

Microcontroller Based Dual Axis Solar Tracker with Internet of Things

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ABSTRACT

Solar energy is one of the most promising renewable energy sources for large-scale development in Indonesia. However, the efficiency of energy absorption in solar panels largely depends on the position and intensity of the sunlight received. This study aims to enhance energy absorption efficiency through the design of a Dual-Axis Solar Tracker system based on an ESP32 microcontroller integrated with the Internet of Things (IoT) platform. The system employs four LDR sensors to detect the direction of sunlight, two servo motors to adjust the panel's position along horizontal and vertical axes, and utilizes the Blynk and Google Sheets applications for real-time monitoring and data logging. Experimental testing was conducted under clear weather conditions at Sparco Anak Air Residence, Jl. Bypass Batipuh Panjang, Koto Tengah, on September 24, 2025, from 10:00 to 12:17 local time (WIB). The results show that the system equipped with the solar tracker produced an average power output of 8.41 W, which is higher than the 5.57 W generated by the non-tracking system. The efficiency of the panel with the tracker reached 4.2%, compared to only 2.78% without the tracker, representing a 50.98% increase in power output. These findings demonstrate that the implementation of an IoT-based dual-axis solar tracker system can significantly improve the performance and energy conversion efficiency of solar panels.

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1. INTRODUCTION

Electrical energy plays a crucial role in supporting various aspects of human life. With the increasing population and industrial development, the demand for electrical energy continues to rise. To date, most sources of electrical energy still rely on fossil fuels such as coal, natural gas, and petroleum, whose availability is depleting and whose use contributes to environmental degradation. Therefore, the utilization of renewable energy has become a strategic alternative to support energy sustainability, one of which is solar energy [1]-[5]. Solar Power Plants (PLTS) utilize solar energy as a clean and sustainable source by converting sunlight into electrical energy through solar panels [6]-[10].

The intensity and direction of sunlight continuously change throughout the day, causing the output power of solar panels to fluctuate [11]-[15]. A solar tracker system is a technology designed to adjust the orientation of solar panels so that they remain perpendicular to the direction of incoming sunlight, thereby maximizing the amount of energy captured [16]-[20]. The tracker system employs light sensors (Light Dependent Resistors, LDR) and is controlled by a microcontroller to regulate motor movement along one or two axes [21]. A single-axis solar tracker only follows the sun's motion from east to west [22], while a dual-axis tracker can adjust the panel's position both horizontally and vertically to achieve optimal alignment with the sun. The dual-axis mechanism allows the solar panel to move horizontally and vertically to maximize energy absorption. Previous studies have developed various solar tracker systems with different

configurations. An Arduino Uno-based system was used to drive DC motors controlled by LDR sensors; however, it was not yet integrated with an Internet of Things (IoT) platform for remote monitoring [23]. Another study proposed a solar tracker without LDR sensors, utilizing the solar panel itself as a light direction detector, but this approach was found to be less responsive to changes in light intensity [24].

Based on these considerations, this research designs and implements a Dual-Axis Solar Tracker system based on the ESP32 microcontroller with IoT integration. The system employs four LDR sensors to detect the direction of sunlight, two servo motors to control the panel's movement along the horizontal and vertical axes, and the Blynk application for real-time monitoring of voltage, current, and power parameters, as well as automated data logging to Google Sheets. The objective of this study is to enhance the efficiency of solar energy absorption while providing a practical and adaptive remote monitoring system that supports the advancement of renewable energy development in Indonesia.

2. METHOD

This research was conducted by designing and testing an automatic solar tracker system for solar panels based on the Internet of Things (IoT), featuring real-time monitoring through the Blynk application and data logging via Google Sheets. The system utilizes an ESP32 microcontroller with inputs from an INA219 sensor and Light Dependent Resistor (LDR) sensors. The output control consists of two motors: a horizontal (H) motor for left-right movement and a vertical (V) motor for up-down movement. To illustrate the relationship between the components used, the overall system block diagram is presented in Figure 1.

