

AI MEETS SOLAR: SMART DUAL-AXIS TRACKING FOR SUSTAINABLE ENERGY AND SOCIAL WELL-BEING

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ABSTRACT

The rising global demand for clean and renewable energy necessitates innovations that improve solar photovoltaic (PV) system efficiency. This study presents the development of AI Meets Solar, a smart dual-axis solar tracker integrating artificial intelligence and fuzzy logic control to optimize panel orientation in real time. The system employs an ESP32 microcontroller, four Light Dependent Resistors (LDRs) in a quadrant configuration, and two high-torque servo motors to continuously align the panel with the sun's position. AI algorithms enable adaptive decision-making, enhancing responsiveness to changing weather and light conditions. Experimental results show a 14% efficiency improvement compared to fixed systems, demonstrating the effectiveness of combining mechanical motion with intelligent control. Beyond technical gains, the research aligns with Islamic principles of environmental stewardship (*hifz al-bi'ah*) and public benefit (*maṣlaḥah*), contributing to sustainable energy use and social well-being. The findings highlight the potential of AI-powered solar tracking as both a technological innovation and an ethical approach to addressing future energy challenges.

Keywords: Dual-Axis Solar Tracker, Artificial Intelligence, Renewable Energy, Environmental Stewardship, Social Well-Being

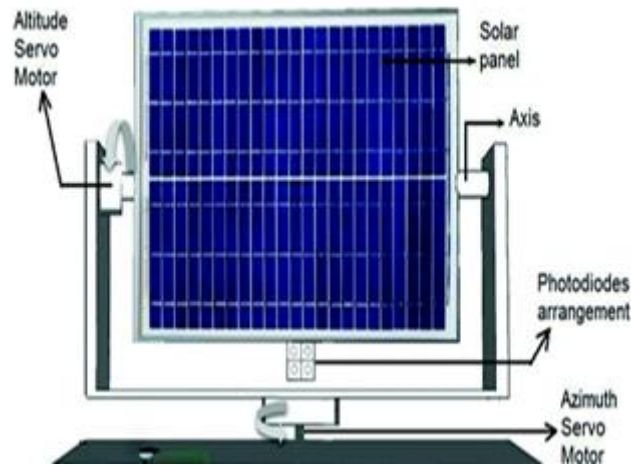
BACKGROUND

The rising demand for clean and renewable energy has intensified the need for efficient solar energy systems (Idris et al., 2024). While solar photovoltaic (PV) systems have gained global traction, their efficiency is often limited by static positioning (Hamad et al., 2020; M. Shyamalagowri et al., 2025). Dual-axis solar trackers, which follow the sun's trajectory throughout the day, offer a significant boost in energy capture compared to fixed systems (Gbadamosi, 2021; Wong et al., 2024). However, traditional control methods are often limited in adaptability and responsiveness (Tahtah & Zahzouh, 2025).

Recent developments in artificial intelligence (AI) and IoT technologies provide promising opportunities to optimize mechanical systems through smart control (Karve et al., n.d.). In mechanical engineering, the integration of AI into renewable energy systems can lead to self-optimizing, responsive, and efficient solutions (Babars et al., n.d.).

This study addresses the inefficiencies in solar tracking by developing a smart, AI-enhanced dual-axis tracking system. The research aims to investigate how AI-based decision-making can improve energy output. The key contribution lies in combining mechanical motion systems with intelligent control, offering sustainable and adaptive solutions for future energy challenges. Additionally, this study incorporates a pyranometer to measure solar irradiance — a tool that is rarely utilized in similar research, yet crucial for accurately evaluating the efficiency of solar panels under varying environmental conditions.

From an Islamic perspective, the pursuit of clean and sustainable energy aligns with the Qur'anic principles of *khilafah* (stewardship) and *amanah* (trust), which call upon humanity to safeguard the Earth's resources for the benefit of current and future generations (Ilhami et al., n.d.)(Susanto, 2024). The development of environmentally friendly technologies, such as AI-powered solar tracking, is not merely a technical innovation but also a moral responsibility to preserve the environment, reduce ecological harm, and promote social well-being(Pemanfaatan Sains Dan Teknologi Anas Suprpto, 2023). By embedding these values into engineering practice, this research contributes to a more ethical and holistic approach to addressing the world's energy needs while ensuring a resilient and sustainable future (Syaiful Alim et al., n.d.).



