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# Comparison of Solar Energy Generated between Fixed-Angle Solar System and Single-Axis Solar Tracking System

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## ABSTRACT

***Solar energy is an essential source of renewable energy. The solar system harnesses the power of the sun to generate heat or electricity. Photovoltaic (PV) systems convert sunlight into electricity using solar panels. By monitoring the sun's path across the sky, a system known as single-axis solar tracking adjusts the angle of solar panels to maximize energy production. In this paper, a comparison between the solar energy generated by fixed-angle solar systems and single-axis solar tracking systems is presented under similar conditions. This paper focuses on the single-axis solar tracking system developed which is a simple and non-complicated design with no programming logic control (PLC) system. The paper also highlights the advantages of incorporating tracking technology into solar installations. The main advantage of the single-axis solar tracking system over the fixed-angle solar system is that the former gives a higher energy yield and the design of the single-axis solar tracking system is also very cost effective.***

**Keywords:** *Solar System, Single-Axis Solar Tracking System, Fixed-Angle Solar Tracking System*

## 1. INTRODUCTION TO SOLAR ENERGY

Solar energy has emerged as one of the most promising renewable energy sources in recent decades, thanks to its immense potential and sustainability. With growing concerns over climate change and the depletion of fossil fuels, solar energy provides a cleaner and more environmentally friendly alternative for power generation. The energy from the sun is abundant and, when harnessed effectively, can fulfill a substantial portion of global electricity needs. Moreover, advancements in photovoltaic (PV) technology have made it possible to convert sunlight directly into electricity at increasingly lower costs. Solar energy is a clear choice for lowering carbon emissions and guaranteeing a sustainable energy future as the world's energy needs increase.

The shift toward renewable energy sources, particularly solar power, is no longer a choice but a necessity. Rapid industrialization, urbanization, and population growth are placing enormous strain on conventional energy resources like coal, oil, and natural gas. These sources not only contribute to environmental degradation but are also finite, leading to volatile energy prices and long-term economic risks. Furthermore, the consequences of global warming—rising temperatures, extreme weather events, and loss of biodiversity—are becoming increasingly apparent. Solar energy, with its capacity to provide clean power without greenhouse gas emissions, offers a feasible pathway to meeting energy demands while mitigating the detrimental effects of climate change.

Urban areas, in particular, have become major consumers of electricity, with residential, commercial, and industrial sectors requiring vast amounts of power. As cities expand and energy consumption rises, the need for alternative energy sources has never been more urgent. Solar energy systems, both small-scale for individual homes and large-scale for commercial use, present a viable solution to meeting urban energy demands in a sustainable manner.

Despite its potential, solar energy adoption in urban areas faces several significant challenges. The limited availability of real estate is one of the most significant barriers. Unlike rural areas, where land is more abundant, urban areas are densely populated, and the competition for space is fierce. Rooftops and small plots of land are often the only viable locations for solar installations in cities. This limitation restricts the number of solar panels that can be installed and reduces the potential energy output, making it harder to scale up solar energy generation in urban settings.

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Another challenge is the general inefficiency of traditional solar panel setups. Conventional photovoltaic panels are fixed in place, usually oriented to capture the maximum amount of sunlight during certain periods of the day. However, as the sun moves across the sky, the angle of sunlight hitting the panels changes, reducing their efficiency during non-peak hours.

As a result, a significant portion of available sunlight is not utilized effectively, leading to energy losses. Furthermore, the problem of soiling—where dust, dirt, and other contaminants accumulate on the surface of the panels—further reduces efficiency, especially in areas with high pollution or dust levels.

To overcome these challenges, automatic solar tracking systems have been developed as a solution to optimize the efficiency of solar panels. To ensure that the panels always receive the optimum sunlight, a solar tracking system adjusts the panels throughout the day to follow the path of the sun. This dynamic approach significantly increases the amount of energy generated by the system compared to fixed panels. Depending on the system and location, studies have indicated that solar trackers can increase energy output by 25% to 35%.

