

# Enhancing Solar Energy Capture: A Comprehensive Study of an Intelligent Single-Axis Tracking System with Integrated Control Logic

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**Abstract** - With the rapid depletion of fossil fuels, maximizing the efficiency of renewable energy systems like solar photovoltaics (PV) has become critical; however, conventional fixed solar panels suffer from reduced energy conversion efficiency due to their inability to maintain an optimal angle with the sun. To overcome this limitation, this paper presents the design and fabrication of an automated, cost-effective single-axis solar tracking system that dynamically optimizes energy harvesting. The system utilizes a microcontroller-based architecture integrated with light-dependent resistors (LDRs) to detect maximum solar irradiance, driving a motor mechanism to continuously align the PV panel perpendicular to the sun's rays. Experimental validation confirms that this tracking action enhances energy conversion efficiency by 20% to 30% compared to stationary installations, while consuming only a minimal fraction of the generated power for its own operation. Fabricated from robust, low-maintenance, and readily available components, this highly viable system offers a scalable solution to reduce the cost per unit of electricity, making it equally suitable for small-scale domestic rooftops and large-scale industrial solar farms contributing to global sustainable development goals.

**Keywords:** Solar Photovoltaics, Single-Axis Tracker, Microcontroller, Light-Dependent Resistors (LDR), Energy Efficiency, Renewable Energy.

## 1. INTRODUCTION

The escalating global energy demand, driven by rapid population growth and industrialization, has heightened international awareness regarding environmental sustainability. Currently, approximately **85% of global energy production remains dependent on fossil fuels**, which serves as a primary source of greenhouse gas emissions and climate change risks [1]. To ensure a resilient energy future, there is a critical need to transition toward cleaner, more sustainable alternatives, among which **solar energy has emerged as a frontrunner** due to its unlimited availability and scalability [2]. Photovoltaic (PV) technology, which converts sunlight directly into electricity via the photoelectric effect, is a cornerstone of this transition; however, the **efficiency of energy conversion** remains a significant challenge often influenced by environmental variables and system orientation [3].

A primary limitation of stationary PV installations is the "**cosine error**," where the captured solar energy is proportional to the cosine of the angle of incidence between the incoming sunlight and the panel surface [4]. Consequently, fixed-tilt arrays only maintain maximum power for a brief period during solar noon, leading to **substantial energy losses during the morning and late afternoon** [5]. To address these limitations, solar tracking systems have been developed to dynamically adjust the orientation of PV panels. These systems are broadly applied in tropical regions where the sun's position is relatively stable, providing a superior **cost-to-performance ratio** compared to static mounts [6].

Modern solar tracking implementations utilize various control strategies, primarily **active sensor-based tracking and astronomical/schedule-based tracking** [7]. These systems seek to minimize the incident angle of direct sunlight by rotating the payload toward the sun's highest intensity [8]. From a mechanical perspective, industrial designs emphasize the use of **self-locking worm gearboxes** to resist wind-induced torque and ensure structural stability over a 20-year operational lifespan [9].

From a **techno-economic perspective**, the implementation of single-axis solar trackers has been shown to reduce the Levelized Cost of Electricity (LCOE) and provide a higher internal rate of return (IRR) for utility-scale projects compared to fixed structures [10]. Improvements in fabrication techniques, such as the development of specialized **conductive silver lamination devices** for circuit components, further support the production of low-cost, high-efficiency controllers [11]. This study focuses on the design, fabrication, and performance evaluation of an intelligent Arduino-based single-axis solar tracker, building on performance benchmarks established in regions with abundant solar resources [12].

## LITERATURE REVIEW

The fundamental importance of solar tracking stems from the need to enhance the efficiency of photovoltaic (PV) systems by keeping panels aligned with the sun's trajectory throughout the day [1]. Modern advancements have integrated Internet of Things (IoT) capabilities into these systems, allowing for real-time detection of solar irradiance and improved energy harvesting through intelligent azimuth adjustment [2]. Comprehensive reviews of tracking technology indicate that while fixed solar panels serve as a stable baseline, single-axis trackers can boost efficiency by approximately 25.6% with moderate mechanical complexity. [3] Dual-axis systems offer the highest theoretical gains—up to 50%—but their adoption is often limited by significantly higher installation and maintenance costs.

The detection of the sun's position and the subsequent analysis of control systems are critical for maintaining the capturing of maximum photon energy [4]. Active tracking methods, which utilize sensors to trigger motor motion, have proven highly accurate for keeping rays perpendicular to the PV surface. Beyond general power generation, specialized applications for single-axis trackers have emerged, such as the use of Arduino-based systems to power brushless DC pumps in hydroponics [5]. Recent research has also focused on extending tracking systems to include comprehensive weather monitoring, integrating temperature and humidity sensors to dynamically adjust positioning based on ambient conditions [6].