Picture 1. Solar Tracker Dula-Axis. (Gaeid et al., 2020a)

A dual-axis solar tracker is a system that moves solar panels in two directions—horizontal (azimuth) and vertical (elevation)—to follow the sun's path throughout the day and year. This design keeps panels facing the sun at the optimal angle, maximizing energy capture compared to fixed or single-axis systems. Dual-axis trackers often use sensors (LDRs), with motors controlled by microcontrollers (ESP32) to adjust both axes in real time (Gaeid et al., 2020b). They are ideal for applications where maximum efficiency is needed, though they require more components, maintenance, and cost than simpler trackers (Indra Rizkiyanto et al., n.d.-a).

RESEARCH METHOD

This research employed a quantitative experimental method using a prototype system built around the ESP32 microcontroller, integrated with two high-torque servo motors and four Light Dependent Resistors (LDRs) arranged in a quadrant configuration. These LDRs detect variations in light intensity from different directions. The system was programmed to compute the illumination differences between the sensors and actuate the servo motors to reorient the panel toward the highest solar intensity, optimizing its alignment throughout the day.

To improve the intelligence of the tracking mechanism, a basic AI algorithm combining fuzzy logic control and reinforcement learning principles was implemented. Fuzzy logic was used to handle imprecise inputs and provide smooth motor commands based on the light differential values, while reinforcement learning was applied to iteratively minimize positioning errors by adjusting the fuzzy rules over time.

1. Microcontroller ESP32

The ESP32 is an intelligent microcontroller with a fast processor, built-in Wi-Fi and Bluetooth connectivity, and numerous analog and digital input/output pins, making it highly suitable for solar tracker systems (Agustian et al., 2025). In a solar tracking application, the ESP32 reads light sensor data such as LDRs to detect differences in sunlight intensity across four quadrants

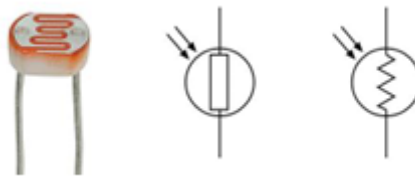
of the panel, then controls motors on the horizontal and vertical axes to keep the panel perpendicular to the sun's rays, or calculates the sun's position based on time, date, and location using astronomical algorithms. This integration enables the ESP32 to function not only as a controller but also as a central hub for monitoring and recording solar panel performance efficiently and cost-effectively (Aezwani et al., 2024).



Picture 2. ESP32 Module. (Kocer et al., 2021)

2. Light Dependent Resistors (LDR)

An LDR (Light Dependent Resistor) is a light-sensitive sensor whose resistance decreases as light increases. In solar trackers, four LDRs arranged in a quadrant with a central shade detect the sun's position by comparing light levels. The ESP32 reads these values via its ADC and drives motors to align the panel for maximum sunlight. LDRs are low-cost, easy to use, and energy-efficient, but require protection and calibration for consistent performance.



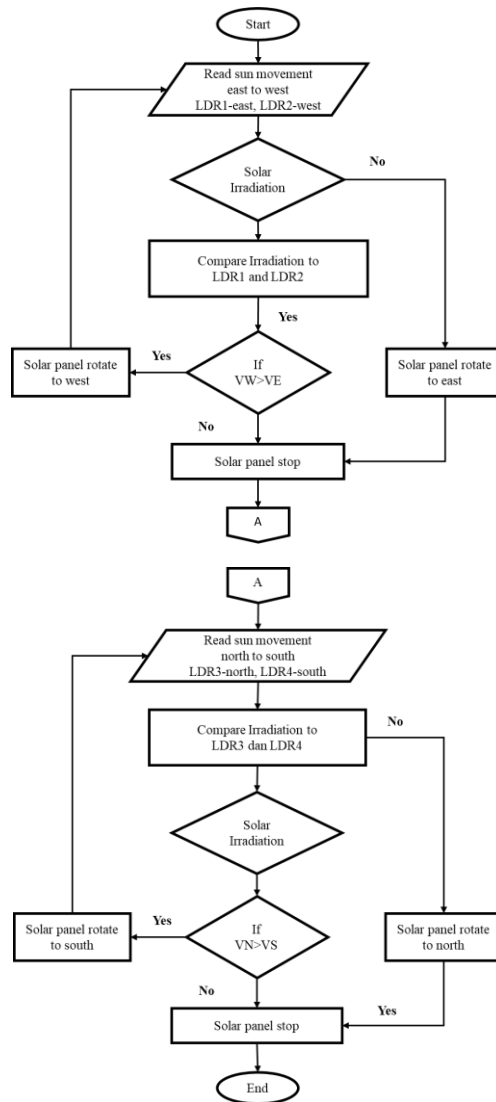
Picture 3. Sensor LDRs and Symbol. (Jadhav et al., 2022)

