Journal of Engineering Science and Technology
Vol. 20, No. 6 (2025) 2022 - 2035


# PERFORMANCE OPTIMIZATION OF A HYBRID VERTICAL AXIS WIND TURBINE AND SOLAR PANEL SYSTEM UNDER VARIABLE TILT AND INCLINATION ANGLES

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## Abstract

This study explores the performance optimization of a hybrid renewable energy system combining a Vertical Axis Wind Turbine (VAWT) and solar panels, designed to harness both wind and solar energy. The system's efficiency was evaluated under varying tilt angles (45°, 60°, and 80°) for solar panels and inclination angles for the wind turbine, considering their impact on electricity generation. A comprehensive methodology was employed, involving real-time data collection using anemometers, solar irradiance, voltage, current, and power output. The results revealed that a tilt angle of 45° for solar panels yielded the highest voltage and current generation due to optimal sunlight exposure. For the VAWT, an inclination angle of 90° produced the highest rotational force and energy output, demonstrating the importance of vertical alignment for stability and efficiency under varying wind speeds. These findings provide valuable insights into the design and deployment of hybrid renewable energy systems, particularly in equatorial regions like Malaysia.

Keywords: Hybrid renewable energy, Inclination angles, Solar panel, Tilt angles, Vertical axis wind turbine.

## 1. Introduction

The growing demand for sustainable energy solutions has driven significant advancements in renewable energy technologies. As the world grapples with the challenges of climate change, energy security, and environmental degradation, harnessing renewable energy sources such as solar and wind has become a critical priority. Hybrid renewable energy systems, which integrate multiple energy sources, are emerging as a viable solution to overcome the limitations of individual technologies and provide a more stable and reliable energy supply.

In this context, Malaysia's geographic location near the equator offers unique advantages for renewable energy generation. With abundant solar irradiance and moderate wind conditions throughout the year, the country is well-positioned to benefit from hybrid systems that combine solar and wind energy. Such systems not only enhance energy reliability but also contribute to reducing greenhouse gas emissions and promoting energy independence.

This study focuses on the design and analysis of a novel hybrid energy system that integrates a Vertical Axis Wind Turbine (VAWT) with solar panels. Unlike conventional systems, where wind turbines and solar panels operate independently, this innovative approach incorporates solar panels directly onto the blades of the wind turbine. This design aims to optimize energy generation by utilizing the turbine's structural components for dual functionality, maximizing space efficiency and energy output.

The research focuses on evaluating the influence of placing solar panels on VAWT blades on overall power output compared to traditional hybrid systems with separate solar and wind units. It also examines the effects of different tilt and inclination angles on the system's electrical performance and evaluates the operation of the hybrid system under varying environmental conditions. Through experimental measurements and analysis, the study aims to determine the optimal configurations for efficient energy generation under varying environmental conditions. The results are expected to provide valuable insights into the feasibility and practicality of hybrid systems in equatorial regions like Malaysia, where renewable energy resources are abundant yet underutilized.

By addressing the challenges of integrating solar and wind technologies, this research seeks to contribute to the development of sustainable energy solutions that are both innovative and practical. The findings have the potential to inform the design of future hybrid systems, promoting the adoption of renewable energy and supporting Malaysia's transition towards a more sustainable energy future.

## 2. Literature Review

With the launch of its National Energy Transition Roadmap (NETR) 2024, Malaysia is actively working towards increasing its use of renewable energy. The roadmap sets an ambitious target of generating 31 % of the nation's electricity from renewable sources by 2025, with plans to raise this share to 40 % by 2035. This strategic framework focuses on accelerating solar energy deployment, utilizing bioenergy resources, optimizing hydroelectric potential, and exploring emerging technologies such as green hydrogen.

The Malaysian government has also introduced policies like the Net Energy Metering (NEM) scheme and initiatives to expand solar panel manufacturing to support

the growth of solar energy [1]. While solar energy has received significant government support, Malaysia's wind energy potential remains limited due to consistently low wind speeds, which are generally insufficient for large-scale wind power generation.

