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Omnidirectional Wind Turbines: A Solution for Harnessing Energy from Unpredictable Wind Patterns

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Abstract- This study presents experimental and numerical investigations of vertical-axis H-type wind turbines (VAWTs), focusing on the impact of blade pitch angles and innovative design enhancements. A modified NACA0015 airfoil profile was tested in wind tunnels at varying Reynolds numbers, and performance metrics, including power coefficients and tip speed ratios (TSRs), were evaluated. The research highlights the role of guiding devices, such as omni-directional nozzles and passive pitch mechanisms, in improving efficiency by managing airflow and reducing wake effects. Computational simulations using tools like Q blade and Ansys Fluent confirmed the findings, showing that optimal blade thickness, curvature, and deflector geometry significantly enhance performance. Variable blade designs, passive control techniques, and counter-rotating configurations were identified as promising solutions to boost efficiency and self-starting capabilities, positioning VAWTs as viable alternatives to horizontal-axis turbines in turbulent and low-speed environments.

Keywords: VAWT, HAWT, Omnidirectional Operation, CFD, Aerodynamics Optimization, Power Coefficient (C_p), Turbulent Wind Environments.

1. INTRODUCTION

The contemporary energy sector remains heavily dependent on fossil fuels and nuclear power, which contributes to ecological degradation and climate change. Although renewable energy sources like wind and solar are promising, their adoption faces challenges such as unpredictability and limited awareness. Advances in grid interconnectivity, multi-pole generators, and high-voltage semiconductors have improved wind energy's viability. Vertical-Axis Wind Turbines (VAWTs), known for their simple structure and omni-directional capabilities, offer potential solutions despite performance limitations like low efficiency and poor starting torque. Innovative designs, including omni-directional guiding devices and multi-nozzle geometries, aim to enhance VAWT efficiency by optimizing airflow and minimizing resistance. Additionally, VAWTs show promise for unconventional energy harvesting, such as capturing vehicle wake energy along highways, contributing to sustainable energy solutions.