3. Fuzzy Logic

Fuzzy logic is a control method that uses approximate reasoning to mimic human decision-making. In solar trackers, it processes sensor inputs like LDR readings to adjust panel movement using flexible rules, allowing smooth and adaptive tracking under varying conditions such as clouds or shading, thus improving accuracy and efficiency (Indra Rizkianto, Suprianto, and Wanarti Rusimamto n.d.) (Nugraha et al., n.d.-b).

4. Flowchart System Solar Tracker Dual-Axis

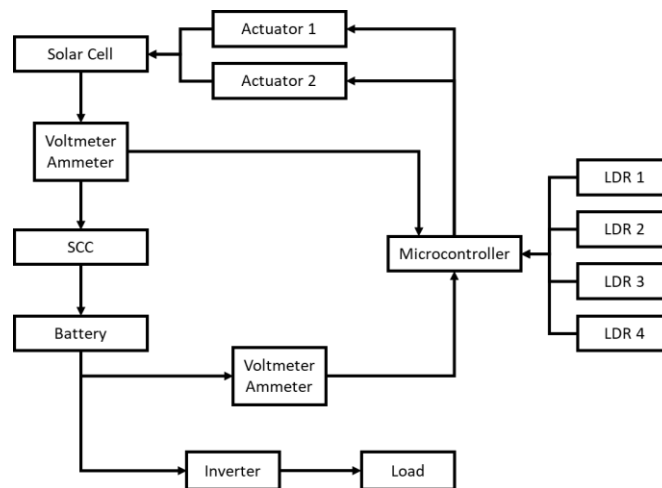
A flowchart for a dual-axis solar tracker system typically illustrates the sequence of operations from sensor reading to motor control. It generally includes these steps:



Picture 4. Flowchart System

5. Diagram Block Solar Tracker Dual-Axis

A block diagram is a basic representation of a system to be designed. From the block diagram below, the functions of the equipment used in the solar tracker design can be identified, showing how the system operates until it is ready for use.



Picture 5. Diagram Block

6. Design Solar Tracker Dual-Axis



Picture 6. Design Solar Tracker Dual-Axis

7. Experimental System Work

A dual-axis solar tracker operates by adjusting a solar panel's position along two axes—azimuth (horizontal rotation) and elevation (vertical tilt)—to keep it facing the sun at the optimal angle throughout the day and year. The system typically uses four Light Dependent Resistors (LDRs) arranged in a quadrant configuration with a small vertical and horizontal divider. As sunlight hits the sensors, the microcontroller (e.g., ESP32) reads the light intensity from each LDR through its analog-to-digital converter (ADC). By comparing the left-right and top-bottom readings, the system determines the sun's direction.

