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Design of a Solar Panel with a Dual-Axis Sun Tracking System

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ABSTRACT

The project focuses on creating a solar panel equipped with a dual-axis sun tracking system. This innovative design allows the solar panel to follow the sun's movement throughout the day, maximizing its exposure to sunlight. By adjusting its angle both horizontally and vertically, the solar panel can capture more energy, leading to increase the efficiency. The approach taken involves a comprehensive hardware design that features a 1200Wp solar panel, light-dependent resistors (LDR) as sensors, and servo motors serving as the actuator. Complementing this hardware is a software design based on an Arduino microcontroller, which effectively processes light intensity data gathered from the sensors. To evaluate the system's performance, tests were conducted comparing the output parameters of the tracking solar panel against those of a static solar panel under typical daily sunlight conditions. The findings from the experiments indicate that the introduced dual-axis sun-tracking system enhances system efficiency by 10.27% relative to a static solar panel setup under the conditions tested. Prior research documented in the literature suggests that dual-axis tracking systems have the potential to boost energy output by around 40–50% in comparison to fixed panels, contingent upon variables such as solar radiation intensity, geographical location, and prevailing weather conditions. The LDR-based solar tracking system paired with the servo motor has demonstrated its effectiveness in boosting the power output of low-capacity solar panels as a promising solution for small scale renewable energy application.

1. Introduction

Solar energy is an abundant and environmentally benign renewable resource, making it an increasingly popular choice for meeting both small and large electricity demands. Solar radiation reaching Earth's surface can be converted into electrical energy using solar panels, also known as photovoltaics [1]. The effectiveness of these panels depends significantly on several factors, including the sun's position in the sky, atmospheric conditions, and the geographic latitude of a location. Ultimately, the performance of solar panels is largely determined by the intensity of direct sunlight they receive [2], [3].

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Solar panels are innovative devices that transform sunlight into electrical energy using the photovoltaic effect [4]. The efficiency of this conversion is significantly affected by the angle at which sunlight strikes the panel's surface. When sunlight hits the panels directly or at a perpendicular angle, they generate maximum power. However, if sunlight arrives at an oblique angle, the power output decreases [5]. In traditional solar energy systems, static panels struggle to capture sunlight efficiently throughout the day. This limitation results in a lower power output than desired. To overcome this challenge, implementing a solar tracker system is essential. Such a system adjusts the position of the panels in response to the sun's movement, thereby maximizing solar radiation capture and significantly increasing energy production. A solar tracker is a mechanical device that adjusts the orientation of solar panels to maintain a perpendicular angle to the Sun [6], [7]. This maximizes energy capture throughout the day. There are two primary types of solar trackers: single-axis and dual-axis. Single-axis trackers rotate about a single axis, typically moving from east to west [8], [9]. In contrast, dual-axis trackers can pivot on two axes, allowing them to follow both the sun’s azimuth and elevation as it moves across the sky [10]. Fig. 1 illustrates the operation of a dual-axis sun tracker.

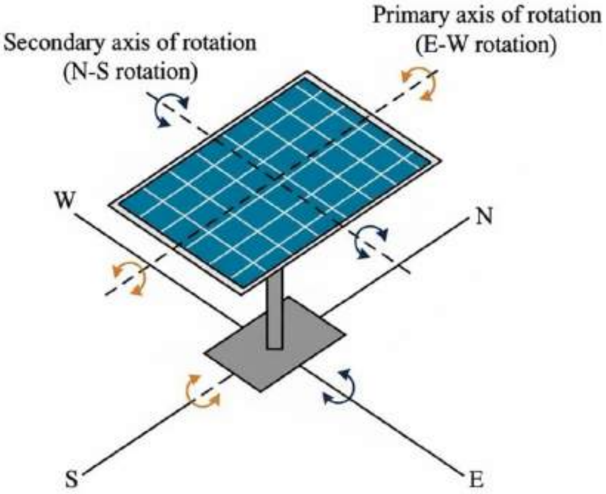


Fig. 1. Dual-axis sun tracker [11]

