

Mechatronics of Energy: Development and Performance of an Automated, Foldable Dual-Axis Solar Tracking System for Enhanced Photovoltaic Back-Up Power

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ABSTRACT

The growing demand for reliable and sustainable energy sources has intensified the need to optimized photovoltaic systems, particularly for device back-up power applications. Standard fixed solar panels are bounded by their inability to continuously align with the sun, causing reduced energy capture over the course of the day. To address this limitation, this study presents the development of an automated, foldable dual-axis solar tracking system using an approach utilizing mechatronics principles to enhance photovoltaic energy yield.

The primary objective of this research is to design, develop, and evaluate a compact and portable solar tracking system endowed with the ability to automatically adjust its orientation along both azimuth and elevation axes. The system incorporates light-dependent resistors (LDRs) for solar position detection, a microcontroller-based control unit for decision-making, and 180° servo motors for precise angle mechanical movement. A foldable structural design is integrated to improve portability, ease of storage, and protection of components during non-operation.

An experimental method was utilized, pertaining to system fabrication, programming, and performance testing under field conditions. Core performance parameters, including voltage, current, and power output were analyzed and compared relative to a fixed solar panel setup operating under similar environmental conditions. The results demonstrate that the outlined dual-axis solar tracking system produces a significantly higher energy output than the fixed panel, demonstrating its effectiveness in optimizing solar energy collection.

To conclude, the constructed automated foldable dual-axis solar tracking system effectively improves photovoltaic performance and offers a practical solution for small-scale device back-up power applications. The integration of automation, portability, and efficient energy harvesting highlights the potential of mechatronics in advancing renewable energy technologies.

Keywords: Solar tracking system, dual-axis solar tracker, mechatronics, photovoltaic back-up power, renewable energy

INTRODUCTION

Energy plays a critical role in modern technological and industrial activities, particularly in the information age where digital devices and automated systems are widely used. Most modern technologies depend on a continuous and reliable energy supply, which has intensified interest in renewable energy sources. Among these, solar energy stands out as an affordable, environmentally friendly, and pollution-free option that requires minimal maintenance.

Solar energy systems operate independently by converting sunlight directly into electrical energy without reliance on external fuel sources. This conversion is achieved through photovoltaic (PV) cells using the

photovoltaic effect, in which incident solar radiation excites electrons and generates an electric current. However, the electrical output of a solar panel is highly dependent on its orientation relative to the sun, with maximum energy generation occurring when the panel surface is perpendicular to the incoming sunlight.

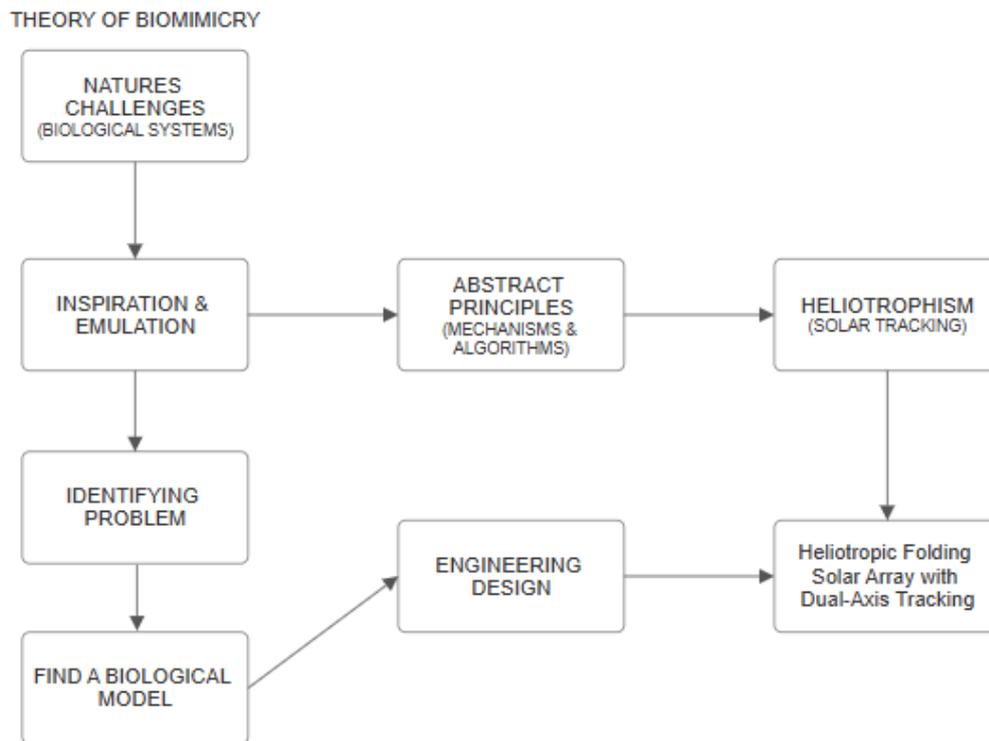
A key challenge in photovoltaic energy harvesting is the continuous movement of the sun, which reduces energy capture when panels are fixed. Manual adjustment is impractical, limiting system efficiency. To address this challenge, this study develops an automated, foldable dual-axis solar tracking system that continuously aligns photovoltaic panels with the sun’s position. The foldable, sunflower-inspired structure not only improves energy capture through dual-axis tracking but also enhances portability, compact storage, and protection of system components during non-operation, making it suitable for small-scale backup power applications.

