

DESIGN AND CONSTRUCTION OF A DUAL-AXIS SOLAR TRACKING SYSTEM WITH UV AND LDR SENSORS ON AN ARDUINO-BASED SOLAR PANEL FOR A 50-WATT LOAD CAPACITY

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ABSTRACT

Keywords:

Dual-Axis
Solar Tracking
Arduino Mega 2560
LDR Sensor
ML8511 UV Sensor
Photovoltaic System

The utilization of solar energy as a renewable energy source in Indonesia remains suboptimal because static solar panels cannot follow the apparent movement of the sun. This condition can reduce solar irradiance absorption, particularly in the morning and afternoon, resulting in lower solar panel output power and less effective battery charging. This study aims to design and test a dual-axis solar tracking system based on an Arduino Mega 2560 to improve solar radiation absorption on a 100 Wp monocrystalline solar panel with a 50 W DC LED lamp load. The research employed a Research and Development (R&D) method with a quantitative descriptive approach. The system uses four Light Dependent Resistor (LDR) sensors to detect the direction of incoming sunlight and control the movement of the panel along the azimuth and elevation axes using two NEMA 23 stepper motors driven by TB6600 drivers. An ML8511 Ultraviolet (UV) sensor is used to monitor changes in ultraviolet radiation intensity during the tracking process. The system is equipped with a 12 V 100 Ah LiFePO4 battery and a Solar Charge Controller (SCC). Testing was conducted for seven days from 08:00 to 16:00 WIB by comparing the performance of the dual-axis solar tracking system with a static solar panel. The results showed that the dual-axis solar tracking system produced an average irradiance of 753.36 W/m², UV intensity of 4.39 mW/cm², and output power of 59.42 W, compared with 592.16 W/m² and 46.58 W, respectively, for the static solar panel. The tracking system also generated 3.33 kWh of electrical energy, compared with 2.61 kWh for the static system, resulting in an energy difference of 0.72 kWh over the seven-day testing period. The higher output power also increased the battery charging current, resulting in faster charging of the 12 V 100 Ah LiFePO4 battery. These results indicate that the proposed dual-axis solar tracking system can improve solar irradiance absorption, electrical energy production, and battery charging performance compared with a static solar panel.

INTRODUCTION

The increasing demand for renewable energy and the need to reduce dependence on fossil fuels have encouraged the development of more effective solar energy utilization technologies. Indonesia has significant potential for solar energy utilization because of its tropical climate and relatively high solar radiation throughout the year. The average solar radiation potential in Indonesia reaches approximately 4.8 kWh/m²/day, indicating that photovoltaic (PV) technology has considerable potential for electricity generation (Sandra Dewi et al., 2025). However, the performance of a fixed PV panel is influenced by the position of the sun, which continuously changes from east to west during the day. Consequently, the angle of incident solar radiation on the PV surface is not always optimal, particularly in the morning and afternoon. Solar tracking systems have been developed to overcome this limitation by adjusting the position of the PV panel according to the direction of sunlight. A dual-axis solar tracking system can provide movement in both horizontal and vertical directions, allowing the PV panel to follow the apparent movement of the sun more effectively than a fixed or single-axis system. Several studies have demonstrated that solar tracking can increase the amount of solar radiation received by PV panels and improve their electrical output (Wijaya et al., 2021; Sudibyo et al., 2021).

Light-dependent resistor (LDR) sensors are commonly used in solar tracking systems because they can detect differences in light intensity from different directions and provide a simple method for determining the direction of movement of the panel.

However, an LDR-based tracking system primarily functions to detect differences in visible light intensity and determine the direction of the PV panel. It does not provide additional information regarding ultraviolet (UV) radiation received during the tracking process. Previous research on dual-axis solar tracking using LDR and UV sensors has shown the potential of combining these sensors for solar energy applications (Sasmita & Widyartono, 2020). Nevertheless, the previous system was implemented on a relatively small 20 Wp PV panel with a 12 V DC load. Therefore, further development is required to implement a dual-axis tracking system on a larger PV system while incorporating UV monitoring as supporting measurement data.

Based on this condition, this research develops an Arduino-based dual-axis solar tracking system using four LDR sensors to determine the direction of sunlight and an ML8511 sensor to monitor UV intensity. The system uses an Arduino Mega 2560 as the main controller and two stepper motors to control the horizontal and vertical axes of the PV panel. The LDR sensors are used as the main input for the tracking mechanism, while the ML8511 sensor is used for UV intensity monitoring and data logging rather than as a control parameter. The developed system is implemented using a 100 Wp monocrystalline PV panel with a 50 W electrical load. The performance of the proposed system is evaluated by comparing solar irradiance, visible light intensity, UV intensity, electrical power, and energy production with a fixed PV panel. This research is expected to provide a practical dual-axis solar tracking system that can improve PV energy utilization while providing additional UV monitoring data during operation.

RESEARCH METHOD

This research used a Research and Development (R&D) method to design, develop, and test a dual-axis solar tracking system based on Arduino. The developed system was designed to optimize the orientation of a photovoltaic panel toward the direction of incoming sunlight. Four Light Dependent Resistor (LDR) sensors arranged in a quadrant configuration were used to detect differences in light intensity on the horizontal and vertical axes. The detected differences were processed by an Arduino Mega 2560 to control two stepper motors through their respective drivers, enabling the photovoltaic panel to adjust its position on the azimuth and elevation axes. An ML8511 sensor was also integrated into the system to monitor ultraviolet (UV) radiation intensity during the measurement process. The system was designed to supply a 50 W DC load. The system performance was evaluated through experimental testing by comparing the photovoltaic panel equipped with the dual-axis tracking system with a panel installed in a fixed position. Measurements were conducted from 08:00 to 16:00 Western Indonesian Time (WIB) using several parameters, including solar irradiance, light intensity, UV radiation intensity, photovoltaic output power, and electrical energy generated. The obtained data were analyzed using a descriptive quantitative method by calculating the measured values, average values, and percentage differences between the tracking and fixed systems. The

results were subsequently presented in tables and graphs to evaluate the performance of the developed dual-axis solar tracking system and determine its effectiveness in improving photovoltaic energy utilization.

Research Steps

This research was carried out through several systematic stages, beginning with problem identification and literature study, followed by system design, hardware and software development, system integration, testing, and data collection. The collected data were then analyzed quantitatively and discussed to evaluate the performance of the developed dual-axis solar tracking system. The flowchart illustrating the stages of the research methodology is presented in Figure 1.

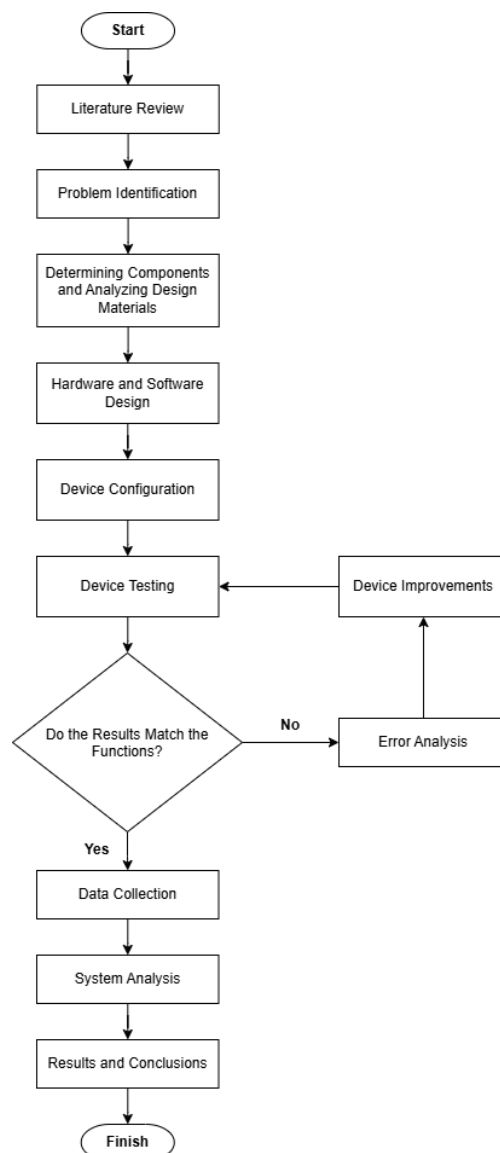


Figure 1. Research Flow Chart
Source : Personal Documents

Here is an explanation of each step in the flowchart:

1. The literature review is part of the data collection process, involving information gathered from books and journals to assist in the development of this research.
2. Problem identification was conducted to determine the issues that arise with statically mounted solar panels in relation to the sun's movement.
3. Component selection and design material analysis were performed following the literature review by calculating component requirements using formulas from previous books and journals.
4. Hardware and software design were carried out after performing calculations on the components and analyzing the design materials used, followed by software design.
5. Device configuration was performed to ensure that each component functions as intended.
6. Equipment testing is conducted to verify that the solar tracking system's performance aligns with the calculations and that the components are functioning correctly.
7. An error analysis of the device must be conducted to determine whether the device functions as intended. However, if an error occurs, corrective measures will be taken; if the device functions as intended, data collection will proceed.
8. Data collection must be conducted through observations during the study using an observation sheet.
9. The system analysis used in this study employs an analytical technique that compares the use of the solar tracking system with UV sensors and LDR sensors based on predetermined parameter data against a static solar panel.
10. Results and conclusions are essential steps for determining the outcomes of the research based on the research data.

