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Performance Analysis of a Dual-Generation of Energy Using Hybrid Wind-Solar System

Muhammad Azizul Hakim Sazali[1], Mohd Anas Mohd Sabri[1,2,*], Wan Aizon W. Ghopa[1,2], Afnizam Abdullah[1], Ahmad Fadzil Shahrol[4], Mohd Asri Mat Teridi[3], Siddig A. Omer[5]

[1] Department of Mechanical & Manufacturing Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor Malaysia
[2] Centre for Automotive Research (CAR) Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor Malaysia, Malaysia
[3] Solar Energy Research Institute (SERI) Universiti Kebangsaan Malaysia, 43600, UKM Bangi, Selangor, Malaysia
[4] Energy Sustainability Focus Group (ESFG), Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[5] Institute of Sustainable Energy Technology, Department of Architecture and Built Environment, Faculty of Engineering, the University of Nottingham, in the United Kingdom

ABSTRACT

The demand for renewable energy technologies has surged due to the global energy transition and the push for decarbonization. This study explores the development of a Hybrid Renewable Energy System (HRES) combining solar and wind energy, focusing on selecting an optimal location in Malaysia based on available resources and analyzing its power generation and efficiency. A site study using anemometers and pyranometers was conducted from 8 am to 5 pm over five days, and SMath Studio was employed for mathematical modeling to determine average wind speed at varying heights, wind energy density, peak sun hours, and the optimal photovoltaic (PV) panel angle. The HRES, consisting of a Savonius turbine blade and a thin-film PV panel, was installed atop the Fakulti Kejuruteraan Alam Bina academic building. The wind turbine achieved an average power output of 0.2129 W, producing 5.11 Wh/day, while the PV panel generated 6.9083 W, yielding 43.45 Wh/day. Combined, the HRES produced 48.56 Wh/day with an efficiency of 7.02%. The findings demonstrate the suitability of the Savonius turbine for low wind speeds and the effectiveness of solar panels under high irradiance conditions. Although the system's overall efficiency was low, it successfully stabilized power output, determined optimal resource utilization, and provided valuable insights into hybrid energy generation. This study offers practical guidelines for developing dual renewable energy systems and advancing sustainable energy solutions.

Keywords:
Hybrid renewable energy system; wind turbine; photovoltaic panel; power generation

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1. Introduction

Renewable energy, derived sustainably from sources such as sunlight, wind, water, geothermal heat, ocean energy, biomass, biodiesel, and biogas, serves as a viable alternative to depleting non-renewable resources while mitigating the impacts of climate change [1]. Crucial for accelerating the

* *Corresponding author.*
E-mail address: anasms@ukm.edu.my

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global energy transition, meeting growing energy demands, and reducing environmental harm, renewable energy technologies have driven the development of hybrid systems that integrate wind turbines and photovoltaic panels. These systems optimize energy production by leveraging the complementary nature of wind and solar resources, ensuring a stable energy supply and reducing emissions, particularly in remote areas [2]. However, challenges such as the integration of multiple renewable sources and efficiency limitations remain significant barriers to widespread global adoption.

Hybrid solar-wind systems are integral to modern renewable energy strategies, combining the complementary energy profiles of solar and wind resources to enhance efficiency and reliability. These systems are particularly valuable in mitigating the intermittent nature of individual renewable sources, enabling consistent energy production across varying environmental conditions. Studies by Leon *et al.,* [3] and de Doile *et al.,* [4] emphasize their applications in both grid-connected and off-grid scenarios, supported by advancements in energy storage systems (ESS) like batteries and flywheels to ensure stability and reliability during peak and off-peak periods. Research highlights the optimization of system design, incorporating algorithms for sizing and operation to minimize costs and maximize energy output. Economic viability is a recurring theme, with regulatory frameworks and policies being crucial for integrating these systems effectively into existing energy grids. For instance, hybrid systems equipped with ESS can also provide ancillary services like load balancing and frequency regulation, enhancing grid performance while offering additional revenue streams.