Several earlier studies that explored the benefits of dual-axis sun-tracking systems are as follows: In [12], the authors developed a sun-motion algorithm for the equatorial mount to improve the performance of existing sun-tracking systems. The tracking system is determined by comparing the actual test movement with the sun movement algorithm. The results indicate that the proposed solar tracker design is feasible for any solar energy application requiring motion perpendicular to the direction toward the sun. A review in [13] examined the advancements, challenges, and future directions of solar tracking systems. It underscores the potential of STS in advancing sustainable energy solutions and emphasizes the need for further research and development in this field.

An additional study was conducted to capture maximum sunlight within a limited area; two solar panels were arranged in a bifacial configuration with reflectors [14]. The dual-axis solar tracking system optimizes solar energy collection by adjusting the panels to the sun's optimal angle, using Light Dependent Resistors (LDRs) and a microprocessor to control servo motors. This system enhances solar energy efficiency, reduces reliance on non-renewable sources, and supports sustainable energy practices, contributing to climate change mitigation and the global transition to renewable energy. Furthermore, a comprehensive review of solar tracker systems, including innovations and advancements, was conducted in [15].

This study presents an off-grid 1200 Wp solar panel system equipped with an advanced dual-axis solar tracking system, and utilizing an LDR sensor and a servo motor. The innovative design enables the panel to follow the sun's path in both azimuth and elevation, significantly enhancing energy absorption. As a result, this prototype achieves greater energy capture efficiency than traditional static panels. The study's urgency lies in addressing the concept of energy security in Indonesia by constructing a solar panel system with a dual-axis sun tracker, a trend in the utilization of solar energy as an environmentally friendly power source.

2. Methodology

2.1 Design and sizing the dual-axis sun tracking

The design aims to keep the panels perpendicular to the sun throughout the day. A sturdy frame structure is required to support the weight of four panels and withstand strong winds. The frame must have two axes, namely, i) Azimuth (Horizontal axis): For east to west movement following the sun, and ii) Elevation (Vertical axis): For up-down movement following changes in the sun's height. The proposed frame design supporting four solar panels connected in series is illustrated in Fig. 2.

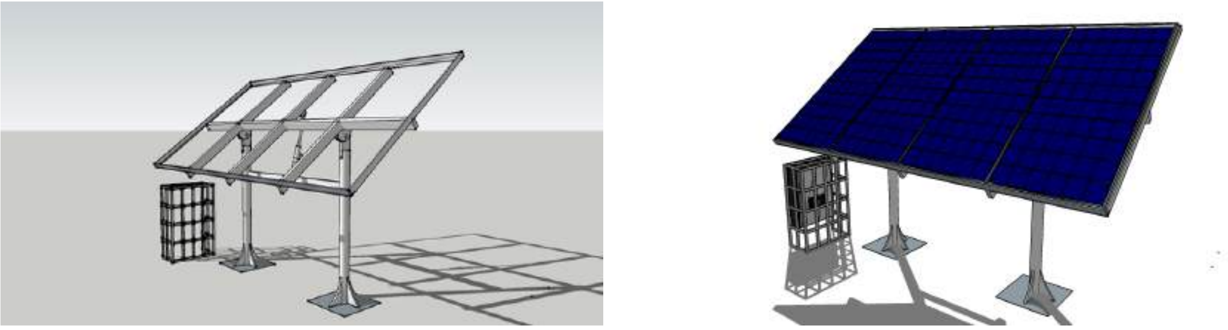


Fig. 2. Illustration of the solar panel’s frame

This innovative frame incorporates a dual-axis solar tracking system that enables movement along both horizontal (azimuth) and vertical (elevation) axes. By enabling precise tracking of the sun's position, this design maximizes energy-absorption efficiency. The frame features a central horizontal axis that permits vertical rotation, enabling adjustments to align with the sun's vertical angle. Additionally, the entire structure, including both the solar panels and their supporting frame, can rotate 360 degrees about the vertical axis. This capability ensures that it follows the sun’s journey across the sky from east to west, optimizing energy capture throughout the day.