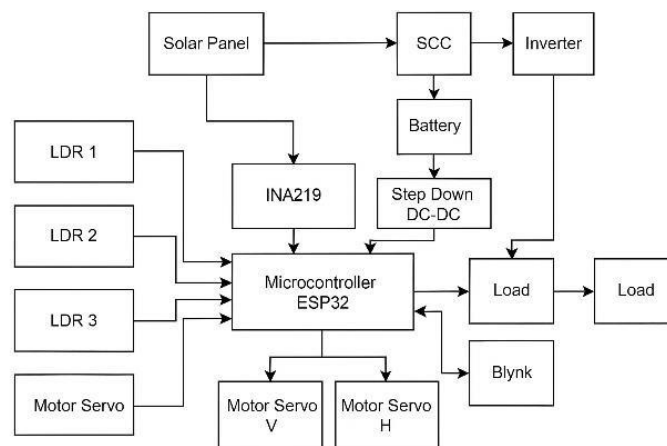


Figure 1. Block Diagram

Figure 1 illustrates the block diagram of the Internet of Things (IoT)-based dual-axis solar tracker system. The diagram provides a fundamental overview of the operational mechanism of the designed device. The following section explains the functions of each block presented in the diagram: 1) Solar Panel serves as the primary energy source in the system, converting solar energy into electrical energy. 2) NodeMCU ESP32 Functions as the main control unit responsible for processing input data and managing the system's output operations. 3) Solar Charge Controller (SCC) regulates the charging process of the battery to ensure optimal and safe energy storage. 4) Battery Acts as an energy storage medium for the electrical power generated by the solar panel. 5) INA219 measures the voltage, current, and power output produced by the solar panel. 6) Inverter Converts the stored electrical energy in the battery from direct DC to AC. 7) DC to DC Step Down unctions as a voltage regulator that steps down the power supply voltage to provide appropriate power to the ESP32 and other system components. 8) LDR (Light Dependent Resistor) Detects the intensity of sunlight to control the servo motor logic for tracking movement. 9) Vertical (V) and Horizontal (H) Servo Motors Drive the solar panel along two axes to adjust its position according to the sun's elevation angle based on input from the LDR sensors. 10) Relay 4 Channel for Controls four load terminals connected to the system. 11) Blynk serves as the IoT platform for real-time monitoring of system performance. 12) Google Sheets Functions as a data logging platform that records monitoring data over time, including voltage, current, power, and the ON/OFF status of the tracker system.

A flowchart is a graphical representation that illustrates the sequence of processes or operational steps of a system using specific symbols connected by arrows to indicate the overall flow of the process. The flowchart of the Internet of Things (IoT)-based dual-axis solar tracker system is presented in Figure 2.