Hybrid solar-wind energy systems have emerged as a critical area of study, integrating two prominent renewable energy sources to address global energy demands and sustainability challenges. Studies have explored the technical feasibility of such systems for specific applications, such as household setups and remote locations. For instance, Figaj *et al.,* [5] demonstrated the potential of a hybrid ground-solar-wind system to reduce energy dependency and achieve 68.6% electrical energy self-sufficiency, albeit with economic challenges, such as long payback periods. Additionally, Shavolkin [6] investigated grid-tied solar-wind systems enhanced by storage batteries, achieving a notable reduction in electricity costs and demonstrating seasonal variations in energy optimization. A key area of focus is the integration of energy storage technologies, which mitigate the challenges of renewable energy intermittency. For example, Shaahid and Ibrahim [7] explored hybrid system configurations utilizing battery storage and highlighted their potential to provide reliable power in remote areas.

Beyond technical design, studies like those by Li *et al.,* [8] emphasize robust optimization models to configure capacities of biogas-solar-wind systems for rural energy needs, demonstrating advancements in integrated energy solutions. These findings collectively underscore the transformative potential of hybrid solar-wind systems while outlining economic and technical challenges that necessitate further exploration and innovation. Furthermore, Sakti *et al.,* [9] explored the spatial integration of solar, wind, and hydropower potentials in Southeast Asia, showcasing how geographic information systems and regional assessments can enhance system planning.

In terms of addressing intermittency, Heidary *et al.,* [10] examined hybrid systems for powering desalination processes, revealing that solar-wind systems can provide consistent energy for such critical applications. Similarly, Ma *et al.,* [11] demonstrated the feasibility of a standalone solar-wind system with pumped hydro storage for remote islands, emphasizing the system's capacity to balance energy supply and demand over extended periods. Solar-wind hybrid systems also play a crucial role in advancing global renewable energy goals. Sabo *et al.,* [12] reviewed oscillation control methods for multi-machine systems, illustrating how these technologies stabilize grid integration amidst variability. Additionally, Lei *et al.,* [13] highlighted the co-benefits of integrating solar and wind energy within carbon-neutral strategies, emphasizing their impact on energy stability and environmental benefits.

Research from other researchers also highlights practical implementations and challenges. Researcher by Emeara *et al.,* [14] designed a hybrid wind-solar energy system tailored for rural residential buildings, focusing on cost-benefit analysis and system sustainability despite high initial costs. Additionally, Fadzli *et al.,* [15] examined a hybrid renewable energy system in Sungai Tiang Camp, Perak, using HOMER Pro for modeling, emphasizing economic and environmental performance while addressing rural energy access. Researcher by Mulyana and Rasidi [16] conducted a technical analysis of wind and solar hybrid systems, underlining the need for nonlinear control systems in regions with variable resources. Hybrid solar-wind systems also extend to specialized applications, as illustrated by Rachmanto *et al.,* [17] in the development of energy management systems for series-parallel hybrid solar vehicles. This innovation reduces fuel consumption by 30% compared to conventional vehicles, emphasizing the role of hybrid technologies in mobility solutions.

This study focuses on analyzing and improving hybrid renewable energy systems in Faculty of Engineering & Built Environment (FKAB), evaluating wind and solar resources, optimizing system performance, and assessing efficiency. Located at Universiti Kebangsaan Malaysia's FKAB, the study uses anemometers and pyranometers to measure wind speed and solar radiation, calculates optimal solar panel angles, and implements a hybrid system with Savonius wind turbines and thin-film photovoltaic panels. Data analysis aims to enhance system efficiency, providing insights for future green energy projects.

2. Methodology

The research methodology of this study is divided into two stages: site selection and performance evaluation of the wind-solar hybrid renewable energy system. The first stage involves careful site selection based on geographical conditions, climate, and potential energy sources. Comprehensive assessments ensure optimal results. The second stage involves an in-depth study of the system's performance at the selected site, aiming to gather data on efficiency and power generation. Various parameters are tested and analyzed to evaluate the system in real-world conditions. Figure 1 illustrates the process flowchart, showing steps for ensuring site suitability and measuring power generation and system efficiency.

