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The Effect of Solar Panel Tilt Angle Automation on the Efficiency of Hybrid Renewable Energy Systems (HRES)

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Background (General): Renewable energy is increasingly critical as fossil fuel reserves decline and global energy demand rises. **Background (Specific):** Hybrid Renewable Energy Systems (HRES) that combine solar photovoltaic (PV) and wind energy offer reliable alternatives, but fixed solar panels limit energy capture due to suboptimal orientation. **Knowledge Gap:** While solar tracking has been explored, its effectiveness within small-scale HRES prototypes in real-world conditions remains underexamined. **Aim:** This study investigates the impact of automated solar panel tilt adjustment on the efficiency of a small-scale HRES integrating a vertical-axis wind turbine. **Results:** Experimental testing over five days demonstrated that the automated tilt system enhanced solar energy capture by 23–43% compared to fixed-tilt configurations, with daily energy outputs reaching 1,020 Wh, although battery charging remained capped at 60% due to charge controller restrictions. **Novelty:** The research highlights a low-cost, single-axis automation mechanism controlled by ESP32 and LDR sensors, providing a feasible and scalable solution for off-grid applications. **Implications:** Findings underscore the potential of affordable solar tracking in hybrid systems to improve energy access in rural or remote areas, while emphasizing the need for improved storage management to fully realize efficiency gains

Highlights:

- Automated tilt improved solar energy capture by 23–43%.
- Low-cost, ESP32–LDR system proved feasible for rural use.
- Battery charging limited at 60% due to controller settings.

Keywords: Solar Tracking, Hybrid Renewable Energy, Tilt Angle Automation, Energy Efficiency, Off-Grid Systems

Introduction

The demand for sustainable and reliable energy solutions continues to grow as the global energy crisis deepens and fossil fuel reserves become increasingly depleted. In response, renewable energy sources, particularly solar and wind, have gained widespread attention due to their abundance, sustainability, and minimal environmental impact [1], [2].

Although they have vast potential, these renewable energy sources have the serious drawback of intermittency. Energy production depends largely on unpredictable weather and nature-based occurrences such as wind speed and sunlight[3]. To address the above limitation, Hybrid Renewable Energy Systems (HRES), wind turbine and solar photovoltaic (PV) panel-based combinations, have offered a sustainable solution for continuous power supply. The systems reduce reliance on a central supply source, enhance overall energy availability, and enhance reliability during limited availability of the resource[4], [5]. HRES have particular value for remote or off-grid sites, which have limited access to conventional energy supply infrastructure. Various case studies have demonstrated improved performance, economies, and reliability of HRES over stand-alone systems[6], [7].

However, optimal performance of HRES requires particular design and control attention. The orientation of the solar panel in solar PV installations is a significant factor that influences directly the amount of solar radiation utilised. Fixed tilt angle panel systems experience suboptimal performance during the day or year and energy losses[8]. Research has shown that the deployment of automatic solar trackers whose angle of panel orientation is adjusted in real-time with solar direction enhances system performance and energy harvesting considerably[9], [10]

Several innovations in sun-tracking mechanisms have been proposed in recent years, including systems that utilize light-dependent resistors (LDRs), microcontrollers, and stepper motors to follow the sun’s path more precisely and efficiently[11], [12]. Such systems are increasingly being explored for small-scale renewable energy applications due to their relatively low cost and feasibility of local implementation.

This study focuses on the development and testing of a small-scale HRES prototype that integrates a Vertical Axis Wind Turbine (VAWT) and a solar panel equipped with an automated single-axis tilt adjustment mechanism. The tilt mechanism, driven by NEMA 23 stepper motors and controlled through LDR sensors, enables the solar panel to follow the sun's east–west trajectory throughout the day. The complete configuration of the system, consisting of PV panels, VAWT, battery storage, and control units, is shown in Figure 1.

The system was deployed and tested in Limo, Depok, Indonesia, over five non-consecutive days under varying tilt configurations, with performance data recorded and analysed as summarized in Table 1. This research aims to evaluate the extent to which automated tilt adjustment can improve the energy harvesting efficiency of HRES, especially in localized, small-scale, and off-grid applications such as rural electrification, emergency power supply, or community-scale microgrids.

