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Enhancing electricity production in Photovoltaic systems using a double-axis solar tracker

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ABSTRACT

The global energy crisis, still heavily reliant on fossil fuels, drives the need for innovations in renewable energy utilization, particularly solar energy. Indonesia, with abundant solar energy potential, has a significant opportunity to enhance solar energy usage through solar tracking technology. This study aims to design and test an Arduino-based double axis solar tracker system that improves solar energy absorption efficiency. The system uses an Arduino Mega 2560 as the main controller, equipped with Light Dependent Resistor (LDR) sensors and other supporting sensors to optimize the solar panel's position. Testing was conducted under three weather conditions: sunny, partly cloudy, and overcast, to compare the performance of the double axis system with single axis and fixed panels. The results indicate that the double axis solar tracker system produced the highest power output under all weather conditions, especially on sunny days, with an increase in power efficiency of up to 30-35% compared to fixed panels. This technology provides an efficient and economical solution for Indonesia to maximize solar energy utilization, supporting national renewable energy targets.

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1. INTRODUCTION

The global energy crisis, dominated by fossil fuel use, remains a major challenge in achieving energy sustainability. In 2022, around 80% of the world's energy demand was still reliant on oil, coal, and natural gas, exacerbating pollution and climate change [1]. This dependency also depletes fossil reserves and triggers global energy price instability [2]. Developing renewable energy, particularly solar energy, is a crucial step toward sustainability [3].

As a tropical country on the equator, Indonesia has significant potential for solar energy development, with an average solar intensity of 4.8 kWh/m²/day over 12 hours [4]-[5]. Despite its high potential, solar energy utilization in Indonesia remains low, with solar power capacity at only 150 MW in 2020, far from the 6.5 GW target for 2025 [6]-[7]. The use of solar trackers can improve solar energy efficiency. Solar trackers allow solar panels to automatically follow the sun's movement, unlike fixed panels, which capture sunlight only at limited angles [8]. Single-axis solar tracker technology can increase efficiency by up to 25% [9], although it is limited to one axis of movement.

As an alternative, double-axis solar trackers allow movement on two axes (azimuth and elevation), thus increasing energy efficiency by 30-35% compared to fixed panels or single-axis systems [10]. This double-axis tracker is highly effective in tropical regions like Indonesia, which experiences high light intensity year-round [11]. However, implementing this technology in Indonesia faces challenges, including high installation costs and limited technical knowledge [12]-[13]. This study develops an Arduino-based double-axis solar tracker, which is more economical and easy to implement. The system uses an Arduino

Uno as the main controller, with a DC motor for azimuth movement, a linear actuator for elevation, and LDR sensors to detect optimal light intensity [14]-[15]. Using Arduino reduces costs and enhances system flexibility, supporting increased solar energy adoption and aligning with Indonesia's renewable energy targets as outlined in the National Energy Plan (RUEN) [16]-[17]..

2. METHOD

The research utilizes an experimental approach to test the improvement in electricity production using a double-axis solar tracker system based on Arduino. The study design aims to enhance solar energy absorption efficiency through controlling the solar panel on two axes: azimuth and elevation. In the system design, one component is a block diagram, which serves as a visual representation to explain the relationships and workflow between the various components of the double-axis solar tracker system in a simplified manner. Figure 1 shows the diagram block of proposed dual axis solar tracker