REVIEW OF RELEVANT THEORY, STUDIES, AND LITERATURE

Theoretical framework

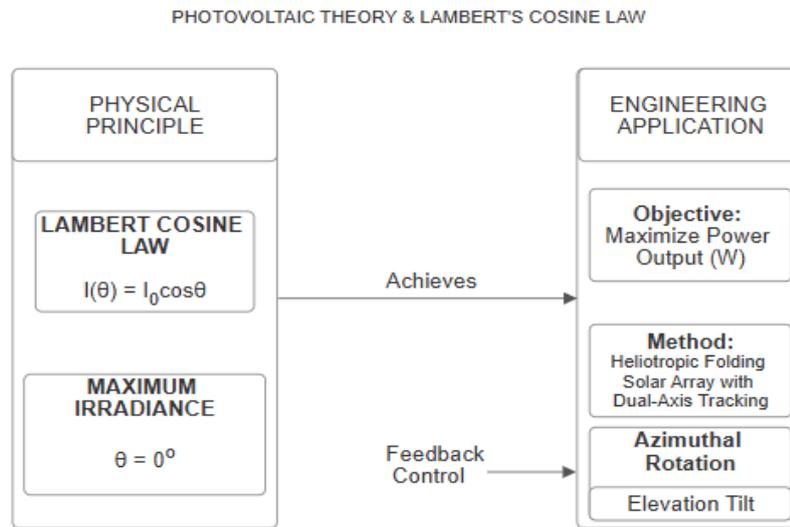
The theoretical framework establishes the engineering and scientific foundations for the Automated Foldable Dual-Axis Solar Tracking System. By integrating mechatronics, biomimetic heliotropism, and photovoltaic optimization, this study provides a structured approach to maximizing energy harvesting. The system synchronizes LDR sensing, Arduino processing, and servo actuation to achieve autonomous solar orientation, ensuring high efficiency within a portable, foldable footprint.

Figure 1. Theory of Biomimicry



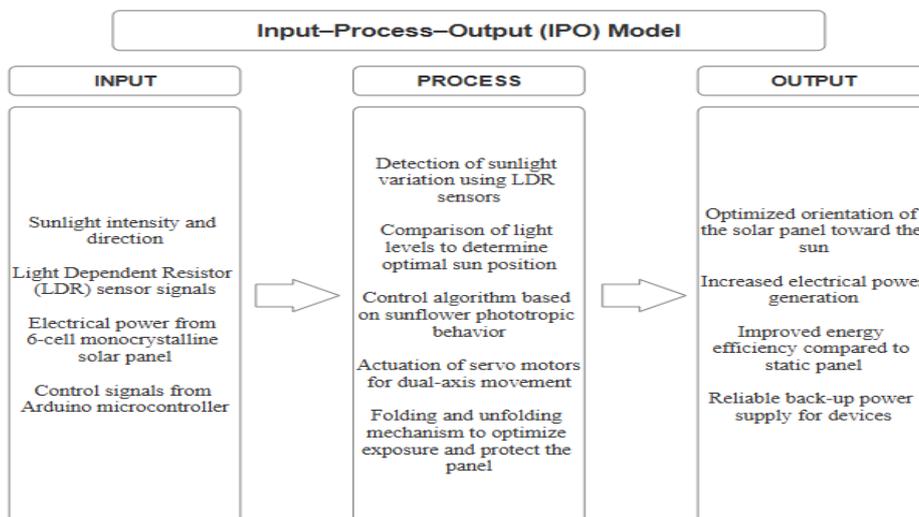
The Theory of Biomimicry, as popularized by Janine Benyus (1997), posits that nature’s time-tested patterns and strategies can be emulated to solve human engineering challenges. In this study, the solar tracking system mimics heliotropism, where sunflowers orient toward sunlight. The foldable “petal” structure and dual-axis movement enable efficient solar alignment and maximize energy capture. This biomimetic design supports both high energy efficiency and compact, portable deployment, directly informing the system’s mechanical architecture.

Figure 2. Lambert’s Cosine Law and Photovoltaic Optimization



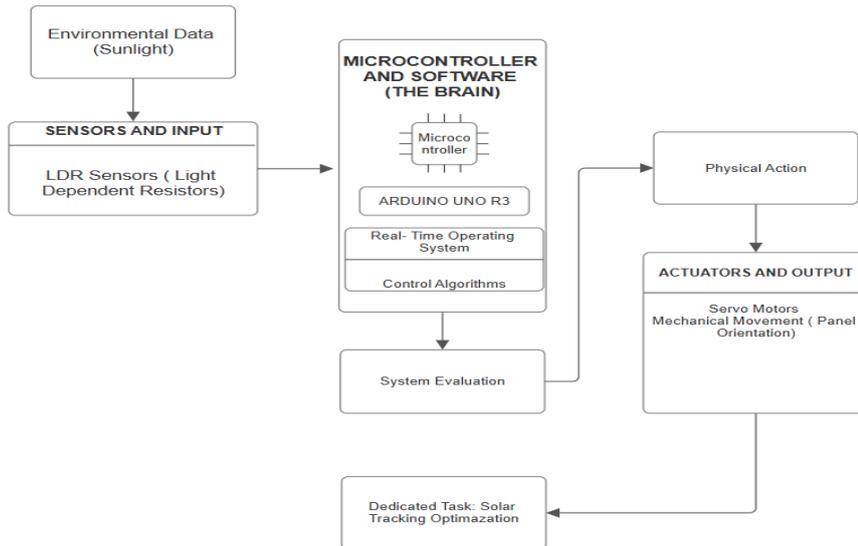
Lambert’s Cosine Law states that the radiant intensity on a surface is proportional to the cosine of the angle between the incident light and the surface normal. In this study, the law guides photovoltaic optimization: maximum energy is harvested when the solar panel is perpendicular to sunlight. The LDR sensors, Arduino controller, and servo motors work together to maintain this alignment, ensuring that dual-axis tracking minimizes cosine loss and maximizes energy capture throughout the day. This principle underpins the transition from static panels to the foldable dual-axis tracking system.

