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DESIGN AND IMPLEMENTATION OF A DUAL-AXIS SOLAR TRACKING SYSTEM USING ARDUINO UNO MICROCONTROLLER

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ABSTRACT

This paper presents a dual-axis solar tracking system developed and evaluated using LDR sensors and stepper motors, controlled by an Arduino Uno microcontroller. The aim was to enhance photovoltaic energy efficiency by designing a system capable of automatically adjusting the position of solar panels to follow the sun's movement throughout the day. Comparative testing between static solar panels and those equipped with solar trackers demonstrated that the latter produced 35% more power on average. Additionally, the dual tracking system showed a 14% improvement in efficiency over previous averages noted in existing references. Analysis of azimuth and elevation angles confirmed that the solar tracker accurately adjusted the panels' position, significantly boosting solar energy capture. This finding is consistent with prior research, which also supports the efficacy of solar trackers in enhancing photovoltaic efficiency. Future research should expand testing to include various weather and environmental conditions and focus on developing more advanced control algorithms to enhance system responsiveness. Continuous advancements in solar tracking technology are vital for maximizing solar energy potential and facilitating a transition to a more sustainable society.

***Keywords**: arduino uno microcontroller, dual-axis solar tracking System, LDR sensors, stepper motors.*

I. INTRODUCTION

FINDING sustainable energy sources to meet the increasing global demand will be a significant challenge for the next half-century. However, the utilization of conventional energy sources such as fossil fuels has led to serious environmental impacts, including global warming, air pollution, and other environmental damages [1], [2]. With population growth and economic development, addressing the energy crisis and mitigating the impacts of global warming have become urgent concerns [3]–[5].

Renewable energy sources offer viable solutions to these problems, and solar energy, derived from solar radiation, holds great potential [6]–[8]. Many studies have explored the crucial role of solar energy in our future and investigated methods to enhance the utilization of solar radiation [9], [10]. However, in implementing solar panel technology, we face significant challenges related to energy efficiency. Traditional solar panels are statically mounted, meaning they cannot optimally track the sun's movement throughout the day. This results in a decrease in energy collection efficiency, especially when the sun is at a low angle in the sky or when weather conditions are suboptimal [11]–[13]. Therefore, innovation is needed to improve solar panel efficiency to maximize solar energy potential.

In efforts to enhance solar panel efficiency, previous research has explored the use of solar tracking systems. These systems allow solar panels to dynamically track the sun's movement throughout the day, ensuring they are always at the optimal angle to capture sunlight [14]–[16]. This can lead to a significant increase in energy collection, helping to improve the overall efficiency and performance of solar panel systems [17]–[19].

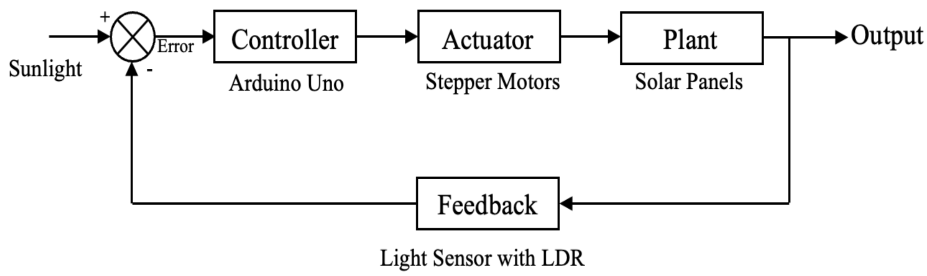

Figure 1. Block Diagram of Closed Loop Solar Tracking System

Recent studies have shown that implementing two-axis solar tracking systems can result in a significant increase in solar panel efficiency. For example, research by Munanga et al. in 2020 noted an increase in energy output of up to 15-20% with the use of dual-axis solar tracking [20]. Meanwhile, research by Hassan et al. reported a net power increase of around 23.15% with single-axis tracking and 29% with dual-axis tracking compared to static solar panel systems [21].

Based on the above references, there is still room for further improvement in optimizing solar tracking systems. This study aims to address this issue by proposing and evaluating an innovative and efficient dual-axis solar tracking system. Here, we conduct research with the primary goal of developing and evaluating a dual-axis solar tracking system. To ensure strong system performance, a new design of the PV dual-axis solar tracking system utilizing feedback control theory, four-quadrant light-dependent resistor (LDR) sensors, and simple electronic circuits is proposed and evaluated. The proposed system employs two DC motors and a standalone system to achieve efficient sun tracking. The control execution is a technical innovation with a simple and effective design that can address the inefficiency of tracking systems in changing weather conditions such as cloudy, overcast, or rainy conditions. In addition to weather conditions, this research also aims to provide insights into the efficiency of using solar trackers in specific regions, particularly in Indonesia.

II. Research Method

The research methodology employed in this study involves an analytical approach combined with the design of solar panels integrated with a solar tracker. The implementation of this methodology consists of the following stages.

1) Literature Review: conducting extensive literature research to gather relevant theories and obtain information from various sources such as books, journals, and online references.
2) Data Analysis: analyzing the collected data and identifying the information required for developing the solar tracking system.
3) Prototype Design: designing a customized prototype of the solar tracking system based on the design requirements derived from the literature review and data analysis.
4) Prototype Implementation: implementing the designed prototype by assembling the components and programming the microcontroller and connecting each component to the program to enable the tool's operation.
5) Testing and Evaluation: performing trials to evaluate the solar tracking system's functionality and assess its alignment with the research objectives and collecting data during the testing phase to validate the system's performance, including its ability to optimize solar panel orientation and enhance energy output.