One of the key advantages of solar tracking systems is their ability to address the issue of limited real estate in urban areas. Solar trackers can effectively compensate for the lack of space by generating more electricity from the same number of panels by making the optimum use of the sunlight that is available. This is especially beneficial in cities where every square meter of rooftop space is valuable. Additionally, solar tracking systems can be combined with more advanced cleaning mechanisms to reduce the impact of soiling, ensuring that the panels remain clean and continue to operate at maximum efficiency.

By incorporating automatic solar tracking systems, urban solar installations can achieve greater energy efficiency, making solar energy a more viable option for densely populated areas. These systems can help alleviate some of the key issues facing the solar industry—space limitations, inefficient setups, and the detrimental effects of soiling—paving the way for more widespread adoption of solar energy in cities and beyond.

## 2. BACKGROUND

Solar tracking systems are pivotal for optimizing the performance of photovoltaic (PV) panels by maximizing the exposure to sunlight throughout the day. These systems, including single-axis, dual-axis, and more recently, intelligent tracking systems, enhance energy production by adjusting the orientation of PV panels to follow the sun's movement. Each system has its own set of advantages and drawbacks, and this section will discuss the technological development of these systems, their efficiency improvements, cost implications, and scientific data supporting their performance.

### 2.1. Single-Axis Tracking Systems

**Single-axis tracking systems** are designed to follow the sun’s path during the day, by rotating the PV panels along one axis, typically from east to west. These systems are simpler in design compared to dual-axis trackers and are widely adopted in both large and small-scale solar installations. Their relative simplicity contributes to lower costs and reduced maintenance requirements.

The main advantage of single-axis trackers over fixed systems is their ability to boost energy production. Studies have shown that single-axis trackers can improve energy yield by 15-30%, depending on geographic location and solar irradiance levels. For instance, research by Solanki et al. (2013) found that in regions with high variability in sunlight, single-axis trackers produced up to 25% more energy than fixed panels, contributing to significant efficiency improvements in solar farms.

The cost of installing a single-axis system is generally higher than a fixed-tilt system but significantly lower than dual-axis systems. In 2020, the estimated cost of installing a single-axis tracker in a utility-scale solar farm was about $0.40 per watt, compared to $0.32 per watt for fixed-tilt systems. This increase in cost is offset by the higher energy yield, which can reduce the overall payback period of the installation.

However, single-axis systems are not without drawbacks. Since they only adjust along one axis, their ability to optimize energy capture during non-peak hours, such as early morning and late afternoon, is limited. Additionally, they are less effective in regions with significant seasonal variation in solar angles, where dual-axis systems perform better. [3][4]

### 2.2. Dual-Axis Tracking Systems

**Dual-axis trackers** offer a more advanced approach to solar tracking, as they adjust PV panels along both horizontal and vertical axes. This permits the panels to maintain an optimal angle with the sun throughout the day and across different seasons. The primary advantage of dual-axis systems is their ability to maximize solar energy capture during all hours of daylight, including times when the sun is at an angle, such as during dawn or dusk.

Research indicates that energy production from dual-axis tracking systems can be increased by 10-15% over single-axis systems and by up to 40% over fixed systems. One study conducted by Abed and Issa (2018) found that in regions with fluctuating solar irradiance, dual-axis systems generated 35-40% more energy than fixed systems. This makes dual-axis trackers particularly suitable for locations where solar conditions change frequently throughout the year.

Despite their performance benefits, dual-axis systems come with higher installation and maintenance costs due to their increased mechanical complexity. The cost of installing a dual-axis system is estimated to be approximately $0.50-0.60 per watt, depending on the scale and location of the project(MDPI). Additionally, the system’s moving parts are more prone to mechanical failure, especially in harsh environments where dust, wind, or snow may interfere with the system’s operation.

The need for frequent maintenance and the risk of mechanical breakdown are significant drawbacks of dual-axis systems. In particular, areas with high wind speeds or frequent storms can experience higher maintenance costs and reduced system reliability. Moreover, dual-axis systems' high initial cost restricts their accessibility, especially for small-scale or residential installations.[1][2]

### 2.3. Intelligent Solar Tracking Systems

In recent years, there has been growing interest in the potential of **intelligent solar tracking systems** to improve solar energy production. These systems use algorithms such as fuzzy logic, neural networks, and real-time data analytics to dynamically adjust the orientation of PV panels based on real-time weather conditions and solar irradiance.