Figure 3. Input–Process–Output (IPO) Model



The Input–Process–Output (IPO) Model explains the operational flow of the foldable dual-axis solar tracking system. In the input stage, Light Dependent Resistor (LDR) sensors detect variations in sunlight intensity and direction. During the process stage, the Arduino microcontroller analyzes the sensor data and applies control logic based on phototropism theory, first described by Charles Darwin (1880), which explains how plants such as sunflowers orient themselves toward light. The controller then determines the appropriate dual-axis movement and folding action of the solar panel. In the output stage, servo motors adjust the orientation of the foldable solar panel to face the sun, resulting in improved energy capture and higher electrical power output compared to a static system.

Figure 4. Embedded System Theory



Embedded Systems Theory, largely influenced by the pioneering work of Wayne Wolf (now known as Marilyn Wolf) describes the integration of dedicated computer hardware and software designed to perform a specific, repetitive functional task within a larger mechanical or electrical system. In the Automated Foldable Dual-Axis Solar Tracking System, the Arduino Uno serves as the embedded core that executes real-time control algorithms based on environmental sensor data. Unlike general-purpose computers, this embedded system is "hard-wired" for a singular purpose: maintaining the solar panel's perpendicularity to the sun. This theory supports the system architecture by defining how the software code (logic) and hardware (microcontroller and sensors) must be co-designed to manage power constraints and respond instantly to changes in light intensity.

Related Study

Cybernetics and Control Systems

Norbert Wiener (1948) established Cybernetics, the study of control and communication in animals and machines. This led to the development of Feedback Control Systems. Automated Foldable dual axis solar tracker system is a classic example of a closed-loop feedback control system. The LDRs provide sensory input, the Arduino acts as the controller, the servo motors are the actuators, and the panel's position is the output that influences the next input (sunlight detected by LDRs). The continuous adjustment based on LDR readings demonstrates the core principle of negative feedback to maintain a desired state (optimal sun alignment).

Related Literature

Two-Axis Sun Tracking System with PLC Control

Abdallah and Nijmeh (2004) presented a dual-axis solar tracking system controlled using a programmable logic controller (PLC). The system was able to follow the sun's movement in both azimuth and elevation directions, resulting in an energy gain of approximately 40% compared to fixed PV panels. However, the design did not include a foldable mechanism and lacked portability, making it less suitable for compact backup power applications.

Solar Tracking System with Dual Axis

Kushal et al. (2023) developed an Arduino-based automated dual-axis solar tracking system using LDR sensors and servo motors. The system demonstrated effective real-time sun tracking and improved photovoltaic energy output. However, the design did not incorporate a foldable structure or focus on photovoltaic backup power applications requiring compact storage.

Comparative Performance Evaluation of Dual-Axis Solar Trackers

In their 2024 study, Jaafar et al. demonstrate the significant efficiency gains possible through advanced solar positioning. By comparing a dual-axis solar tracking system directly against a standard fixed photovoltaic installation, the researchers found that the tracking system increased energy output by roughly 45%.

While the tracking mechanism proved highly effective at maximizing sun exposure, Jaafar et al. (2024) noted that their evaluation focused strictly on energy yield. Consequently, the study did not explore the potential benefits of foldable mechanical structures or how these trackers might integrate with secondary backup power systems.

Table 1. Comparison Matrix of Related Studies and Current Research

Study (Authors)	Sensor Used	Platform Technology	Key Feature(s)	Gap Addressed by This Study
Abdallah & Nijmeh (2004)	Sun position sensors	PLC-based dual-axis system	Two-axis solar tracking with improved energy capture	No foldable structure; limited portability
Kushal, Y. et al. (2023)	LDR sensors	Arduino-based dual-axis tracker	Automated dual-axis tracking using servo motors	No foldable design; no backup-power focus
Jaafar, S. S. et al. (2024)	Light sensors	Dual-axis mechanical tracking system	~45% increase in PV energy output	No portability or foldable mechanism
Current Study	LDR sensors	Arduino-based mechatronic system	Automated tracking, foldable structure, enhanced PV efficiency	Addresses portability and compact storage

Previous dual-axis solar trackers have demonstrated significant energy gains compared to fixed panels. Abdallah & Nijmeh (2004) reported a 40% increase using a PLC-controlled system but lacked a foldable design. Kushal et al. (2023) developed an Arduino-based dual-axis tracker with improved real-time alignment, yet it did not incorporate portability or backup power applications. Jaafar et al. (2024) achieved approximately 45% energy gain with a rigid dual-axis tracker. Unlike these studies, the proposed system integrates a foldable sunflower-inspired mechanism, achieving comparable daily energy gains while providing portability, compact storage, and protection of components during non-operation. This highlights both the system's performance and novelty, addressing limitations in portability and applicability for small-scale backup power.