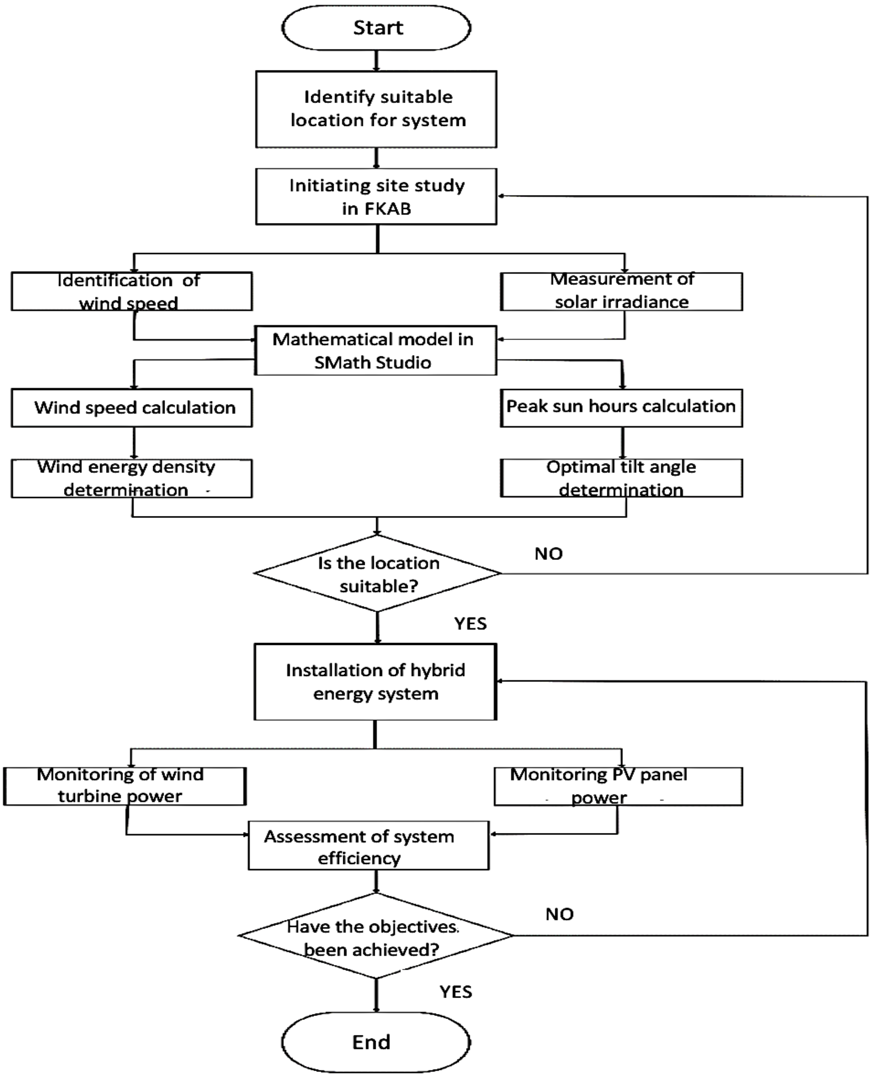


Fig. 1. Flow chart for this study

2.1 Site Study

A digital anemometer (Figure 2) was utilized in this study, beginning with steps such as checking the device's condition, selecting an open location, and setting measurement units. Wind speed data was collected hourly from 8 am to 5 pm for 5 days and recorded for further analysis. The average wind speed is calculated to evaluate the overall wind condition. This data is vital for classifying wind energy potential and estimating wind speeds at turbine blade heights [18]. Then, theory and formulas regarding the effects of height and surface roughness on wind speed were applied because the turbine blade is located at a height of 3.05 meters, where v is wind velocity, v_0 is wind velocity at 10 meters, H is height above sea level, H_0 is height at 10 meters, and α is surface roughness.

$$v = (v_0 \cdot \left(\frac{H}{H_0}\right))^{\alpha} \tag{1}$$

Daily wind energy density is then determined from the formula below, where ρ_{air} is air density, v_{avg} is average wind velocity, and t is time in hour.