For a wind energy project to be economically viable, sustained wind speeds of at least 4 to 6 meters per second are required, whereas Malaysia's average wind speeds fall below this threshold, particularly in high-demand energy areas [2]. Despite Malaysia's limited wind potential, wind energy has become a major renewable resource worldwide. As of 2020, wind energy has been a growing source of renewable power, with hundreds of thousands of large turbines in wind farms generating over 650 GW of electricity, and 60 GW being added annually [3]. Wind turbines play a significant role in reducing energy costs and dependence on fossil fuels.

Among the various wind turbine designs, VAWTs are particularly notable. Unlike conventional turbines, where the main rotor shaft is positioned horizontally, VAWTs have a vertical rotor shaft, allowing them to harness wind energy from all directions. This eliminates the need for a yaw mechanism to adjust the turbine's position relative to the wind. VAWTs are especially beneficial in urban areas and locations with inconsistent or turbulent wind conditions, making them a viable option for decentralized renewable energy generation [4].

Different configurations of VAWTs have been developed, with the Darrieus and Savonius models being among the most extensively researched. The Darrieus turbine utilizes lift-based aerodynamic principles, enabling it to generate higher power output. In contrast, the Savonius turbine depends on differential drag forces acting on its curved blades, making it more suitable for low wind speed conditions. However, its relatively low efficiency limits its wider application [5-7].

To overcome some of the limitations of traditional Savonius turbines, researchers have developed modifications such as the Helix Savonius Wind Turbine shown in Fig. 1, which enhances efficiency through a twisted blade design. Conventional Savonius turbines utilize semi-cylindrical blades that rely on drag forces to capture wind energy, making them well-suited for low wind speeds and turbulent conditions, albeit with lower efficiency. The helical modification introduces a twisted blade design, creating a smooth, continuous curve along the blade's length, which helps improve aerodynamic efficiency and overall performance [8, 9].

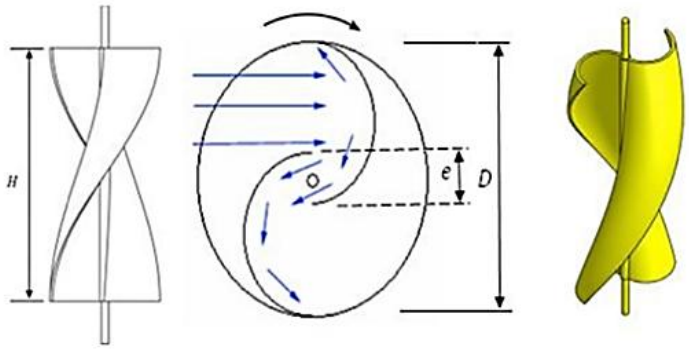


**Fig. 1. Helical Savonius style VAWT [10].**

Integrating wind and solar energy into a hybrid system offers a promising solution to address the intermittent challenges inherent in renewable energy sources. Such systems combine photovoltaic (PV) panels and wind turbines, providing a more stable and reliable power supply by leveraging the complementary nature of these energy sources [11, 12]. While solar energy generation peaks during sunny daytime hours, wind energy can contribute during evenings, overcast conditions, or periods of higher wind activity, thereby enhancing overall energy efficiency and reducing dependence on fossil fuels.

In Malaysia, despite generally low wind speeds, certain coastal and highland regions, as well as offshore locations, have sufficient wind activity to support small and medium-scale wind power generation. By strategically positioning wind turbines in these areas, hybrid systems can take advantage of localized wind resources while maximizing the benefits of Malaysia's high solar potential. Studies on hybrid solar-wind microgrids have shown that such systems can significantly enhance the energy mix in remote communities, reducing dependence on diesel generators and lowering operational costs [13-15].

Table 1 presents a summary of recent studies, highlighting the potential of hybrid VAWT and PV systems to improve overall energy efficiency and enhance energy reliability, especially in variable weather conditions and urban environments [16-22]. Existing research has evaluated the benefits of combining wind and solar energy, including the use of Internet of Things (IoT) based monitoring to enhance system reliability. Notably, this study introduces a novel aspect by integrating solar panels directly onto wind turbine blades, a design approach that has not been previously explored and offers a unique contribution to hybrid renewable energy solutions.