METHODOLOGY

Hardware implementation

This section describes the selection and integration of hardware components used to implement the automated foldable dual-axis solar tracking system, hardware installation, and prototyping design. This project consists of using several electronic components to build up the solar tracking mechanism. The main components used are Arduino UNO R3, light-dependent resistor (LDR), servo motor, and solar panel. This section discusses the specifications of components used.

Arduino uno r3

Arduino Uno R3 is based on the ATmega 328p microcontroller that can execute instructions in a single clock cycle, and the ATmega16U microcontroller that is managing the USB connection and ICSP bootloader. Arduino UNO R3 consists of 14 digital pins and 6 analog pins where there are 6 pins that are used as Pulse

Width Modulation (PWM) pins to control the speed of the motor. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started.

Light-dependent resistor (LDR)

This device is commonly used in electronic circuit design where it can detect the presence of light. LDR is made from semiconductor materials such as cadmium sulfide (CdS) and lead sulfide, PbS. It works on the principle of photoconductivity, where the resistance of LDR will be changed when detecting light. A significant drop in the resistance will occur when the level of light intensity increases. LDR with module is chosen to be used in this project because it includes built-in essential components, such as resistors and integrated circuits (IC), for resistance regulation, along with a potentiometer for the configuration of the LDR sensitivity.

Servo motor

A servo motor is a type of motor that can rotate with high accuracy. It consists of a control circuit that provides feedback on the current position of the motor shaft, this feedback allows the servo motors to rotate with great precision. SG90 servo motor is selected to work in this project as it is relatively cheap and able to be controlled by pulse-width modulation (PWM) pulse which is provided by the microcontroller. The servo motor consists of 3 wires; two wires will be used for the power supply while one wire used for the signal that is to be sent from the motor control unit. Servo motors operate with 5V to 6V power supply, and are normally able to give accurate control angles of 45°, 90° and 180°.

Solar panel

The solar panel is an electrical device that can convert light energy from the Sun into electricity by the photovoltaic effect. Electrical parameters such as voltage, current, and resistance will be varying when the solar cell is exposed to sunlight.

Table 2. SOLAR SPECIFICATION

Parameter	Detail
Type	0.05W 0.5V Monocrystalline Solar Panel
Solar Cell Material	High-Purity Single Crystal Silicon
Number of Cells	6 Cells
Maximum Power	0.05W (50mW)
Voltage at Max Power	0.5V x 6 in series connection
Current at Max Power	100mA
Short Circuit Current	~110mA
Efficiency	~17% - 22%
Dimensions	53mm x 18mm x 2.5mm
Weight	~3g

Requirements

The functional requirements of the foldable dual-axis solar tracking system focus on automatic sunlight detection and panel alignment. The system uses LDR sensors to sense changes in light intensity and direction, which are processed by the Arduino microcontroller to control the horizontal, vertical, and folding movements of the solar panel. The tracker adjusts its orientation to maintain optimal exposure to sunlight, allowing the solar panel to generate electrical energy that is stored for back-up power use.

The non-functional requirements address the system’s efficiency, reliability, and operational stability. The tracker is designed to respond smoothly to variations in sunlight without abrupt movements. Mechanical and electrical components operate within safe limits to ensure durability and consistent performance. The system maintains stable operation while improving energy output under changing environmental conditions.

Table 3. Variables and Conditions of the Automated, Foldable Dual Axis Solar Tracking System

Variable Component /	Type (Input / Output)	Parameter Measured / Controlled	Condition or Range	System Response / Action
Light Dependent Resistor (3 pin LDR with module) (4 LDRs)	Input	Sunlight intensity and direction	Varies with light level (analog input range 0–5 V)	Sends light data to Arduino for comparison of horizontal and vertical light differences
Arduino Uno Microcontroller	Controller	Processes sensor data and executes control logic	Operates at 5 V logic; continuous real-time evaluation	Analyzes LDR signals, determines optimal sun position, and sends control signals to servo motors
SG90 SERVO (180°)	Output	Left–right rotation of solar panel	Typical range: 0°–180°	Rotates the panel horizontally to align with maximum sunlight direction
SG90 SERVO (180°)	Output	Up–down tilt of solar panel	Typical range: 0°–180°	Tilts the panel vertically to optimize solar incidence angle
SG90 SERVO (360°)	Output	Opening and closing of panel structure	Open / Close positions	Controls deployment and folding of the sunflower-inspired solar panel
Foldable “Sunflower” Solar Panel Array (6 Cells)	Output (Energy Generation)	Electrical power generation (V, A, W)	Max rated voltage ≈ 3 V; $P_{max} = 0.05$ W	Converts solar energy into electrical energy for storage and use
3.7 Large Capacity lithium Battery	Output	Energy storage for back-up power	Charged within panel output limits	Stores generated energy for later use as device back-up power

Hardware design

The solar tracking system receives analog signals from four LDR sensors arranged in four quadrants (top-left, top-right, bottom-left, bottom-right). The Arduino Uno R3 microcontroller processes these signals and

generates PWM control pulses for the servo motors. The servos adjust the panel orientation along both horizontal and vertical axes to align with the direction of maximum light intensity, enabling dual-axis tracking.