Overall Schematic Block Diagram

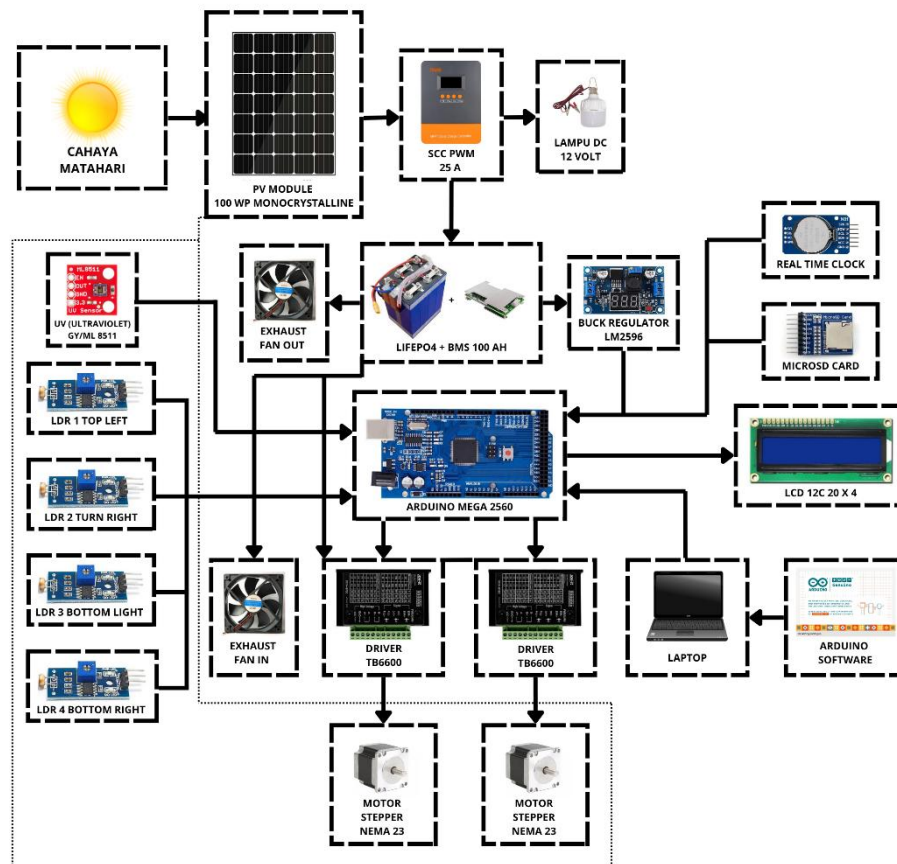


Figure 2. Block Diagram Configuration of the Device
Source : Personal Documents

The block diagram provides a comprehensive overview of the interconnections and operating flow of the components used in the Arduino-based dual-axis solar tracking system. The system uses a 100 Wp monocrystalline PV module as the primary energy source, which is connected to a 25 A PWM Solar Charge Controller (SCC) to regulate the charging of the 12 V 100 Ah LiFePO₄ battery and supply the 12 V DC lamp load. The Arduino Mega 2560 functions as the main controller, receiving inputs from four LDR sensors consisting of top-left, top-right, bottom-left, and bottom-right LDRs to detect differences in sunlight intensity along the horizontal and vertical axes. Based on the detected light intensity differences, the Arduino controls two TB6600 drivers, which drive two NEMA 23 stepper motors to adjust the photovoltaic panel position along the horizontal and vertical axes. The ML8511 UV (Ultraviolet) sensor is used to monitor ultraviolet radiation intensity during the testing process. The system is also equipped with an RTC module for time-based operation, a microSD card module for data storage, and an LCD I2C 20×4 for displaying measurement data and system conditions. An LM2596 buck converter is used to regulate the voltage supplied to the electronic components, while exhaust fans are used to provide cooling for the system components. System programming

and configuration are performed using the Arduino IDE through a laptop. The overall block diagram of the developed dual-axis solar tracking system is presented in Figure 2.

Single Line Diagram Solar Power Plant

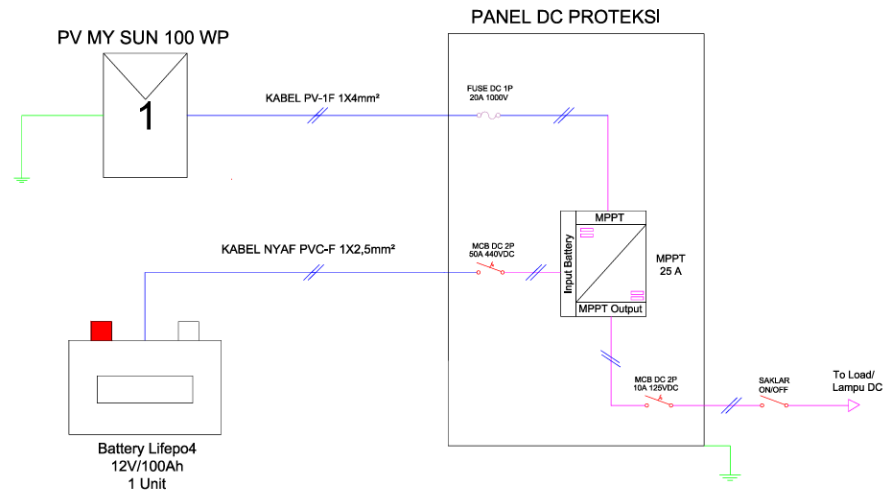


Figure 3. Single Line Diagram Solar Power Plant
Source : Personal Documents

The single-line diagram in Figure 3. illustrates the configuration of the Solar Power Plant (PV system) used as the energy source for the dual-axis solar tracking system. The system employs a 100 Wp MY SUN monocrystalline photovoltaic module as the primary energy source, which delivers electrical power through a 1×4 mm² PV-F cable to a 1P 20 A/1000 VDC DC fuse for protection on the photovoltaic side. The generated power is then supplied to a 25 A MPPT Solar Charge Controller through a 2P 50 A/440 VDC DC circuit breaker to regulate and optimize the battery charging process. The stored energy in the 12 V 100 Ah LiFePO₄ battery is subsequently distributed to the DC load through a 2P 10 A/250 VDC DC circuit breaker and an ON/OFF switch. In addition to supplying the DC lamp load, the battery also serves as the power source for the solar tracking control system. The 12 V battery voltage is stepped down to 5 V using a buck converter to meet the voltage requirements of the electronic components, particularly the Arduino Mega 2560, DS3231 RTC, and Micro SD Card module, which are used for system control, time management, and test-data storage, respectively. The battery also supplies two 12 V exhaust fans installed inside the panel box to improve air circulation and maintain a suitable operating temperature for the electronic components during the 8-hour daily operation. This configuration integrates power generation, electrical protection, charge regulation, energy storage, and power distribution to the control system and loads, thereby supporting the integrated operation of the dual-axis solar tracking system.