**Table 1. Summary of previous studies on hybrid systems [16-22].**

| Title | Source (Year) | Focus / Summary |
|---|---|---|
| Harnessing Energy from Solar PV-Wind Hybrids with Vertical Helical Savonius Turbines for Steady Power [16] | Springer (2025) | Integration of 100 W helical Savonius VAWT and 100 W solar PV using PWM controller. Reliable hybrid energy under variable weather, tested for 24V DC applications. |
| Generation of Electricity by Hybrid Mode of-Vertical Axis Wind Turbine With Solar Panel [17] | IRJET (2023) | Practical hybrid implementation with simple power management. Demonstrates feasibility in rural areas, basic energy support. |
| Solar Integrated Vertical Axis Wind Turbine: A Hybrid Approach [18] | IRJET (2025) | The VAWT is optimized using Flow Analysis to improve aerodynamic efficiency with IoT-based real-time monitoring. Enhances reliability compared to standalone systems. |
| Hybrid Power Generation Using | IJRES (2022) | Analyse the solar and wind characteristics and selecting a suitable location where both solar |

| | | |
|---|---|---|
| VAWT and Solar Panel [19] | | and wind energy are strong enough for hybrid power generation and choosing suitable wind turbine for this purpose. Cost-effective and low-maintenance solution. |
| Techno-economic Evaluation and Comparison of the Optimal PV/Wind and Grid Hybrid System with Horizontal and Vertical Axis Wind Turbines [20] | Renewable Energy Journal (2024) | Evaluates HAWT vs. VAWT in PV-wind-grid hybrid systems. VAWT shows promise in urban settings with lower wind speeds. |
| Design and Fabrication of Vertical Axis Windmill with Solar System [21] | Materials Today: Proceedings (2020) | Describes the fabrication process of a hybrid VAWT-PV prototype. Demonstrates mechanical integration and basic hybrid working. |
| Energy Harvesting Using Rooftops in Urban Areas: Estimating the Electricity Generation Potential of PV and Wind Turbines Considering the Surrounding Environment [22] | Energy and Buildings (2024) | Assesses urban rooftop PV and VAWT potential using GIS & CFD. Urban wind and solar harvesting are feasible. |

Placing solar panels on wind turbine blades is a way to combine two energy systems into one compact design. Normally, solar panels and wind turbines are installed separately, requiring more space and complex setups. This design mounts solar panels directly onto the blades of a VAWT, making better use of space and simplifying the installation process. This approach involves a specific structural arrangement and a carefully designed mounting strategy to ensure the solar panels are securely attached without affecting the turbine's performance. Environmental data, such as wind speed and solar irradiance, are validated to ensure the system performs well under real-world conditions.

Overall, integrating solar panels into VAWT blades offers a cost effective, space saving, and easy to deploy hybrid system, ideal for regions with moderate wind and consistent solar irradiance. With appropriate planning, infrastructure investment, and policy support, hybrid solar-wind technology can play a vital role in Malaysia’s renewable energy landscape, supporting the country’s transition towards a more sustainable and diversified energy system.

## 3. Methodology

This study employed a mixed-methods approach to thoroughly evaluate the performance of an innovative hybrid renewable energy system that integrates a VAWT with solar panels. The system is designed to generate electricity from both wind and solar energy, ensuring a reliable and sustainable power supply. The wind energy is converted into rotational energy by the turbine and subsequently into

electrical energy via a generator. Similarly, solar energy is harnessed through photovoltaic cells, which convert sunlight into electricity. The generated energy is regulated by a charge controller to prevent battery overcharging, ensuring reliable storage and supply to the connected load. The system is designed with a two-way capability, allowing it to function using either wind or solar energy independently. This mitigates the challenges posed by variability in natural energy sources.