Figure 5. Block diagram of the automated foldable dual-axis solar tracking system.

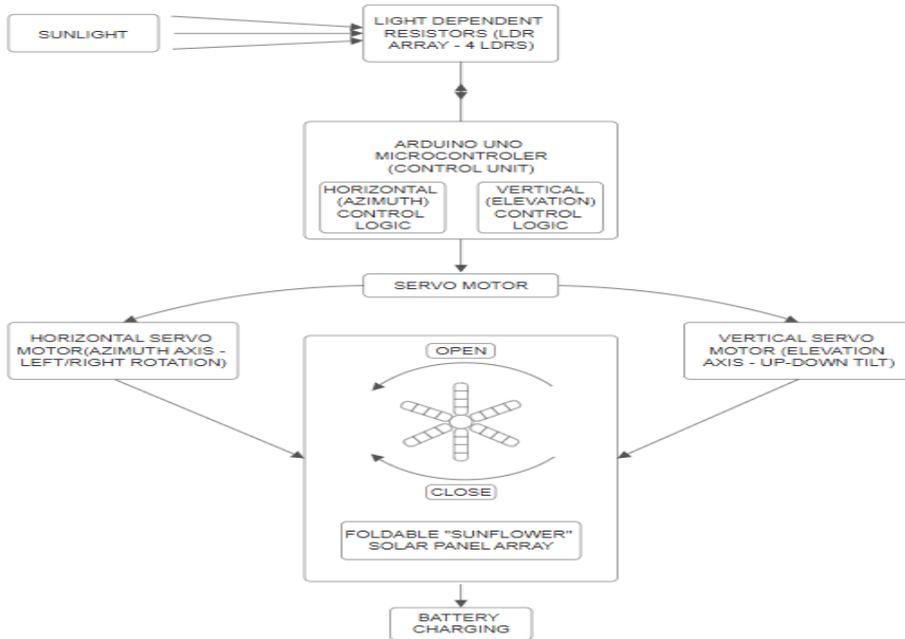


Figure 5 illustrates the functional block diagram of the foldable dual-axis solar tracking system. Four LDR sensors detect sunlight intensity variations along horizontal and vertical axes. The Arduino Uno microcontroller processes these signals using azimuth and elevation control logic to determine the optimal panel orientation. Based on this analysis, the microcontroller drives the servo motors to adjust panel position along both axes and operate the folding mechanism of the sunflower-inspired structure. The aligned panel then delivers energy to the battery for storage, enabling reliable small-scale backup power.