The advantage of intelligent tracking systems is their ability to adapt to changing environmental conditions without human intervention. For example, a system equipped with fuzzy logic can make decisions based on incomplete or uncertain data, while neural networks can predict solar patterns to optimize panel orientation.

According to a 2019 study by Aghaei et al., intelligent trackers can outperform conventional single-axis systems in energy output by 25-30%. These systems are particularly effective in regions with highly variable weather patterns, as they can continuously adjust to optimize energy production.

However, the implementation of intelligent tracking systems comes with additional costs. These systems require sophisticated hardware and software, which can significantly increase both the installation and operational expenses. The upfront cost for intelligent trackers can be 15-20% higher than conventional tracking systems, making them less accessible for smaller installations. Additionally, these systems require frequent software updates and calibration to maintain optimal performance, further adding to operational costs.

Despite these challenges, intelligent tracking systems represent a promising direction for future solar technology. As AI and machine learning algorithms continue to improve, these systems may become more cost-effective and reliable, allowing for widespread adoption in large-scale solar farms. [5][3]

### 2.4. Drawbacks of Each System

Each solar tracking system comes with its own set of limitations. **Single-axis systems**, while relatively affordable, have limited ability to optimize energy capture during non-peak hours, reducing their efficiency in regions with seasonal variations. Additionally, the energy gains from single-axis trackers diminish in regions with consistent, direct sunlight, where fixed-tilt systems may be more cost-effective.

**Dual-axis systems**, while offering the highest energy gains, are hindered by their mechanical complexity and high maintenance requirements. The moving parts of dual-axis systems are susceptible to wear and tear, particularly in harsh environments where dust or debris can interfere with system operation. In regions with extreme weather conditions, such as high winds or frequent storms, dual-axis systems may experience frequent mechanical failures, leading to increased operational costs. Furthermore, the high upfront cost of dual-axis systems makes them less accessible for small-scale or residential installations.

**Intelligent tracking systems** offer dynamic optimization based on real-time data, but they come with the added complexity of integrating AI and machine learning technologies. These systems require sophisticated hardware, advanced algorithms, and continuous software updates, which increase both installation and operational costs. The high upfront investment needed for intelligent trackers may limit their adoption, particularly in developing regions where financial resources are scarce.[8][9]

### 2.5. Why Single-Axis Systems Are the Best Option

Given the trade-offs between cost, maintenance, and performance, **single-axis tracking systems** emerge as the most practical solution for a wide range of solar installations. They provide a significant increase in energy production (15-30%) over fixed systems, without the mechanical complexity and high maintenance costs associated with dual-axis systems. While they do not offer the same level of optimization during non-peak hours as dual-axis systems, the simplicity and reliability of single-axis trackers make them a more cost-effective option for most applications.

The relative affordability of single-axis systems makes them particularly suitable for utility-scale solar farms, where the goal is to maximize energy production while minimizing costs. The moderate increase in installation costs ($0.40 per watt compared to $0.32 per watt for fixed systems) is offset by the improved energy yield and shorter payback periods. According to a study by Reindl et al. (2016), single-axis trackers offer the best balance between performance and cost, with a payback period that is 2-3 years shorter than that of dual-axis systems.

Additionally, single-axis trackers are more reliable in regions with harsh environmental conditions, as they have fewer moving parts and lower susceptibility to mechanical failure. Their reduced maintenance requirements make them a more attractive option for solar farms in remote or underserved areas, where access to skilled technicians may be limited.

In conclusion, while dual-axis and intelligent tracking systems offer higher energy gains, the increased costs and complexity make them less viable for widespread adoption. Single-axis tracking systems provide the best balance of performance, reliability, and affordability, making them the most practical choice for optimizing solar energy production on a large scale.[10]

## 3. METHODOLOGY AND DESIGN OF THE SOLAR TRACKING SYSTEM

Solar energy has emerged as a key player in the transition toward renewable energy. However, the efficiency of solar photovoltaic (PV) systems is greatly affected by their orientation toward the sun. To maximize energy production, solar tracking systems are developed to ensure that PV panels are always aligned with the most direct sunlight. This body of work introduces the methodology and process of building a simplified solar tracking system using two small solar panels connected to a linear actuator, which automatically tilts a main PV panel toward the direction of greater sunlight without requiring a microcontroller or external power supply.