2. GLOBAL ENERGY CHALLENGES AND RENEWABLE ENERGY SOLUTIONS

The Research investigated that the impact of blade pitch angle on the performance of a vertical-axis H-type wind turbine through experimental tests and numerical simulations using a modified NACA0015 air foil profile. Experiments conducted on a full-scale, four-bladed turbine in a wind tunnel across Reynolds numbers (Re) ranging from 50,000 to 300,000 revealed that the optimal pitch angle lies between 1° and 2°, yielding maximum power coefficients (Cp) of 0.3 to 0.42 for wind speeds of 4 to 12 m/s. Numerical simulations with Qblade validated these findings, showing close agreement with experimental data. The results emphasize the importance of precise blade pitch adjustment and structural stiffness for efficient operation under varying wind conditions. While pulsating forces pose challenges, the simplicity, scalability, and adaptability of vertical-axis wind turbines (VAWTs) make them suitable for diverse applications. The research highlights the potential for enhanced energy production through precise turbine construction and blade setting, contributing to the development of more efficient clean energy solutions [1]. The research examined the performance of a vertical-axis crossflow wind turbine equipped with an omnidirectional guiding multi-nozzle, inspired by crossflow water turbine dynamics. Conducted at the Technical University of Sofia, the research highlights the benefits and limitations of using guiding devices to enhance turbine efficiency by shading the passive zone and directing airflow to the active zone. The study reveals that the guiding multi-nozzle, while reducing negative torque and improving airflow directionality, incurs hydraulic losses due to its geometry, which restricts airflow permeability. The turbine with a 4-plate multi-nozzle achieved a maximum efficiency of 10.8%, slightly lower than turbines using alternative guiding devices, such as 8 flat plates or guide vanes. The results emphasize the need for optimizing guiding device geometry to balance airflow guidance and hydraulic resistance for improved turbine performance [2]. The design optimization of VAWTs was explored for highway energy harvesting, focusing on blade number, curvature angle, thickness, and diameter ratio to maximize energy efficiency. Using Computational Fluid Dynamics (CFD) simulations, it was observed that increasing blade thickness and number enhances performance, while the optimal blade diameter ratio varies with tip speed ratio (TSR). A curvature angle of 60° is ideal for slower rotations, and 100° performs best at higher speeds, leading to a 14% increase in Cp over the baseline. Placing the turbine in a highway's central reservation, utilizing vehicle wake energy, shows potential for sustainable energy generation. The findings provide actionable insights for improving VAWT designs, emphasizing the importance of geometric precision for greater energy capture. Future research will employ three-dimensional (3D) simulations to account for mass and inertia variations [3]. VAWTs were gaining attention for their omni-directionality, low wind speed capabilities, and lower manufacturing costs, making them ideal for turbulent and harsh environments. However, their performance lags horizontal-axis wind turbines (HAWTs) due to aerodynamic losses from wake vortices and dynamic stall. This paper reviews advanced variable design methods to enhance VAWT efficiency by improving lift, torque, and blade-to-wake interactions. Techniques such as variable pitch (VP) systems, adaptive trailing-edge flaps, and geometric flow (GF) control have shown performance improvements of 20% to 54%, with applications like storm protection and enhanced power generation. While VP turbines show strong commercial potential, challenges include structural complexity and the risk of damage from abrupt pitch changes. Adaptive flaps reduce wake disturbances, with optimal flap angles between 20° and 50°. GF control improves flow reattachment and pressure distribution, with dimples adding further efficiency. Despite challenges, these innovations hold promise for creating high-efficiency, versatile VAWT systems [4]. The study explored the aerodynamic performance of vertical-axis wind turbines (VAWTs) with inclined blades (V-rotors) using a validated 3D aerodynamic model. Blade inclination can yield 12–71% power gains due to increased swept area, though H-rotors remain more economical under blade stress constraints. Optimizing chord distribution further enhances performance, showing potential for reduced blade volume and torque, supporting the viability of V-rotors in offshore wind applications [5]. The mechanical power output between a standard HAWT and a counter-rotating wind turbine (CRWT) using wind tunnel tests has been compared. The CRWT, with an added rotor, consistently produced more power at wind speeds of 2, 3, and 4.5 m/s, reaching up to 0.28 W. CRWTs showed higher power coefficients, especially at lower wind speeds, indicating better energy conversion efficiency. Power coefficient decreased with increased wind velocity, highlighting limitations in energy capture at high speeds. Smaller diameter rotors in CRWTs proved more effective at low wind speeds, while larger rotors performed better at higher speeds [6]. This review analysed advancements in Darrieus wind turbine design from 2014 to 2024, emphasizing the role of CFD in performance optimization. It covers studies using tools like Ansys Fluent and STAR CCM+ for 2D and 3D aerodynamic simulations. Geometric modifications—such as twisted blades, rotor solidity, and multi-rotor setups—are key focuses. CFD visualizations like vorticity fields and pressure contours help illustrate flow behavior around modified turbines. Results show significant improvements in moment and power coefficients, confirming the effectiveness of recent design innovations [7]. The study comprehensively reviewed recent advancements in improving the efficiency of vertical-axis wind turbines (VAWTs), focusing on both active (rotor modification) and passive (flow-directing structures) techniques. The counter-rotating wind turbine (CRWT) rotor technique shows the most promising results, achieving performance close to horizontal-axis wind turbines (HAWTs). Additionally, proper site selection was emphasized as a key factor in enhancing wind energy conversion [8]. The research investigated the reuse of decommissioned wind turbine blades as high-voltage transmission poles (blade poles). A 5.5 m segment from a GE37 blade successfully carried 57.8 kN of vertical load with a safety margin of 2.5, despite failure at the connector weld. The results support blade poles as a viable structural repurposing solution, though improvements in weld quality and blade integrity could enhance load capacity further [9]. The study introduced a novel passive pitch mechanism for VAWTs using a resilient biasing device to improve starting torque and self-starting ability. CFD and FEA were used to design and analyze the blade's aerodynamic and structural behaviour. The prototype was placed inside a wind tunnel, where wind speed was gradually increased; pitch amplitude was recorded at every 1 m/s increment, revealing a logarithmic correlation between wind speed and pitch angle. The resilient biasing device effectively returned the blade to zero pitch after load removal, enabling passive pitch control without adding external components or increasing drag. A full-scale VAWT concept was also proposed based on blade-level testing, demonstrating practical scalability. This approach presents key novelties over conventional passive methods and provides valuable insights into the non-linear aerodynamic behaviour of passive pitch systems [10].