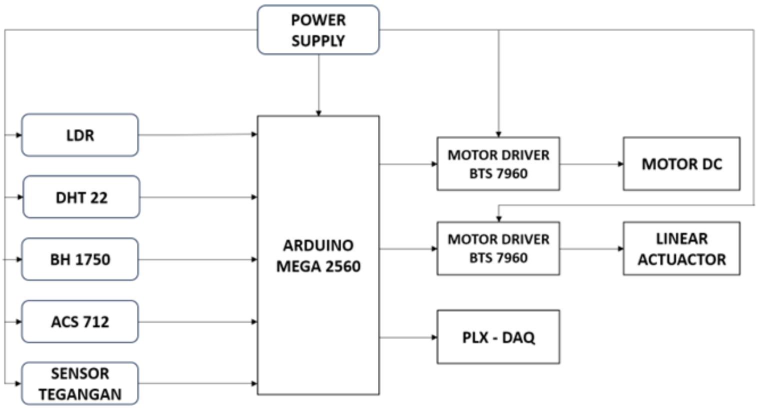

Figure 1 Diagram Block of proposed dual axis solar tracker

The block diagram of the Arduino Mega 2560-based double Axis Solar Tracker system consists of input, microcontroller, and output sections, all working to optimize the solar panel's position relative to sunlight. The primary inputs come from LDR, BH1750, DHT22, ACS712, and voltage sensors. LDR and BH1750 detect light intensity to determine the panel's direction, while the DHT22 measures temperature and humidity, and ACS712 along with the voltage sensor monitor the system's power consumption.

The Arduino Mega 2560 serves as the central control unit, processing data from these sensors to adjust the solar panel's movement. Controlled by the Arduino, the BTS7960 motor driver operates a DC motor on the azimuth axis and a linear actuator on the elevation axis, in response to changes in light intensity. The system outputs include the movement of the DC motor and linear actuator, which adjust the solar panel's position. Operational data is sent to a computer through PLX-DAQ for monitoring and further analysis. This system ensures that the solar panel maintains an optimal position for efficiently capturing sunlight. Figure 2 shows the design of the Double Axis Solar Tracker.

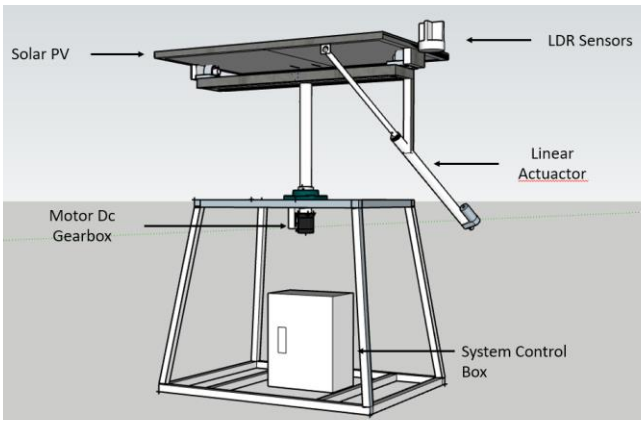

Figure 2. Mechanical Design of Double Axis Solar Tracker

After completing the mechanical design, the next step is assembling the electrical circuit. The electrical circuit plays an important role in monitoring the power generated by the solar panel and in controlling all actuators. During the assembly process, a schematic diagram, as shown in Figure 3, is required.