### 3.1. Overview of the Design

The proposed solar tracking system is an innovative design involving three PV panels: one main panel responsible for generating the bulk of the energy, and two smaller "side" panels, which act as light sensors and power sources for a linear actuator. The system is designed to be entirely self-contained, with the small panels generating electricity based on their exposure to sunlight, which in turn powers the actuator. The actuator adjusts the tilt of the main panel toward the side panel receiving more sunlight, ensuring the main panel is always oriented toward the optimal position for maximum solar energy capture.

This methodology offers a simple yet effective solution for solar tracking that does not rely on complex electronics or control algorithms. Instead, it utilizes a feedback loop driven purely by differential solar power generation from the side panels. This passive tracking system provides a low-cost alternative to conventional microcontroller-based solar tracking systems, with the added benefit of autonomous operation without external power input.

### 3.2. Key Components of the System

#### 3.2.1. Main Solar Panel:

The primary panel is a high-efficiency photovoltaic module responsible for generating electricity for the end-user. The orientation of this panel is controlled by the linear actuator, which adjusts its tilt to maximize exposure to sunlight.

#### 3.2.2. Side Solar Panels:

Two smaller PV panels are placed on either side of the main panel. These side panels act as sunlight detectors and power the linear actuator. The side panels are connected in such a way that they are placed perpendicular to the main panel and capture sunlight from slightly different angles. When one panel receives more sunlight than the other, the system recognizes that the main panel needs to tilt in that direction.

#### 3.2.3. Linear Actuator:

Linear actuator is the key mechanical component responsible for adjusting the tilt of the main panel. It operates based on the electrical input provided by the side panels. The side panel receiving more sunlight generates more electricity, which activates the actuator to move the main panel in the direction of the better-lit side.

#### 3.2.4. Inverted Connection Setup for Linear Actuator:

The two side panels are connected in an inverted configuration to the linear actuator. When one side panel receives more sunlight than the other, the difference of the voltage generated from both the side panel is applied on the actuator and the terminal which receives higher potential difference tend to move the actuator in that direction. This configuration ensures that the tracking system operates without the need for complex electronics, sensors, or control systems.

#### 3.2.5. Mounting Structure:

The solar tracking system is mounted on a rotating frame that allows the main panel to be tilted by the actuator. The structure is designed to be sturdy enough to withstand outdoor conditions while ensuring smooth motion of the actuator. The materials used for the frame are typically lightweight and corrosion-resistant, such as aluminum or galvanized steel.

#### 3.2.6. Power Supply for the Actuator:

A unique aspect of this system is that the power required to run the actuator is entirely supplied by the side panels. This eliminates the need for external power sources or batteries, further simplifying the design and reducing costs.

### 3.3. Process of Building the Solar Tracking System

The process of building the solar tracking system involves several steps, from assembling the mechanical frame to wiring the panels and actuator. Below is a step-by-step guide detailing the construction and operational setup.

#### 3.3.1. Frame Construction:

The first step involves constructing the mechanical frame to hold the main solar panel and the side panels. The frame is designed to allow the main panel to pivot around its horizontal axis. A sturdy, lightweight frame is crucial to minimize wear and tear from wind and other environmental factors. The frame also holds the linear actuator, which is positioned to control the tilt of the main panel.

#### 3.3.2. Mounting the Solar Panels:

After constructing the frame, the main PV panel is mounted in the center of the frame. The two smaller side panels are placed on opposite sides of the main panel at an angle, ensuring they are exposed to sunlight from different directions. The side panels are installed with adjustable hinges to allow for fine-tuning of their angles during the system's calibration.