A. *System Block Diagram*

The system block diagram illustrates the components of the designed system, including input components, plant components, output components, and feedback components as depicted in Figure 1. The system implemented in this design is a closed loop control system, incorporating feedback from the output to the input. The position of the output is determined by the input, which is influenced by the output itself. In simpler terms, the output and the input position are interrelated, where the output position indirectly affects the input.

For example, the position of the solar panel, which receives the light source, serves as the input for the sensor, constituting the system's input. The input comprises four light sensors, specifically Light

Dependent Resistors (LDRs), responsible for detecting the four cardinal directions. The microcontroller processes these four sensors and serves as a reference for controlling the motor [11].

The plant component represents the solar panel, which is controlled to face the direction of the sunlight. To achieve precise directional control, the system incorporates two axes or degrees of freedom, necessitating the use of two motors as the driving force.

B. Work Principle

The circuit operates based on a defined working principle. It begins with the power supply, which provides current to all components, enabling the system to function as programmed. A light sensor plays a crucial role by converting the intensity of light into a corresponding voltage. This sensor, in conjunction with a fixed resistor, forms a voltage divider circuit, where the sensor's resistance determines the voltage division [22]. The output voltage from the sensor reflects the detected light intensity. The analog output from the sensor is then connected to the microcontroller's analog input. The system incorporates four LDRs as sensors, each connected to a separate analog input of the microcontroller. The microcontroller converts the analog voltage into digital data and performs calibration to obtain the corresponding voltage values. To assess the intensity condition of each sensor, the program compares the four voltage values using the equations presented.

$$Error(e0) = absolute[north\ LDR(V) - south\ LDR(V)] \tag{1}$$

$$Error(e1) = absolute[east\ LDR(V) - west\ LDR(V)] \tag{2}$$

Equation (1) calculates the error (e0) as the absolute difference between the voltages from the north and south LDRs, while Equation (2) determines the error (e1) between the voltages from the east and west LDRs. If either the error (e0) or the error (e1) exceeds 0.2V, the microcontroller will respond by initiating a corrective step. This involves activating the stepper motor to adjust the position of the solar panel until the error approaches zero or falls within the specified tolerance of 0.2V. The microcontroller aims to minimize position errors by controlling the motors and moving the panel as required. The system consists of actuators in the form of two stepper motors, where each motor represents the north-south and east-west axis. This operating principle ensures continuous operation of the circuit as long as it receives a stable power supply. The system block diagram illustrates the components of the designed system, including input components, plant components, output components, and feedback components. The system implemented in this design is a closed-loop control system, which incorporates feedback from the output to the input. The output position is determined by the input, which is influenced by the output itself. In simpler terms, the output position and input are interrelated, where the output position indirectly affects the input.

C. System Flowchart

A flowchart serves as a diagram illustrating the sequential flow of work processes from start to finish within a single work cycle. Figure 2 displays the system flow diagram to be designed, where the process begins with initialization to establish the initial conditions of input/output parameters. Following the initialization, the program reads the input through the analog input, specifically from A0 to A3. The values of LDR as an analog are converted to the digital value as a form of data in the internal ADC. The data represents the voltages where the magnitudes are compared to determine the differences or errors. Error 1 reflects the disparity between sensors 1 and 2, while error 2 corresponds to the variation between sensors 3 and 4. If both errors exceed 0.2V, the microcontroller initiates corrections by activating the motor and adjusting the solar panel's position until the error approaches zero or reaches the tolerance of 0.2V. The adjustments are performed sequentially, beginning with motor 1, followed by subsequent positions after reaching each new position. The control circuit is designed to serve as the system controller, responsible for processing inputs and controlling outputs. It utilizes the Arduino microcontroller as its core component and is supported by various sensors and output components. The sensor employed in this circuit is the LDR. Specifically, the Arduino Uno microcontroller with an ATmega328 chip is chosen for this design. The programming of the microcontroller is carried out using the C language within the Arduino IDE version 1.8.9.