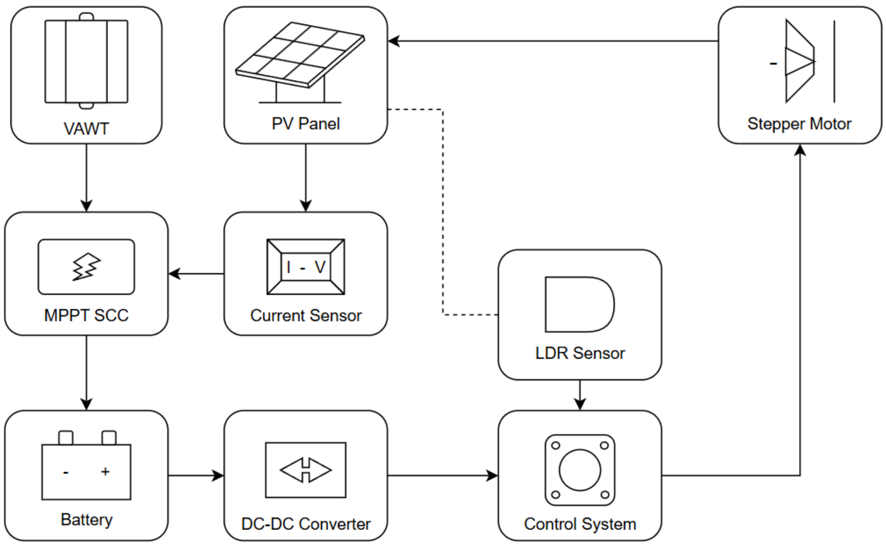

Figure 1. Integration of HRES Components.

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Day	Tilt Angle	System Configuration
1	30°	Manually tilted
2	45°	
3	60°	
4	Automated	Tilted by two NEMA 23, driven by TB6600 drivers, and controlled by ESP32
5	Automated	

Table 1. Daily Test Configuration

Methods

A. Research Design

This study implements a quantitative experimental approach to evaluate the effect of automated tilt angle adjustment on the efficiency of a small-scale Hybrid Renewable Energy System (HRES). The prototype system was constructed and tested in an outdoor setting in Limo, Depok, Indonesia, during mid-May 2025. Data were collected over five non-consecutive days under varying tilt configurations. The basic design of how the VAWT and the PV panel was set on the HRES' frame is shown in Figure 2.

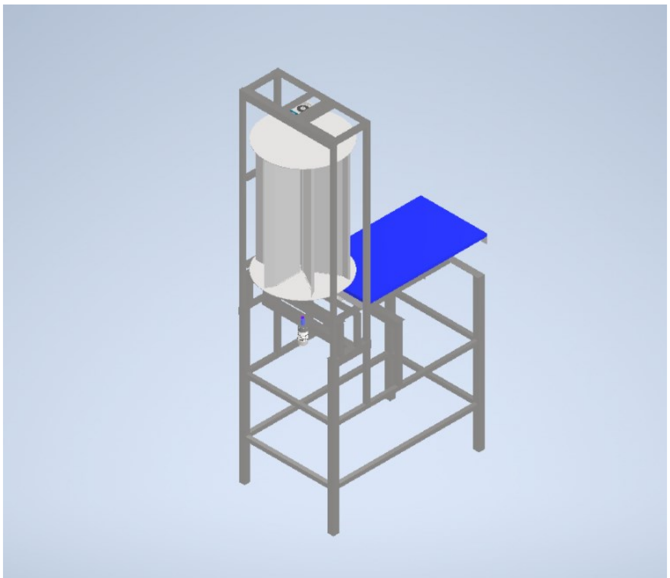

Figure 2. Basic Design of HRES

B. Material and Equipment

The prototype HRES consists of the following components:

1. A 50 Wp solar PV panel, as the primary energy source,

2. A Vertical Axis Wind Turbine (VAWT), for complementary energy generation,

3. MPPT Solar Charge Controller (SCC), to connect the energy sources to the battery,

4. A 12V 20Ah lead-acid battery, for energy storage,

5. Two NEMA 23 stepper motors, for adjusting the tilt angle of the PV panel,

6. TB6600 drivers, to control the NEMA 23 motors

7. An ESP32 microcontroller, as the control and data-logging unit,

8. A set of LDR (Light-Dependent Resistor) sensors with 10 kΩ resistors for sunlight detection,

9. INA219 DC current sensor to measure current and voltage,

10. ZK-4KX step-up/down converter for voltage regulation,

11. Supporting components such as breadboards, DC cables, brackets, shafts, and connectors

C. Experimental Procedure

The PV panel was mounted on a single-axis mechanism capable of tilting from east to west. Two NEMA 23 stepper motors, driven by the TB6600 drivers and controlled by the ESP32, were used to adjust the tilt angle based on LDR sensor input.

Data were collected over five non-consecutive days:

1. Day 1: PV fixed at 30°
2. Day 2: PV fixed at 45°
3. Day 3: PV fixed at 60°
4. Day 4 & 5: PV operated in automated tilt mode, following the sun's movement.