The VAWT illustrated in Fig. 2 is designed with a compact cylindrical shape, measuring 82.2 cm in height and 24.3 cm in base diameter, making it suitable for small-scale energy applications. It is constructed from Polylactic Acid (PLA), a lightweight yet robust material commonly used in 3D printing, ensuring both durability and efficiency. The turbine comprises three blade sections. Its helical blade arrangement enables efficient wind energy capture from multiple directions while reducing torque fluctuations. This design enhances its adaptability for residential and remote locations, with the potential for integration into solar-assisted systems to maximize energy generation. A high-power brushless direct current (DC) motor with bidirectional rotation capabilities is used as the wind turbine's generator, ensuring efficient electricity generation even at low wind speeds.

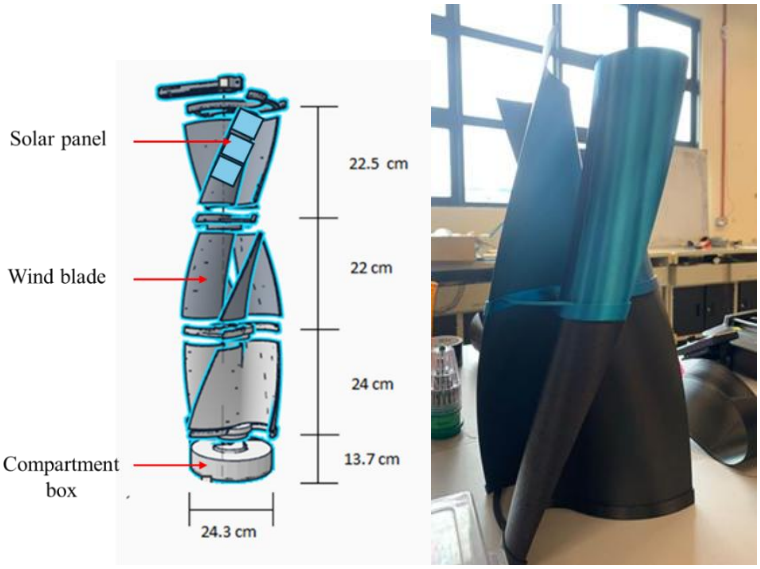


**Fig. 2. Design of VAWT.**

A DC-DC converter regulated the power output, while a compact monocrystalline solar cell panel rated at 5 V, 1 W, with dimensions of 55 x 60 mm, served as a reliable source of solar energy. The solar panel are mounted directly on the wind blade using adhesive and connected in series between each solar panel. To facilitate energy transfer, the solar panels are connected via slip rings to the central hub of the turbine. This allows the electrical energy generated by the solar panels to be transferred to the charge controller without interfering with the turbine's rotation. The energy flow is efficiently managed by a DC 12V/24V pulse width modulation (PWM) solar charge controller, ensuring optimal battery charging and controlled energy distribution to the connected load. The DC motor,

battery, and other components are securely placed inside a compartment box to protect them from potential damage during the measurement process.

The experimental setup involved installing the VAWT and solar panel in an open environment to optimize wind and solar energy capture. The instruments like anemometers and irradiance meter are used to measure wind speed and solar irradiance, respectively. Additionally, a multimeter and clamp meter are utilized to accurately measure the output voltage and current respectively, ensuring comprehensive data collection for performance evaluation. The study involves an evaluation of the performance of a VAWT and a solar panel hybrid system under varying inclination and tilt angles.

The experimental setup included a VAWT mounted on a pole with adjustable inclination angles (90° for vertical and 60° for inclined) and a solar panel configured at tilt angles of 45°, 60°, and 80°. Performance data for the VAWT, including rotor speed, voltage, current, and power output, are recorded at different wind speeds using an anemometer for wind speed measurement.

Similarly, the solar panel's performance metrics, such as voltage and current, and power output, are measured under varying levels of solar irradiance. The complete setup is prepared for testing, measurement, and data collection by securing the prototype to a pole with height from the ground is 1.5 m as shown in Fig. 3.