A critical debate in tracking logic involves the comparison of sensor-based systems versus astronomical/schedule-based management. While Light Dependent Resistor (LDR) sensors are effective in clear conditions, they often fail to accurately determine the sun's position during cloudy or rainy weather due to light scattering [7]. Conversely, schedule-based trackers, which utilize mathematical algorithms to calculate solar coordinates, have been shown to be 4.2% more efficient in adverse weather and consume 60% less motor power by avoiding the "hunting" behavior typical of sensor-based systems. This technological choice is vital for minimizing the "cosine error," where misalignment between sunlight and the panel surface leads to substantial energy losses during non-peak hours [8].

The mechanical reliability of tracking systems is largely determined by their drive units. Engineering guides for OEM manufacturers emphasize the use of stepper motors for their high holding torque and cost-efficiency in open-loop systems [9]. These designs frequently incorporate self-locking worm gearboxes to resist wind-induced torque or "galloping," ensuring the tracker remains stable for a projected 20-year operational life [9]. From a techno-economic perspective, implementing such one-axis systems in high-irradiation regions like Cyprus has proven financially superior to fixed structures, offering a 12% higher equity internal rate of return (IRR) and a 9% shorter loan payback period [10].

Continuous improvements in fabrication techniques, such as the development of specialized conductive silver lamination devices for circuit components, further support the production of low-cost, high-efficiency tracking controllers [11]. Localized performance studies highlight the significant role these systems play in regions with abundant solar resources; for instance, investigations in Delta State, Nigeria, demonstrated that single-axis trackers can provide nearly 96.5 kWh of user-available energy annually. These findings underscore the transformative potential of intelligent solar tracking for maximizing energy harvest and improving the sustainability of global PV infrastructure [12].