The closed-loop algorithm of solar trackers is designed to optimize the alignment between incoming sunlight and the photovoltaic surface of the panels [16], [17]. This system utilizes an Arduino-based controller that processes feedback from LDRs in conjunction with an operational amplifier. The core functionality relies on comparing the output intensity of these sensors, which are amplified to produce an error voltage. This voltage represents the difference between the North-South and East-West sensor readings, resulting in an imbalance that needs correction. Fig. 3 illustrates the flow of the closed-loop design of the sun-tracking, while Fig. 4 illustrates the Arduino Uno R3 based on the Atmega328P.

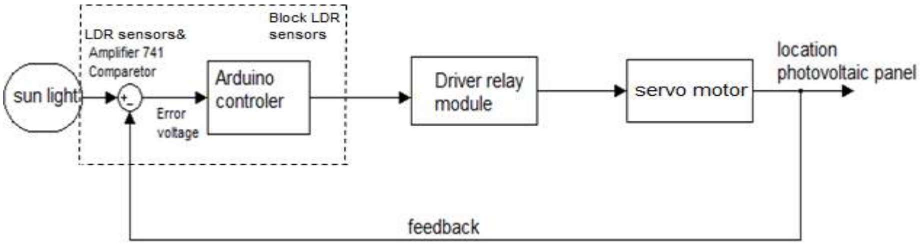


Fig. 3. Block diagram of closed-loop solar tracking system

Fig. 4. Arduino Uno R3 based on the Atmega328P

To achieve maximum performance, the actuator, either a linear extending rod or a retracting mechanism, adjusts to enhance elevation movement. A servo motor enables precise azimuth adjustments, ensuring optimal tracking of the sun's position throughout the day. Ultimately, the controller continuously monitors both photovoltaic panels and solar radiation levels. It sends a differential signal that prompts adjustments in panel positioning until the error voltage approaches zero, thereby maximizing energy efficiency.

2.2 Design and sizing of the solar panel systems and components

A 300 Wp solar panel serves as the system's primary energy source. This panel effectively transforms sunlight into direct current (DC) electrical energy, operating at a voltage range of approximately 32.7-36.7 volts. This voltage is crucial for configuring the system properly, as it helps select the appropriate solar charge controller and inverter to match the battery system's voltage.

In a single day, a 300Wp solar panel can produce around 900-1500 watt-hours of electrical energy [18]. During daylight hours, these solar panels capture sunlight and convert it into electrical energy, which is then stored in batteries. This stored energy is utilized to power lighting and various electronic devices that require alternating current (AC). The proposed system consists of 4 units of 300 Wp solar panels connected in series. Fig. 4 shows the series connection of 4 300 Wp solar panels. Each solar panel has a nominal voltage (V_{mp}) of 30–40 V, an open-circuit voltage (V_{oc}) of 35–45 V, and a maximum current (I_{mp}) of 8–10 A.

Fig. 4. Mounting 300Wp solar panels in series

Due to tracking efficiency, the solar panel's output power can exceed its nominal value. Total system output (series):

- Total voltage: 4×V_{mp} or 4×V_{oc} per panel is 38 V; total voltage is 4×38 V = 152 V.
- Total current: per panel, 9 A; total current, 9 A.
- Total power: 152 V × 9 A = 1368 Wp.

To accurately size the battery, begin by calculating the average daily energy consumption. Then, decide how many "days of autonomy" are required. This refers to the number of backup days necessary when there is no sunlight. By understanding these factors, it is easy to ensure that the battery size meets the energy needs efficiently. Battery sizing must follow the following steps [19], [20].

Step 1: Calculate daily energy consumption. Firstly, list all appliances that need to be powered and estimate their total daily energy use in Watt-hours (Wh). Assume that a daily consumption of electricity is 2.4 kWh.