Figure 6. Schematic Diagram

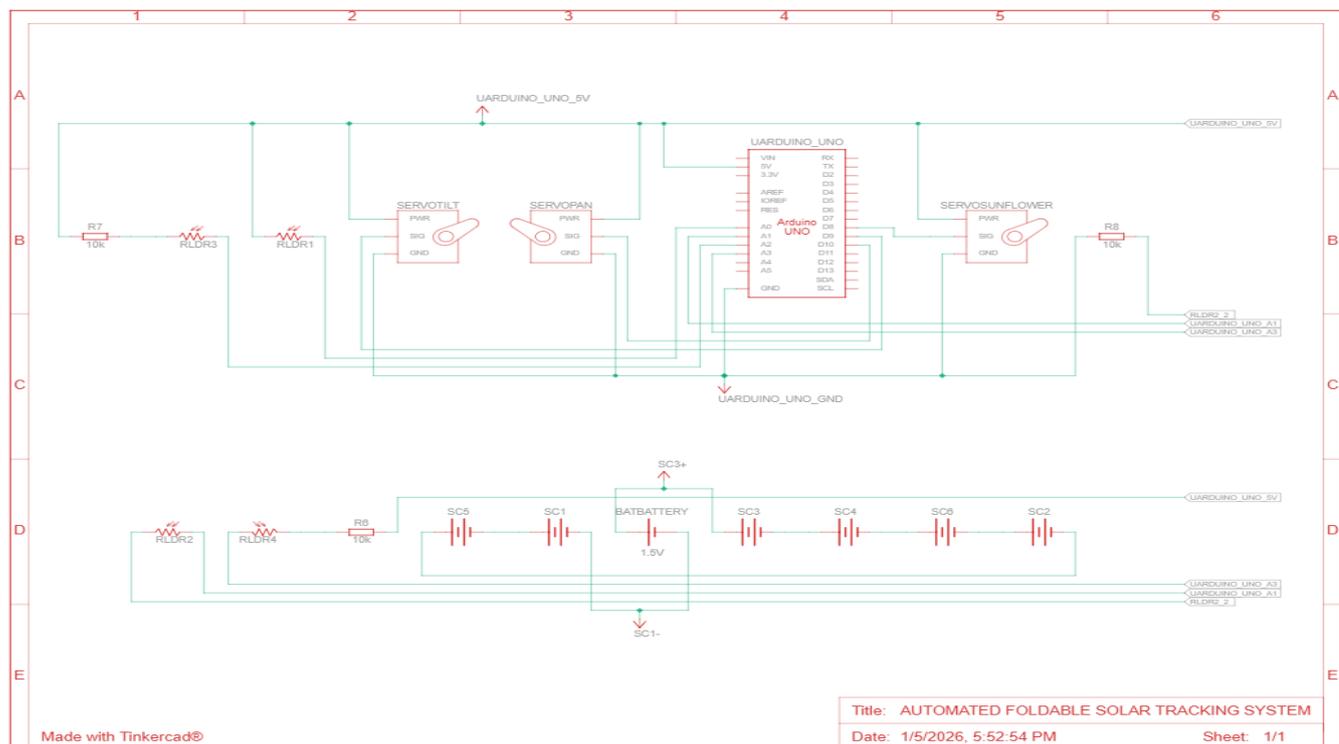


Figure 6 presents the schematic wiring of the foldable dual-axis solar tracking system, showing how the electronic components are connected to the Arduino Uno for automated sun tracking. The LDR sensors are interfaced with the Arduino's analog input pins to detect changes in sunlight direction. Servo motors for horizontal, vertical, and folding motions are connected to PWM output pins, enabling precise control of the solar panel orientation. The solar panel output is linked to the power management circuit for energy utilization. This schematic highlights the integration of sensors, actuators, and the microcontroller to improve photovoltaic performance and provide reliable back-up power.

Software implementation

The software of the solar tracking system was developed using the Arduino platform. It continuously reads analog signals from four LDR sensors and generates PWM control pulses for the servo motors. These pulses adjust the panel orientation along both horizontal and vertical axes, enabling dual-axis tracking to maintain optimal alignment with the sun.

Algorithm of solar tracking system

The algorithm is constructed using Arduino programming. After the microcontroller receives the digital signals from ADC, then it will proceed to compute the average voltage of the corresponding LDR pairs.

The average value computed is used to determine what control signal is sent to the servo motor. Equations 1 until 4 show the average method that needs to be utilized.

$$\text{The average value of the top part, Avg1} = \frac{\text{Top left} + \text{Top right}}{2} \quad (1)$$

$$\text{The average value of the bottom part, Avg2} = \frac{\text{Bottom left} + \text{Bottom right}}{2} \quad (2)$$

$$\text{The average value of the left part, Avg3} = \frac{\text{Top left} + \text{Bottom left}}{2} \quad (3)$$

$$\text{The average value of the right part, Avg4} = \frac{\text{Top right} + \text{Bottom right}}{2} \quad (4)$$

Experimental setup

This section is explained about experimental setup and the mathematical method used to obtain the parameter of the solar panel. To improve the accuracy of the result, this experiment is held outdoors and the venue to experiment must be a wide-open area. Thus, there would be no obstacles blocking the irradiance of sunlight. Furthermore, this experiment is conducted from 9 a.m. to 6 p.m. to observe the performance of solar panels in different periods. After done with the experiment setup, the experiment is then started to collect data for analysis. To discriminate the performance, power output, solar irradiance, and efficiency of the overall system will be determined in this experiment. The parameters of the solar panel such as voltage and current flow are measured using digital multimeters. For an electric element, the electric power is defined as the potential difference across the electric element multiple by current flow. Therefore, the power of solar panels is determined by using Equation 5:

$$P = VI$$

where P is the electric power of the solar panel, V is the voltage output, and I is the value of current.

Solar irradiance is known as the measurement of solar power and it is defined as the amount of electromagnetic radiation received from the sun per unit area [8]. Solar irradiance of solar panel can be calculated using Equation 6 below:

$$E = \frac{P}{A}$$

where E is the solar irradiance, P is the electric power of the solar panel and A is the surface area of the solar panel.

To compare the performance of the solar tracking prototype with the tracking mechanism and without the tracking mechanism, the efficiency of the overall system will be calculated using Equation below.

$$\eta = \frac{\text{Average Power (T)} - \text{Average Power (S)}}{\text{Average Power (S)}} \times 100\%$$

Where η is the efficiency of the overall system, *Average Power (T)* is the average power of solar panels with a solar tracking system and *Average Power (S)* is the average power of a static panel.

RESULTS AND DISCUSSION

The discussion and comparison about the gathered data will be in this section. The experiment is conducted to compare the result between a static solar panel and a solar panel with a tracker. The experiment is conducted for 9 hours (9:00am - 6:00pm) and all the data and results are gathered hourly.

Comparison Results

The comparison of results will be in this section. This section discusses the difference between the results of static solar panel and solar panel with tracker in terms of their performance quality, output power, current, voltage, and solar irradiance. And the comparison will be tabulated and plotted in the graph. The data gathered and calculated will also be seen in the table.

Table 4. Comparison of power output between fixed panel and dual-axis tracking system.

Time (Hours)	Static Voltage (V)	Static Current (A)	Static Power (W)	Static Irradiance (W/m ²)	Tracking Voltage (V)	Tracking Current (A)	Tracking Power (W)	Tracking Irradiance (W/m ²)
9:00 AM	2.05	0.020	0.041	42.97	2.40	0.038	0.0912	95.5
10:00 AM	2.38	0.045	0.107	112.3	2.65	0.052	0.1378	144.5
11:00 AM	2.73	0.047	0.128	134.0	2.75	0.049	0.1348	140.9
12:00 PM	3.00	0.045	0.135	141.7	3.00	0.045	0.135	141.7
1:00 PM	2.90	0.044	0.1276	134.0	2.92	0.047	0.1372	144.0
2:00 PM	2.80	0.040	0.112	117.5	2.82	0.042	0.1184	124.1
3:00 PM	2.40	0.025	0.060	62.9	2.65	0.042	0.1113	116.6
4:00 PM	2.15	0.020	0.043	45.1	2.50	0.041	0.1025	107.5
5:00 PM	1.90	0.015	0.0285	29.9	2.20	0.038	0.0836	87.6
6:00 PM	1.00	0.005	0.005	5.24	1.90	0.020	0.038	39.8

Total Power (W)			0.8901				1.1976	
Average Power (W)			0.089				0.120	

Observation

Total Power Increase

$$\text{Percentage Increase} = \frac{1.1976 - 0.8901}{0.8901} \times 100 = 34.5\%$$

Voltage Pattern

Morning and Afternoon boosted, tracker > static Midday peak capped at 3V.