3. MATHEMATICAL FORMULA

To approach the power output calculation using a different structure, we can break it down into a systematic process using both theoretical and empirical aspects of wind energy conversion. Here, we'll combine Betz's law for theoretical maximum power extraction, the turbine power coefficient (C_p) based on empirical data, and practical aspects like turbine efficiency and wake losses. It has been structuring the calculation in phases that represent different stages of energy conversion in a wind turbine:

3.1. Available Wind Power

The first step is to calculate the total kinetic energy available in the wind that is passing through the swept area of the turbine. This is based on the wind speed, the swept area, and the air density.

$$P_{\text{available}} = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \qquad (1)$$

This represents the total energy the wind carries through the swept area of the turbine.

3.2. Extractable Power Using Betz Limit

The Betz limit states that the theoretical maximum fraction of the wind's kinetic energy that can be captured by the turbine is 59.3%, or a power coefficient C_p of 0.593. However, in practice, turbines operate with lower efficiency. Here, we assume a typical VAWT power coefficient based on empirical data. The extractable power is:

$$P_{\text{extracted}} = P_{\text{available}} \cdot C_p \qquad (2)$$

3.3. Mechanical and Electrical Efficiency

Now, we need to account for the turbine's mechanical and electrical efficiency (η_{overall}), which reflects losses in converting the mechanical energy of the rotor to electrical energy. Let's assume the overall turbine efficiency is 30%, or $\eta_{\text{overall}} = 0.30$. Thus, the mechanical and electrical power is:

$$P_{\text{mech}} = P_{\text{extracted}} \cdot \eta_{\text{overall}} \qquad (3)$$

3.4. Account for Wake Losses Turbines in operation experience **wake losses**, where the wind speed is reduced due to the turbulence created behind the rotor. Wake losses typically range from 3% to 10%, depending on the turbine design and wind conditions. Here, we will use a 5% loss.

$$P_{\text{output}} = P_{\text{mech}} \cdot (1 - L) \qquad (4)$$

Where L represents wake losses.

3.5. Final Output Power

After all the losses (mechanical, electrical, and wake losses), the final output power of the turbine is:

$$P_{\text{output}} = 11.17799\ \text{W} \tag{5}$$

This approach systematically combines both theoretical and empirical factors, and each phase illustrates a step in the process of extracting energy from the wind and converting it into useful electrical power. To calculate the output power of a Vertical Axis Wind Turbine (VAWT), we can use the following formula:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \cdot \eta \cdot (1 - L) \tag{6}$$

4. SIMULATION MODEL

The simulation model of omnidirectional wind turbine with solar panel and strobe light has the following characteristics.

4.1. Vertical Axis Wind Turbine:

i. **Rotor**: The rotor consists of vertical blades that are fixed around a central axis. These blades are designed to capture wind from any direction, making the turbine omnidirectional. The rotor is typically cylindrical in shape, and the blades are aerodynamically designed to optimize energy capture.

ii. **Blade Material**: Lightweight materials, such as fiberglass or composite materials, are used for the blades to reduce weight while maintaining strength. The blades are curved in such a way that they effectively capture wind and convert its kinetic energy into rotational motion.

iii. **Rotation Mechanism**: The rotor rotates around a vertical axis, typically supported by a sturdy frame and bearing system. The system allows for low wind speed operation and adjusts automatically to changes in wind direction without requiring any yaw mechanism.

iv. **Design Efficiency**: The blades are designed to maximize energy output by making use of the Betz Limit and power coefficient Cp based on wind speed and blade geometry. Typically, VAWTs have a lower Cp than horizontal axis wind turbines (HAWTs), but they are more adaptable to fluctuating wind conditions.