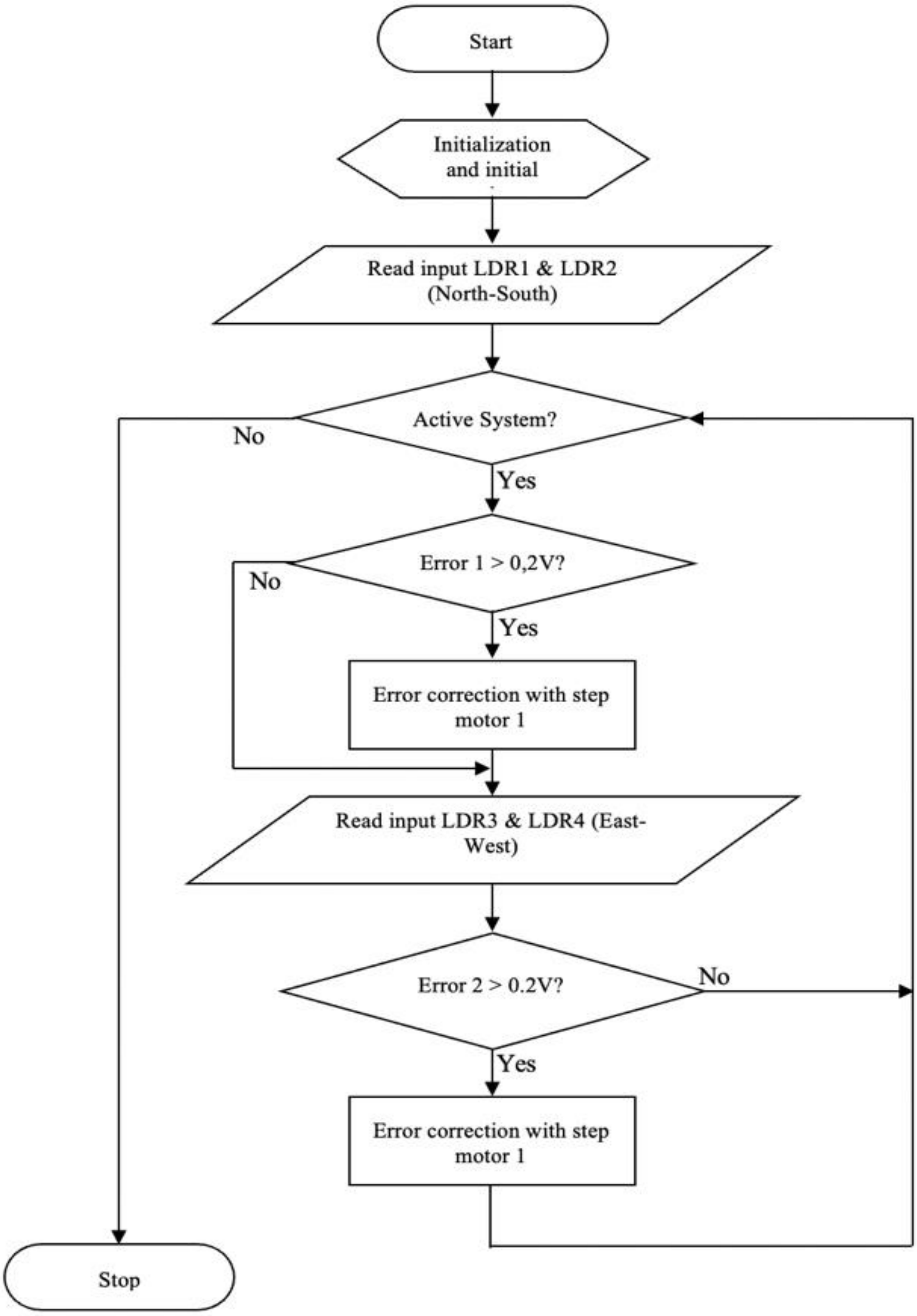

Figure 2. Flowchart Diagram of the System

D. Control Program Design

Nowadays, many individuals prefer Arduino due to its simplified version of C++ and the availability of pre-programmable Arduino microcontrollers, which can be easily programmed, erased, and reprogrammed as needed [23]. Among the various open-source hardware platforms, Arduino™ UNO stands out due to its flexibility, affordability, and supportive developer community [24]. For the control program in this project, Arduino IDE was utilized as the programming environment. Arduino Uno, an open-source single-board microcontroller based on the ATMega328, was employed. A 5V USB connection or an external power supply can power it. The hardware consists of an ATmega328 microcontroller, 14 digital input/output pins, six analog inputs, a power jack, and a USB connection [25]. The board's programming is performed using the Arduino software, using the C language with the Arduino library. The capabilities of the Arduino Uno were considered sufficient for controlling the solar panel mechanism. The control circuit is designed to serve as the system controller, responsible for processing inputs and