Current Pattern

Slightly higher in tracking panel off-peak hours, boosts total energy.

Power Pattern

Midday peak roughly same (~0.135W), tracker advantage mainly in non-peak hours.

Irradiance

Recomputed using $E = \frac{P}{0.000954 \text{ m}^2}$, shows tracking captures more sunlight in morning & evening.

Figure 7. Power output versus time comparison graph

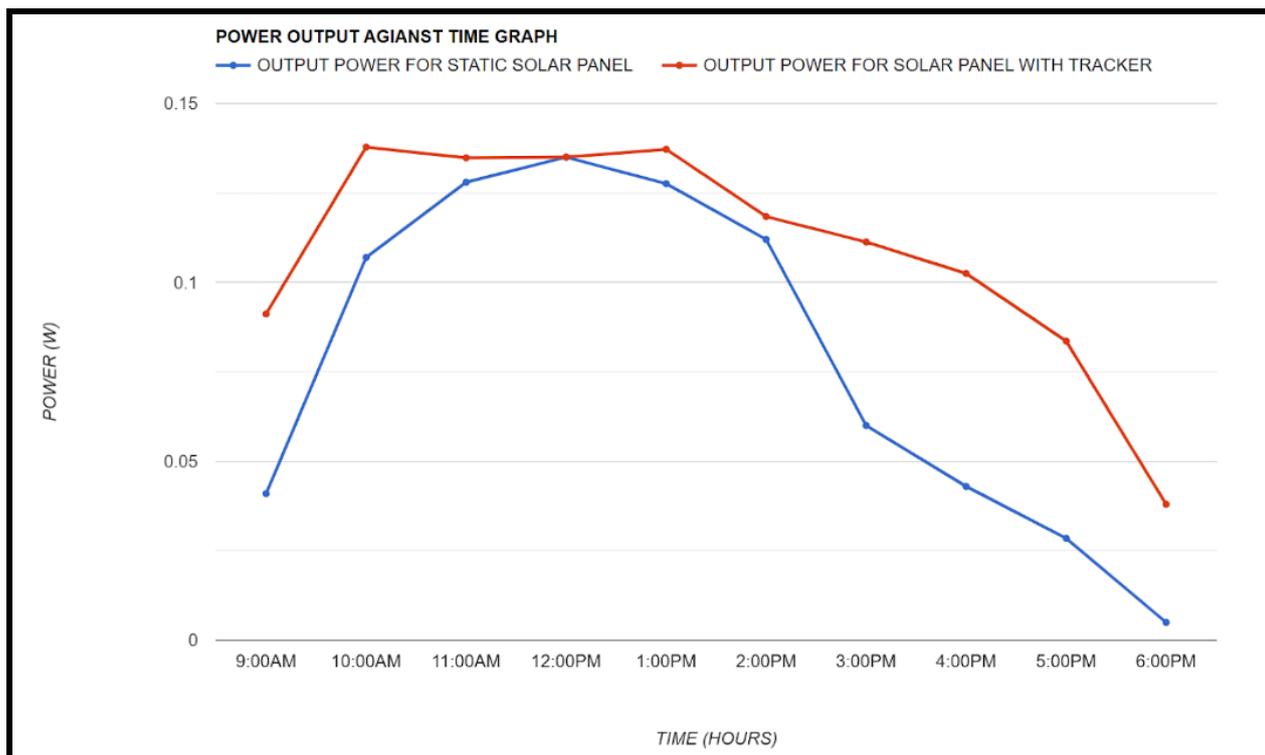
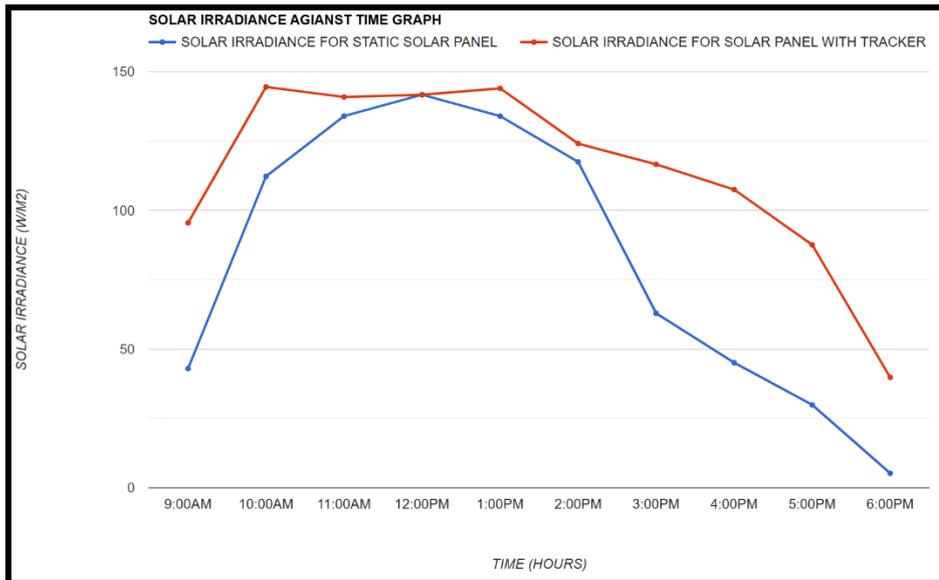