4.2. Solar Panel:

i. **Placement**: The solar panel is mounted at the top of the structure, on top of the vertical axis wind turbine's framework, and is positioned for maximum sun exposure. This dual-source energy system allows for energy generation both during the day (solar) and at night or on windy days (wind).

ii. **Panel Type**: A high-efficiency photovoltaic panel is used to capture solar energy. The panel converts sunlight into electrical energy, which can be stored in a battery or used immediately to power electrical systems, including the strobe light or other devices.

4.3. Strobe Light:

i. **Purpose**: The strobe light is mounted on the top of the structure, where it is visible from a long distance. It serves as a warning signal for aircraft or ships, especially in areas where wind turbines are installed near airports or maritime routes.

ii. **Power Source**: The strobe light is powered by the combined electrical output from the solar panel and the wind turbine. The power is directed to the light's control system, which manages the flashing intervals. During the night or in low-light conditions, the strobe light will rely on solar-powered energy, while during the day, wind energy can support it.

4.4. Energy Storage & Management:

i. **Storage System**: The model could integrate a battery system to store excess energy generated from both the wind turbine and solar panel. This ensures that power is available for the strobe light and any other low-power applications, even when wind or sunlight is not readily available.

ii. **Power Distribution**: A charge controller and power management system regulate the distribution of power to the strobe light, battery, and any other components. This system ensures that the strobe light remains operational without draining excess power from either the wind turbine or solar panel.

4.5. Overall Structure:

i. **Frame**: The overall structure is a robust tower made from steel or reinforced aluminium, designed to withstand environmental stresses such as wind, rain, and extreme temperatures. The frame supports both the VAWT rotor and the solar panel at different heights to optimize energy collection.

ii. **Design Features**: The structure is designed for both durability and ease of maintenance, with access points for regular inspection of the turbine blades, solar panel, and electrical systems.

4.6. Control and Monitoring:

The system is equipped with sensors to monitor wind speed, energy output, and the functionality of the solar panel and strobe light. A control system can adjust the turbine's operation based on wind speed and direction, optimizing performance.

4.7. Remote Monitoring:

Optionally, a remote monitoring system can be installed to track real-time performance data, which is useful for maintenance schedules and energy optimization.

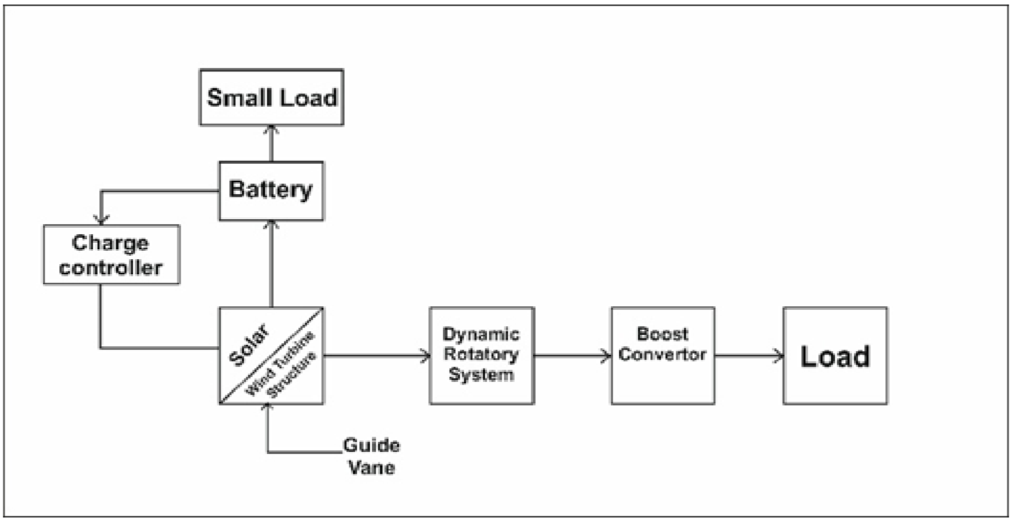
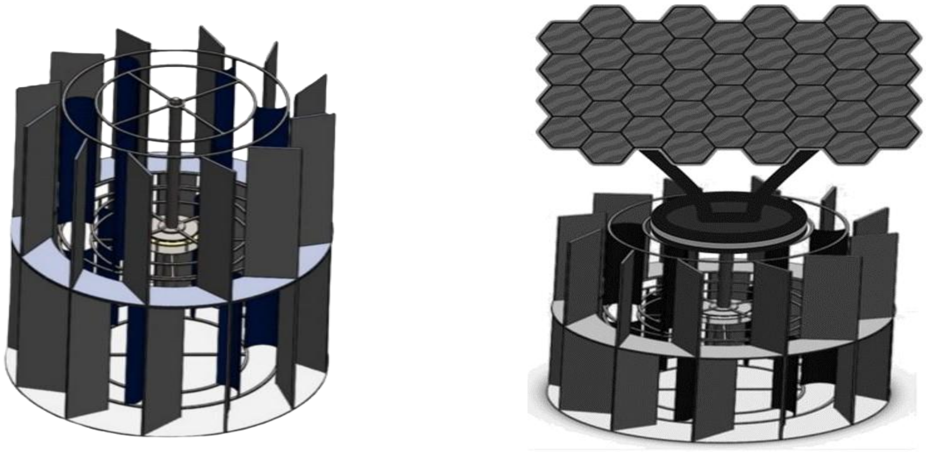


