https://doi.org/10.51594/estj.v5i2.752

Aihara, A., Mendoza, V., Goude, A., & Bernhoff, H. (2022). Comparison of Three-Dimensional Numerical Methods for Modeling of Strut Effect on the Performance of a Vertical Axis Wind Turbine. *Energies*, *15*(7). https://doi.org/10.3390/en15072361

Díaz, A. V., Moya, I. H., Castellanos, J. E., and Lara, E. G. (2024). Optimal Positioning of Small Wind Turbines Into a Building Using On-Site Measurements and Computational Fluid Dynamic Simulation. *Journal of Energy Resources Technology*, 146(8). https://doi.org/10.1115/1.4065381

Ebrahimpour, M., Shafaghat, R., Alamian, R., and Shadloo, M. S. (2019). Numerical investigation of the Savonius vertical axis wind turbine and evaluation of the effect of the overlap parameter in both horizontal and vertical directions on its performance. *Symmetry*, *11*(6), 1–16. https://doi.org/10.3390/sym11060821

https://doi.org/ 10.5281/zenodo.13429763 **ISSN 2488-8648**

Fan, X., Ge, M., Tan, W., and Li, Q. (2021). Impacts of coexisting buildings and trees on the performance of rooftop wind turbines: An idealized numerical study. Renewable energy, pp. 177, 164–180. https://doi.org/10.1016/j.renene.2021.05.090

Hu, J., Wang, X., Yang, H., and Huang, B. (2024). Experimental study on the rooftop flow field of the building based on the operation of vertical-axis wind turbines. *Journal of Renewable and Sustainable Energy*, 16(3). https://doi.org/10.1063/5.0205549

Jooss, Y., Rønning, E. B., Hearst, R. J., and Bracchi, T. (2022). Influence of position and wind direction on the performance of a roof-mounted vertical axis wind turbine. *Journal of Wind Engineering and Industrial Aerodynamics*, p. 230, 105177. https://doi.org/10.1016/j.jweia.2022.105177

Kong Johan Kong, N., Abu Bakar, R., Yi Leang, L., and Adnin Hamidi, M. (2020). The analysis of wind blade on the performance of Vertical Axis Wind Turbine. *IOP Conference Series: Materials Science and Engineering*, *788*(1). https://doi.org/10.1088/1757-899X/788/1/012080

Kwok, K. C. S., and Hu, G. (2023). Wind energy system for buildings in an urban environment. Journal of Wind Engineering and Industrial Aerodynamics, 234, 105349. https://doi.org/10.1016/j.jweia.2023.105349

Malge, A. and Belvekar, A. (2023). Structural analysis of wind booster for a multistorey vertical axis wind turbine. *International Journal of Ambient Energy*, 45(1). https://doi.org/10.1080/01430750.2023.2268082

Mohammed, G., Ibrahim, A., Mohammed Kangiwa, U., and Benjamin Wisdom, J. (2021). Design and Testing of Building Integrated Hybrid Vertical Axis Wind Turbine. *Journal of Electrical and Electronic Engineering*, *9*(3), 69. https://doi.org/10.11648/j.jeee.20210903.12

ÖĞÜÇLÜ, Ö. (2020). Structural Design and Stress Analysis of A Helical Vertical Axis Wind Turbine Blade. *Sakarya University Journal of Science*, *24*(6), 1151–1161. https://doi.org/10.16984/saufenbilder.719223

Peng, H. Y., Dai, S. F., Lin, K., Hu, G., and Liu, H. J. (2020). Experimental investigation of wind characteristics and wind energy potential over rooftops: Effects of building parameters. Journal of Wind Engineering and Industrial Aerodynamics, 205, 104304. https://doi.org/10.1016/j.jweia.2020.104304

Rafiei, B., Gharali, K., and Soltani, M. (2023). Optimized configuration with economic evaluation for shrouded vertical axis wind turbines applicable for urban structures. Energy Science Engineering, 11(10), 3699-3720. https://doi.org/10.1002/ese3.1547

Rana, M., Sonyy, S. M., Loganathan, B., and Chowdhury, H. (2022). In Situ Performance Measurement and Characterization of Wind Turbine. *AIP Conference Proceedings*, *2681*(November). https://doi.org/10.1063/5.0117101

Rezaei, F., & Paraschivoiu, M. (2023). Computational study of the effect of building height on the performance of roof-mounted VAWT. Journal of Wind Engineering and Industrial Aerodynamics, 241, 105540. https://doi.org/10.1016/j.jweia.2023.105540

Siddiqui, M. S., Khalid, M. H., Zahoor, R., Butt, F. S., Saeed, M., and Badar, A. W. (2021). A numerical investigation to analyze the effect of turbulence and ground clearance on the performance of a rooftop vertical–axis wind turbine. Renewable energy, pp. 164, 978–989. https://doi.org/10.1016/j.renene.2020.10.022

Surve, M. L., Deshmukh, P. D., Kale, B. S., Ghadge, A. R., and Patil, M. V. (2023). Development of a roof-mounted stand-alone wind turbine system for household power generation. Engineering Research Express, 5(4), 045082. DOI 10.1088/2631-8695/ad1085

Turhan, C., and Saleh, Y. A. S. (2024). A Case Study for Small-Scale Vertical Wind Turbine Integrated Building Energy Saving Potential. Journal of Building Design and Environment, 3(1). https://doi.org/10.37155/2811-%200730-0301-5

Vadhyar, A., Sridhar, S., Reshma, T., and Radhakrishnan, J. (2024). A critical assessment of the factors associated with implementing rooftop VAWTs: A review. Energy Conversion and Management: X, 100563. https://doi.org/10.1016/j.ecmx.2024.100563

Xu, W., Li, Y., Li, G., Li, S., Zhang, C., & Wang, F. (2021). High-resolution numerical simulation of the performance of vertical axis wind turbines in an urban area: Part II, an array of vertical axis wind turbines between buildings. Renewable energy, pp. 176, 25–39. https://doi.org/10.1016/j.renene.2021.05.011

Yin, X., & Muhieldeen, M. W. (2024). Impact of vertical shading designs on the cross-ventilation performance of a high-rise office building. Results in Engineering, p. 21, 101676.

https://doi.org/10.1016/j.rineng.2023.101676

Winslow, A. (2019). Urban Wind Generation: Comparing Horizontal and Vertical Axis Wind Turbines at Clark University in Worcester, Massachusetts. In *International Development, Community and Environment (IDCE)*. https://commons.clarku.edu/idce_masters_papers/127

Zamre, P., &\and Lutz, T. (2022). Computational-fluid-dynamics analysis of a Darrieus vertical-axis wind turbine installation on the rooftop of buildings under turbulent-inflow conditions. *Wind Energy Science*, *7*(4), 1661–1677. https://doi.org/10.5194/wes-7-1661-2022