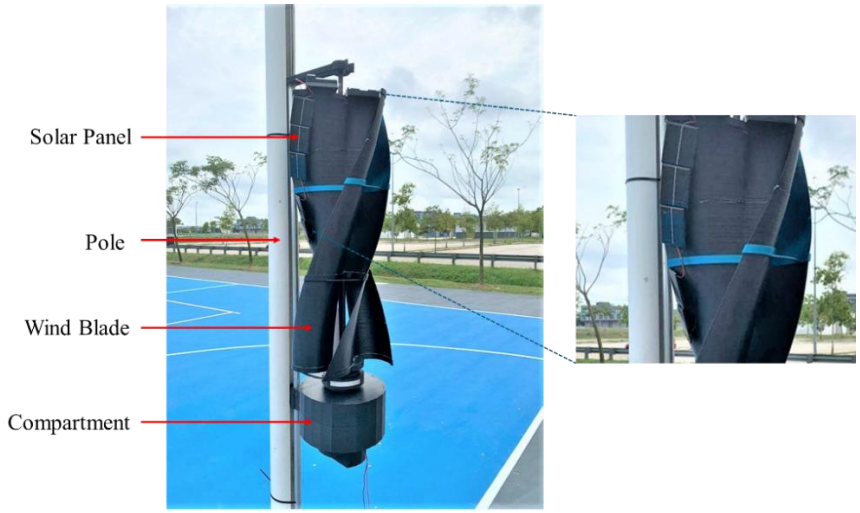


**Fig. 3. Complete setup for hybrid solar and VAWT system including zoomed-in view of the solar panel mounted on the wind blade.**

This methodology provides a comprehensive framework for evaluating hybrid renewable energy systems. By addressing the integration of wind and solar technologies, it offers valuable insights into the optimization of such systems in equatorial regions like Malaysia, where renewable energy resources are abundant but underutilized. The findings aim to contribute to the development of sustainable and efficient energy solutions, supporting global efforts to transition toward renewable energy adoption.

## 4. Results and Discussion

Initially, the angles for each source are adjusted and measured, as their performance is significantly affected by weather conditions, as well as the inclination of the wind turbine and the tilt angle of the solar panel. The measurements are conducted at angles of 45°, 60°, and 80° to identify the optimal tilt for solar panels to achieve maximum voltage and current generation. Additionally, the inclination angle of the wind turbine is evaluated to determine the position that generates the highest rotational force under varying wind conditions.

### 4.1. Analysis of solar panel titled

The solar panel's performance is tested to analyse the impact of tilt angle on its efficiency, voltage consistency, and power output under varying irradiance conditions. Table 2 shows the analysis of the solar panel performance at different tilt angles of 45°, 60°, and 80°. The observation aligns with the theory that the tilt angle has a limited impact on solar panel performance in regions near the equator [23, 24]. Malaysia, situated between latitudes 1° and 7° North, benefits from consistent sunlight exposure throughout the year, making the effect of tilt angles less pronounced compared to regions with more seasonal variation in solar angles [25].

**Table 2. Result of solar panel at different titled angles.**

| Tilt Angle (°) | Irradiance (W/$m^2$) | Voltage (V) | Current (A) | Power (W) |
|---|---|---|---|---|
| **45** | 462 | 15.42 | 0.20 | 3.08 |
| | 509 | 15.44 | 0.25 | 3.86 |
| | 650 | 15.47 | 0.25 | 3.87 |
| | 765 | 15.48 | 0.30 | 4.64 |
| | 827 | 15.47 | 0.30 | 4.64 |
| **60** | 303 | 15.46 | 0.10 | 1.55 |
| | 401 | 15.42 | 0.10 | 1.54 |
| | 506 | 15.45 | 0.15 | 2.32 |
| | 512 | 15.41 | 0.15 | 2.32 |
| | 616 | 15.44 | 0.20 | 3.08 |
| **80** | 351 | 15.08 | 0.15 | 2.26 |
| | 439 | 15.43 | 0.20 | 3.08 |
| | 510 | 15.44 | 0.20 | 3.09 |
| | 613 | 15.44 | 0.30 | 4.63 |
| | 645 | 15.45 | 0.30 | 4.64 |