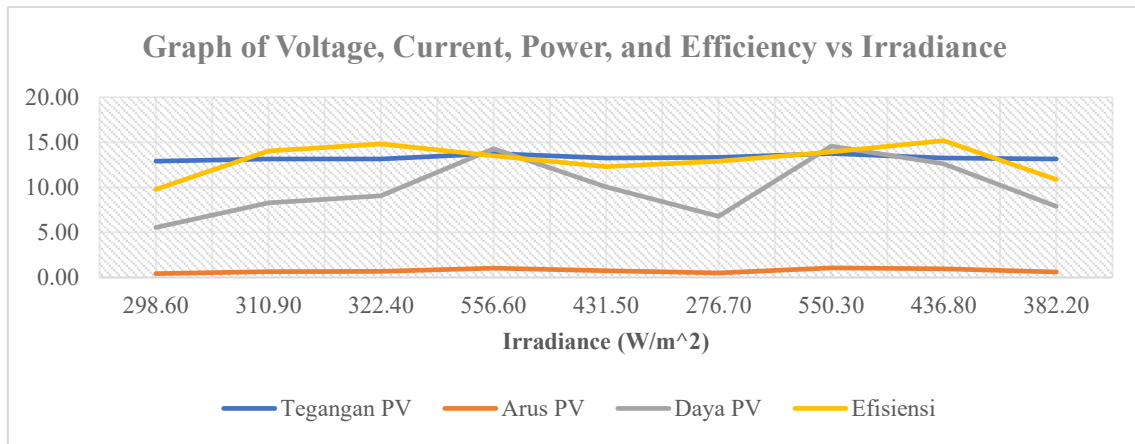
If the light intensity is higher on one side, the controller activates the appropriate motor—stepper or DC—to rotate the panel either horizontally or vertically until the readings from opposing sensors are balanced. This process runs continuously, allowing the tracker to respond to the sun's movement and changes in light conditions, such as clouds or shading. In advanced designs, artificial intelligence or fuzzy logic is integrated to improve decision-making, reduce unnecessary movement, and adapt to environmental variations, thus maximizing energy output and operational efficiency.



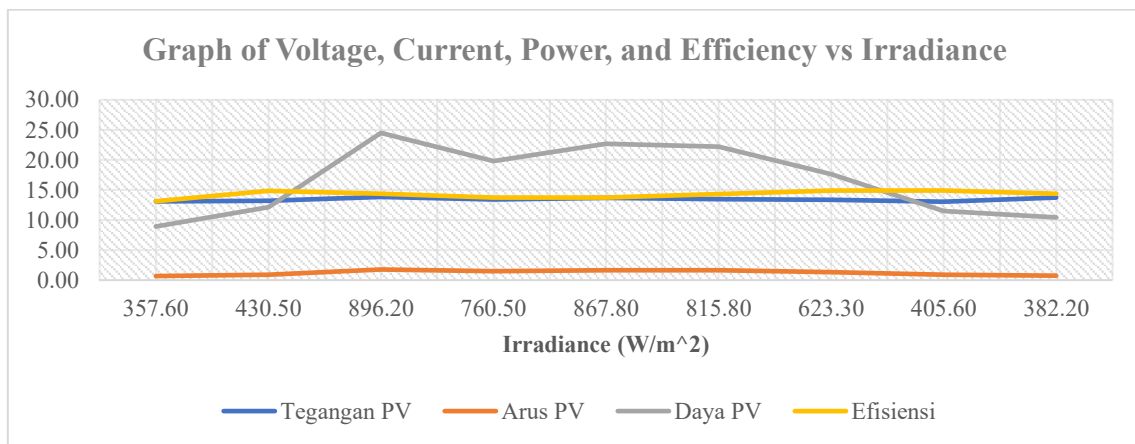
Picture 7. Solar Panel with Solar Tracker Dual-Axis

RESEARCH FINDINGS

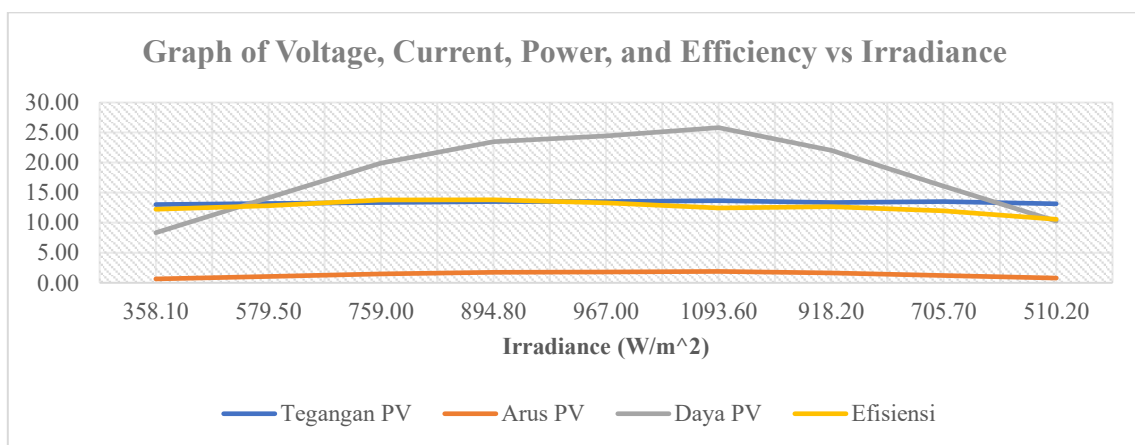
The experimental investigation on *AI Meets Solar: Smart Dual-Axis Tracking for Sustainable Energy and Social Well-being* was carried out using a solar panel integrated with an AI-based dual-axis solar tracker. The testing was conducted over a period of three consecutive days to evaluate the system's performance in real outdoor conditions. The collected data provide insights into voltage, current, power output, efficiency, and energy generation, which are then compared with the behavior of a conventional fixed solar panel.