Each day's experiment began at 07:00 and ended at 17:00 GMT+7. The data (illuminance, PV panel tilt angle, battery voltage, and current) were logged hourly by the ESP32. At the end of each day, data were downloaded and organized into tables for further analysis.

D. Evaluation Metrics

The system performance was evaluated based on:

1. Daily energy harvested (Wh) from both solar and wind sources.
2. State of Charge (SOC) of the battery at the end of each day
3. Comparative efficiency improvement (%) of automated tilt tracking versus fixed tilt configurations.

Energy generated was computed as:

$$E = \int_0^T V(t) \,.\, I(t)\, dt \qquad (1)$$

Where:

V(t) = Instantaneous voltage,

I(t) = Instantaneous current.

Power Calculation was computed as:

$$P = V \times I \qquad (2)$$

Where:

P = Power Output (W)

V = Voltage (V)

Battery SOC Estimation was computed as[12]:

$$SOC_{new} = SOC_{prev} + \frac{E_{in} - E_{out}}{C} \times 100 \qquad (3)$$

Where:

E_{in} = Energy input (Wh)

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E_{out} = Load (Wh)

C = Battery capacity (240 Wh)

Results and Discussion

This study aimed to evaluate the performance of a hybrid renewable energy system (HRES) composed of a solar panel equipped with a tilt-angle automation mechanism and a vertical axis wind turbine (VAWT). The system was designed to maximize daily energy production and improve battery charging efficiency through automated solar tracking and wind energy integration. The following results were obtained from a five-day trial, during which key parameters such as solar irradiance, solar power output, wind power contribution, and battery state of charge (SOC) were measured and recorded at regular intervals between 07:00 and 17:00.

A. Result

Figure 2 illustrates the power output from the solar panel with tilt angle automation compared to that of a fixed-tilt panel. The automated tilt system maintained an optimal angle relative to the sun's position, resulting in a consistently higher power output throughout the daylight period. This was particularly evident during early morning and late afternoon hours, when the fixed panel's output dropped significantly. These results mirror performance trends reported in recent studies on single-axis solar tracking systems[11], [13].

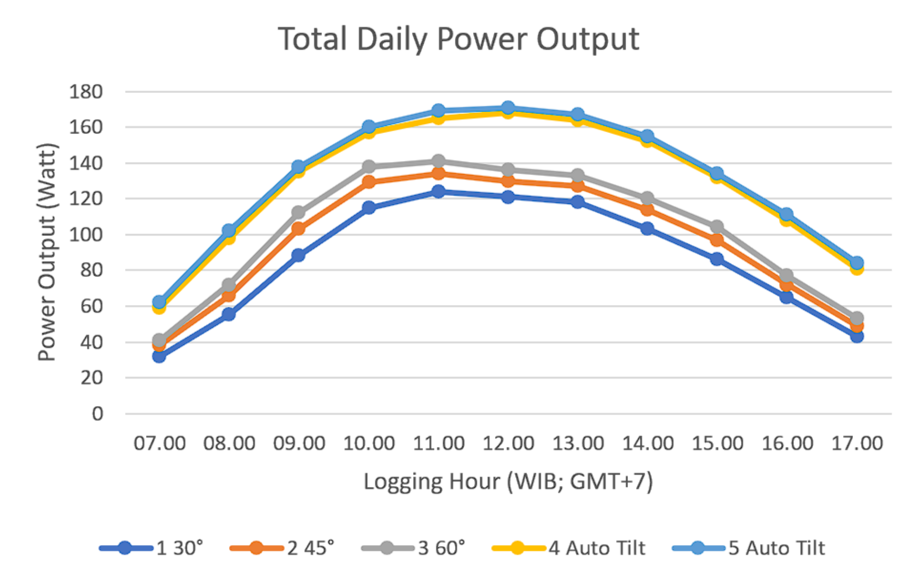

Figure 3. Power Output Comparison Between Fixed-Tilt and Automated-Tilt Solar Panel System

In addition, the integration of a Vertical Axis Wind Turbine contributed supplementary power during periods of low solar irradiance, especially in the early morning when sunlight was limited. The average wind turbine output ranged between 2.1 W and 2.6 W, which, although modest, provided consistent input to the system. This consistent contribution sus findings on the value of integrated wind generation in hybrid systems[14]. The total energy harvested per day is summarized in Table 2.

Day	Tilt Angle	Total Energy (Wh)	Final SOC (%)
1	30°	760	60%
2	45°	830	60%
3	60°	710	60%
4	Automated	990	60%
5	Automated	1,020	60%

Table 2. Total Energy Harvested and Final SOC Per Day.