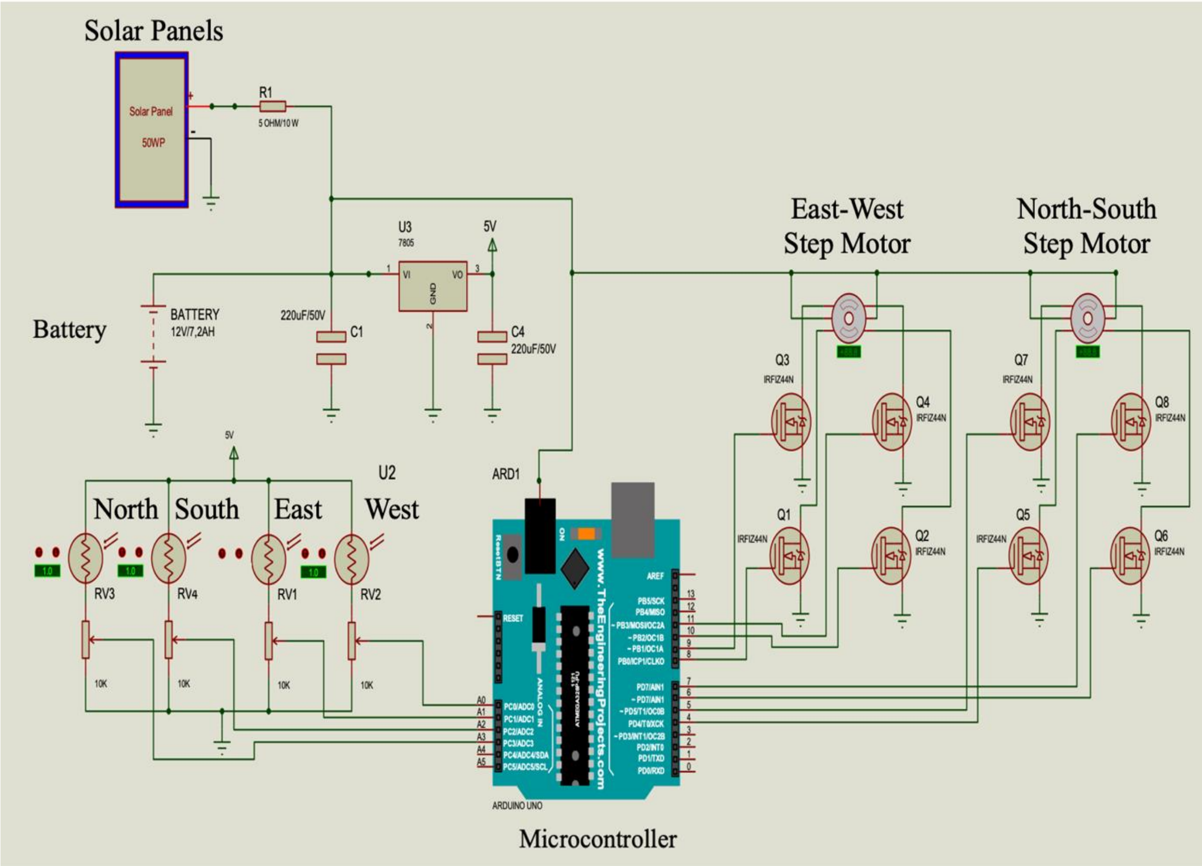

Figure 3. Circuit of The System

controlling outputs. It utilizes the Arduino microcontroller as its core component and is supported by various sensors and output components. The sensor employed in this circuit is the light-sensitive resistor (LDR). Specifically, the Arduino Uno microcontroller with an ATmega328 chip is chosen for this design. The programming of the microcontroller is carried out using the C language within the Arduino IDE version 1.8.9.

E. Control Circuit Design

The control circuit is designed to function as the system controller, responsible for input processing and output control. The designed system utilizes an Arduino microcontroller as its core component and is supported by various sensors and output components. The sensors used in this circuit are LDRs. Specifically, the Arduino Uno microcontroller with ATmega328 chip was chosen for this design. Microcontroller programming is done using the C language in Arduino IDE version 1.8.9. The design of the control circuit can be seen in Figure 3.

The system output involves mechanical movement, achieved through a pair of unipolar stepper motors. A driver or current amplifier is required to control these stepper motors using the microcontroller. In this circuit, P-type MOSFETs are used as current amplifiers, functioning as switches to control the periodic current flow to the motor coils. The diagram below illustrates the overall circuit design for the dual-axis solar tracking system control circuit with two degrees of freedom.

III. Result and Discussion

After successfully constructing the solar tracker device, as depicted in Figure 4, the testing process is carried out using equipment such as a voltmeter to assess the functionality of the device. This testing involves the evaluation of key components and comprehensive testing to ensure the overall effectiveness of the device in tracking the movement of the sun and optimizing solar energy capture. Evaluation of key components includes testing light sensors, battery systems, and system performance to ensure stable and responsive operation. The results of these tests will provide a better understanding of the solar

TABLE 1
TECHNICAL SPECIFICATION

Output Voltage	12-14V DC
Solar panel capacity	50 Wp
Battery capacity	12V/6350 mAh
Maximum current	4.4A
Battery operation time	12 Hours
Battery charge duration	Minimum 4.5 Hours
Battery type	Lead-Acid
Number of Axis	2
Motor type	Stepper unipolar
Microcontroller	Arduino Uno
Sensor	LDR
Motor driver	Mosfet
Axis Angle x	130°
Axis Angle y	60°

TABLE 2
LIGHT SENSOR TESTING RESULTS WITH VARIATIONS IN LAMP DISTANCE

Input Voltages (V)	Lamp Distances (m)	Intensity (Lux)	Output Voltages (V)
5.0	1.2	70	1.25
5.0	1.0	150	1.55
5.0	0.9	378	1.89
5.0	0.8	497	2.03
5.0	0.7	652	2.44
5.0	0.6	833	2.86
5.0	0.5	1029	3.17
5.0	0.4	1390	3.32
5.0	0.3	1850	3.87
5.0	0.11	2739	4.02
5.0	0.07	4892	4.37
5.0	0.03	6337	4.89

Figure 4. Solar Tracker Dual-Axis

tracker device's capabilities in enhancing solar panel efficiency and its contribution to the development of sustainable solar energy.

A. Device Specifications

The specifications of the developed solar tracker device were determined based on testing results, available component data, and calculations. These specifications form the foundation for understanding the device's capabilities and performance in tracking the sun's movement and optimizing solar energy absorption. A thorough understanding of these specifications allows for an evaluation of how well the device meets specific needs in solar energy applications. Table 1 provides detailed specifications of the successfully developed solar tracker device.