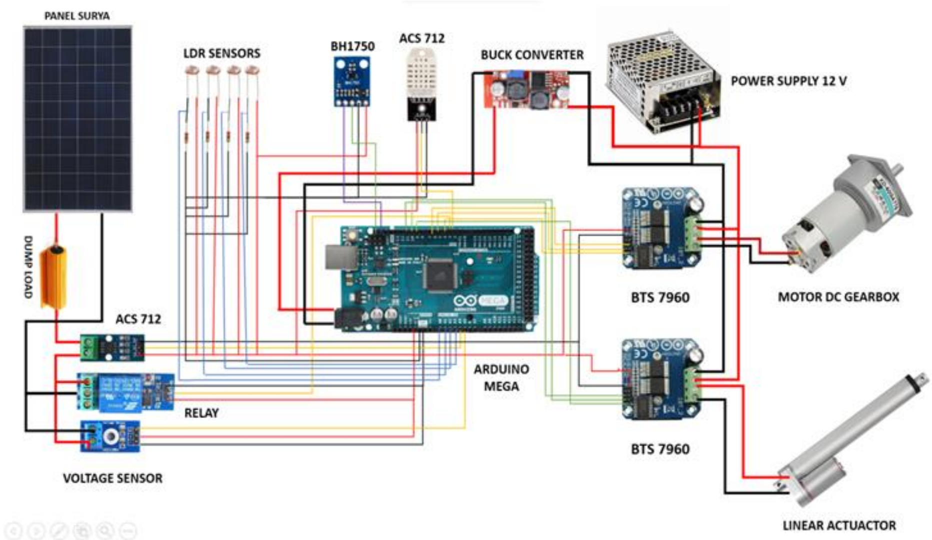

Figure 3. Electrical Schematic Design

The schematic diagram in Figure 3 shows the electrical circuit design for a solar-powered monitoring and actuator control system. The system uses an Arduino Mega as the main controller to manage inputs from multiple sensors, including LDR sensors for light detection, a BH1750 light intensity sensor, and ACS712 and voltage sensors for current and voltage monitoring. Power is supplied through a 12V power supply and a buck converter, which stabilizes the voltage for the components. The system controls a DC motor gearbox and a linear actuator via two BTS7960 motor drivers, enabling precise movement in response to the monitored solar power levels. Figure 4 shows the flowchart of the working system of this device.

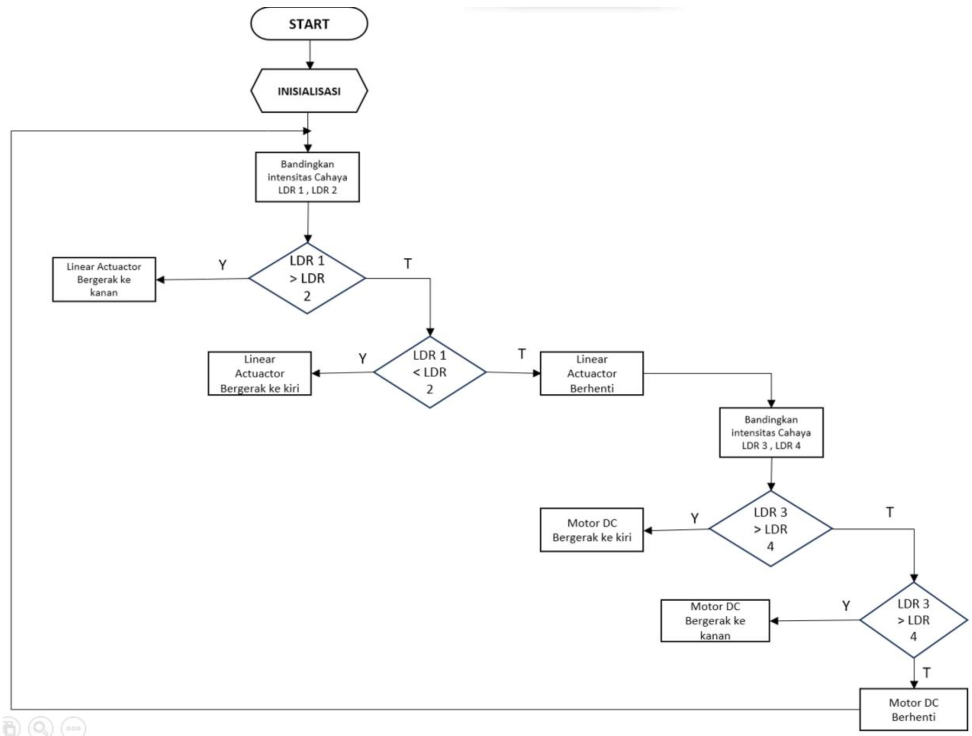

Figure 4. Flowchart System

The flowchart in Figure 4 illustrates the control logic for the dual-axis tracking system on the solar tracker, ensuring that the solar panel remains in the optimal position relative to sunlight. The vertical axis is controlled by a Linear Actuator, while the horizontal axis is managed by a DC Motor. The process begins with device initialization. On the vertical axis, the light intensity between LDR1 and LDR2 is compared; if the intensity of LDR1 is higher, the Linear Actuator moves to the right, and if LDR2's intensity is higher, the actuator moves to the left. The Linear Actuator halts when the intensities of both sensors are balanced. Subsequently, the system controls the horizontal axis by comparing the intensities on LDR3 and LDR4. If the intensity of LDR3 is greater, the DC Motor moves left; if LDR4's intensity is greater, the motor moves right. The DC Motor stops when the intensities of both sensors are equal, indicating the optimal position for the panel.