Solar Tracking Schematic Cable Diagram

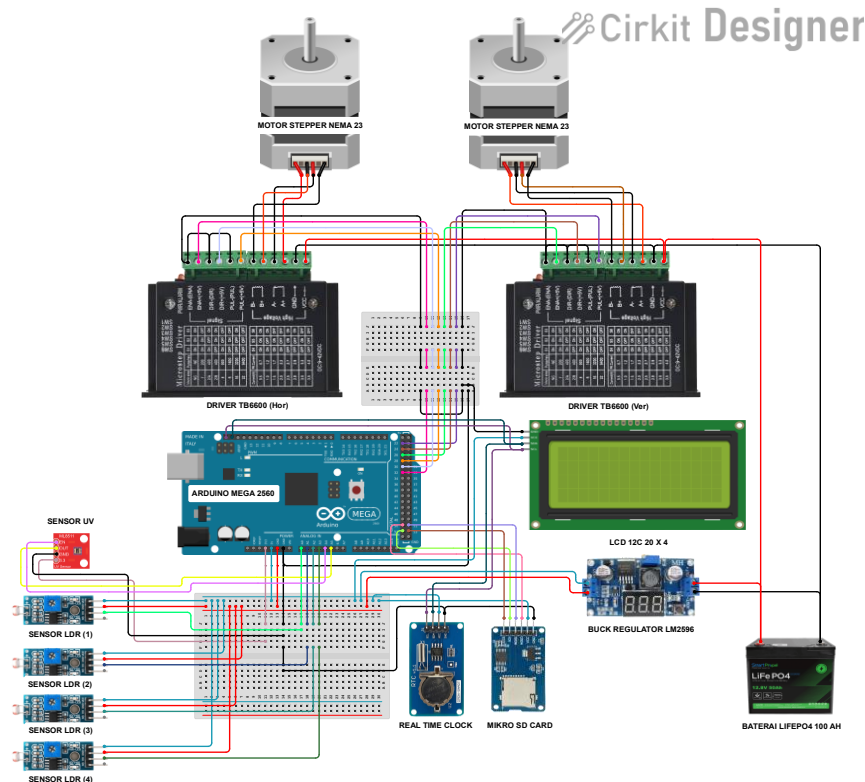


Figure 4. Wiring Diagram Solar Tracking of the Device
Source : Personal Documents

The wiring diagram illustrates the electrical connections of the Arduino-based dual-axis solar tracking system and shows the integration of the main control, sensing, actuator, monitoring, and data storage components. The Arduino Mega 2560 functions as the main controller, receiving input signals from four LDR sensors and the ML8511 UV sensor. The LDR sensors are used to detect differences in sunlight intensity to determine the panel position, while the UV sensor is used to monitor ultraviolet radiation during the measurement process. The Arduino controls two TB6600 drivers, which drive two NEMA 23 stepper motors to adjust the photovoltaic panel position along the horizontal and vertical axes. The system is also equipped with an RTC module for time-based operation, a microSD card module for data recording, and a LCD I2C 20 × 4 for displaying system information. An LM2596 buck regulator is used to regulate the voltage supplied to the electronic components from the 12 V 100 Ah LiFePO₄ battery. The wiring configuration is designed to ensure proper communication and power distribution among the components, enabling the system to perform automatic panel positioning, monitoring, and data recording during operation.

RESULTS AND DISCUSSION

This research resulted in an Arduino Mega 2560-based dual-axis solar tracking system designed to increase solar radiation received by the solar panel. Tests were conducted on several key aspects, namely solar panel performance with tracking and fixed configurations, solar irradiance, light intensity, UV intensity, electrical power output, and generated energy.

Results of the Tools Design



Figure 5. Overall View Results of the Dual-Axis Solar Tracking
Source : Personal Documents



Figure 6. Solar Tracking Control Box Panel
Source : Personal Documents



Figure 7. Dual-Axis Solar Tracking Mechanism
Source : Personal Documents

Software Configuration and System Operation



Figure 8. LCD Display to Monitor Tracking Operations
Source : Personal Documents

The software was developed using an Arduino Mega 2560 to control the dual-axis solar tracking system. At the beginning of operation, the system initializes the RTC DS3231, LCD I2C 20×4, four LDR sensors, ML8511 ultraviolet sensor, TB6600 stepper motor drivers, and SD card. The system then reads the real-time clock to determine the operating period from 08:00 to 16:00 WIB. During the tracking period, the four LDR sensors measure the incoming light intensity, while the ML8511 sensor is used only to monitor and record ultraviolet intensity. The average values of the top, bottom, left, and right LDRs are calculated to obtain the horizontal (DiffH) and vertical (DiffV) differences. When the absolute value of DiffH or DiffV exceeds the threshold value of 20, the corresponding stepper motor is activated to adjust the horizontal or vertical position of the solar panel toward the stronger light direction.



Figure 9. LCD Display to Monitor Parking Operations
Source : Personal Documents

Outside the operating period, the system enters parking mode. The accumulated horizontal and vertical motor steps are used to calculate the required return movements to the initial position. The system displays the time, UV intensity, and operating status on the LCD, while tracking data and UV intensity data are recorded on the SD card for further analysis. After the horizontal and vertical motors complete the return process, the solar panel reaches its initial position, and the operating cycle is completed.

Seven-Day Solar Panel Test Results

The next stage involved data collection to determine the performance difference between the developed dual-axis solar tracking system and the fixed solar panel configuration. Testing was conducted outdoors for seven days, from 08:00 to 16:00 WIB, under sunny and partly cloudy conditions. The solar panel performance was compared between tracking and fixed positions based on variations in solar radiation and electrical output.

1. First-Day Testing of Solar Panel Performance Results

Table 1. First Day Solar Tracking Measurement Testing

Testing Solar Tracking								
No	Time (WIB)	Weather	Solar Irradiance Meter (W/m ²)	Lux Meter (Lux/m ²)	Sensor UV (mW/cm ²)	Multimeter		Power (Watt)
						(Volt)	(Ampere)	
1.	08.00 - 09.00	Bright	735,6	97610	2,62	18,71	3,36	62,8656
2.	09.00 - 10.00	Bright	726,3	127000	3,81	18,42	3,65	67,233
3.	10.00 - 11.00	Bright	866,2	155900	5,23	18,14	4,23	76,7322
4.	11.00 - 12.00	Bright	867,3	163300	4,78	18,15	4,49	81,4935
5.	12.00 - 13.00	Bright	866,1	166200	5,03	18,16	4,26	77,3616
6.	13.00 - 14.00	Bright	822,8	140500	5,07	18,00	4,24	76,32
7.	14.00 - 15.00	Bright	705,3	103600	5,52	18,52	3,60	66,672
8.	15.00 - 16.00	Bright	524,6	46040	3,85	18,39	2,46	45,2394
Average Power Generated								69,24

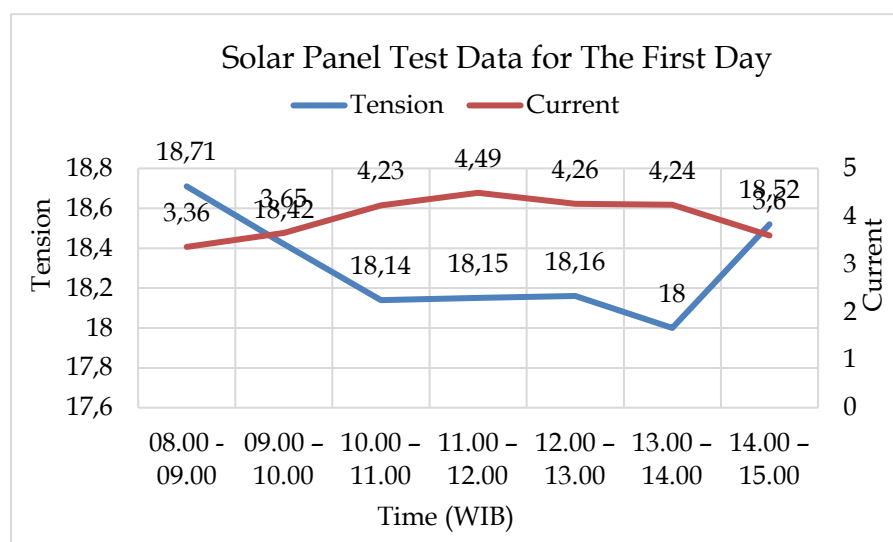


Figure 10. Current and Voltage Graph of Solar Tracking on the First Day
Source : Personal Documents