$$E_{density} = \frac{1}{2} \cdot \rho_{air} \cdot {v_{avg}}^3 \cdot t \tag{2}$$

The first step in solar radiation measurement is selecting an appropriate location for placing the pyranometer, ensuring it is open and free from obstructions such as trees or buildings that could block sunlight. The pyranometer as shown in Figure 3 needs to be carefully calibrated before use to ensure accurate readings in W/m². Once calibrated, the pyranometer is securely installed, and solar irradiance data is consistently collected every hour from 8 am to 5 pm. Regular monitoring of the pyranometer is necessary to ensure proper functioning.

Fig. 2. Wind speed data record

Fig. 3. Solar irradiance data record

Peak sun hours, *PSH* are a crucial parameter used to determine the number of hours during which sunlight is sufficiently intense to be utilized in solar energy systems. This parameter is measured in hours and helps assess the potential use of photovoltaic panels at a specific location. Measurements are taken hourly using W/m² units to determine the available peak sun hours. This data is essential for calculating the potential energy output from photovoltaic panels and determining the required number of panels. Accurate calculation using the appropriate formula allows conversion from daily sunlight intensity to peak sun hours, which is vital for optimizing solar energy systems.

$$P.S.H = \frac{\Sigma\, Solar\ Irradiance\ \left(\frac{Wh}{m^2}\right)}{Benchmark\ \left(\frac{W}{m^2}\right)} \tag{3}$$

The optimum tilt angle is the most effective angle for installing photovoltaic panels based on the latitude of the location. This angle allows the panels to absorb sunlight to the maximum extent, enhancing efficiency in energy generation. By selecting the correct tilt angle, panels can absorb more sunlight directly and consistently, thereby producing more electrical energy from the sunlight [19].

$$\delta = 23.45 \sin(360° \cdot \frac{(n-81)}{365}) \tag{4}$$

$$\beta = 90° - L + \delta \tag{5}$$

$$tilt = 90° - \beta \tag{6}$$

2.2 System Study

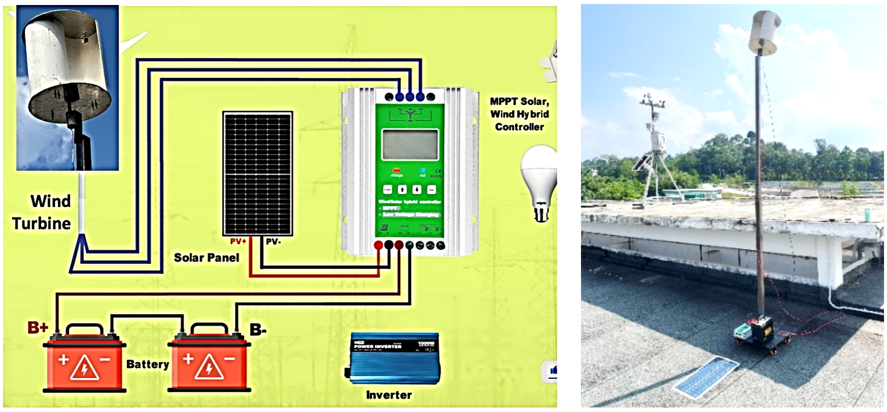
The Vertical Axis Wind Turbine (VAWT) as displayed in Figure 4 is selected for this research project due to its high efficiency at low wind speeds. VAWT can generate electricity from any wind direction because its blades rotate around a vertical axis, eliminating the need for wind direction adjustments.

The turbine design employs Savonius blade type known for its superior efficiency compared to Darrieus or H-Darrieus types at low wind speeds [20]. These turbine blades have a height of 0.4 meters and diameter of 0.3 meters, respectively. It was made of Polyvinyl Chloride (PVC) due to its lightweight nature, allowing the blades to rotate at low wind speeds. The widespread availability of PVC makes it easy to obtain at an affordable price compared to other turbine materials.