TABLE 3
BATTERY CHARGING AND DISCHARGING PROCESS

Time (minutes)	Battery Charging Process		Battery Discharging Process	
	Voltage (V)	Current (A)	Voltage (V)	Current (A)
0	10.2	1.58	12.5	1.25
30	10.6	1.46	12.4	1.24
60	10.9	1.42	12.3	1.23
90	11.2	1.28	12.1	1.21
120	11.6	1.16	12.05	1.2
150	12.1	0.92	12.02	1.2
180	12.9	0.78	11.7	1.17
210	13.2	0.38	11.4	1.14
240	13.7	0.33	10.8	1.07
270	14.4	0.22	10.3	1.02

TABLE 4
ENERGY PRODUCTION RESULTS FROM FIXED SYSTEM AND DUAL AXIS SYSTEM

Date	Fixed System (W)	Dual Axis System (W)
01/11/22	166.12	221.32
02/11/22	180.86	237.16
03/11/22	180.08	298.39
04/11/22	194.79	240.77
05/11/22	54.92	59.30
08/11/22	230.37	308.05
09/11/22	128.42	168.67
10/11/22	215.96	282.29
11/11/22	175.30	234.29
12/11/22	216.66	290.72
15/11/22	198.24	305.80
16/11/22	197.17	264.23
17/11/22	225.09	296.29
18/11/22	218.36	310.55
19/11/22	146.59	190.74
22/11/22	208.36	266.30
23/11/22	174.86	255.81
24/11/22	161.94	207.70
25/11/22	231.05	294.53
26/11/22	169.57	218.85
29/11/22	155.29	198.84
30/11/22	187.59	267.37
01/12/22	133.98	146.35
02/12/22	211.52	288.37
03/12/22	115.80	153.03
06/12/22	168.35	244.68
07/12/22	86.99	102.68
08/12/22	151.17	198.16
09/12/22	172.99	234.44
10/12/22	91.59	115.77
13/12/22	196.31	265.16
14/12/22	87.41	117.82
15/12/22	152.12	220.69
16/12/22	211.97	288.86
17/12/22	180.37	250.11

B. Light Sensor Circuit Test

The results of the light sensor testing were obtained by exposing it to a constant input voltage while varying the intensity of the light source, as shown in Table 2. An LED lamp was used as the light source, and the distance between the lamp and the sensor was adjusted. The intensity was measured using a Lux meter. The table presents the results, showing that the output voltage changes in response to intensity changes. This confirms that the sensor successfully converts light into voltage, allowing the microcontroller to detect it.

C. Battery Test

A Lead-Acid dry cell battery is used as the voltage source for the solar tracker system. The battery is fully charged and discharged to an empty state. Table 3 shows the charging process, with a duration of 270 minutes (4.5 hours) and a charging voltage of 14.4V (20% above the standard 12V battery voltage). Discharge testing is performed with a constant load using a 10 ohm 5-watt resistor. The test results indicate a battery capacity of 6.35 Ampere Hours.