(a)

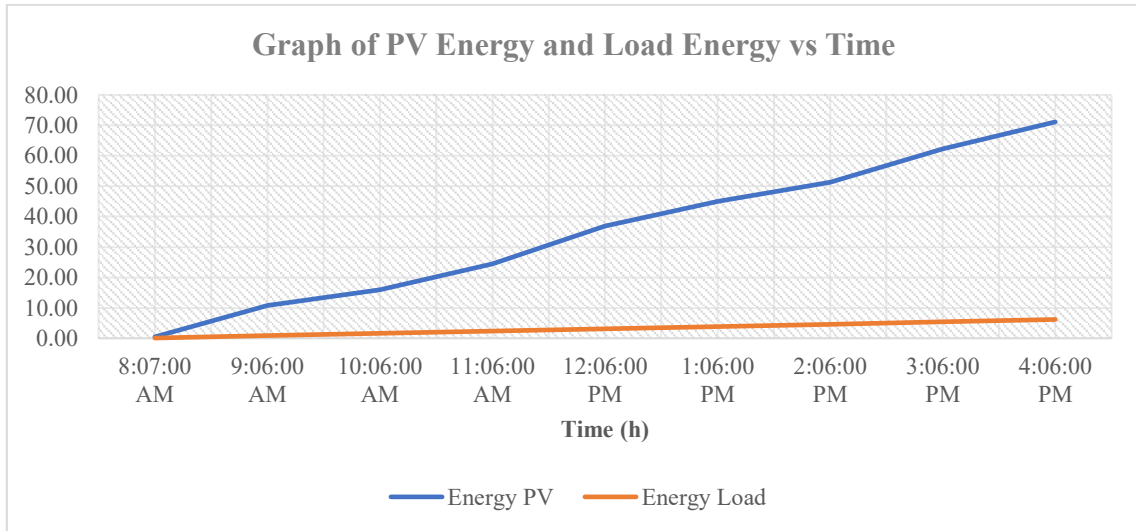


(b)