Fig. 4. Savonius turbine blade

To optimize the hybrid system, a VAWT turbine with adjustable caster wheels is selected to harness wind effectively and allow users to move it to better wind locations if needed. The turbine site dimensions are 500 mm in length, 250 mm in width, and 5 mm in thickness. Figure 5 shows the schematic diagram and the installation of the system. It is a tower design consist of wind turbine, photovoltaic panel, controller, battery and inverter. The tower design comprises three main sections: the base pole, middle pole, and top pole, ensuring portability. The combined height of the base and top poles is 3.05 meters, with varying slot holes and hole positions for each pole to facilitate easy movement and setup.

The study uses a 100 Watt thin-film photovoltaic panel (Figure 6), chosen for its lightweight and flexible nature, allowing installation on various surfaces, including roofs that cannot support heavier traditional panels [21]. A solar panel multimeter measures electrical parameters to ensure proper and efficient panel operation. It measures the open circuit voltage (V_{oc}), which is the maximum voltage produced when not connected to a load, and the operating voltage (V_{mp}). Additionally, it measures the short circuit current (I_{sc}), the maximum current produced when the panel terminals are shorted, to assess the panel's current generation capability [22].



(a) (b)

Fig. 5. Wind-solar system (a) Schematic diagram (b) The system installed at the roof top of FKAB

Wind turbines and photovoltaic panels send energy to a hybrid Maximum Power Point Tracker (MPPT) charge controller via PV+ (red) and PV- (black) wires as shown in Figure 7. The controller optimizes this energy, directing it to the batteries and load. Battery connections are labeled B+ (positive) and B- (negative). Wind turbines connect via blue wires, and solar panels via red and black wires. This setup ensures a continuous energy supply by managing the flow from both sources to charge the batteries. Turbine blades capture wind, rotate, and transfer motion through a gearbox to increase speed, driving a generator to produce electricity.

Fig. 6. Thin film photovoltaic panel

Fig. 7. MPPT charge controller

The power generated by a wind turbine is calculated using a specific formula as follows:

$$P_{turbine} = \frac{1}{2} \cdot \rho_{air} \cdot A_{turbine} \cdot {v_{avg}}^3 \quad (7)$$

The power generated by a photovoltaic panel depends on its surface area, sunlight intensity, and efficiency. A larger surface area collects more sunlight, while sunlight intensity varies with location, weather, and time of day. Panel efficiency is determined by the technology and materials used. This study uses a 100 Watt thin-film photovoltaic panel, which can absorb 100 Watts of solar energy, serving as a benchmark to compare input and generated power.

$$P_{panel} = A_{panel} \cdot G_{sun} \cdot \eta_{panel} \quad (8)$$

Wind turbine efficiency is the comparison between the electrical output power generated by the wind turbine and the wind energy received by the turbine. This parameter is crucial to measure how much wind energy is successfully converted into electrical energy, and it is an important factor in evaluating the performance and effectiveness of wind energy generation. The formula for wind turbine efficiency is:

$$\eta_{turbine} = \frac{P_{out\ turbine}}{P_{in\ turbine}} \times 100\% \quad (9)$$

The efficiency of a photovoltaic panel is similarly determined by comparing the electrical power generated by the panel to the solar energy received by the panel.

$$\eta_{pv} = \frac{P_{out\ pv}}{P_{in\ pv}} \times 100\% \quad (10)$$

In a hybrid system using wind turbines and photovoltaic panels, it is important to assess the overall system efficiency. This efficiency reflects how well the system converts received wind and solar energy into electrical energy. The formula to calculate system efficiency is:

$$\eta_{system} = \frac{P_{out\ turbine+pv}}{P_{in\ turbine+pv}} \times 100\% \tag{11}$$

By understanding and measuring this efficiency, we can determine how well wind and solar energy are converted into electrical energy, enabling improvements in the design and operation of wind turbines and photovoltaic panels. All analyses in this study have been modeled in Smath Studio software to facilitate calculations and reduce errors as shown in Figure 8.