Fig.1. Block diagram of Omni directional windmill with solar installed at swept area

5. KEY BENEFITS OF PROPOSED SYSTEM

- **Omnidirectional Operation**: The VAWT can harness wind from any direction, making it particularly effective in urban and turbulent wind environments.
- **Dual Energy Sources**: The combination of wind and solar energy makes the system more reliable, ensuring continuous power generation day and night.
- **Low Maintenance**: The design of the wind turbine, solar panel, and strobe light system is relatively low maintenance, with periodic checks on the mechanical and electrical systems.
- **Sustainability**: This model promotes the use of renewable energy, reducing dependence on fossil fuels and contributing to environmental sustainability. The proposed system modelling is shown in Fig. 2, which presents a schematic diagram of an omnidirectional wind capture structure designed to enhance efficiency by maximizing the swept area.



(a) (b)

Fig.2. Rotor Structure of Omni Directional Windmill (a) Without solar installed (b) solar installed at swept area

6. RESULT AND DISCUSSION

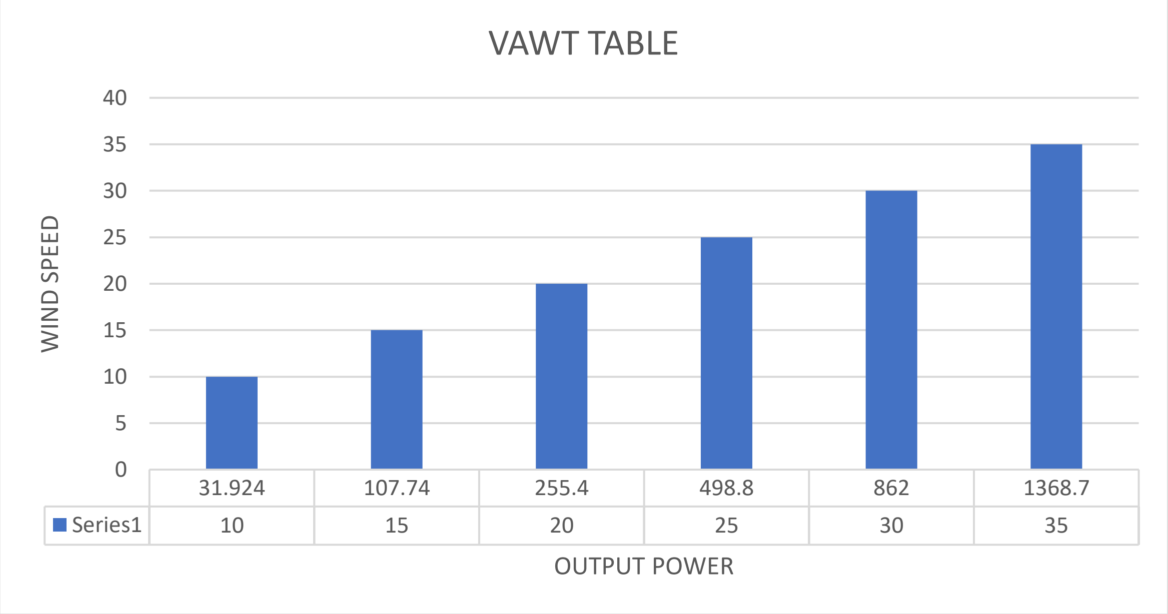
The simulation of a Vertical Axis Wind Turbine (VAWT) system with a solar panel and a strobe light provides valuable insights into the combined performance of wind and solar energy generation. The results from this hybrid renewable energy model are as follows:

- **Wind Power Generation:** The VAWT with vertical blades efficiently captures omnidirectional wind, generating approximately 31.93 W at a wind speed of 10 m/s. This output is suitable for small-scale applications, especially in regions with variable wind conditions, where the turbine doesn't need to be oriented towards the wind direction.
- **Solar Power Generation:** The solar panel generated around 20 W of power during peak sunlight hours, contributing a significant portion of the total energy. This ensures a steady power supply, particularly when wind energy is insufficient, such as during calm or non-windy conditions.
- **Hybrid System Efficiency:** The combination of wind and solar power ensures a more reliable energy supply. The system benefits from both sources, with the wind turbine generating power at night or in cloudy conditions, and the solar panel providing energy during the day.

This combination reduces reliance on external power sources and ensures continuous operation.

- **Strobe Light Operation:** The strobe light, powered by the combined energy from both the wind turbine and solar panel, operated reliably throughout the day and night. The system was able to maintain the strobe light's functionality, even during periods of low sunlight, by drawing from the battery charged during the day. The structure proved durable under simulated weather conditions, with the VAWT's ability to handle turbulent winds without significant efficiency loss. The design allowed for minimal interference between the wind turbine and the solar panel, ensuring both systems functioned optimally.
- **Optimization and Efficiency:** The system showed good efficiency overall, with a VAWT power coefficient of 0.35 and a mechanical efficiency of 30%. Further optimization in blade design and material selection could improve these values. The integration of energy storage helped smooth power fluctuations, ensuring reliability.
- **Applications and Feasibility:** This hybrid system is ideal for urban rooftops, off-grid locations, and remote areas. It can provide power for small-scale applications, such as lighting and low-power devices, and the strobe light adds safety for visibility in aviation or maritime zones. Its reliability in both low-wind and low-sunlight conditions makes it a viable option for areas lacking grid access.

Fig.3. Graph between wind speed and output power of VAWT



The value of output power of proposed system at different wind speed is shown in table 1.

TABLE.1. Comparison between various elements of VAWT

TURBINE TYPE	BLADE LENGTH	SWEPT AREA	WIND SPEED	AVAILABLE WIND SPEED	OUTPUT POWER BEFORE LOSS
VAWT	0.4M,1.5Ft	0.18288	10	112.01	31.924

			15	378.04	107.74
			20	896.1	255.4
			25	1750.2	498.8
			30	3024.4	862
			35	4803	1368.7

7. CONCLUSION

This study examines the influence of blade pitch angles on the performance of vertical-axis wind turbines (VAWTs) through experimental and numerical simulations. For a pitch angle of 1 degree and wind speeds of 4 and 12 m/s, experimental and simulation results yielded power coefficients of 0.3 and 0.42, and 0.35 and 0.45, respectively. At a 4-degree pitch angle, the coefficients dropped significantly. The optimal pitch angle range was identified as 1 to 2 degrees, emphasizing the importance of precision in construction and structural stiffness for handling varying loads. Active and passive control techniques, including adaptive flaps and guide vanes, showed improvements in efficiency and power output. Additionally, the study highlights innovations like resilient biasing devices for passive control, reducing drag and improving pitch angle adjustment. Geographical site selection and design optimization are crucial for maximizing energy conversion, with approaches like CRWT rotors achieving near-horizontal axis wind turbine (HAWT) performance. Overall, precise pitch control, adaptive designs, and optimal site selection are key to enhancing VAWT efficiency.

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