Voltage data recorded at different tilt angles, as highlighted in Table 2, demonstrate minimal variation in irradiance, confirming that solar panels can produce electricity effectively even in a vertical position alongside a wind turbine. The data demonstrates the relationship between the tilt angle of solar panels and their performance in terms of irradiance, voltage, current, and power output. At a tilt angle of 45°, irradiance values range from 462 W/m² to 827 W/m², with voltage remaining stable between 15.42 V and 15.48 V. This stability in voltage indicates that solar panels maintain consistent voltage output regardless of variations in irradiance [26].

As irradiance increases, current rises from 0.20 A to 0.30 A, resulting in higher power output, which peaks at 4.64 W. At a 60° tilt angle, irradiance levels are generally lower, ranging from 303 W/m² to 616 W/m², while voltage remains consistent around 15.41–15.46 V. Current values range from 0.10 A to 0.20 A, leading to reduced power output compared to 45°. At 80°, irradiance ranges from 351 W/m² to 645 W/m², and voltage remains stable between 15.08 V and 15.45 V. Current increases proportionally with irradiance [27, 28], ranging from 0.15 A to 0.30 A.

Overall, the results reveal that voltage remains relatively unaffected by changes in tilt angle, while current and power output are strongly correlated with irradiance. The highest power output is achieved at a tilt angle of 45° with maximum irradiance, suggesting this angle is optimal under the tested conditions. However, the consistent voltage and reasonable current values across 60° and 80° indicate that variations in tilt angle have a minimal impact on performance. This finding supports the practicality of fixed installations in regions like Malaysia, where high levels of solar irradiance ensure efficient performance across a range of tilt angles [23, 24].

From this analysis, it also can be concluded that the tilt angle of solar panels in Malaysia has a minimal impact on their efficiency due to the country's near-equatorial location. Research by Nageh et al. [29] shows that adjusting PV module tilt monthly or seasonally increases energy output by only 1.59 % to 7.24 %. The consistent of solar irradiance throughout the year ensures that fixed-angle solar panels perform almost as well as those with optimized tilt angles. This supports the broader adoption of solar energy in the region without the need for complex and costly adjustable tilt mechanisms.

## 4.2. Analysis of wind turbine inclination angle

The experiments for VAWT are conducted to assess its ability to generate power at low wind speeds, its starting torque, and rotational stability under vertical and inclined configurations. Data from both systems are analysed to identify trends, evaluate the relationship between environmental conditions and system performance, and validate findings. The results as shown in Table 3 are used to provide recommendations for optimal system configurations in equatorial regions, emphasizing practical solutions for addressing challenges such as starting torque for inclined VAWTs and efficiency loss in solar panels at non-optimal tilt angles.

The data illustrates the impact of inclination angle and wind speed on the performance parameters of a wind turbine, including rotor speed, voltage, current, and power output. At a vertical inclination of 90°, the turbine demonstrates operation across a range of wind speeds, starting as low as 1.6 m/s with a rotor speed of 34.713 rpm and a power output of 0.50 W. As wind speed increases, the rotor speed, voltage, and current all rise, culminating in a power output of 4.98 W at a wind speed of 2.9 m/s and a rotor speed of 102.44 rpm. This indicates that a vertical configuration enables the turbine to generate electricity even at relatively low wind speeds.

In contrast, at an inclined angle of 60°, the turbine fails to generate power at wind speeds of 1.8 m/s and 2.1 m/s, with recorded rotor speed, voltage, and current all at zero. This can be attributed to the increased difficulty in overcoming starting torque at an inclined position, which restricts the turbine's ability to initiate rotation in low wind conditions. However, at higher wind speeds, such as 3.2 m/s and above, the

turbine begins to operate effectively, with a rotor speed of 74.507 rpm at 3.2 m/s and a peak rotor speed of 135.90 rpm at 4.3 m/s, producing a power output of 15.52 W.