## Experimentation

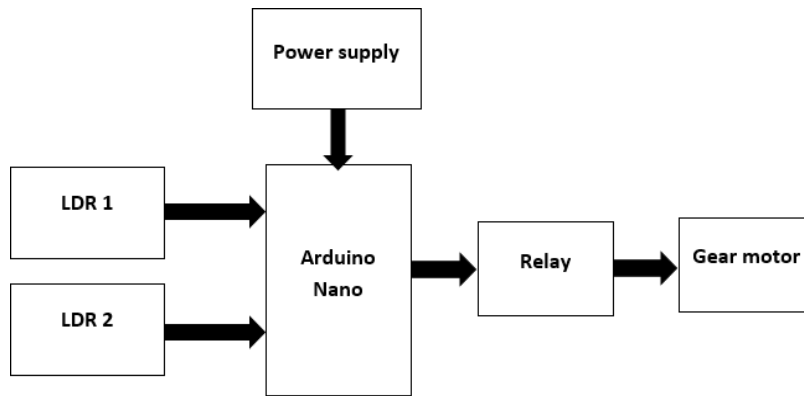


Fig. 1 SOLAR TRACKER BLOCK DIAGRAM

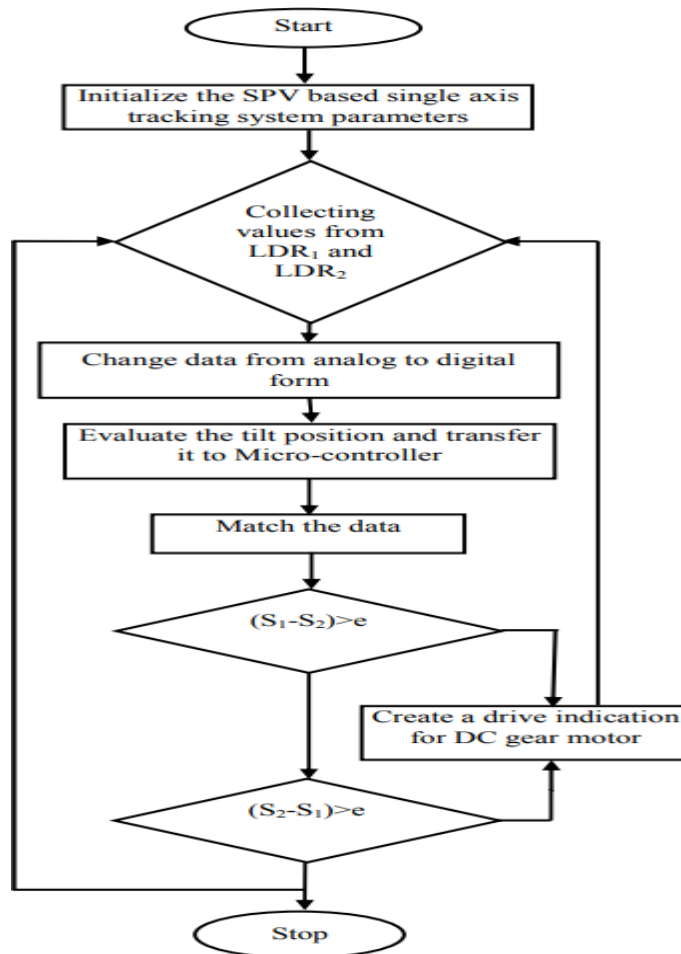


Fig. 2 PROGRAM FLOW CHART

Initially SPV based supply system is connected to the experimental setup then voltage inputs signals Start Initialize the SPV based single axis tracking system parameters Change data from analogue to digital form Evaluate the tilt position and transfer it to Micro-controller Match the data Stop Create a drive indication for DC gear motor Collecting values from LDR1 and LDR2  $(S_1-S_2) > e$   $(S_2-S_1) > e$   $S_1$  and  $S_2$  from 02 LDRs are collected for comparison.

1. Analog inputs are taken then converted into the digital form.
2. Yielded digital numbers are correlated and variation between them found.

3. This coming difference is the disturbance proportional angle for DC servomotor acceleration.
4. If voltages of LDR is same then servo motor cutoff. On the other hand, the servo motor moves until variation is matching.

Operational procedure of the experimented technique is presented through flow chart in the Figure 4. The coming signals enters into the system are voltages of 02 LDRs by pin numbers 23 and 24 of Atmega 328 then transfer of analog voltages into their digital numbers. The higher values of two signals are transferred to the system circuit which runs DC servo motor to the way with increased intensity of light.