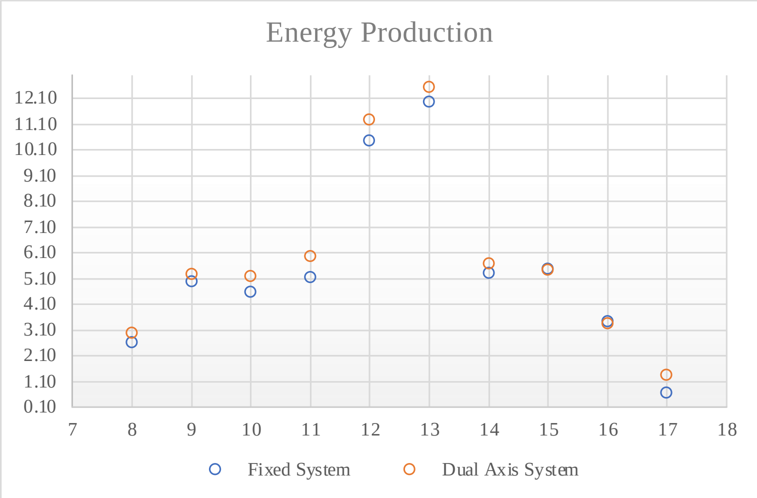

Figure 5. Energy Production on Friday, November 5, 2022

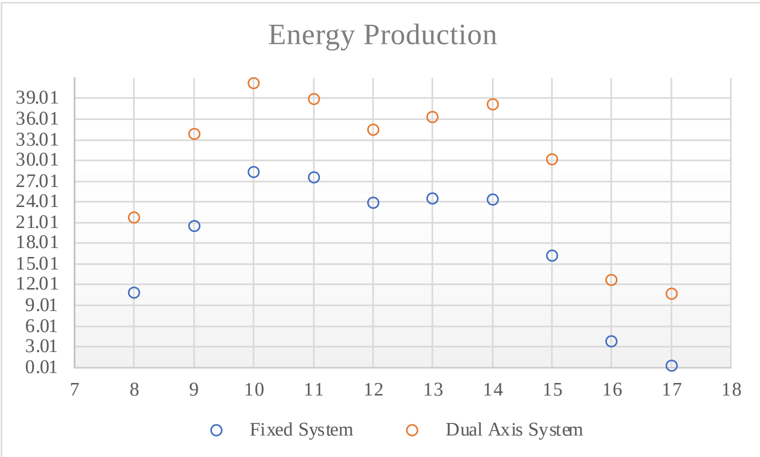

Figure 6. Energy Production on Wednesday, November 3, 2022

D. Analysis of Static Solar Panels versus Dual Axis Solar Panels

Testing was conducted at HKBP Nommensen University, where static solar panels and solar panels equipped with a solar tracker were tested under identical conditions. This analysis compares the output power of static solar panels to that of panels with a solar tracker. The experiments spanned 35 days, from November 1, 2022, to December 17, 2022, with testing conducted from Monday to Friday under varying weather conditions. Power output for each system was measured hourly from 08:00 AM to 05:00 PM. For the static solar panels, the panels were oriented facing upwards, perpendicular to the ground.

Based on Table 4, it is found that the production of electricity is influenced by weather conditions. The weather conditions affecting energy production are rain, overcast skies, sunny weather, and cloudy skies. On Friday, November 5, 2022, the weather conditions were overcast with rain. This resulted in low electricity production from both the fixed system and the dual-axis system, showing insignificant differences. The detailed differences can be seen in Figure 5.

On Wednesday, November 3, 2022, there was a 66% difference in energy production between the fixed system and the dual-axis system. The weather conditions were partly cloudy, occasionally shading the solar panels of the fixed system and reducing their energy output. In contrast, the dual-axis system, designed to track the sun's position, was less affected by clouds, thus maximizing energy production. This difference is illustrated in Figure 6.

The highest energy production in the fixed system during the testing period occurred on Thursday, November 25, 2022, facilitated by predominantly clear skies that day. Consequently, the energy output of the fixed system was maximized, although it still did not match the performance of the dual-axis

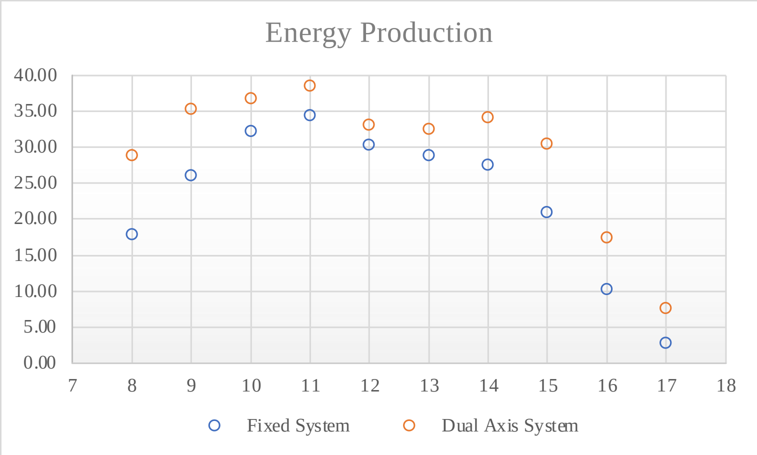

Figure 7. Energy Production on Thursday, November 25, 2022

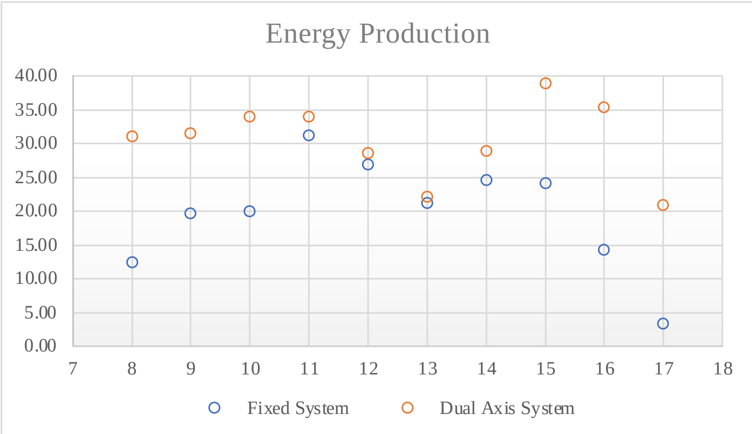

Figure 8. Energy Production on Thursday, November 18, 2022

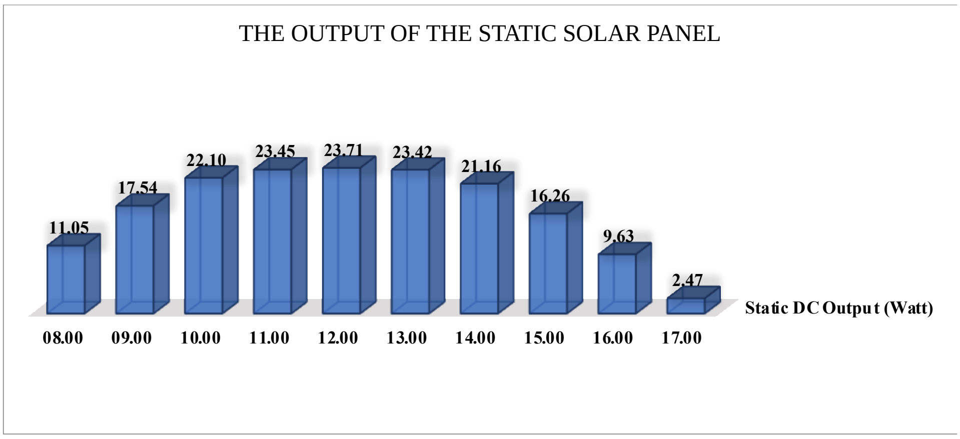

Figure 9. The Output of the Static Solar Panel

system, as depicted in Figure 7. Conversely, the peak energy production for the dual-axis system occurred on Thursday, November 18, 2022. The morning began with clear skies, but rain and thick clouds later reduced energy production for about four hours. As the weather improved, the dual-axis system resumed maximizing its energy output, as detailed in Figure 8.