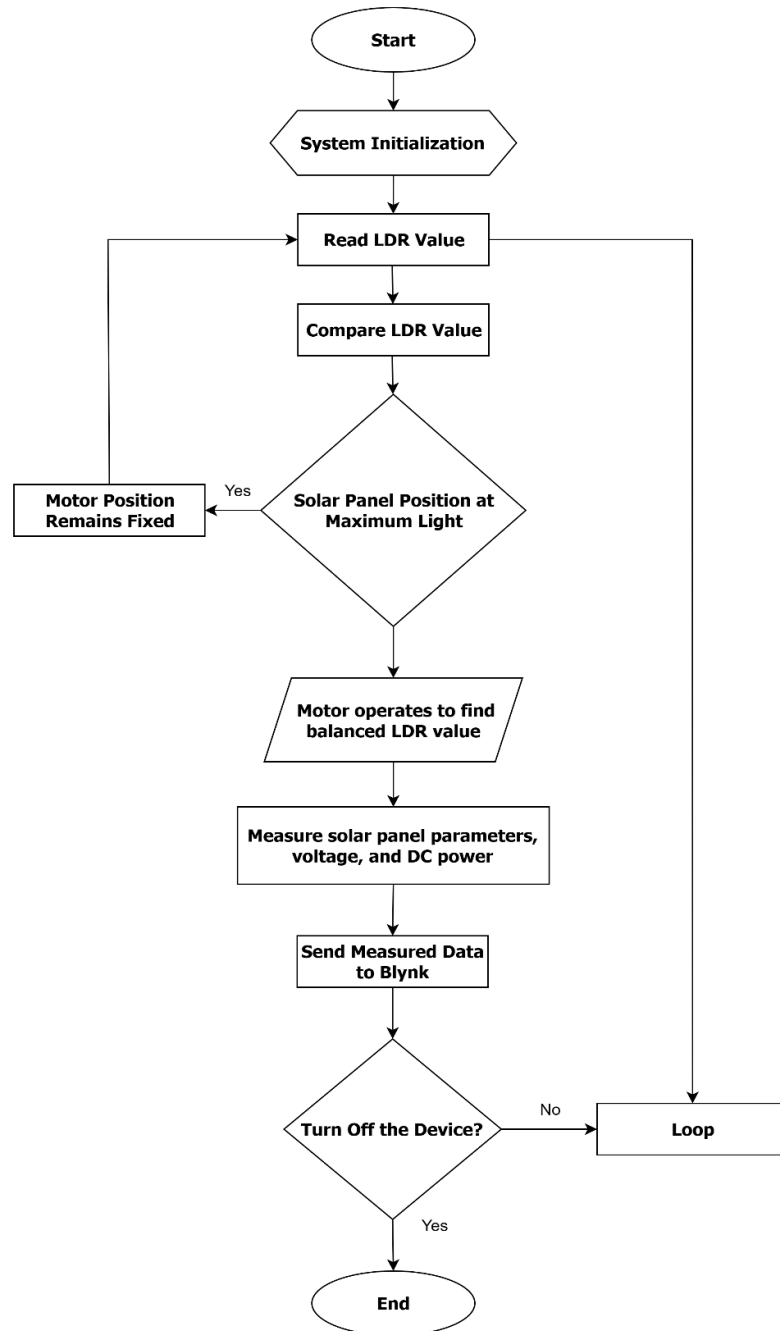


Figure 2. Flowchart of the Solar Tracker System

The electrical design of the dual-axis solar tracker system employs an ESP32 microcontroller as the main control unit, integrating all electronic components to optimize the performance of the solar panel. Four LDR sensors are utilized to detect light intensity from four directions, ensuring accurate sun-position tracking. The system is actuated by TD8120MG and MG996R servo motors on the horizontal and vertical axes, respectively, and is supported by a 4-channel relay module that regulates power flow. Voltage, current, and power monitoring are performed using an INA219 sensor, while DC-to-AC power conversion is carried out by a 500-watt inverter. The generated energy is stored in a 12V battery, with charging managed by a Solar Charge Controller (SCC). The entire system is integrated within an Internet of Things (IoT) platform, enabling real-time monitoring and control through an internet connection. The electrical system design is illustrated in Figure 3.

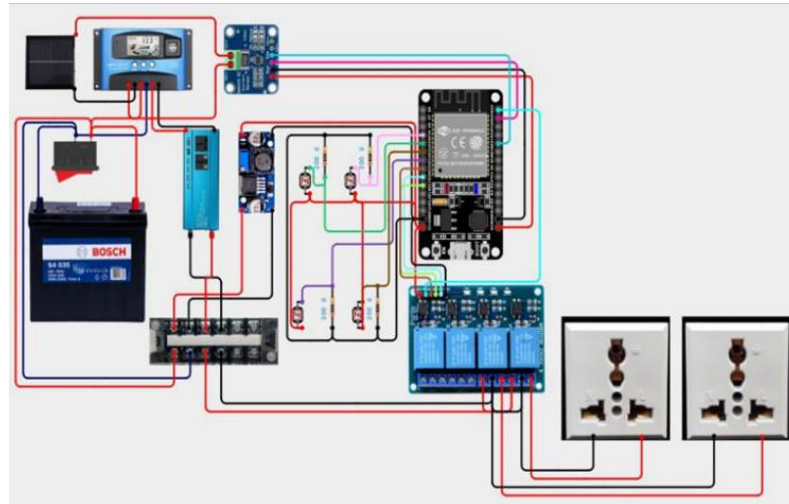


Figure 3. Electrical system design

The structural design of the device functions as a mounting frame for the solar panel and tracker to ensure the system operates as intended. The construction consists of a central frame that supports the main components, with the upper section serving as the solar panel mount. The panel mount is equipped with two drive motors: one positioned at the lower center of the panel to control horizontal movement, and another located on the side of the panel to control vertical movement. The structural design of the system is illustrated in Figure 4.