Table 2. First Day of Non-Solar Tracking Measurement Testing

Testing Non Solar Tracking						
No	Time (WIB)	Weather	Solar Irradiance Meter (W/m ²)	Multimeter		Power (Watt)
				(Volt)	(Ampere)	
1.	08.00 - 09.00	Bright	640,4	17,90	3,08	55,132
2.	09.00 - 10.00	Bright	668,8	18,35	3,48	63,858
3.	10.00 - 11.00	Bright	805,3	17,87	3,70	66,119
4.	11.00 - 12.00	Bright	813,8	17,91	4,11	73,6101
5.	12.00 - 13.00	Bright	710,8	18,05	3,79	68,4095
6.	13.00 - 14.00	Bright	603,2	18,19	3,14	57,1166
7.	14.00 - 15.00	Bright	464,7	18,20	2,95	53,69
8.	15.00 - 16.00	Bright	279,3	18,58	1,43	26,5694
Average Power Generated						58,06

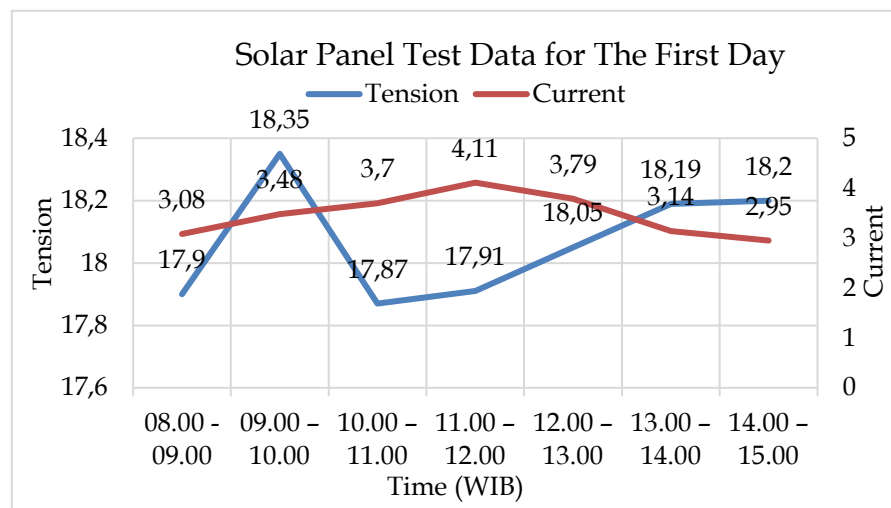


Figure 11. Non-Solar Tracking Current and Voltage Graph Day One
Source : Personal Documents

The first-day testing was conducted as an initial comparison between the solar panel performance with and without the dual-axis solar tracking system. The test was carried out from 08:00 to 16:00 WIB under bright weather conditions, with measurements recorded at one-hour intervals. The parameters measured in the solar tracking test included solar irradiance, visible light intensity, UV intensity, voltage, current, and power, while the non-tracking test focused on solar irradiance, voltage, current, and power. Based on the first-day measurements, the solar tracking system produced an average power output of 69.24 W, while the non-tracking condition produced 58.06 W. The tracking condition therefore resulted in an average power difference of 11.18 W, or approximately 19.26% higher than the non-tracking condition. The highest power output with tracking was 81.49 W at 11:00–12:00 WIB, with a solar irradiance of 867.3 W/m². Meanwhile, the highest power output without tracking was 73.61 W at the same time interval, with an irradiance of 813.8 W/m².

The difference in output became more noticeable during the afternoon. At 15:00–16:00 WIB, the tracking system generated 45.24 W at an irradiance of 524.6 W/m², whereas the non-tracking system generated only 26.57 W at an irradiance of 279.3 W/m². This result illustrates the effect of maintaining the panel orientation as the apparent position of the sun changes throughout the day. The tracking system was able to maintain a more favorable orientation, while the fixed panel experienced a greater reduction in solar energy received during the afternoon. These first-day results serve as an example of the hourly performance comparison between the tracking and non-tracking conditions. The data from this initial test are then used as part of the overall evaluation, while the subsequent seven-day testing results are presented using aggregated data to describe the general performance of the developed solar tracking system.

2. Average Results of Solar Panel Performance Test Over Seven Days

Table 3. Average Results of Solar Tracking Power Measurements Over 7 Days

Average Testing Solar Tracking								
No	Time (WIB)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1.	08.00 - 09.00	62,8656	62,4246	66,0024	62,9703	78,912	75,6378	61,0408
2.	09.00 - 10.00	67,233	68,838	33,1116	68,0785	79,639	81,087	77,873
3.	10.00 - 11.00	76,7322	73,5672	38,961	81,718	77,1975	83,49	38,7348
4.	11.00 - 12.00	81,4935	71,1693	37,185	81,928	80,1175	80,344	35,0784
5.	12.00 - 13.00	77,3616	75,4208	34,8425	78,7086	33,1936	78,2691	39,0246
6.	13.00 - 14.00	76,32	75,39	33,6338	88,2156	29,348	69,125	36,2408
7.	14.00 - 15.00	66,672	64,9873	32,7956	61,116	28,476	62,53	33,3135
8.	15.00 - 16.00	45,2394	50,6275	34,475	43,8275	30,845	44,6974	20,1285
Total Power/Day		69,24	67,80	38,75	70,82	54,72	71,90	42,68

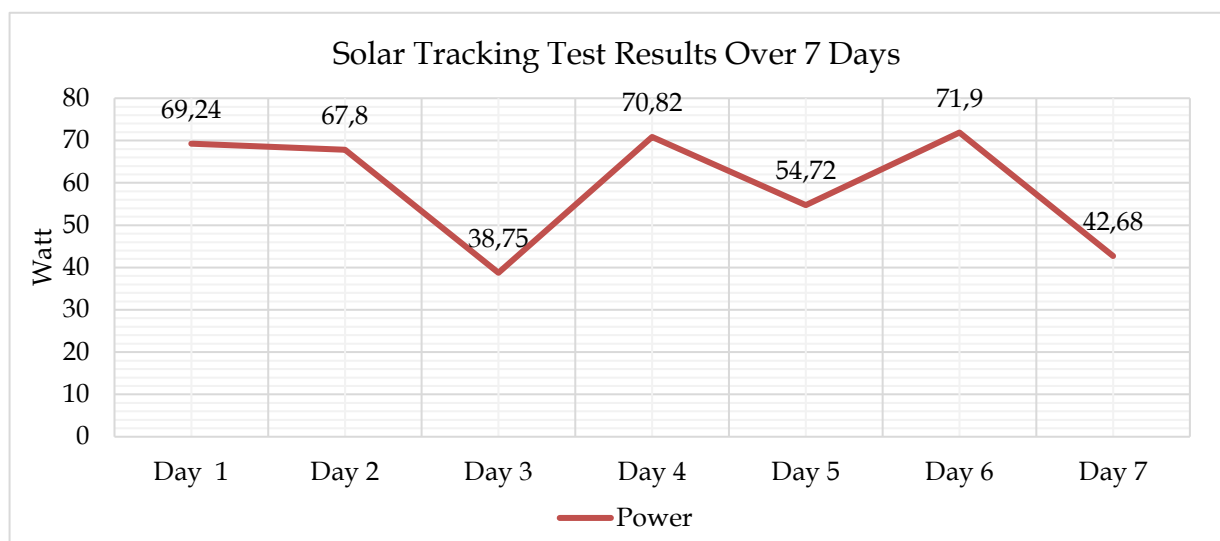


Figure 12. Average Results of Solar Tracking Power Testing Over 7 Days

Source : Personal Documents

Next, the average value of the electric power generated by the solar panel is calculated based on all the power measurement results over the 7-day testing period. The calculation is done by adding up all the power values obtained at each measurement interval, then dividing it by the number of measurement data. The calculation was performed as follows:

$$\begin{aligned} \text{It is known} &= \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7}{7} \\ &= \frac{69,24 + 67,80 + 38,75 + 70,82 + 54,72 + 71,90 + 42,68}{7} \\ &= \frac{415,91}{7} \\ &= 59,415714 \approx 59,42 \text{ Watt.} \end{aligned}$$

Based on those calculations, the average power value obtained is 59.415714 W. After rounding to two decimal places, the average power value comes out to 59.42 W.