Figure 9 illustrates the average power the static solar panels generated during the 35-day measurement period. The average maximum power generated by the system was 23.71 Watts at 12:00 PM, and the average minimum power was 2.47 Watts at 05:00 PM. The average total power generated during the measurement period was 170.80 Watts.

During testing, the solar tracker system was activated, enabling the solar panels to automatically follow the sun's movement. Figure 10 illustrates the average power generated by these panels over the 35-

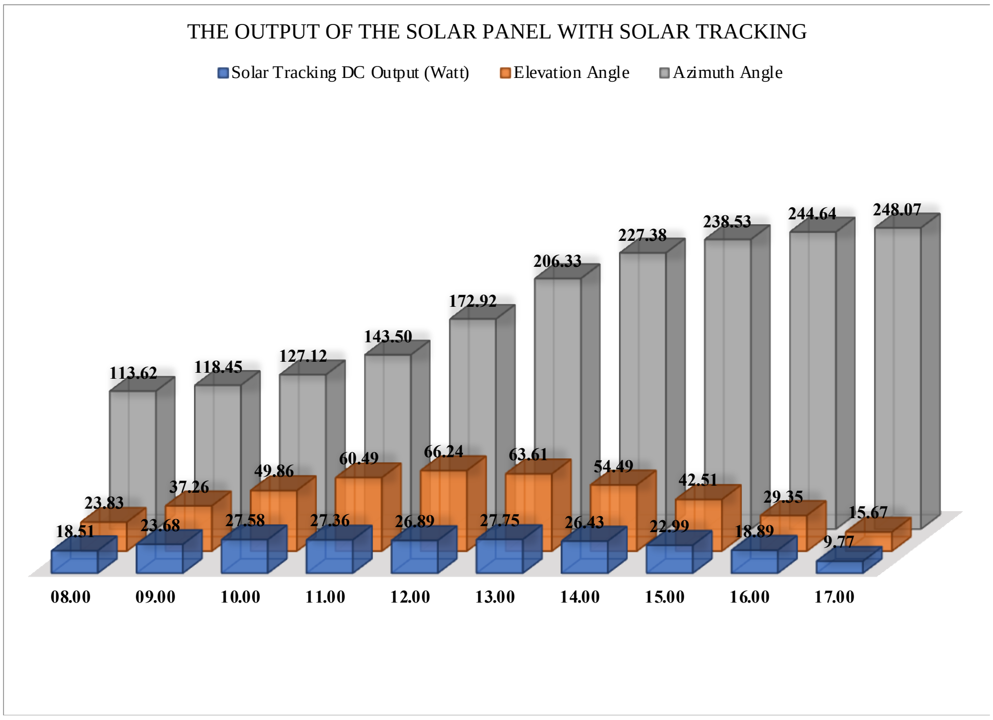

Figure 10. The Output of the Solar Panel with Solar Tracking

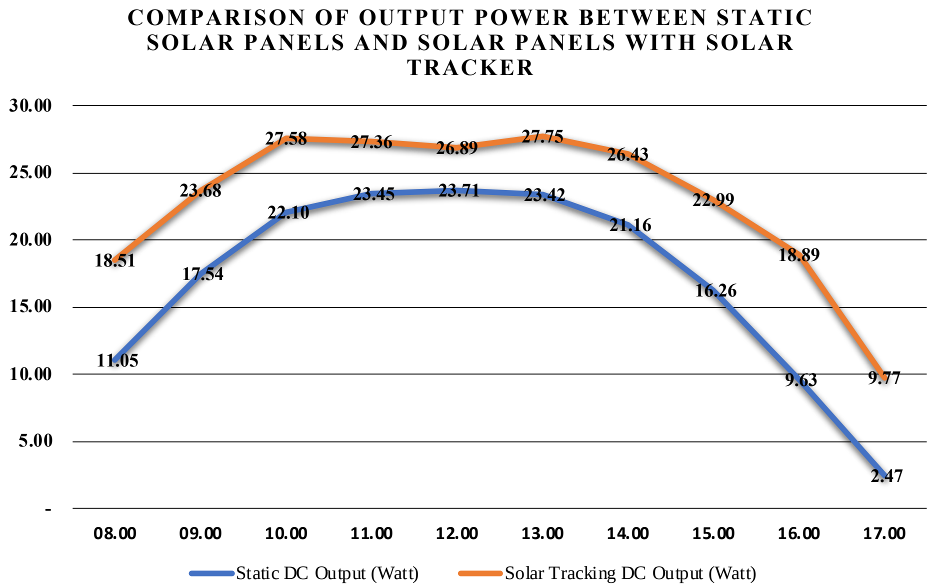

Figure 11. The Output of the Solar Panel with Solar Tracking

day measurement period. The system produced an average maximum power of 27.75 Watts at 01:00 PM and an average minimum power of 9.77 Watts at 05:00 PM. The total average power generated during the measurement period was 229.83 Watts.