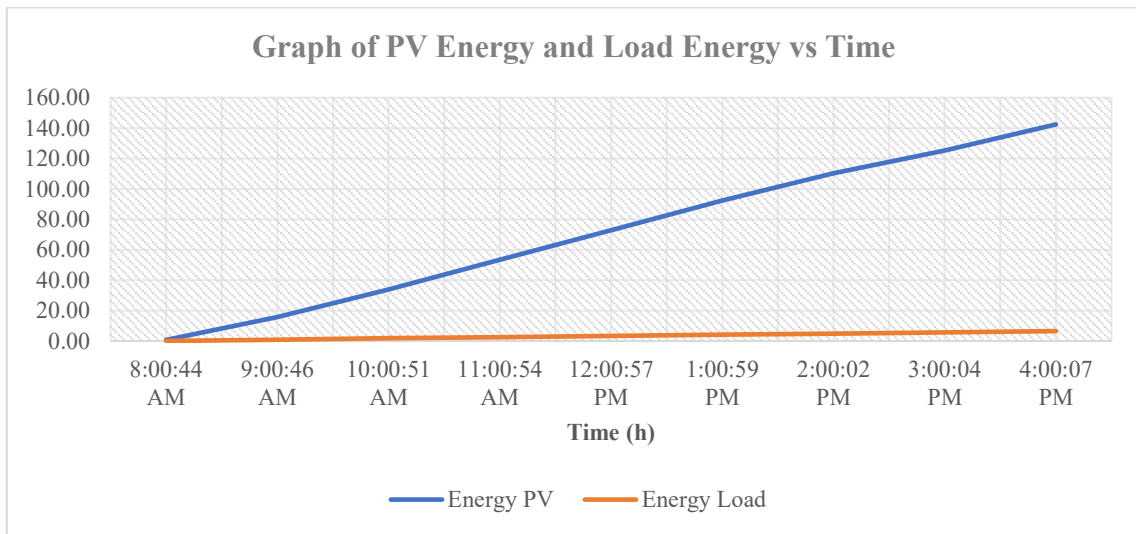


Picture 8. Graph of Voltage, Current, Power and Efficiency vs Irradiance (a) day-1, (b) day-2, (c) day-3

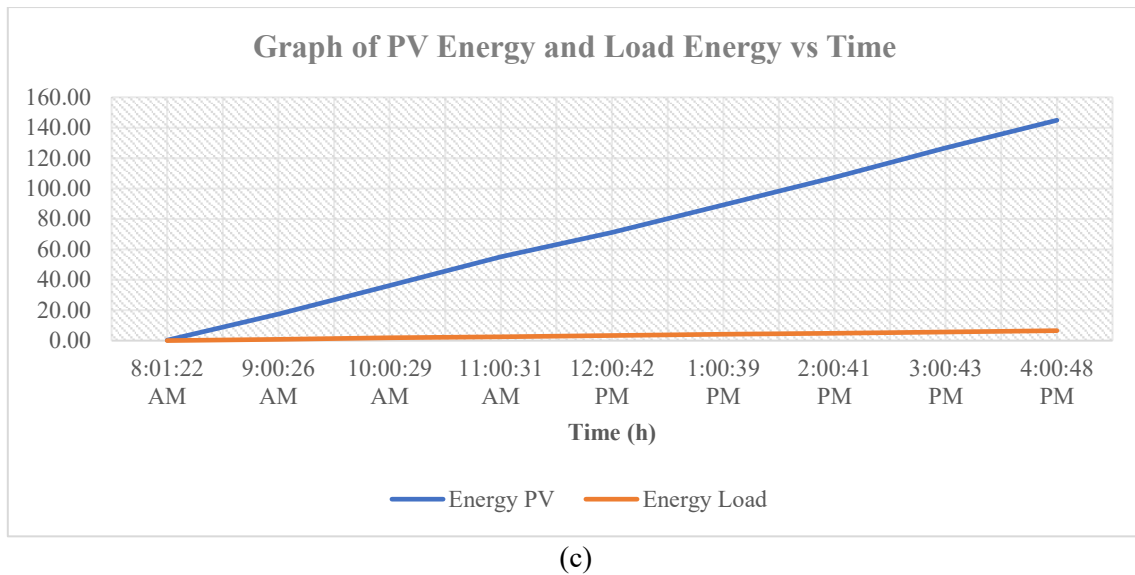
Picture 8. present the relationship between irradiance and the electrical characteristics of the PV system equipped with an AI-based dual-axis solar tracker over three days of testing. In all graphs, an increase in irradiance generally leads to higher PV current and power output, showing that the system can effectively capture solar energy as sunlight intensity rises. The PV voltage remains relatively steady with slight variations, indicating stable operating conditions of the panel, while efficiency increases along with irradiance up to an optimal point before stabilizing. These patterns consistently demonstrate that the AI-controlled solar tracker is capable of maintaining proper alignment with the sun, ensuring better energy conversion and reliable performance under fluctuating irradiance conditions.



(a)



(b)



Picture 8. Graph of Energy vs Time (a) day-1, (b) day-2, (c) day-3

Picture 8 show the relationship between PV energy generation and load energy consumption over time during three days of testing with the AI-based dual-axis solar tracker. In all cases, PV energy (blue line) increases steadily throughout the day as sunlight exposure accumulates, indicating consistent energy harvesting performance of the system. By contrast, load energy (orange line) remains relatively constant at a much lower level, suggesting that the energy demand of the connected load is significantly smaller than the energy produced by the PV system. This consistent gap between PV energy and load energy demonstrates that the system not only meets the load requirements but also generates a surplus of energy, highlighting the effectiveness of the AI-controlled tracker in optimizing solar energy production under varying daily conditions.