Step 2: Determine backup days and system voltage. Decide how many consecutive days the battery must run on stored power without solar input. 2 days of autonomy is a common, balanced recommendation for off-grid systems. For a 1200Wp system, a 24V setup is recommended.

Step 3: Calculate the usable battery capacity. Lithium-ion batteries (specifically LiFePO4) are recommended for solar panel systems because they have a high Depth of Discharge (DoD), typically 80%, meaning they can be safely used up to 80% of their total capacity.

Thus, the calculation of the capacity of the battery size is,

$$\frac{(\text{Daily load in Wh} \times \text{Days of autonomy})}{(\text{System voltage in V} \times \text{DoD})} = \text{Battery bank capacity in Ah}$$

$$\frac{(2400 \times 2)}{(24 \times 80\%)} = 250Ah$$

A 1200Wp solar array in perfect sun would take at least 5 hours (6000Wh/1200W) to charge it from empty, not accounting for system losses.

For a 1200 Wp solar system, the ideal inverter size typically ranges from 1000 to 1500W. By using a dual-axis sun tracker, it is easy to enhance solar panel performance, allowing them to maintain maximum output for extended periods. This improvement makes it easier and more effective to match the inverter size to the DC capacity of the solar array. A dual-axis tracker enhances both the consistency and duration of peak power generation. As a result, it makes the risk of short-circuiting, which occurs when the inverter cannot handle the generated power, more predictable. To optimize energy capture from a tracker, it's important to size the inverter to match the array's full 1200 Wp DC capacity closely.

Choosing a quality inverter is crucial for dependable off-grid power. A pure sine-wave inverter is essential for protecting sensitive electronics and ensuring that all appliances operate smoothly. For your system, a 1200W off-grid MPPT hybrid inverter is an excellent choice [21]. It efficiently manages the charging of either a 24V or 48V battery bank while providing reliable AC power.

3. Results

3.1 Sun tracking system testing

To analyze a dual-axis sun tracker, several important aspects, namely the servo motor as actuator, controller, and LDRs as sensors, need to be considered so that the system runs optimally, efficiently, and produces maximum energy output.

3.1.1 Servo motor

The proposed solar panel system with sun-tracking employs the M995G servo motor for the elevation axis and the TD8120MG for the azimuth axis [22]. We selected these servo motors for their ability to generate sufficient torque, ensure precise angular rotation, and enable straightforward control via a PWM signal from the microcontroller (Arduino). The test is conducted to evaluate the performance characteristics of the servo motors under idle, light-load, and full-capacity conditions. The results of these tests are presented in Table 1.

Table 1
Power testing on the servo motor as the prime mover

Motor details	**Azimuth**	**Elevation**
Servo motor	TD8120MG	M995G
Voltage	5-6 Volt	5-6 Volt
Current (max.)	3 A	2.5 A
Torque	20 Kg/cm	12 Kg/cm
Max. Angle	0-180°	0-17°
Consumed power	Peak power: 13W	Peak power: 11W
	Light load: 0.3W	Light load: 0.4W
	Full capacity: 0.1W	Full capacity: 0.1W

3.1.2 Controller

The Arduino Uno R3, based on the Atmega328P, is used as the system's control centre. This versatile development board is equipped with the well-known ATmega328P and the ATmega16U2 processor [23]. This device processes data from the LDR sensors and sends control signals to the servo motors to drive the solar panels. The Arduino also provides programming flexibility, enabling further system development. The test results show that the ATmega328P Arduino can efficiently execute all control functions in this tracking system, with very low power consumption, and operate stably for an extended period without system disruption. Energy absorption efficiency increases by about 10-12% compared to static systems. The servo motor is tested using commands from an ATmega328P-based Arduino, enabling it to move in response to data from a light sensor [24]. To conduct the test, the LDR is partially covered, and the servo motor's response is observed as the panel moves toward the light source. Both the mechanical and electronic systems function effectively, demonstrating that the servo motor responds accurately to variations in light intensity.