The comparison reveals that a vertical configuration (90°) demonstrates significantly better performance, particularly at lower wind speeds, due to enhanced starting torque, rotational stability, and the ability to operate effectively in varied wind conditions. This finding is consistent with Pranavanand et al. [30], who highlighted that VAWT performs optimally in vertical orientations, offering stable and efficient energy generation even under fluctuating wind environments. On the other hand, the inclined configuration (60°) encounters limitations, such as reduced rotational force and stability at low wind speeds, though it can still provide satisfactory performance when wind speeds are higher. These observations underline the importance of maintaining a vertical orientation to maximize energy output and operational consistency.

**Table 3. Result of VAWT at different inclination angles.**

| Inclination Angle (°) | Wind Speed (m/s) | Rotor Speed (rpm) | Voltage (V) | Current (A) | Power (W) |
|---|---|---|---|---|---|
| **90** | 1.6 | 34.713 | 3.47 | 0.50 | 1.74 |
| | 1.8 | 95.728 | 5.36 | 0.51 | 2.73 |
| | 2.0 | 37.737 | 8.45 | 0.52 | 4.39 |
| | 2.6 | 53.228 | 9.41 | 0.53 | 4.98 |
| | 2.9 | 102.44 | 10.02 | 0.55 | 5.51 |
| **60** | 1.8 | 0 | 0 | 0 | 0 |
| | 2.1 | 0 | 0 | 0 | 0 |
| | 3.2 | 74.507 | 7.88 | 0.472 | 3.72 |
| | 3.9 | 108.26 | 11.04 | 0.449 | 4.96 |
| | 4.3 | 135.90 | 15.52 | 0.315 | 4.88 |

The integration of VAWTs with solar panels on turbine blades provides a novel approach to hybrid renewable energy systems, particularly when considering blade inclination and system configuration. Research by Morgan et al. [31] highlights the impact of blade inclination on VAWT performance, showing power gains of up to 71 % depending on blade length and aspect ratio. This supports the importance of optimizing blade inclination to maximize energy capture, aligning closely with the objectives of this study. These findings underscore the need to evaluate the aerodynamic characteristics of VAWTs under varying inclination angles, a core aspect of this research. This demonstrates the potential for innovative designs, like those presented in this study, to enhance hybrid system efficiency.

This research holds significant potential for practical applications, particularly in regions with abundant renewable energy resources, such as Malaysia and Southeast Asia. The hybrid system is uniquely suited for rural electrification, providing reliable power to remote areas with limited grid access. Urban retrofits are another promising application, as the system's space-saving design makes it adaptable to high-density environments.

Future extensions of this research include integrating energy storage systems and smart controllers to enhance energy efficiency and ensure seamless energy

management. Furthermore, an economic analysis and life-cycle assessment will be conducted to establish the cost-effectiveness and environmental sustainability of the system. Scaling up and deploying the system at real sites in Malaysia and Southeast Asia will provide valuable insights into its performance under local conditions, paving the way for broader adoption of this innovative technology.

## 5. Conclusions

This study demonstrates that optimizing the tilt angle of solar panels and the inclination angle of a VAWT significantly enhances the overall performance of a hybrid renewable energy system. The findings indicate that a 45° tilt angle maximizes solar panel efficiency by ensuring optimal sunlight exposure, while a 90° inclination for the VAWT enhances rotational force and energy generation under variable wind speeds. These results highlight the importance of system configuration in achieving stable and efficient power generation, particularly in equatorial regions like Malaysia. The insights gained from this study can inform future designs of hybrid renewable energy systems, promoting sustainable and reliable energy solutions for off-grid and urban applications. Further research could explore the integration of energy storage systems and advanced control strategies to optimize performance under fluctuating environmental conditions.

## Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through MDR (vot Q707).

**Abbreviations**

| | |
|---|---|
| IoT | Internet of Things |
| NEM | Net Energy Metering |
| NETR | National Energy Transition Roadmap |
| PLA | Polylactic Acid |
| PV | Photovoltaic |
| PWM | Pulse Walve Modulation |
| VAWT | Vertical Axis Wind Turbine |

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