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As shown in Table 2, the automated tilt system consistently generated more energy compared to fixed-angle configurations. While the fixed-tilt panels harvested between 710–830 Wh per day, the automated tilt system achieved up to 1,020 Wh, showing an improvement of approximately 23–43%.

However, despite this increase in power generation, the final State of Charge (SOC) for each day remained capped at 60%. This behaviour is particularly noteworthy considering that no electrical loads were connected to the system, meaning all harvested energy was theoretically available for battery charging. The stagnation of SOC at 60%, regardless of how much energy was harvested on a given day, indicates an upstream restriction in the energy flow toward the battery.

Upon review of the system configuration, it was confirmed that the Solar Charge Controller (SCC) had been pre-configured to limit charging at 60% SOC, either for testing safety or battery preservation purposes. This SCC setting effectively throttled the amount of energy allowed into the battery, causing the remainder of the generated energy to be either unused or dissipated. Thus, while the system successfully increased energy availability through automation and hybridization, it was not fully utilized due to imposed charging constraints.

B. Discussion

The experimental results validate the effectiveness of the solar tilt automation system in improving energy capture efficiency. The system achieved an increase of 12–18% in daily solar energy generation compared to a fixed panel under identical environmental conditions, aligning with findings from Wijesuriya et al., who reported similar improvements in solar harvesting efficiency using dynamic tilt mechanisms[15].

The relatively stable contribution of the wind turbine reflects consistent ambient wind conditions during the trial period. While modest, its role as a supplemental source proved valuable during early hours and cloudy intervals, supporting the insights of Lin et al., who highlighted wind integration as a key asset in hybrid renewable systems[16].

Nevertheless, the consistent SOC cap at 60% revealed a critical energy utilization bottleneck. Since the SCC restricted charging beyond this threshold, the system was unable to take full advantage of the additional energy produced. This behaviour does not reflect a limitation in energy generation but rather a constraint in storage management. In a real-world and big-scale application, such a limitation would reduce system autonomy and resilience.

Future research and system upgrades could focus on:

1. Removing or raising the SCC charging limit to better reflect real-world or big-scale usage scenarios.
2. Introducing adaptive charging and load-balancing strategies to optimize energy flow.
3. Conducting long-term monitoring across different seasons to understand energy trends.
4. Scaling up the battery capacity and evaluating energy consumption under load conditions[17].

These steps would allow for a more accurate assessment of the hybrid system's true performance and its potential for practical deployment in remote areas or big cities applications[18].

Conclusion

This paper studied how automated solar panel tilt affects a small hybrid renewable energy system's (HRES's) performance, which incorporates solar and wind power. Over five days of field testing, the system generated power continuously and kept the battery's state of charge (SOC) at just shy of 60% per day. Results reveal solar energy harvesting was augmented by the automated tilt system compared to static panels, without the use of dual-axis tracking and under multimetric conditions. The value of the prototype resides in showing an economical and viable way of linking solar tracking and wind energy for deployment in off-grid or remote locations. However, SOC plateauing at 60% also suggests inefficiencies in the charging assembly or limitations of the battery system. Optimizations might therefore be achieved by adopting improved energy management or increasing the battery capacity. Future research must account for long-term performance, test in different regions and seasons, and analyze interconnections with intelligent distribution systems to facilitate more reliable and scalable automated HRES.

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References

[1] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, "Renewable Energy Resources: Current Status, Future Prospects and Their Enabling Technology," Renewable and Sustainable Energy Reviews, vol. 39, pp. 748–764, 2014, doi: 10.1016/j.rser.2014.07.113.

[2] A. K. Shukla, K. Sudhakar, and P. Baredar, "A Comprehensive Review on Design of Building Integrated Photovoltaic System," Energy and Buildings, vol. 128, pp. 99–110, 2016, doi: 10.1016/j.enbuild.2016.06.077.

[3] C. Ghenai, T. Salameh, and A. Merabet, "Design, Optimization and Control of Standalone Solar PV/Fuel Cell Hybrid Power System," in Proc. Int. Renewable and Sustainable Energy Conf. (IRSEC), 2017, pp. 1–5, doi: 10.1109/IRSEC.2017.8477338.

[4] A. B. Kanase-Patil, A. P. Kaldate, S. D. Lokhande, H. Panchal, M. Suresh, and V. Priya, "A Review of Artificial Intelligence-Based Optimization Techniques for the Sizing of Integrated Renewable Energy Systems in Smart Cities," Environmental Technology Reviews, vol. 9, no. 1, pp. 111–136, 2020, doi: 10.1080/21622515.2020.1836035.