3. RESULTS AND DISCUSSION

After completing the device design, the dual-axis solar tracking system was constructed and tested under three weather conditions: clear, partly cloudy, and overcast with rain. The testing aimed to evaluate the performance of the dual-axis system in generating electrical energy, comparing it with a fixed solar panel and a single-axis tracking system. The setup of the solar panel with the fixed system and dual-axis tracker for testing purposes is shown in Figure 5.
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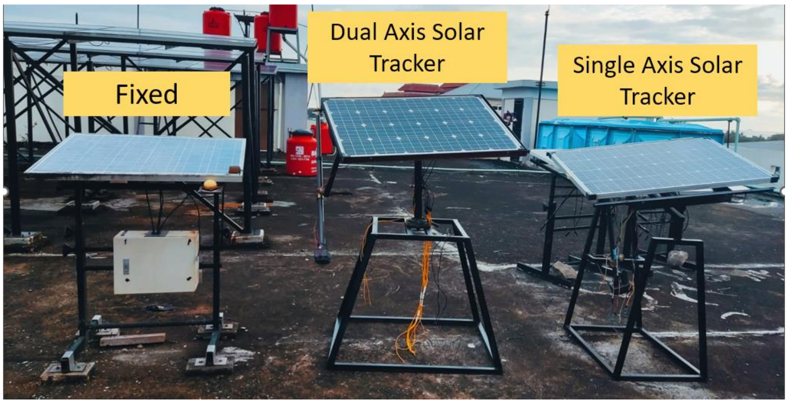

Figure 5. System Testing

The solar panels with fixed, single-axis, and dual-axis tracking systems were installed for testing, as shown in Figure 5. Comparisons power output generated by the three systems across different weather conditions are illustrated in Figures 6 through 8. The test results demonstrate that the dual-axis tracking system produced the highest energy output, followed by the single-axis tracker and then the fixed system under all weather conditions. However, on overcast and rainy days, the energy output pattern of the single-axis and dual-axis trackers differed slightly from that observed in other weather conditions. The Power comparison between the three systems under sunny weather conditions is shown in Figure 6.

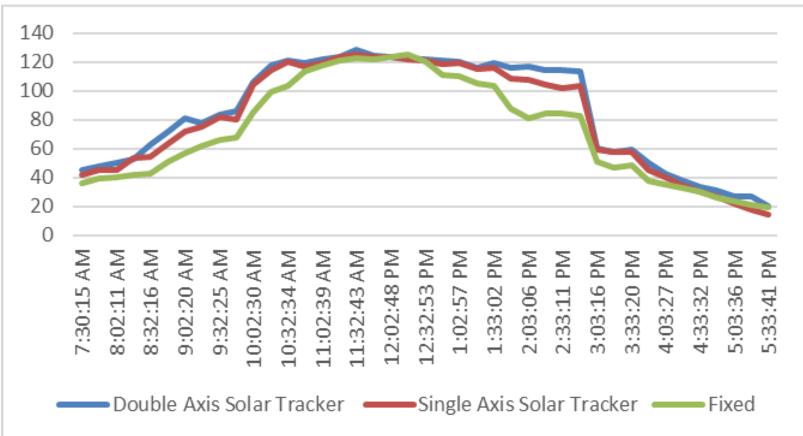

Figure 6. Comparison of power values in sunny weather

The graph shows that power output varies across the day for the Double Axis Solar Tracker, Single Axis Solar Tracker, and Fixed systems. The Double Axis Tracker consistently achieves the highest power, especially around 11:00 AM to 1:00 PM, due to its full alignment with the sun, maximizing energy absorption. The Single Axis Tracker generates slightly less power as it follows the sun on only one axis but still outperforms the Fixed system, which has the lowest output due to its static position and suboptimal energy absorption outside peak sunlight hours. This analysis highlights that tracking systems, especially dual-axis, significantly enhance solar power generation on sunny days. Figure 7 shows the power comparison of the three systems under cloudy conditions.