Fig. 8. SMath Studio

3. Results

3.1 Wind Energy

Data on wind speed in meters per second was measured at a height of 46 meters above sea level at the FKAB building. The calculated average wind speed from this dataset is 2.83 ms^{-1} meters per second. The graph of wind velocity based on height is shown in Figure 9. It indicates that the higher the height of a location, the higher its wind velocity. This modelling is important for assessing the required height to achieve the desired wind velocity. From the relationship, the average wind speed at the turbine blade height, 49.5 meters, has been identified as 2.88 ms^{-1}.

The analysis of energy density per square meter at the location based on height is modelled in a graph like Figure 10. Similar to average wind speed, higher locations generally have higher energy density in the wind. This modelling is also essential for assessing the required height to obtain the necessary wind energy for power generation. From the relationship depicted in this graph, the average energy density at the blade height of the wind turbine, 49.5 meters, has been identified as 352.38 W/m^2 over a 24-hour period.

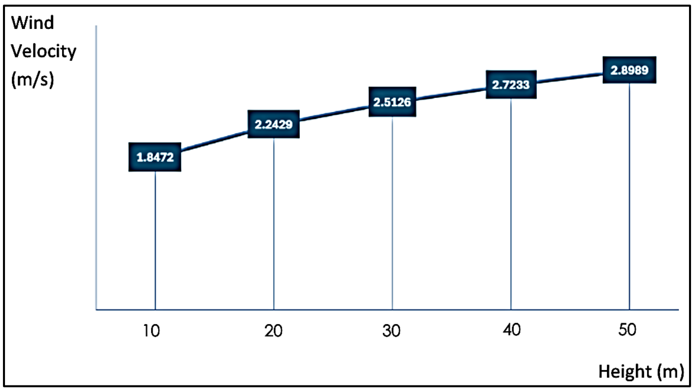


Fig. 9. Average wind velocity versus height of the location

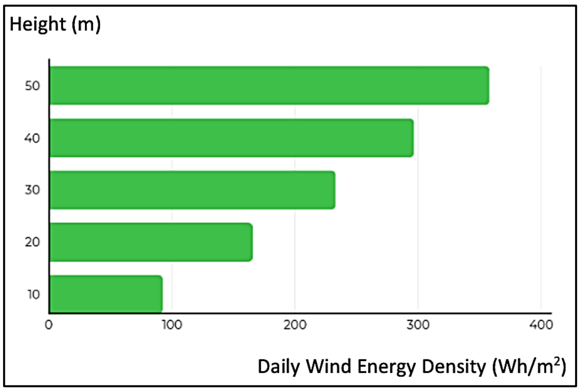


Fig. 10. Wind energy density versus height

3.2 Solar Energy

Data on solar irradiance in watts per square meter was measured on the roof of the FKAB building from 8 am to 5 pm over five straight days. This solar irradiance data was measured to determine the average daily solar irradiance, which is 6293.14W/m^2. Additionally, the average solar irradiance for each hour was also found for constructing a graph in Figure 11 to illustrate the solar irradiance conditions at the location each day. Theoretical calculations show 6.29 peak sunshine hours at this location, crucial for planning and optimizing solar energy systems. This data allows accurate estimates of daily energy generation, helping determine necessary energy storage capacity and planning energy usage to meet daily demands. It also aids in evaluating the system's effectiveness and efficiency. Overall, the 6.29 peak sunshine hours provide a solid foundation for developing an efficient solar energy system.

Figure 12 shows the optimum tilt angle at specific month throughout the year. The academic building location at the Faculty of Engineering and Built Environment (FKAB) has a latitude of 2.9198° North which influenced the optimum tilt angle for photovoltaic panels. It shows a decreasing trend from January to June, followed by an increasing trend from July to December. The maximum optimum tilt angle is 23.06° southward in January, while the minimum optimum tilt angle is 0° around mid-March and mid-September. The optimum tilt angle starts to become negative from mid-March to mid-September, meaning photovoltaic panels need to face the north due to the changing orientation of the Earth placing the location below the vertical line with the sun.