Figure 4. Structural Design of the System (a) Solar Panel Frame, (b) Tracker Mechanism Design

3. RESULTS AND DISCUSSION

This section discusses the experimental results of the Internet of Things (IoT)-based Dual-Axis Solar Tracker system that has been designed and implemented. The system is equipped with real-time monitoring features for voltage, current, and power output of the solar panel via the Blynk platform, as well as automatic data recording using Google Sheets. The testing aims to evaluate the system's performance in adjusting the solar panel position to continuously track the sun's direction optimally, and to verify the proper integration between the hardware and software components.

The experiment was conducted using a 30 WP solar panel under two observation conditions: with the solar tracker system activated and with a static (non-tracking) configuration. Testing was performed under clear weather conditions to obtain accurate measurement results corresponding to variations in solar irradiance. The test data, including voltage, current, and power output of the solar panel for each condition, are presented in Table 1 for the overall system testing and in Table 2 for the performance comparison between the tracking and non-tracking systems.

Table 1. Overall System Testing Data

Time	Voltage (V)	Current (A)	Power (W)	Tracker Status (ON/OFF)
10.01.00	18.01	0.43	7.74	OFF
10.01.30	18.04	0.43	7.75	OFF
10.02.42	18.43	0.46	8.47	ON
10.03.04	18.23	0.47	8.56	ON
10.15.06	18.46	0.42	7.75	OFF
10.15.39	18.44	0.41	7.56	OFF
10.16.37	18.57	0.43	7.98	ON
10.16.58	18.51	0.43	7.95	ON
10.30.03	18.38	0.45	8.27	OFF
10.30.36	18.41	0.44	8.10	OFF
10.31.28	18.61	0.44	8.18	ON
10.31.56	18.46	0.45	8.30	ON
10.45.08	18.68	0.44	8.21	OFF
10.45.42	18.68	0.44	8.21	OFF
10.46.19	19.00	0.44	8.36	ON
10.46.43	19.91	0.44	8.76	ON
11.00.02	18.84	0.44	8.28	OFF
11.00.34	18.81	0.43	8.08	OFF
11.01.17	19.17	0.44	8.43	ON
11.01.49	19.88	0.45	8.94	ON
11.15.09	18.99	0.43	8.16	OFF
11.15.34	18.88	0.44	8.30	OFF
11.16.25	19.21	0.45	8.64	ON
11.16.51	19.07	0.45	8.58	ON
11.30.10	18.91	0.43	8.13	OFF
11.30.41	18.88	0.44	8.30	OFF
11.31.37	19.02	0.44	8.36	ON
11.31.56	19.10	0.45	8.59	ON
11.45.02	18.28	0.44	8.04	OFF
11.45.33	18.23	0.44	8.02	OFF
11.46.21	18.91	0.44	8.32	ON
12.00.04	19.01	0.45	8.55	OFF
12.00.36	18.94	0.45	8.52	OFF
12.01.21	19.43	0.45	8.74	ON
12.01.59	19.01	0.45	8.55	ON
12.15.09	19.01	0.45	8.55	OFF
12.15.41	18.89	0.45	8.50	OFF
12.16.46	19.06	0.45	8.57	ON
12.17.04	19.05	0.45	8.57	ON

Table 2. Comparative Data of the System With and Without the Solar Tracker

No	Without Solar Tracker			Using Solar Tracker		
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
1	18.01	0.43	7.74	18.43	0.46	8.47
2	18.04	0.43	7.75	18.23	0.47	8.56
3	18.46	0.42	7.75	18.57	0.43	7.98
4	18.44	0.41	7.56	18.51	0.43	7.95
5	18.38	0.45	8.27	18.61	0.44	8.18
6	18.41	0.44	8.10	18.46	0.45	8.30
7	18.68	0.44	8.21	19.00	0.44	8.36
8	18.68	0.44	8.21	19.91	0.44	8.76
9	18.84	0.44	8.28	19.17	0.44	8.43
10	18.81	0.43	8.08	19.88	0.45	8.94
11	18.99	0.43	8.16	19.21	0.45	8.64
12	18.88	0.44	8.30	19.07	0.45	8.58
13	18.91	0.43	8.13	19.02	0.44	8.36
14	18.88	0.44	8.30	19.10	0.45	8.59
15	18.28	0.44	8.04	18.91	0.44	8.32
16	18.23	0.44	8.02	19.04	0.44	8.37
17	19.01	0.45	8.55	19.43	0.45	8.74
18	18.94	0.45	8.52	19.01	0.45	8.55
Average	18.59	0.43	8.23	19.12	0.44	8.50

The following figures (Figures 5, 6, and 7) present a comparison of the voltage, current, and power generated by the solar panel when operated with and without the solar tracker system.