Table 4. Average Results of Visible Light Radiation Intensity from Solar Tracking Over 7 Days

Sensor Testing Light Dependent Resistor (LDR) (Lux/m ²)								
No	Time (WIB)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1.	08.00 - 09.00	97610	83780	87980	80,280	154,000	156,200	135,300
2.	09.00 - 10.00	127000	118700	118900	124,900	174,900	181,900	165,600
3.	10.00 - 11.00	155900	153700	133400	126,200	171,200	182,700	169,900
4.	11.00 - 12.00	163300	123700	123400	177,300	182,800	164,100	177,900
5.	12.00 - 13.00	166200	143500	133900	173,900	177,900	168,500	154,300
6.	13.00 - 14.00	140500	142900	141100	169,800	163,700	163,000	142,700
7.	14.00 - 15.00	103600	90880	119500	124,900	137,500	131,000	104,600
8.	15.00 - 16.00	46040	40560	398100	73,900	86,750	65,440	36,220
Average Radiation Visible Light		125,01	112,21	157,03	131,40	156,09	151,61	135,82

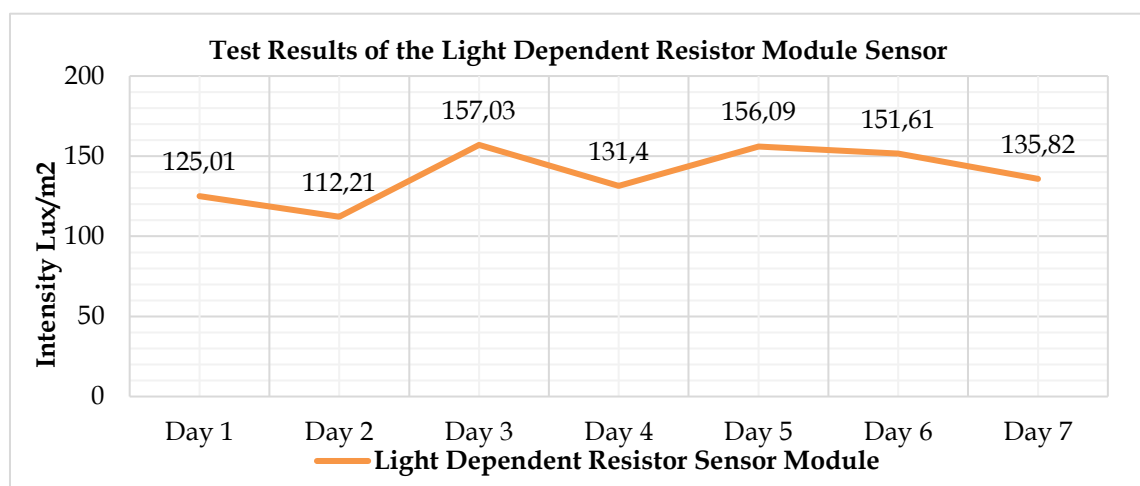


Figure 13. Average Test Results of the Light Dependent Resistor Sensor Module Over 7 Days
Source : Personal Documents

Design And Construction Of A Dual-Axis Solar Tracking System With UV And LDR Sensors On An Arduino-Based Solar Panel For A 50-Watt Load Capacity

The LDR sensor was tested for seven days to see how it reacts to changes in sunlight. The sensor readings were compared with a lux meter as a benchmark. From the test results, we got the average visible light intensity over the seven days, which we used to evaluate the LDR sensor's performance. Here are the average visible light intensity results from the seven days of testing. The calculation was performed as follows:

$$\begin{aligned}
 \text{It is known} &= \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7}{7} \\
 &= \frac{125,018 + 112,215 + 157,035 + 131,40 + 156,09 + 151,61 + 135,82}{7} \\
 &= \frac{969,188}{7} \\
 &= 138,455428 \approx 138,46 \text{ Lux/m}^2.
 \end{aligned}$$

Table 5. Average Results of Ultraviolet Radiation Intensity from Solar Tracking Over 7 Days

Ultraviolet Sensor Testing (UV) ML8511 (mW/cm ²)								
No	Time (WIB)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1.	08.00 - 09.00	2,62	3,48	2,83	2,83	2,75	2,05	2,99
2.	09.00 - 10.00	3,81	5,03	5,03	3,56	5,88	5,76	5,39
3.	10.00 - 11.00	5,23	3,92	5,35	5,39	6,05	5,52	5,43
4.	11.00 - 12.00	4,78	3,64	4,38	4,09	3,44	4,53	4,87
5.	12.00 - 13.00	5,03	4,99	4,09	4,94	5,15	5,03	5,19
6.	13.00 - 14.00	5,07	5,35	4,70	4,82	4,91	4,91	4,50
7.	14.00 - 15.00	5,52	3,68	4,87	5,27	5,15	4,62	4,21
8.	15.00 - 16.00	3,85	1,11	3,85	3,56	4,05	3,77	3,15
Average Ultraviolet Radiation		4,49	3,90	4,39	4,30	4,67	4,52	4,47

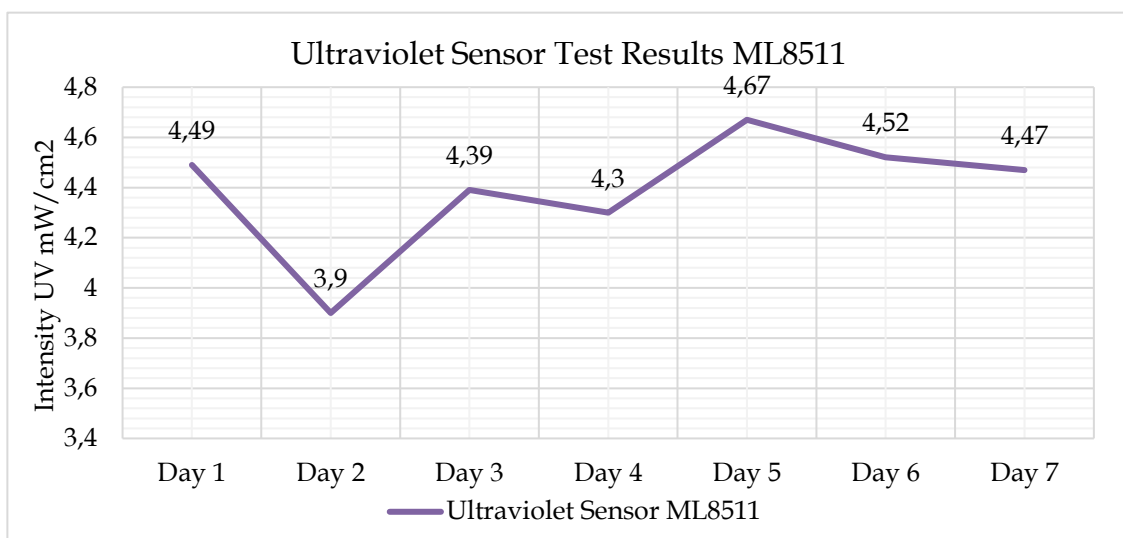


Figure 14. Average Test Results of the ML8511 Ultraviolet (UV) Sensor Over 7 Days
Source : Personal Documents

Design And Construction Of A Dual-Axis Solar Tracking System With UV And LDR Sensors On An Arduino-Based Solar Panel For A 50-Watt Load Capacity

The UV sensor ML8511 was tested over seven days to see how the sensor responds to changes in ultraviolet radiation intensity during the testing period. The sensor readings were recorded in mW/cm² at each measurement time and used to observe changes in UV intensity throughout the testing process. Based on the test results, the average UV intensity in mW/cm² over the seven days was obtained, which serves as the basis for evaluating the performance of the ML8511 sensor. Here are the average UV intensity results over the seven days of testing.

$$\begin{aligned}
 \text{It is known} &= \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7}{7} \\
 &= \frac{4,49 + 3,90 + 4,39 + 4,30 + 4,67 + 4,52 + 4,47}{7} \\
 &= \frac{30,74}{7} \\
 &= 4,391428 \approx 4,39 \text{ mW/cm}^2.
 \end{aligned}$$