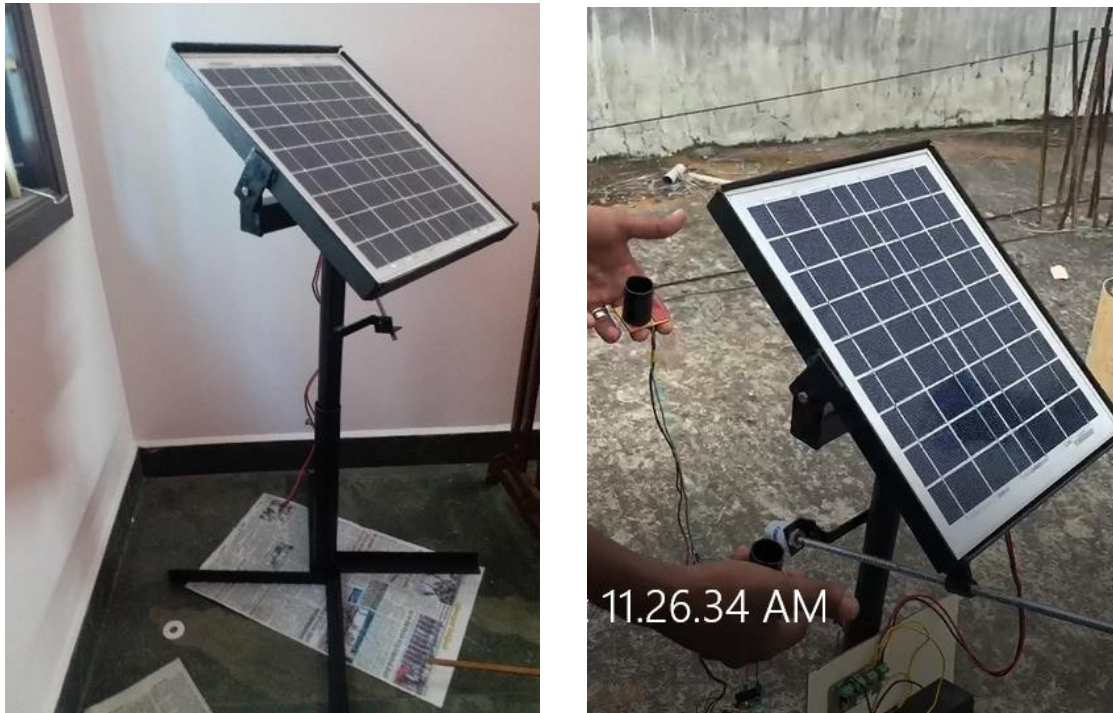


Fig. 3 Experimental setup

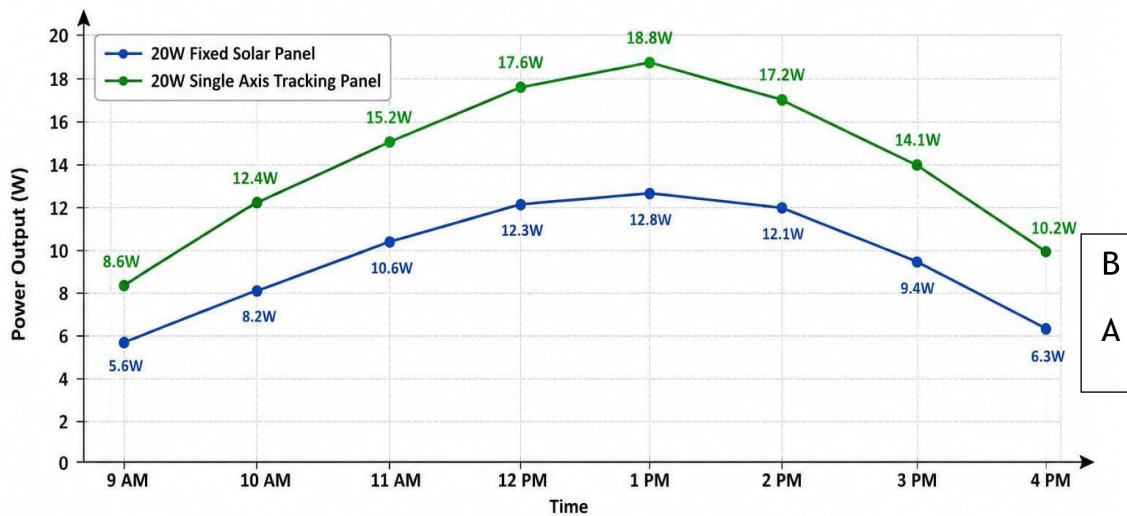
## Results and Discussion

Table. 1 Performance Summary

PARAMETER	FIXED PANEL	SINGLE AXIS TRACKING PANEL
Panel Rating	20 W	20 W
Average Output	9.6 W	13.8 W
Peak Output	12.8 W	18.8 W
Daily Energy Generated	67.2Wh	96.6Wh

EFFICIENCY IMPROVEMENT = 43.75 %

## EFFICIENCY COMPARISON



A – Fixed solar panel  
 B – Single axis tracking panel

Fig. 4 (Fixed Panel Vs Single Axis Tracking Panel)

### Inferences from the graph

The graph compares the performance of a 20W fixed solar panel and a 20W single axis tracking solar panel from 9 AM to 4 PM. The X-axis represents time, while the Y-axis represents power output in watts (W). The blue line indicates the power produced by the fixed solar panel, and the green line represents the power produced by the single axis tracking solar panel. From the graph, it is clear that the single axis tracking panel generates higher power output throughout the day compared to the fixed panel. This is because the tracking panel continuously follows the movement of the sun, allowing the solar rays to fall directly on the panel surface for a longer duration. At 9 AM, the fixed panel produces 5.6W, whereas the tracking panel produces 8.6W. As sunlight intensity increases during the day, the power output of both panels also increases. The maximum power output occurs at 1 PM, where the fixed panel produces 12.8W and the tracking panel produces 18.8W. After 1 PM, the power output gradually decreases due to the reduction in sunlight intensity during the evening hours. However, the tracking panel still maintains better performance than the fixed panel.

The total daily energy generated by the fixed panel is 67.3 Wh, while the single axis tracking panel generates 96.9 Wh. The average power output of the fixed panel is 9.6W, whereas the tracking panel achieves 13.8W. The graph shows that the single axis tracking solar panel provides approximately 43.9% higher energy output compared to the fixed solar panel. Therefore, single axis solar tracking systems improve the overall efficiency and energy generation of solar panels.

## CONCLUSION

The paper successfully delivers a fully automated, cost-effective single-axis solar tracking system that dynamically optimizes energy harvesting. By integrating a microcontroller with light-dependent resistors (LDRs), the system continuously detects maximum solar intensity and automatically adjusts the photovoltaic panel's orientation via a motor drive. Experimental implementation confirms that maintaining a perpendicular angle to the sun's rays enhances energy conversion efficiency by 20–30% compared to conventional fixed installations. The engineered tracking mechanism is highly energy-efficient, drawing only a minimal fraction of the generated power to operate its electronic and mechanical components. Additionally, the final prototype features a robust, low-maintenance design fabricated from readily available materials, ensuring high economic viability. This project ultimately validates single-axis tracking as a scalable solution for both small-scale rooftop systems and large-scale industrial solar farms. By maximizing localized clean energy production, this tracking technology lowers the cost per unit of electricity while directly reducing greenhouse gas emissions.

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