3.1.3 LDR

This system features four LDRs arranged in a cross formation to effectively measure sunlight intensity from all four directions: up, down, left, and right. The main purpose of these sensors is to compare the light levels detected in each direction. By doing so, the system can identify the location of maximum sunlight and adjust the panel's position accordingly. Additionally, the sensors were tested to analyse how their resistance changes with varying light intensities. The results are shown in Table 2.

Table 2
LDR testing results

Inquiries	Specification
Type	LDR GL5537 – 5mm
Voltage	0.7 – 5 V
Signal	Analog (resistance)
Resistance	When dark: 149KΩ
	When bright: 3.4KΩ
Respond speed	20 – 30 ms

The test results show that the four-unit LDR sensor provides a relatively fast and accurate response to changes in light direction and intensity, making it suitable for use as the primary input system in an automatic sun-tracking system.

3.2 Parameter measurement on solar panels

To assess the effectiveness of the solar panel system with dual-axis sun tracking, it must be compared with a static system. Table 3 presents the solar panel test results obtained at a static tilt angle of 90 degrees, without any sun-tracking mechanisms. This table illustrates a typical daily performance trend of a solar power generation system. The highest power output happens at midday (approximately 11:30 to 12:00 am), when sunlight is most intense. The lowest power output occurs in the morning and late afternoon (around 7:00 am and 6:00 pm). The unusual reading at 6:00 pm warrants further examination, but it likely results from small, insignificant variations.

Table 3
Measured parameter on solar panels without sun-tracking

Period	Voltage (V)	Current (A)	Power (Watt)
07.00	5,4	0,01	0,054
07.30	7,1	0,17	1,207
08.00	7,6	0,21	1,596
08.30	14,5	0,35	5,075
09.00	16	0,63	10,08
09.30	18,9	1,1	20,79
10.00	19,1	1,12	21,392
10.30	19,3	1,26	24,318
11.00	19,4	1,39	26,966
11.30	19,9	1,42	28,258
12.00	19,9	1,42	28,258
12.30	19,1	1,4	26,74
13.00	18,7	1	18,7
13.30	18,5	0,98	18,13
14.00	18,2	0,96	17,472
14.30	17,8	0,91	16,198
15.00	17,5	0,8	14
15.30	17,2	0,63	10,836
16.00	17	0,57	9,69
16.30	16,6	0,4	6,64
17.00	14,6	0,37	5,402
17.30	12,4	0,3	3,72
18.00	14	0,33	4,62

Table 3 illustrates the common behaviors of solar panels that do not utilize sun-tracking technology. As the sun moves into its optimal position, energy output increases, peaking at 28.258 W. However, as the sun shifts away from this optimal angle, the energy production declines. These data reveal a notable difference between the minimum output of 0.054 watts and the maximum power output, indicating that performance is significantly limited during off-peak periods.

Table 4 presents the solar panel test results set using the dual-axis sun-tracking system. It appears that the peak power (Wp) of the solar panel was obtained at 10.30 am and then decreased at 2.30 pm. The performance of this panel showcases the key advantages of sun-tracking technology. It delivers higher, more stable, and longer-lasting electrical output than static systems (non-tracking) setups. These findings indicate that dual-axis tracking systems can achieve efficiency increases of 40-50%. The system's performance is higher in the morning, peaks at noon, and then declines in the afternoon and evening. This indicates that power output is strongly influenced by environmental factors, particularly the amount of light available.

The adoption of a dual-axis sun-tracking system with a capacity of 1200 Wp introduces several practical considerations concerning scalability, structural integrity, and auxiliary power usage. From the standpoint of scalability, the prototype illustrates that the tracking mechanism can be effectively integrated with a small-scale photovoltaic array comprising four 300 Wp panels. However, as one aims to scale up to larger photovoltaic systems, the mechanical intricacies and control demands may escalate considerably. This escalation necessitates more powerful actuators, sturdier structural supports, and sophisticated control methodologies to ensure accurate tracking performance.