Table 6. Average Solar Tracking Irradiance Absorption Over 7 Days

Solar Irradiance Meter Testing (W/m ²) Solar Tracking								
No	Time (WIB)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1.	08.00 - 09.00	735,6	713,5	734,4	717,1	868,5	823,3	760,4
2.	09.00 - 10.00	726,3	814,3	853,4	752,9	828,3	919,0	857,2
3.	10.00 - 11.00	866,2	806,8	826,4	824,7	849,9	911,8	865,0
4.	11.00 - 12.00	867,3	747,5	786,5	834,8	881,2	825,2	888,9
5.	12.00 - 13.00	866,1	812,5	806,8	890,3	838,6	839,8	838,6
6.	13.00 - 14.00	822,8	818,8	782,9	789,7	775,4	798,8	756,9
7.	14.00 - 15.00	705,3	682,0	677,8	647,0	658,0	666,6	580,0
8.	15.00 - 16.00	524,6	525,8	410,6	466,5	479,3	502,5	337,7
Average Irradiance		764,28	740,15	734,85	740,38	772,40	785,88	735,59

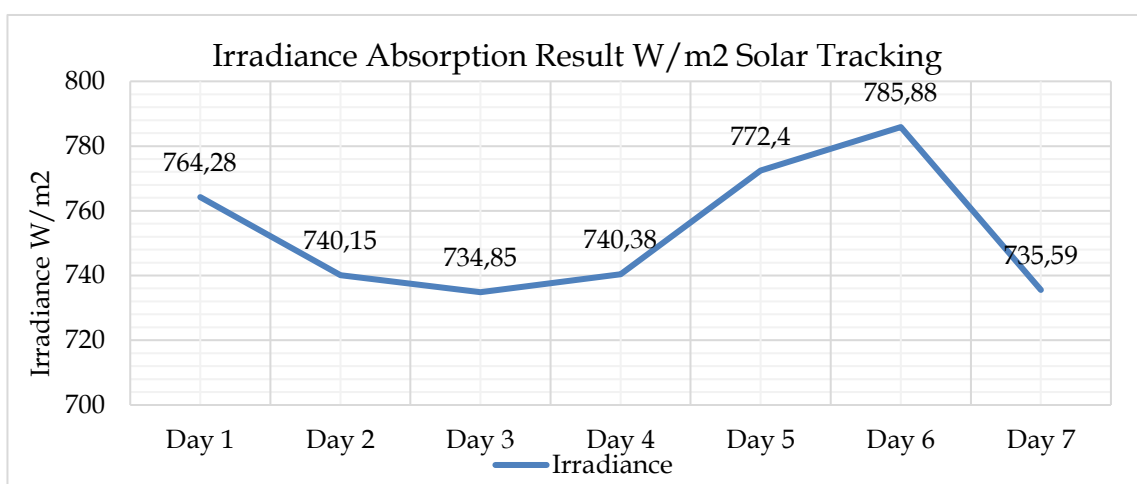


Figure 15. Average Solar Tracking Irradiance Absorption Over 7 Days
Source : Personal Documents

Design And Construction Of A Dual-Axis Solar Tracking System With UV And LDR Sensors On An Arduino-Based Solar Panel For A 50-Watt Load Capacity

The intensity of solar radiation was measured using an irradiance meter over seven days and recorded in W/m². The data were averaged for each day to show the daily solar radiation intensity. These daily averages were then used to assess the solar irradiation conditions during the seven days of solar panel testing.

$$\begin{aligned}
 \text{It is known} &= \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7}{7} \\
 &= \frac{764,28 + 740,15 + 734,85 + 740,38 + 772,40 + 785,88 + 735,59}{7} \\
 &= \frac{5273,53}{7} \\
 &= 753,36 \text{ W/m}^2.
 \end{aligned}$$

Based on seven days of testing, the average solar radiation intensity was 753.36 W/m² on the solar tracking system. Next up are the non-solar tracking data, which include average power and irradiance to see how the two sets of data compare.

Table 7. Average Measurement Power Non Solar Tracking Over 7 Days

No	Time (WIB)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1.	08.00 - 09.00	55,132	48,097	39,20	51,264	42,5646	35,7344	36,7866
2.	09.00 - 10.00	63,858	60,6685	20,16	60,72	67,528	62,859	19,451
3.	10.00 - 11.00	66,119	70,8369	20,82	58,2294	66,4686	76,896	20,8678
4.	11.00 - 12.00	73,6101	79,2527	21,00	72,7592	71,56	73,4868	20,7442
5.	12.00 - 13.00	68,4095	69,9811	20,4714	74,55	55,233	65,504	21,6540
6.	13.00 - 14.00	57,1166	60,1250	21,1260	56,4339	54,8432	56,0252	20,9144
7.	14.00 - 15.00	53,69	50,703	36,396	46,3616	52,416	42,224	21,1575
8.	15.00 - 16.00	26,5694	26,0260	23,424	24,7725	22,7427	25,7011	17,4414
Total Power /Day		58,06	58,21	22,82	55,63	54,16	54,80	22,37

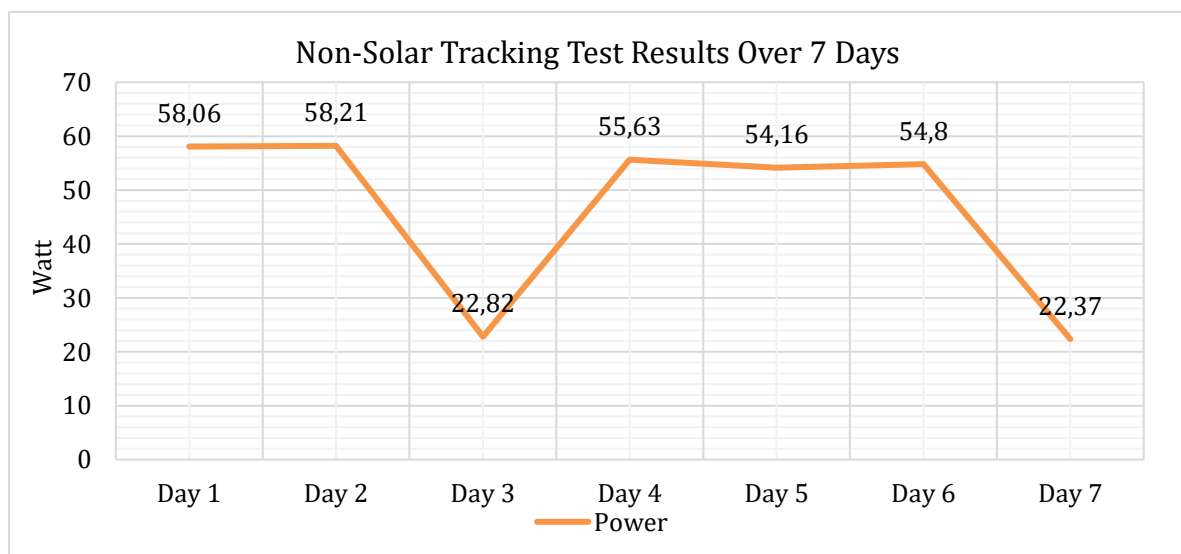


Figure 16. Average Power Results of Testing Without Solar Tracking Over 7 Days
Source : Personal Documents

Design And Construction Of A Dual-Axis Solar Tracking System With UV And LDR Sensors On An Arduino-Based Solar Panel For A 50-Watt Load Capacity

The non-solar tracking test was conducted to evaluate the performance of the solar panel without the dual-axis tracking system. Measurements were carried out from 08:00 to 16:00 WIB at one-hour intervals under the same testing conditions. The measured parameters included solar irradiance, voltage, current, and power. The collected data were used to determine the average power output of the solar panel under non-tracking conditions.

$$\begin{aligned}
 \text{It is known} &= \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7}{7} \\
 &= \frac{58,06 + 58,21 + 22,82 + 55,63 + 54,16 + 54,80 + 22,37}{7} \\
 &= \frac{326,05}{7} \\
 &= 46,57857143 \approx 46,58 \text{ Watt.}
 \end{aligned}$$