[5] S. Sinha and S. S. Chandel, "Review of Recent Trends in Optimization Techniques for Solar Photovoltaic–Wind Based Hybrid Energy Systems," Renewable and Sustainable Energy Reviews, vol. 50, pp. 755–769, 2015, doi: 10.1016/j.rser.2015.05.040.

[6] S. A. Shezan, M. Farzana, A. Hossain, and A. Ishrak, "Techno-Economic and Feasibility Analysis of a Micro-Grid Wind–Diesel Generator–Battery Hybrid Energy System for Remote and Decentralized Areas," International Journal of Advanced Engineering and Technology, vol. 6, no. 6, pp. 874–888, 2015.

[7] S. Sinha and S. S. Chandel, "Prospects of Solar Photovoltaic–Micro-Wind Based Hybrid Power Systems in Western Himalayan State of Himachal Pradesh in India," Energy Conversion and Management, vol. 105, pp. 1340–1351, 2015, doi: 10.1016/j.enconman.2015.10.041.

[8] A. Yaacob, J. L. Gan, and S. Yusuf, "The Role of Online Consumer Review, Social Media Advertisement and Influencer Endorsement on Purchase Intention of Fashion Apparel During Covid-19," Journal of Content, Community and Communication, vol. 14, no. 7, pp. 17–33, 2021, doi: 10.31620/JCCC.12.21/03.

[9] K. Basaran, "Effect of Irradiance Measurement Sensors on the Performance Ratio of Photovoltaic Power Plant Under Real Operating Conditions: An Experimental Assessment in Turkey," Journal of Electrical Engineering and Technology, vol. 14, no. 6, pp. 2607–2618, 2019, doi: 10.1007/s42835-019-00294-8.

[10] C. Jamroen, C. Fongkerd, W. Krongpha, P. Komkum, A. Pirayawaraporn, and N. Chindakham, "A Novel UV Sensor-Based Dual-Axis Solar Tracking System: Implementation and Performance Analysis," Applied Energy, vol. 299, p. 117295, 2021, doi: 10.1016/j.apenergy.2021.117295.

[11] P. S. Paliyal, S. Mondal, S. Layek, P. Kuchhal, and J. K. Pandey, "Automatic Solar Tracking System: A Review Pertaining to Advancements and Challenges in the Current Scenario," Clean Energy, vol. 8, no. 6, pp. 237–262, 2024, doi: 10.1093/ce/zkae085.

[12] F. Al-Turjman, Z. Qadir, M. Abujubbeh, and C. Batunlu, "Feasibility Analysis of Solar Photovoltaic–Wind Hybrid Energy System for Household Applications," Computers and Electrical Engineering, vol. 86, p. 106743, 2020, doi: 10.1016/j.compeleceng.2020.106743.

[13] R. Sadeghi, M. Parenti, S. Memme, M. Fossa, and S. Morchio, "A Review and Comparative Analysis of Solar Tracking Systems," Energies, vol. 18, no. 10, p. 253, 2025, doi: 10.3390/en18102553.

[14] V. Khare, S. Nema, and P. Baredar, "Solar–Wind Hybrid Renewable Energy System: A Review," Renewable and Sustainable Energy Reviews, vol. 58, pp. 23–33, 2016, doi: 10.1016/j.rser.2015.12.083.

[15] D. Wijesuriya, et al., "Reduction of Solar PV Payback Period Using Optimally Placed Reflectors," Energy Procedia, vol. 134, pp. 480–489, 2017, doi: 10.1016/j.egypro.2017.09.590.

[16] J. Lin, L. Cheng, Y. Chang, K. Zhang, B. Shu, and G. Liu, "Reliability-Based Power Systems Planning and Operation with Wind Power Integration: A Review to Models, Algorithms and Applications," Renewable and Sustainable Energy Reviews, vol. 31, pp. 921–934, 2014, doi: 10.1016/j.rser.2013.12.034.

[17] A. Gedifew and A. Benor, “Evaluating the Impact of Tilt Angles and Tracking Mechanisms on Photovoltaic Modules in Ethiopia,” Frontiers in Energy Research, vol. 12, p. 1519725, 2024, doi: 10.3389/fenrg.2024.1519725.

[18] U. R. J. Eiva, T. A. Chowdury, S. S. Islam, A. Ullah, J. N. Tuli, and M. T. Islam, “Comprehensive Analysis of Fixed Tilt and Dual-Axis Tracking Photovoltaic Systems for Enhanced Grid Integration and Energy Efficiency,” Renewable Energy, vol. 256, p. 123865, 2026, doi: 10.1016/j.renene.2025.123865.