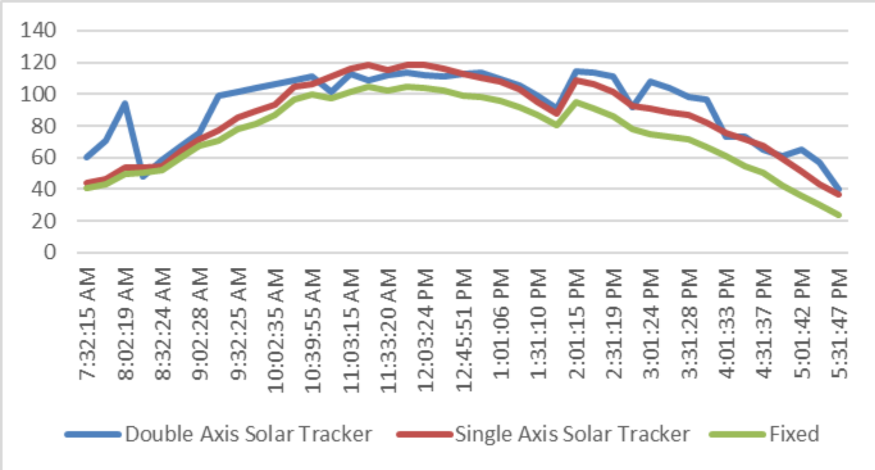

Figure 7. Comparison of power values in cloudy weather

The graph shows that power output varies throughout the day for the Double Axis Solar Tracker, Single Axis Solar Tracker, and Fixed systems, even under cloudy conditions. The Double Axis Tracker consistently achieves the highest output, especially around midday, due to its ability to follow the sun both horizontally and vertically, maximizing energy absorption despite reduced sunlight. The Single Axis Tracker, limited to one-axis movement, generates less power but still outperforms the Fixed system, which shows the lowest output due to its static position. This analysis highlights that, even on cloudy days, tracking systems especially dual-axis significantly enhance solar power generation compared to fixed systems. Figure 8 shows the power comparison of the three systems under overcast with rain conditions.

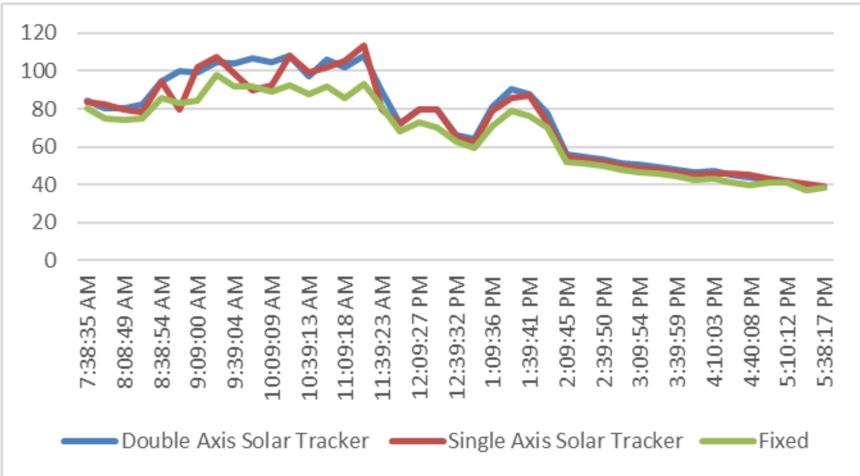

Figure 8. Comparison of power values in overcast with rain

The graph shows power output for the Double Axis Solar Tracker, Single Axis Solar Tracker, and Fixed systems under overcast, rainy conditions. All systems produce significantly lower power compared to sunny days. However, the Double Axis Solar Tracker achieves slightly higher output, especially from morning to midday, due to its ability to adjust horizontally and vertically, capturing more light even with reduced intensity.