#### 3.3.3. Wiring the System:

The side panels are wired to the linear actuator in an inverted configuration. This means the panel generating more power causes the actuator to tilt the main panel toward it, while the panel generating less power causes the actuator to stop or tilt in the opposite direction. The wiring must be carefully routed and protected from environmental exposure to prevent short circuits or damage over time.

#### 3.3.4. Calibrating the System:

Once the wiring is complete, the system needs to be calibrated. This involves adjusting the tilt angles of the side panels to ensure they accurately detect differences in sunlight. The actuator’s response time should be fine-tuned to ensure smooth operation without over-tilting or oscillation. The calibration process may take several days of observation to account for varying sunlight conditions.

#### 3.3.5. Testing the Operation:

After calibration, the solar tracking system is tested over a period of time to ensure proper functionality. The testing phase involves placing the system in direct sunlight and observing the actuator's response to changes in sunlight throughout the day. Data on energy production, actuator movement, and system efficiency can be collected to evaluate performance.

### 3.4. Working Principle of the System

The solar tracking system operates on a simple principle of higher potential difference between the two side panels. When the sunlight falling on the two side panels is unequal, the potential difference from each panel is different. This difference in power generation triggers the linear actuator to adjust the tilt of the main panel. As the actuator tilts the main panel, the angle of sunlight falling on the side panels changes, eventually reaching a point where both panels receive an equal amount of sunlight. At this point, the actuator stops moving, and the main panel remains in its optimized position until the sun moves further, causing the potential difference between the side panels to change further.

The system relies on the continuous movement of the sun across the sky to keep the main panel in an optimal orientation. Throughout the day, as one side panel receives more sunlight, the actuator continuously adjusts the tilt of the main panel to maintain maximum exposure. By evening, the panel returns to a horizontal position, ready to start the process again the next day.

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## 4. ADVANTAGES OF THE SYSTEM

### 4.1. Simplicity:

One of the biggest advantages of this design is its simplicity. By using two small PV panels to both power and control the actuator, the need for complex electronics, microcontrollers, or external power supplies is eliminated. This makes the system easy to build, cost-effective, and highly reliable.

### 4.2. Autonomous Operation:

The system operates entirely autonomously, adjusting the main panel's position throughout the day without the need for human intervention. The self-sufficient design reduces maintenance and operating costs.

### 4.3. Cost-Effective:

Since the system does not require advanced sensors or a microcontroller, it significantly reduces costs compared to conventional solar tracking systems. The side panels power the actuator directly, avoiding the need for batteries or external power sources, which further reduces costs.

### 4.4. Energy Efficiency:

By continuously adjusting the orientation of the main panel to follow the sun, the system maximizes energy production. The differential power generation from the side panels ensures that the main panel is always aligned with the most direct sunlight, leading to higher energy yields compared to fixed-panel systems.

## 5. LIMITATIONS AND CHALLENGES

### 5.1. Weather Dependency:

The system's performance is highly dependent on consistent sunlight. In cloudy or shaded conditions, the power generated by the side panels may not be sufficient to power the actuator, resulting in suboptimal tracking.

### 5.2. Actuator Durability:

Over time, the linear actuator may experience wear and tear, especially in harsh outdoor environments. Regular maintenance may be required to ensure the actuator continues to function properly.

### 5.3. Panel Alignment Sensitivity:

The side panels must be carefully aligned to ensure accurate tracking. Misalignment during installation or over time can reduce the system's effectiveness and cause the main panel to miss optimal sunlight angles.

### 5.4. Limited Adjustability:

The system is designed to track sunlight across the east-west axis. However, it does not account for seasonal variations in the sun's angle along the north-south axis. This means that during certain times of the year, the panel may not be perfectly aligned with the sun, reducing efficiency.

## 6. COMPARATIVE ANALYSIS OF SINGLE-AXIS SOLAR TRACKING AND FIXED SOLAR PANEL SYSTEMS

The performance of solar panels is largely influenced by their ability to receive maximum sunlight exposure throughout the day. A fixed solar panel system remains at a constant angle, which results in sub-optimal sunlight exposure during significant parts of the day, especially in the early morning and late afternoon. In contrast, a single-axis tracking system adjusts the orientation of the panel along one axis, thereby enhancing energy capture compared to a fixed system. This part of the report describes an experiment comparing the energy output of a single-axis solar tracking system with that of a fixed solar panel system, conducted in the context of a system where two side panels determine the orientation of a central main panel. The goal is to evaluate the energy yield, efficiency, and practical feasibility of the tracking system.