Table 8. Average Irradiance Results Non Solar Tracking Over 7 Days

Testing a Solar Irradiance Meter (W/m ²) Non Solar Tracking								
No	Time (WIB)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1.	08.00 - 09.00	640,4	430,2	412,1	485,4	520,2	412,4	501,4
2.	09.00 - 10.00	668,8	538,1	578,4	503,1	601,8	618,8	608,8
3.	10.00 - 11.00	805,3	709,8	708,9	509,1	805,3	822,3	705,3
4.	11.00 - 12.00	813,8	829,6	803,1	865,6	816,8	844,8	802,8
5.	12.00 - 13.00	710,8	723,1	763,4	803,0	717,8	850,8	720,8
6.	13.00 - 14.00	603,2	623,2	612,7	708,1	788,2	613,2	601,2
7.	14.00 - 15.00	464,7	364,7	468,2	654,1	467,7	464,7	365,7
8.	15.00 - 16.00	279,3	259,3	245,4	269,1	241,3	209,3	206,3
Average Irradiance		623,28	559,75	574,02	599,68	619,88	604,53	564,03

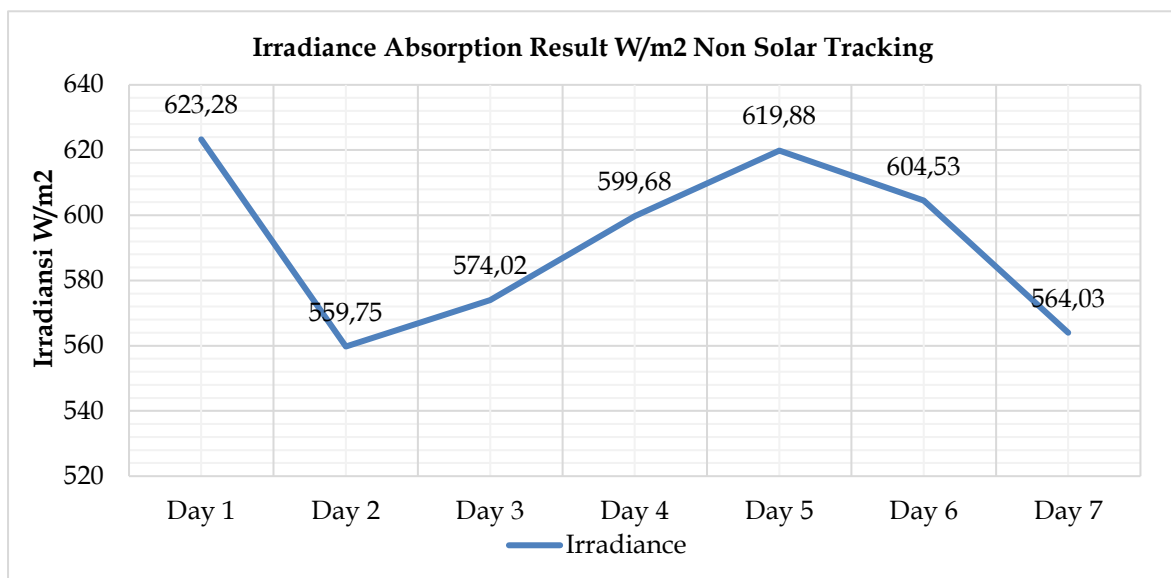


Figure 17. Average Non-Solar Tracking Irradiance Over 7 Days
Source : Personal Documents

The non-solar tracking test was conducted to measure the solar radiation intensity received by the fixed solar panel without the dual-axis tracking system. Measurements were taken from 08:00 to 16:00 WIB at one-hour intervals using an irradiance meter and recorded in W/m². The data were used to determine the average solar radiation intensity under non-tracking conditions, calculated using the following equation.

$$\begin{aligned} \text{It is known} &= \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7}{7} \\ &= \frac{623,28 + 559,75 + 574,02 + 599,68 + 619,88 + 604,53 + 564,03}{7} \\ &= \frac{4145,17}{7} \\ &= 592,16 \text{ W/m}^2. \end{aligned}$$

Based on the seven-day testing results, the implementation of the dual-axis solar tracking system increased the solar radiation received and the power output of the solar panel compared with the non-tracking condition. The average irradiance received by the panel with solar tracking reached 753.36 W/m², while the non-solar tracking condition recorded 592.16 W/m², resulting in a difference of 161.20 W/m² or approximately 27.22%. The higher irradiance was accompanied by an increase in the average power output from 46.58 W to 59.42 W, representing an increase of 12.83 W (27.52%). In addition, the solar tracking system recorded an average visible light intensity of 138,46 Lux/m² and an average UV intensity of 4.39 mW/cm². After determining the irradiance received by the photovoltaic panel, the electrical energy generated by the solar tracking system was calculated based on the average power output recorded during the seven-day testing period. The calculation was performed to determine the daily energy production of the photovoltaic system under outdoor operating conditions. The daily energy production was calculated using the following equation (Abdillah et al., 2022), The daily energy production was calculated using the following equation:

$$E = P \times t$$

where:

- E = daily energy production (Wh)
- P = average power output (W)
- t = operating duration (h)

It is known that testing was carried out for 8 hours a day for 7 days using a solar tracking system, so the total operating time during the testing can be calculated as follows:

$$t = 8 \times 7 = 56 \text{ Hours}$$

then the energy produced by the solar tracking system is calculated with the following equation:

$$\begin{aligned} E_{ST} &= 59,42 \times 56 \\ &= 3,327,52 \text{ Wh} \\ &= \frac{3.327,52}{1000} \end{aligned}$$

$$= 3,32752 \approx 3,33 \text{ kWh}$$

Description: E_{st} = Solar Tracking Energy (Wh)
 P = Average Power Over 7 days (W)
 t = Operating Hours for 7 days (Hours)

Table 9. Daily Energy Production of the Solar Tracking System

Daily Energy Production (kWh/day)				
No	Day	Average Power (W)	Daily Energy (Wh)	Daily Energy (kWh)
1.	Day 1	69,24	553,92	0,554
2.	Day 2	67,80	542,40	0,542
3.	Day 3	38,75	310,00	0,310
4.	Day 4	70,82	566,56	0,567
5.	Day 5	54,72	437,76	0,438
6.	Day 6	71,90	575,20	0,575
7.	Day 7	42,68	341,44	0,341
Average		59,42	475,33	0,475
Total		59,42	3,327,52	3,327

Based on the daily energy production from the dual-axis solar tracking system, the average power produced over the seven-day test was 59.42 W. Daily energy output varied each day depending on sunlight conditions, with the lowest being 310.00 Wh on day 3 and the highest 575.20 Wh on day 6. On average, the system produced 475.33 Wh or 0.475 kWh per day. Considering the average power generated during the eight hours of operation from 8:00 AM to 4:00 PM, the total energy produced over the seven days amounted to 3,327.52 Wh or 3.327 kWh. These results show that the dual-axis solar tracking system can reliably generate electricity throughout the testing period, although daily energy output varied depending on sunlight availability.

$$\begin{aligned}
 E_{non} &= 46,58 \times 56 \\
 &= 2,608,48 \text{ Wh} \\
 &= \frac{2,608,48}{1000} \\
 &= 2,60848 \approx 2,61 \text{ kWh}
 \end{aligned}$$

Description: E_{non} = Energy Non Solar Tracking (Wh)
 P = Average Power Over 7 days (W)
 t = Operating Hours for 7 days (Hours)

The difference in energy generated during tests with solar tracking and without solar tracking is calculated to see the comparison during the system test:

$$\begin{aligned}\Delta E &= 3,32752 - 2,60848 \\ &= 0,71904 \approx 0,72 \text{ kWh}\end{aligned}$$

Table 10. Daily Energy Production of the Non Solar Tracking System

Daily Energy Production (kWh/day)				
No	Day	Average Power (W)	Daily Energy (Wh)	Daily Energy (kWh)
1.	Day 1	58,06	464.48	0.464
2.	Day 2	58,21	465.68	0.466
3.	Day 3	22,82	182.56	0.183
4.	Day 4	55,63	445.04	0.445
5.	Day 5	54,16	433.28	0.433
6.	Day 6	54,80	438.40	0.438
7.	Day 7	22,37	178.96	0.179
Average		46,58	372.63	0.373
Total		46,58	2,608,48	2,608

The test results show that the dual-axis solar tracking system improved the measured performance compared with the non-tracking system. The average irradiance increased from 592.16 W/m² to 753.36 W/m², while the average UV intensity was 4.39 mW/cm². This improvement contributed to an increase in average output power from 46.58 W to 59.42 W. In terms of energy production, the solar tracking system generated 3.33 kWh during seven days of testing, compared with 2.61 kWh for the non-tracking system, resulting in an energy difference of 0.72 kWh.