Moreover, structural stability is a crucial consideration; the dual-axis frame must be capable of supporting the total weight of the solar modules while also enduring environmental forces such as wind and vibrations. Consequently, it is essential to meticulously design the supporting structure to guarantee adequate rigidity and durability in outdoor operating scenarios. Furthermore, the tracking system requires a modest amount of electrical power for the functioning of components such as the Arduino controller and servo motors. Although this power consumption is relatively minor compared to the additional energy obtained through optimized solar alignment, it remains an important factor in system design and energy balance assessments. In summary, these considerations underscore that although dual-axis tracking systems have the potential to enhance energy collection, their practical deployment necessitates thorough attention to structural integrity, control complexity, and auxiliary energy requirements.

Table 4
Measured parameter on solar panels with sun-tracking

Period	Voltage (V)	Current (A)	Power (Watt)
07.00	3,4	0,01	0,034
07.30	8,1	0,17	1,377
08.00	13,6	0,21	2,856
08.30	15,2	0,35	5,32
09.00	17,7	0,63	11,151
09.30	18,9	1,1	20,79
10.00	19,1	1,12	21,392
10.30	19,3	1,26	24,318
11.00	19,4	1,39	26,966
11.30	19,9	1,42	28,258
12.00	19,9	1,42	28,258
12.30	19,1	1,4	26,74
13.00	18,7	1	18,7
13.30	18,5	0,98	18,13
14.00	18	0,96	17,28
14.30	17,8	0,91	16,198
15.00	17,5	0,8	14
15.30	17,2	0,63	10,836
16.00	17	0,57	9,69
16.30	16,6	0,55	9,13
17.00	15,6	0,48	7,488
17.30	15,3	0,45	6,885
18.00	14	0,33	4,62

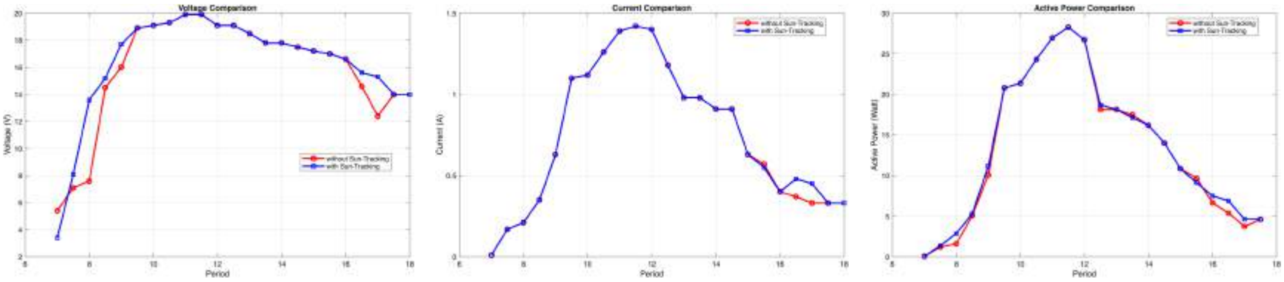
3.2 System efficiency

Compared with static systems, tracking technology is superior at capturing solar energy beyond peak sun hours. This ultimately leads to substantial improvements in overall efficiency. Now that the test data are available, the difference between the power measured in watts (W) and the efficiency expressed as a percentage (%) for both systems can be calculated.

$$\eta = \frac{Psun\ tracking\ system - Pstatic\ system}{Psun\ tracking} x100\%$$

$$\eta = \frac{330{,}417 - 320{,}142}{330{,}417} x100\% = 10.27\%$$

The data show that the sun-tracking system requires the most power around midday, but it operates efficiently at the beginning and end of the day. At its peak, the system consumes 1.02 W at noon, which could affect how we design solar systems, as these tracking devices require power even when sunlight is low. However, when comparing the energy consumed by the tracker with the energy gained from tracking, as shown in previous tables, the tracker's energy use appears quite small. This suggests that the advantages of using a sun-tracking system typically surpass its electrical costs. Graphical information on the system voltages, currents, and power for both the no-sun-tracking and sun-tracking systems is shown in Figure 9.