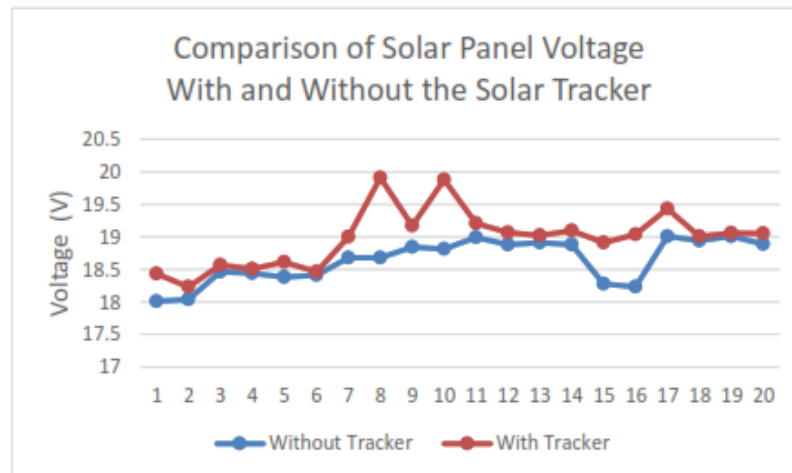


Figure 5. Comparison Graph of Solar Panel Output Voltage

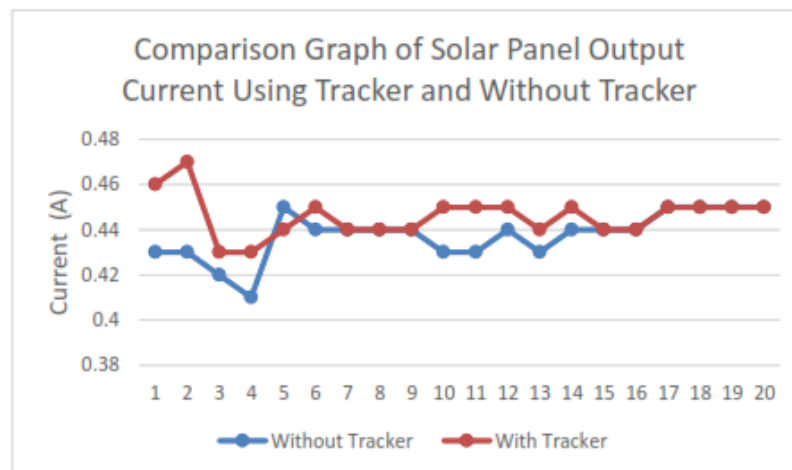


Figure 6. Comparison Graph of Panel Output Current

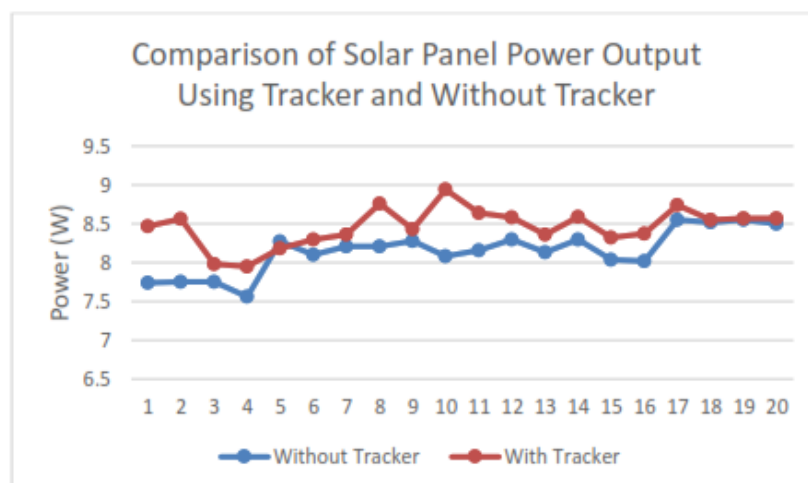


Figure 7. Comparison Graph of Panel Output Power

The following is the Blynk interface display, which includes voltage, current, and power readings, as well as push buttons for the tracker's On and Off conditions.