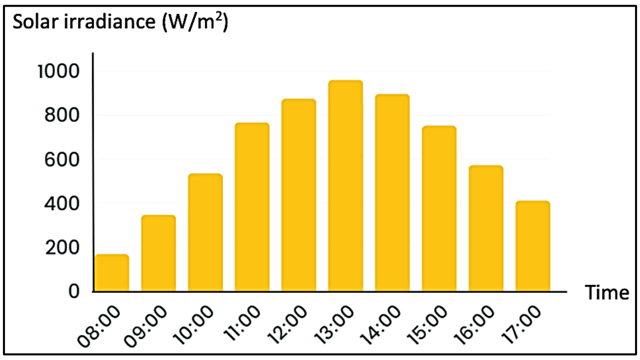


Fig. 11. Average solar irradiance at specific time

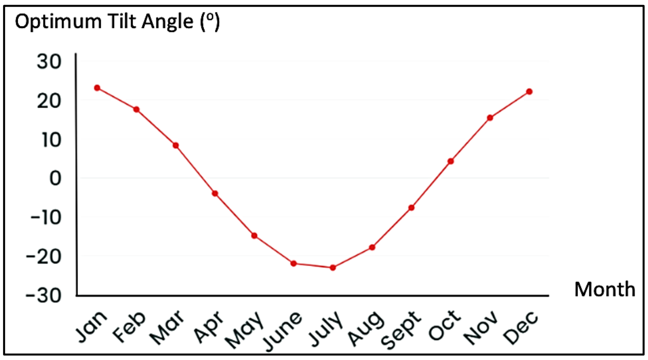


Fig. 12. Optimum tilt angle at specific month

3.3 Power Generated

Table 1 shows the average power generated identified from the average voltage and current on a specific day. Table 2 shows the daily energy calculated by multiplying the average power generated on a specific day by the total number of hours in a day, which is 24 hours. This calculation assumes the generated power is continuous throughout the day. Figure 13 illustrates the daily energy trend to show the range and variation in the energy generated by wind turbines on different days. From this depiction, it can be concluded that the energy generation by wind turbines is less consistent. Meanwhile Table 3 shows the average power generated identified from the average voltage and current on a specific day.

Table 1
Average wind turbine power

Day	1	2	3	4	5
Power (W)	0.1975	0.2067	0.1983	0.2129	0.2096

Table 2
Average wind turbine energy

Day	1	2	3	4	5
Energy (Wh)	4.74	4.96	4.76	5.11	5.03

Table 3
Average photovoltaic panel power

Day	1	2	3	4	5
Power (W)	6.9083	6.7782	6.7592	6.5706	6.8444

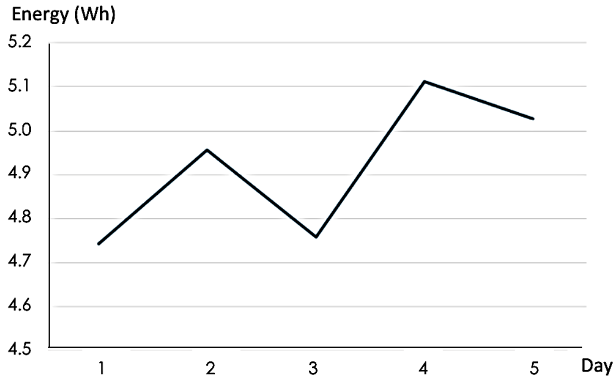


Fig. 13. Graph of wind turbine energy versus days

Table 4, on the other hand, shows the daily energy calculated by multiplying the average power generated on a specific day by the peak sunshine hours in a day, which is 6.29 hours. This calculation assumes that the generated power is continuous during daylight hours. Figure 14 illustrates the daily energy trend to observe the range and variation in the energy generated by photovoltaic panels on different days. From this depiction, it can be concluded that energy generation by photovoltaics is more consistent, although there is a noticeable drop on the fourth day.