The Single Axis Tracker outperforms the Fixed system, though the difference is smaller than on sunny days. The Fixed system's inability to track the sun results in the lowest output throughout the day. This analysis shows that tracking systems, especially dual-axis, remain more efficient in capturing energy, even in overcast and rainy weather. Figure 9 shows a comparison of average values in different weather conditions

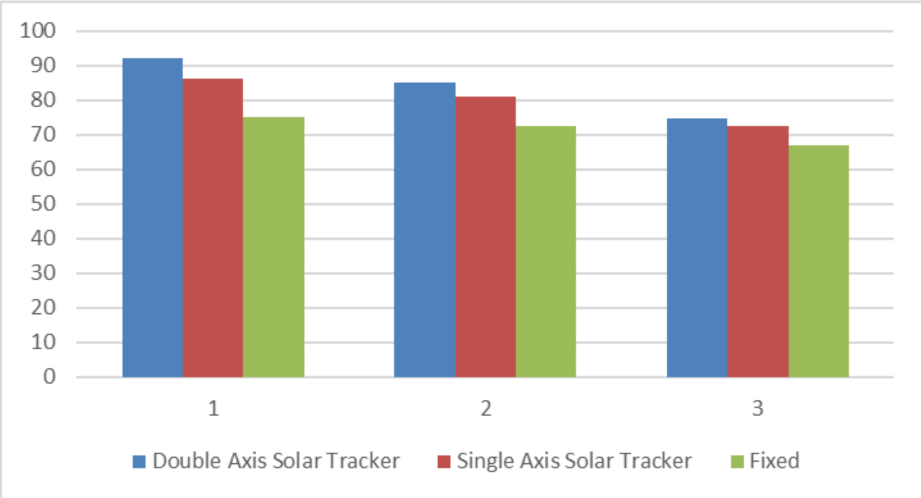

Figure 9. Comparison of average power in different weather

Figure 18 shows the average power output over three days. On the first day, which was sunny, the Double Axis Solar Tracker generated the highest power at around 100 watts, followed by the Single Axis Tracker at 90 watts, and the Fixed Panel at 80 watts. The Double Axis system's advantage lies in its ability to fully track the sun's position. On the second day, which was cloudy, all systems experienced a decrease in power. The Double Axis Tracker remained the highest with 85 watts, followed by the Single Axis at 75 watts, and the Fixed Panel at 65 watts. This reduction was due to cloud cover blocking direct sunlight, although the Double Axis system benefited from capturing more diffuse light.

On the third, overcast day, power output dropped significantly, with the Double Axis producing 70 watts, the Single Axis 60 watts, and the Fixed Panel 55 watts. Despite the low light, the Double Axis still performed best by tracking the limited sunlight available. Overall, the Double Axis Solar Tracker demonstrated superior performance across all weather conditions, especially on sunny days. The Single Axis Tracker performed well under high sunlight, while the Fixed Panel consistently generated the least power, highlighting its limitation in adapting to the sun's changing position.

4. CONCLUSION

This research shows that the Arduino based dual axis solar tracker system significantly improves solar energy absorption efficiency compared to fixed panel systems and single axis solar trackers. Under various weather conditions, the dual axis solar tracker is able to generate higher power, especially on sunny days, consistently achieving better efficiency than other systems. On cloudy and overcast days, even as light intensity decreases, the dual axis system still demonstrates optimal performance in maximizing sunlight capture. This system dynamically tracks the sun's position, making more effective use of the available light intensity. Thus, dual axis solar tracker technology holds great potential for enhancing solar energy utilization in Indonesia, particularly in regions with high year-round sunlight intensity. Additionally, the Arduino-based approach in designing this system offers a more economical solution that can be widely implemented, supporting the achievement of national renewable energy targets..

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