Additionally, measurements were taken for the azimuth and elevation angles. In a solar tracker, both angles are used together to optimize the absorption of solar energy by the solar panels. The solar tracker automatically moves the solar panels to track the sun's movement throughout the day by adjusting the azimuth and elevation angles. From the average maximum power generated at 01:00 PM, the optimal azimuth angle was 206.33°, and the optimal elevation angle was 63.61° for maximum solar energy absorption.

When comparing the testing results between static solar panels and solar panels with a solar tracker, there is a difference in the average power generated. Figure 11 illustrates the comparison, showing that the average total power generated by static solar panels is 170.80 Watts, while solar panels with a solar

TABLE 4
SUMMARY OF PERCENTAGE YIELD OF SUN TRACKING OVER FIXED SYSTEMS

Year	Location	Reference	Percentage Yield
2011	USA	Lubizt	34%
2013	Mexico	Lee, Rahim, and Al-Turki	23%
2013	UK	Lee, Rahim, and Al-Turki	23%
2013	Estonia	Lee, Rahim, and Al-Turki	10-20%
2013	Taiwan	Lee, Rahim, and Al-Turki	24.5%
2016	Stuttgart, Germany	Sharaf, Abd-Elhady, and Kandil	16.8%
2016	Cairo, Egypt	Sharaf, Abd-Elhady, and Kandil	10.61%
2016	Aswan, Egypt	Sharaf, Abd-Elhady, and Kandil	8.16%
2016	Stuttgart, Germany	Sharaf, Abd-Elhady, and Kandil	16.8%
2019	Menya, Egypt	Hassan, Elbaset, Hasouna, and Emad	29%
2020	Zimbabwe	Munanga, Chinguwa, Nyemba, and Mbohwa	15-20%
2021	Spain	Flores-Hernández, Luviano-Juárez, Lozada-Castillo, Gutiérrez-Frías, Domínguez, and Antón	27%
2022	Mexico	Angulo-Calderón, Salgado-Tránsito, Trejo-Zúñiga, Paredes-Orta, Kesthkar, and Díaz-Ponce,	27-28%
2023	Turkey	Tuğçe, Hakan, Burak, and Manolya	32-33%

tracker generate 229.83 Watts. This indicates a difference of 59.03 Watts, with solar panels with a solar tracker generating 35% more power than static solar panels.

E. Discussion of Research Results Compared to Similar Studies

Comparison with previous research indicates consistency in findings that the use of dual-axis solar tracking systems significantly enhances the energy collection efficiency of solar panels. These findings align with earlier studies stating that solar trackers can substantially increase energy output. In Table 5, we will outline some findings from similar studies conducted between 2005 and 2020 [26]–[31].

However, the findings from this study suggest that the use of dual-axis solar tracking systems can provide even greater improvements in energy efficiency than previously estimated. This research notes an increase in energy output of up to 35% with the use of dual-axis solar tracking systems. This highlights the significant potential of solar tracker technology to enhance solar energy performance significantly, especially when applied correctly and optimized according to environmental conditions and specific needs.

Furthermore, comparisons with previous research also highlight that higher results in energy efficiency improvements may be due to factors such as more sophisticated system designs, the use of more accurate sensors, and more efficient control algorithms. This emphasizes the importance of continuous innovation and further research in the development of solar tracker technology to maximize the potential of solar energy.

These results underscore the practical advantages of using dual-axis solar tracking systems to enhance photovoltaic energy generation. By dynamically adjusting the orientation of solar panels to track the sun's movement, the system significantly boosts energy efficiency and contributes to the advancement of renewable energy technology. This suggests that further development of solar tracking systems could be a pivotal step in accelerating the transition to clean and sustainable energy sources.

IV. CONCLUSION

This study successfully developed a dual-axis solar tracking system using four LDR sensors and two stepper motors, controlled by an Arduino Uno microcontroller. The research found that solar panels equipped with solar trackers produced, on average, 35% more power than static solar panels. Additionally, the dual tracking system showed a 14% improvement in efficiency compared to the efficiencies reported in previous articles. Measurements of azimuth and elevation angles demonstrated that the solar tracker effectively adjusts the solar panel's position to optimize solar energy absorption. During peak power generation, the optimal angles were an azimuth angle of 206.33° and an elevation angle of 63.61°.

Comparison with previous research shows consistent findings that the use of dual-axis solar tracking systems significantly increases the efficiency of solar panel energy collection. This highlights the substantial potential of solar tracker technology in improving solar energy performance.

It is recommended that future research include broader testing with variations in weather and environmental conditions to evaluate system performance in more realistic scenarios. Additionally, further research should focus on developing more sophisticated control algorithms to enhance the responsiveness and precision of the solar tracking system. By doing so, we can continue to refine and optimize solar tracker technology, maximizing the potential of solar energy and supporting the transition toward a more sustainable society.

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