Figure 8. Solar irradiance versus time comparison graph



GRAPH DISCUSSION

Performance Comparison & Quantitative Analysis

The comparative analysis of output power and solar irradiance demonstrates that the dual-axis foldable solar tracking system outperforms a fixed-tilt photovoltaic (PV) array. As shown in Figure 8, the tracking system maintains a higher and more stable incident solar irradiance throughout the day, particularly during the morning and evening, by continually minimizing the angle of incidence. This directly translates into the power generation profile in Figure 7, where the tracking system exhibits a wider and flatter power curve, a higher peak, and greater total energy output compared to the steep, bell-shaped curve of the static panel.

The primary advantage of the dual-axis tracker is the reduction of cosine losses, which are most pronounced during early morning and late afternoon hours. While static panels experience rapid decreases in irradiance and power output during these periods, the tracking system prolongs high-performance operation, providing a more predictable and stable energy supply and increasing the PV system’s capacity factor. Quantitatively, the system achieved a ~34.5% increase in daily energy output compared to the fixed panel. This performance is comparable to prior studies, such as Jaafar et al. (2024), who reported a ~45% gain using a rigid dual-axis tracker. Unlike previous systems, the proposed design integrates a foldable sunflower-inspired mechanism, offering portability, compact storage, and protection of components during non-operation, which addresses gaps in practical deployment and small-scale backup applications.

Limitations & Scalability

Despite these performance gains, the system has several limitations. Mechanical wear of the servo motors and hinges may occur over prolonged use, potentially affecting tracking accuracy. The foldable structure, while enhancing portability, adds mechanical complexity that could impact long-term reliability. Additionally, scalability is limited; larger PV panels would require stronger actuators and reinforced structural components, which could increase costs and maintenance requirements. Future work should explore durability testing, optimized material selection, and modular designs to enhance reliability and scalability for broader deployment.

Overall, the data confirm that foldable dual-axis tracking system effectively maximizes daily energy yield by optimizing incident irradiance while offering practical advantages in portability and compactness. Although the system incurs higher initial costs and mechanical complexity compared to static panels, the increased energy output and operational flexibility justify these trade-offs, particularly in high-electricity-cost locations or small-scale backup power applications.

Table 5. Variables and Conditions of the Automated, Foldable Dual Axis Solar Tracking System

Test #	Input Condition	Observed Output	Expected Output	Pass / Fail	Remarks / Behavior Explanation
1	Main switch OFF	System inactive; all servos OFF	System remains OFF	✓ Pass	Main switch successfully disables all operations.
2	Main switch ON, low light	The panel bloomed; however, the motion was not smooth due to wire tangling, causing irregular deployment	The panel is bloom smoothly, with each segment properly aligned and operating without obstruction	✓ Pass	Wire tangling caused irregular panel deployment, indicating potential mechanical interference that may require adjustment or lubrication.
3	Equal LDR readings	Panel remains stationary	No movement required	✓ Pass	Balanced light detected; optimal alignment assumed.
4	LDR left > LDR right	Panel rotates CCW	Moves toward higher light	✓ Pass	Correct horizontal tracking response.
5	LDR right > LDR left	Panel rotates CW	Moves toward higher light	✓ Pass	Correct horizontal tracking response
6	Upper LDR > lower LDR	Panel tilts upward	Vertical alignment toward sun	✓ Pass	Accurate elevation tracking achieved.
7	CCW limit switch triggered	CCW motion stops	Prevent over-rotation	✓ Pass	Mechanical protection confirmed.
8	CW limit switch triggered	CW motion stops	Prevent over-rotation	✓ Pass	Servo safely halted at limit.
9	No sunlight detected	The panel folded, although alignment accuracy was not achieved.	Safe folding executed with proper panel alignment	✓ Pass	Foldable sunflower mechanism works correctly.
10	Full sunlight, aligned panel	Minimal servo motion; max power	System holds optimal position	✓ Pass	Stability achieved at peak energy output.

CONCLUSION AND RECOMMENDATION

In conclusion, the foldable and automated dual-axis solar tracking system proved to offer a better photovoltaic performance than a fixed solar panel. The experimental findings depicted that the tracking system generated a greater total and average power production, primarily because it has the capability of tracking the movement of the sun over the day. The results of both systems showed that both were able to achieve similar peak power in midday, but the tracker was more successful in energy collection in the morning and later in the afternoon.

These findings verify that dual-axis solar tracking is a good system to improve the total energy collection and can be used in small-scale backup power.

For future research, it is recommended to develop a detailed three-dimensional (3D) model of the system prior to physical fabrication to enhance design accuracy and reduce construction errors. The use of higher-power solar panels is also suggested to enhance energy output and overall system efficiency. Additionally, integrating a more advanced microcontroller with built-in Wi-Fi capability would allow real-time online monitoring of power generation, enabling better performance analysis and remote system management.

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