(a) Voltage (b) Current (c) Active Power

Fig. 5. Comparison of measured parameters of sun-tracking

This figure represents the actual performance derived from the experimental data collected during this investigation. The enhancement is attributed to the tracking mechanism's ability to continuously optimize the orientation of the solar panel, maintaining an angle close to perpendicular to incoming solar radiation throughout the day, thereby maximizing effective solar energy capture during both morning and afternoon periods.

Previous literature suggests that dual-axis tracking systems can potentially boost energy yield in photovoltaic systems by approximately 40–50% compared to static panels. However, these estimates are general performance potentials reported in broader studies and are highly contingent on factors such as geographical location, solar radiation intensity, atmospheric conditions, and system configuration. Thus, while the 40–50% improvement should be regarded as a theoretical range based on literature, the 10.27% value represents the actual performance metrics obtained from the prototype developed in this study.

From an engineering standpoint, deploying a dual-axis sun-tracking system with a capacity of 1200 Wp presents practical challenges related to scalability, structural integrity, and auxiliary power consumption. The prototype constructed for this research employs four 300 Wp photovoltaic panels mounted on a dual-axis frame regulated by an Arduino-based control system and servo motors. Although results affirm the viability of this setup for small-scale renewable energy applications, scaling up to larger photovoltaic arrays may necessitate more robust mechanical structures, higher-torque actuators, and advanced control algorithms to ensure precise tracking performance. Structural integrity is crucial since the supporting framework must endure not only the weight of the solar modules but also dynamic environmental loads such as wind and vibrations. Consequently, meticulous mechanical design and judicious material selection are vital for ensuring the long-term reliability of the tracking structure.

Furthermore, operating the tracking system incurs auxiliary power consumption from both controllers and servo motors. Despite these components' energy consumption being relatively minimal compared to the additional energy generated through improved solar alignment, it remains an important factor in evaluating overall system energy balance. The findings indicate that enhanced energy capture outweighs the electrical power required for operating the tracking mechanism, suggesting that, from an energy efficiency perspective, the system remains advantageous.

Nevertheless, it is important to acknowledge that this study's testing scope is limited. The experimental measurements were conducted over a brief observation period at a single geographic site. As such, observed performance improvements reflect specific environmental conditions encountered during experimentation, including local solar radiation levels and weather patterns, as well as site characteristics. Given that photovoltaic performance can vary considerably across different climates and seasons, the results presented here may not fully represent long-term efficacy under diverse environmental scenarios. Therefore, future research should encompass prolonged experimental monitoring across multiple seasons and various locations for a more thorough assessment of system performance and reliability.

4. Conclusions

The sun-tracking system enables the panels to capture direct sunlight more effectively throughout the day, resulting in higher, more stable voltage, current, and power outputs over extended periods. While the tracking system draws some power, peaking around midday and lower levels in the morning and evening, the average consumption is minimal relative to the additional energy produced by the optimally positioned panels.

The findings of this research validate that the implementation of a dual-axis sun-tracking mechanism can significantly enhance photovoltaic energy collection by optimizing the orientation of solar panel surfaces in relation to incoming solar radiation. The prototype developed in this study demonstrated a marked increase in experimental efficiency, achieving an enhancement of 10.27% when compared to a stationary photovoltaic system. This illustrates the promising capabilities of tracking technology for small-scale solar energy initiatives. Although the efficiency gains noted in this investigation are less pronounced than those reported in the existing literature, these results offer valuable insights into the practical performance of a prototype tracking system under defined experimental conditions. With additional optimization, prolonged testing, and improved structural design, dual-axis solar tracking systems could play a crucial role in enhancing both the efficiency and reliability of photovoltaic energy generation systems.

Additionally, future inquiries could focus on contrasting the suggested LDR tracking method with sensor-less or algorithm-driven tracking techniques, such as sun-position algorithms or astronomical models. Such comparative analyses would elucidate the respective benefits of each methodology concerning accuracy, dependability, maintenance needs, and overall efficiency of the system.

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