Table 1. Results over three days show a clear relationship between solar irradiance and the output of the photovoltaic (PV) system

No	Day	Irradiance [W/m ²]	Tegangan pv	Arus pv	Daya pv	Energi pv	Tegangan load	Arus load	Daya load	Energi load	Efisiensi
1	Day-1	396,22	13,29	0,74	9,90	35,36	13,32	0,06	0,85	3,13	13,03
2	Day-2	615,50	13,43	1,24	16,65	71,88	13,34	0,07	0,91	3,34	14,27
3	Day-3	754,01	13,36	1,36	18,27	72,02	13,42	0,07	0,97	3,33	12,62

The experimental results over three days show a clear relationship between solar irradiance and the output of the photovoltaic (PV) system. As irradiance increased from Day-1 (396.22 W/m²) to Day-2 (615.50 W/m²), both PV power and energy rose significantly, with PV energy more than doubling from 35.36 Wh to 71.88 Wh. From Day-2 to Day-3, irradiance further increased to 754.01 W/m², which raised PV power slightly but kept PV energy almost constant, likely due to temperature effects on the panel or limited exposure duration. Overall, the system achieved an average efficiency of 13.31%, with the highest efficiency recorded on Day-2 (14.27%). However, only around 5–9% of the harvested energy was utilized by the load, indicating surplus energy that was either stored or unused. This highlights opportunities for further optimization in load management and system integration.

Artificial Intelligence (AI) can play a vital role in overcoming these challenges and maximizing the benefits of green energy. By predicting irradiance and temperature patterns, AI can proactively adjust the solar tracker angle and MPPT control to maintain optimal performance under fluctuating conditions.

Intelligent algorithms can also detect anomalies, prevent efficiency losses, and schedule loads adaptively to absorb more clean energy during peak production. With these advancements, AI not only enhances the efficiency and reliability of solar power systems but also ensures that renewable energy is utilized to its fullest potential—delivering sustainable electricity without producing pollution.

DISCUSSION

The research indicates that implementing the AI Meets Solar dual-axis tracking system improved the solar panel's energy conversion efficiency by approximately 14% compared to a fixed installation only 2,7% on panel fixed (NurHidayat, 2021). This improvement is primarily due to the tracker's ability to maintain optimal panel orientation throughout the day, ensuring maximum exposure to solar radiation. The integration of artificial intelligence enables adaptive adjustments, allowing the system to respond to real-time environmental changes such as cloud cover or shifting sunlight patterns.

From an engineering perspective, the efficiency gain demonstrates the potential of combining sensor-based tracking with AI algorithms to significantly enhance renewable energy systems. This has direct implications for reducing dependence on fossil fuels, lowering greenhouse gas emissions, and promoting cleaner energy production—key steps toward achieving global sustainability goals. Moreover, the use of relatively low-cost components such as LDR sensors and microcontrollers (ESP32) makes this technology accessible to broader communities, including rural or underdeveloped areas.

From an Islamic perspective, technological advancements such as AI-powered solar trackers align with the principles of *ḥifz al-bi'ah* (preservation of the environment) and *maṣlaḥah* (public benefit). The Qur'an emphasizes humanity's role as *khalifah* (stewards) on Earth, entrusted to manage natural resources responsibly: "And do not commit abuse on the earth, spreading corruption" (QS. Al-Baqarah: 60). By harnessing solar energy—an abundant, renewable, and non-polluting resource—this research supports efforts to safeguard nature while meeting human needs.

Furthermore, increasing energy efficiency directly contributes to *kesejahteraan masyarakat* (social well-being) by providing affordable and sustainable power for current and future generations. In the context of *maqāṣid al-sharī'ah* (the higher objectives of Islamic law), this aligns with protecting life, promoting welfare, and ensuring justice in resource distribution. Thus, the AI-based dual-axis solar tracker is not only a technological innovation but also a moral and ethical step toward building a sustainable and equitable future.

CONCLUSION

The AI Meets Solar dual-axis tracking system increased solar panel efficiency by about 14% compared to fixed systems. By combining AI with sensor-based control, the tracker optimizes panel orientation in real time, enhancing energy yield and supporting clean energy adoption. This innovation aligns with Islamic principles of environmental stewardship (*ḥifz al-bi'ah*) and public benefit (*maṣlaḥah*), contributing to sustainable development and community welfare for present and future generations.

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