Battery Charging and Performance

The battery charging test was conducted to compare the charging performance of the solar tracking and non-solar tracking systems. The test was performed three times on Day 1, Day 4, and Day 6, when the battery required recharging. No load was connected during testing to ensure that the measured current represented the battery charging current through the Solar Charge Controller (SCC). Measurements were recorded from 08:00 to 16:00 WIB at 60-minute intervals, including PV output power, charging current, and battery voltage before and after charging. One representative result is presented in Table 11.

Table 11. Representative Results of Solar Tracking Charge Test on the First Day

Charging Solar Tracking						
No	Time (WIB)	PV Power (Watts)	First Day			Charging Time (Minutes)
			After Current to SCC (A)	Battery Voltage Before (V)	Battery Voltage After (V)	
1.	08.00 - 09.00	62,8656	3,78	18,71	13,82	60
2.	09.00 - 10.00	67,233	4,40	18,42	13,93	60
3.	10.00 - 11.00	76,7322	5,10	18,14	14,04	60
4.	11.00 - 12.00	81,4935	5,13	18,15	14,07	60
5.	12.00 - 13.00	77,3616	5,11	18,16	14,10	60
6.	13.00 - 14.00	76,32	4,85	18,00	14,10	60
7.	14.00 - 15.00	66,672	4,15	18,52	14,02	60
8.	15.00 - 16.00	45,2394	2,86	18,39	13,85	60
Average		69,24	4,42	18,31	13,99	480

Table 12. Representative Results of Non Solar Tracking Charge Test on the First Day

Charging Non Solar Tracking						
No.	Time (WIB)	PV Power (Watts)	First Day			Charging Time (Minutes)
			After Current to SCC (A)	Battery Voltage Before (V)	Battery Voltage After (V)	
1.	08.00 - 09.00	55,132	3,58	17,90	13,89	60
2.	09.00 - 10.00	63,858	4,17	18,35	13,65	60
3.	10.00 - 11.00	66,119	4,80	17,87	13,69	60
4.	11.00 - 12.00	73,6101	4,88	17,91	13,71	60
5.	12.00 - 13.00	68,4095	4,34	18,05	13,72	60
6.	13.00 - 14.00	57,1166	3,79	18,19	13,66	60
7.	14.00 - 15.00	53,69	2,85	18,20	13,58	60
8.	15.00 - 16.00	26,5694	1,58	18,58	13,58	60
Average		58,06	3,74	18,13	13,68	480

Based on the test results presented in Tables 11 and 12, the solar tracking system produced an average PV power of 69.24 W, which was higher than the 58.06 W obtained from the non-solar tracking system. The average charging current supplied to the SCC reached 4.42 A for the solar tracking system, compared with 3.74 A for the non-solar tracking system. During the 480-minute test period, the average battery voltage before charging was 18.31 V for the solar tracking system and 18.13 V for the non-solar tracking system, while the corresponding voltages after charging were 13.99 V and 13.68 V, respectively. These results indicate that the solar tracking system produced higher PV power and charging current than the non-solar tracking system under the test conditions.

Table 13. Comparison of Battery Charging Test Results

No	Parameter	Solar Tracking	Non-Solar Tracking	Difference
1.	Average PV Output	69,24 W	58,06 W	+11,18 W (19,26%)
2.	Battery Average Charge Current	4,42 A	3,74 A	+0,68 A (18,18%)
3.	Battery Voltage Before Charging	18,31 V	18,13 V	+0,18 V (0,99%)
4.	Battery Voltage After a Charge	13,99 V	13,68 V	+0,31 V (2,27%)
5.	Testing Duration	480 Min	480 Min	480 Min

The comparison presented in Table 13 shows that the solar tracking system produced an average PV output of 69.24 W, which was 11.18 W or 19.26% higher than the 58.06 W obtained from the non-solar tracking system. The average charging current also differed by 0.68 A or 18.18%, with values of 4.42 A and 3.74 A for the solar tracking and non-solar tracking systems, respectively. Meanwhile, the average battery voltage before charging differed by 0.18 V (0.99%), while the voltage after charging differed by 0.31 V (2.27%). Both systems were tested for the same duration of 480 minutes. These results indicate that, under the test conditions, the solar tracking system provided higher PV output and charging current than the non-solar tracking system, while the differences in battery voltage were relatively smaller.

Battery Discharging and Performance

Battery discharging and performance testing was conducted to evaluate the battery condition during energy consumption by a connected load. The test aimed to determine the battery voltage variation and the amount of battery capacity used during a predetermined discharge period. The first measurement was performed for 4 hours with the load connected and without PV input, allowing the battery discharge process to be observed independently of solar energy generation. Measurements were recorded periodically to evaluate the battery voltage and discharge performance during the test. The results of the first battery discharge test are presented in Table 14.

Table 14. Battery Discharging Measurement Test

No	Time (Minutes)	Battery Starting Capacity (%)	Battery Capacity Used Load (Ah)	Percent (%)
1.	0 – 30 minute	98	1,010	1,01
2.	30 – 60 minute	1,010	1,896	1,896
3.	60 – 90 minute	1,896	2,914	2,914
4.	90 – 120 minute	2,914	4,236	4,236
5.	120 – 150 minute	4,236	6,321	6,321
6.	150 – 180 minute	6,321	7,319	7,319
7.	180 – 210 minute	7,319	8,362	8,362
8.	210 – 240 minute	8,362	9,362	9,362
Average use				5,18%

Battery discharging and performance testing was conducted to evaluate the reduction in the available capacity of the 100 Ah LiFePO₄ battery during load operation. The battery was initially charged to 98%, and the discharge process was monitored for 240 minutes (4 hours) without PV input. Battery capacity consumption was recorded at 30-minute intervals to determine the cumulative capacity used during system operation. During the test, the cumulative capacity used increased from 1.010 Ah in the first 30 minutes to 9.362 Ah after 240 minutes, corresponding to 9.362% of the total 100 Ah battery capacity. The average capacity used during the measurement intervals was 5.18%. These results indicate that the battery used 9.362 Ah, or 9.362% of its nominal capacity, during 4 hours of load operation.

CONCLUSION

Based on the design, testing, and analysis of the developed dual-axis solar tracking system, the following conclusions can be drawn:

1. The Arduino-based dual-axis solar tracking system was successfully developed according to the proposed design. The system was able to move the solar panel along two axes, namely the azimuth (horizontal) and elevation (vertical) axes, using NEMA 23 stepper motors controlled by four Light Dependent Resistor (LDR) sensors to detect the direction of incoming visible sunlight. Meanwhile, the ML8511 ultraviolet sensor was used to monitor changes in ultraviolet radiation intensity during the testing process. The implementation of LDR sensors for solar panel positioning and the ML8511 sensor for UV monitoring enabled the system to follow the apparent movement of the sun and maintain a more favorable panel orientation toward solar radiation.
2. The dual-axis solar tracking system produced higher electrical output than the fixed solar panel system. Based on seven days of testing, the tracking system achieved an average solar irradiance of 753.36 W/m², an average UV intensity of 4.39 mW/cm², and an average solar panel output power of 59.42 W. In comparison, the non-

tracking system recorded an average solar irradiance of 592.16 W/m² and an average output power of 46.58 W. In terms of energy production, the tracking system generated 3.33 kWh, while the non-tracking system generated 2.61 kWh during the seven-day testing period, resulting in an energy difference of 0.72 kWh. The results indicate that the dual-axis tracking configuration provided higher electrical output than the fixed configuration. However, system performance was affected by the limited battery capacity and cloudy weather conditions, which reduced the available solar irradiance and UV intensity.

3. The higher solar panel output obtained from the dual-axis tracking system resulted in a higher charging current, allowing energy to be delivered to the battery more rapidly than in the non-tracking system. During the seven-day testing period, the battery approached the full-charge condition, causing the Solar Charge Controller (SCC) to automatically limit the charging current. This indicates that battery charging time was influenced not only by the solar panel output power, but also by the battery capacity, solar irradiance, battery temperature, and the current regulation mechanism of the Solar Charge Controller (SCC).

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