Table 4
Average photovoltaic panel energy

Day	1	2	3	4	5
Energy (Wh)	43.45	42.63	42.52	41.33	43.05

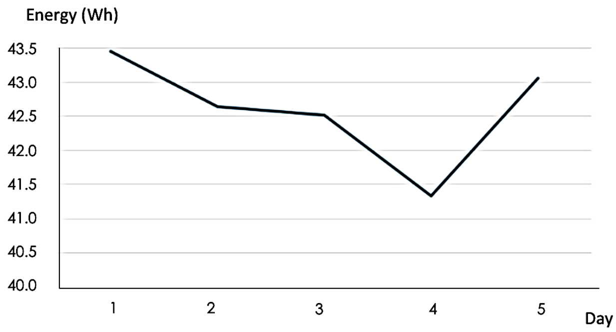


Fig. 14. Graph of photovoltaic energy versus day

3.4 Efficiency Analysis

Table 5 shows the wind turbine power and its efficiency. The actual wind power calculations involve the incoming power considering a wind speed of 2.88 ms^{-1}, blade area of 0.09 m^2, and air density of 1.225 kgm^{-3}. The identified wind power under these conditions is 1.32 Watt. Meanwhile, the maximum power generated by the wind turbine in this study is 0.21 Watt, obtained from the average highest current and voltage. This power is used as the output power. The calculation of the wind turbine efficiency shows an efficiency of 16.11%, which is within the range of Betz's Law but considered low due to significant deviation from the maximum theoretical efficiency of 0.59 [23].

Meanwhile Table 6 display the power and efficiency of photovoltaic panel. The actual solar power calculations refer to the amount of power absorbed by the photovoltaic panel at the location. Referring to sunlight levels exceeding 100 Watts during peak sunlight conditions, the absorbed power aligns with the panel's specification of 100 Watts. Meanwhile, the maximum power generated by the photovoltaic panel identified in this study is 6.91 Watts. This power is used as the output of the PV system. The identified efficiency of the photovoltaic panel is 6.91%. This efficiency is considered low due to significant deviation from the values obtained in previous studies.

Table 7 the combine power and efficiency of the system. The Savonius wind turbine in this study generates 0.21 W, while the photovoltaic panel produces 6.91 W. The total power generated by both systems is 7.12 W. This calculation shows that the photovoltaic panel contributes more to the total generated power, which is typical as wind turbines often have lower efficiency in low wind speed conditions. To understand the true efficiency of the system, the total input power also needs consideration. The wind turbine receives an input power of 1.32 W based on wind speed, blade area, and air density at the study location. Conversely, the photovoltaic panel receives an input power of 100 W, based on its technical specifications. Therefore, the total input power for the system is 101.32 W.

Table 5
Wind turbine power and efficiency

Power input	Power output	Efficiency
1.32 W	0.21 W	16.11%

Table 6
Photovoltaic panel power and efficiency

Power input	Power output	Efficiency
100 W	6.91 W	6.91%

Table 7
System power and efficiency

Power input	Power output	Efficiency
101.32 W	7.12 W	7.02%

The overall efficiency of the hybrid system can be calculated by dividing the total power output by the total input power. Based on this calculation, the overall efficiency of the system is 7.02%. While this value appears low compared to theoretical maximum efficiencies such as Betz's Law for wind turbines or maximum efficiency of photovoltaic panels, it still demonstrates the effectiveness of the system in combining both energy sources.

4. Conclusions

The project successfully achieved its objectives through a systematic approach and thorough literature review, contributing to technological advancement. Firstly, the study at FKAB effectively analysed wind speed and solar radiation, providing valuable insights into the site's renewable energy potential. Secondly, implementing a hybrid renewable energy system demonstrated feasibility based on specific location criteria, setting a precedent for future installations. Thirdly, the study highlighted the hybrid system's capability to produce renewable energy despite challenges like manual data collection and weather variability by measuring power generation and assessing system efficiency. To enhance efficiency, recommendations include adopting IoT for automated data collection, implementing weather protection measures, conducting regular maintenance, and ensuring sufficient resources for uninterrupted operation. Overall, while technological progress is evident, addressing practical challenges is crucial for improving system performance and promoting sustainable energy development.

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