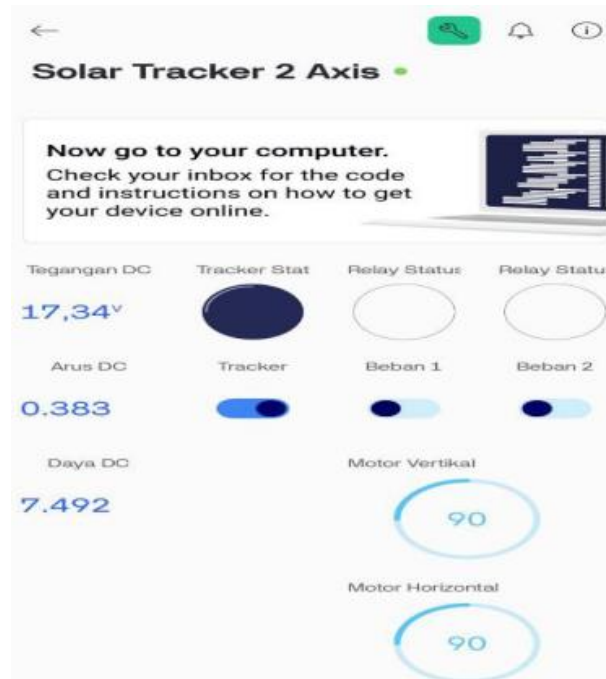


Figure 8. Monitoring and Control Display on Blynk

The data logging in Google Sheets includes the date, time, voltage, current, and power parameters, as well as the On/Off status of the tracker. The recorded data display in Google Sheets is shown in Figure 9.

A	B	C	D	E	F	G	H	I
Tanggal dan Waktu	Tegangan Panel	Arus Panel	Daya Panel	Beban 1	Beban 2	Status Beban 1	Status Beban 2	Status Tracker
24/09/2025 10:01:00	18.01	0.43	7.74	OFF	OFF	OFF	OFF	OFF
24/09/2025 10:01:30	18.04	0.43	7.75	OFF	OFF	OFF	OFF	OFF
24/09/2025 10:02:01	18.10	0.44	7.98	OFF	OFF	OFF	OFF	OFF
24/09/2025 10:12:42	18.43	0.46	8.47	OFF	OFF	OFF	OFF	ON
24/09/2025 10:03:04	18.23	0.47	8.56	OFF	OFF	OFF	OFF	ON
24/09/2025 10:03:39	18.40	0.43	7.91	OFF	OFF	OFF	OFF	ON
24/09/2025 10:15:06	18.46	0.42	7.75	OFF	OFF	OFF	OFF	OFF
24/09/2025 10:15:39	18.44	0.41	7.56	OFF	OFF	OFF	OFF	OFF
24/09/2025 10:16:04	18.31	0.42	7.69	OFF	OFF	OFF	OFF	OFF
24/09/2025 10:16:37	18.57	0.43	7.98	OFF	OFF	OFF	OFF	ON
24/09/2025 10:16:58	18.51	0.43	7.95	OFF	OFF	OFF	OFF	ON

Figure 9. Data Logging in Google Sheets

Based on the obtained test data, it was shown that the average power output using the tracker was 8.41 W, which is higher than the system without the tracker, which only produced an average power of 5.57 W. The panel efficiency with the tracker reached 4.2%, while without the tracker it was only 2.78%. From these average power values, it can be concluded that there was a power increase of 50.98% when using the solar tracker system.

4. CONCLUSION

Based on the test results obtained, it was proven that the implementation of the solar tracker effectively increased the absorption of solar energy, as the panel was continuously adjusted to the optimal position following the sun's movement. This significant improvement aligns with the theory that the more perpendicular the angle of sunlight incidence is to the surface of the panel, the greater the light intensity absorbed, resulting in higher electrical power output.

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