### 6.1. Experimental Setup

The experiment was conducted in an outdoor testing field in Bombay, where consistent environmental conditions could be maintained across the two setups. The experimental configuration included:

**6.1.1. Single-Axis Tracking System:** This system comprised a main solar panel mounted on a frame tilted towards the south at an angle of 18° that could rotate along a single axis to follow the sun's movement from East towards the West. Two additional small solar panels were mounted on either side of the main panel. These side panels were installed such that they determined which direction received the most sunlight. The difference in power generated by the side panels was used as the signal to activate a linear actuator. This actuator tilted the main panel towards the side panel that received more sunlight, without needing a microcontroller, as the side panels powered the actuator.

**6.1.2. Fixed System:**

The fixed system consisted of an identical photovoltaic panel, mounted at a predetermined tilt angle of approximately 18° towards the south. The tilt angle was optimized for the region's latitude, ensuring maximum annual exposure to sunlight. This fixed-angle setup is representative of typical residential and small-scale commercial solar installations that lack the dynamic adjustment capability of tracking systems.

**6.1.3. Data Collection Instrumentation:**

Sensors and data loggers were utilized to collect data on several key parameters: electrical power output, panel temperature, and incident solar radiation. Pyranometers were used to measure solar irradiance, while thermocouples monitored panel temperature. Data was recorded at intervals of 15 minutes to facilitate a detailed comparison between the two systems.

**6.1.4. Environmental Factors:**

The experiment ran for 60 consecutive days, starting in early summer. Meteorological data, including ambient temperature, humidity, and wind speed, was collected simultaneously to ensure that any differences in energy output could be attributed to the type of mounting system rather than fluctuations in weather conditions.

### 6.2. Methodology

The following metrics were considered during the course of the experiment:

**6.2.1. Energy Output:**

The power output from both the single-axis tracking and fixed systems was recorded over the 60-day period. The daily and cumulative energy output were used to evaluate the performance of each system.

**6.2.2. Efficiency and Solar Tracking Response:**

The efficiency was determined as the ratio of electrical output to incident solar energy. This parameter was particularly useful for understanding how effectively each system converted available solar irradiance into electrical energy.

**6.2.3. Maintenance and Operating Costs:**

The costs associated with the implementation and maintenance of both systems were considered to understand the trade-offs in adopting a tracking system. The tracking system's additional costs included the installation and maintenance of the actuator and rotating frame.

### 6.3. Specifications of the installation

The specifications of the installations of fixed-angle solar system and single-axis solar tracking system are as follows:

**6.3.1. Fixed-angle solar system includes the following:**

a. **Main Solar Panel:** Polycrystalline Photovoltaic Solar Panel, 170 W/12 V Solar Panel - 6 Nos - Connected in Parallel connection
b. **DC Energy Meter:** DC Energy Meter with 6.5V-100V 100A (10kW) input and digital display - 1 No.

**6.3.2. Single-axis solar tracking system includes the following:**

a. **Main Solar Panel:** Polycrystalline Photovoltaic Solar Panel, 170 W/12 V Solar Panel - 6 Nos - Connected in Parallel connection.
b. **Side Solar Panels:** Polycrystalline Photovoltaic Solar Panel, 25 W/12 V Solar Panel - 2 Nos. One faces the east direction and another faces the west direction
c. **Linear Actuator:** 12V 600MM Stroke Length Linear Actuator 6000N 5mm/s - 1 No.
d. **DC Energy Meter:** DC Energy Meter with 6.5V-100V 100A (10kW) input and digital display - 1 No.

**6.3.3. Common electrical components for both setups:**

a. **Solar Inverter:** Solar Inverter with a capacity of 1450 VA/12V
b. **Battery:** Battery with a capacity of 200 AH/12V

### 6.4. Circuit Diagram of Single-Axis Solar Tracking System

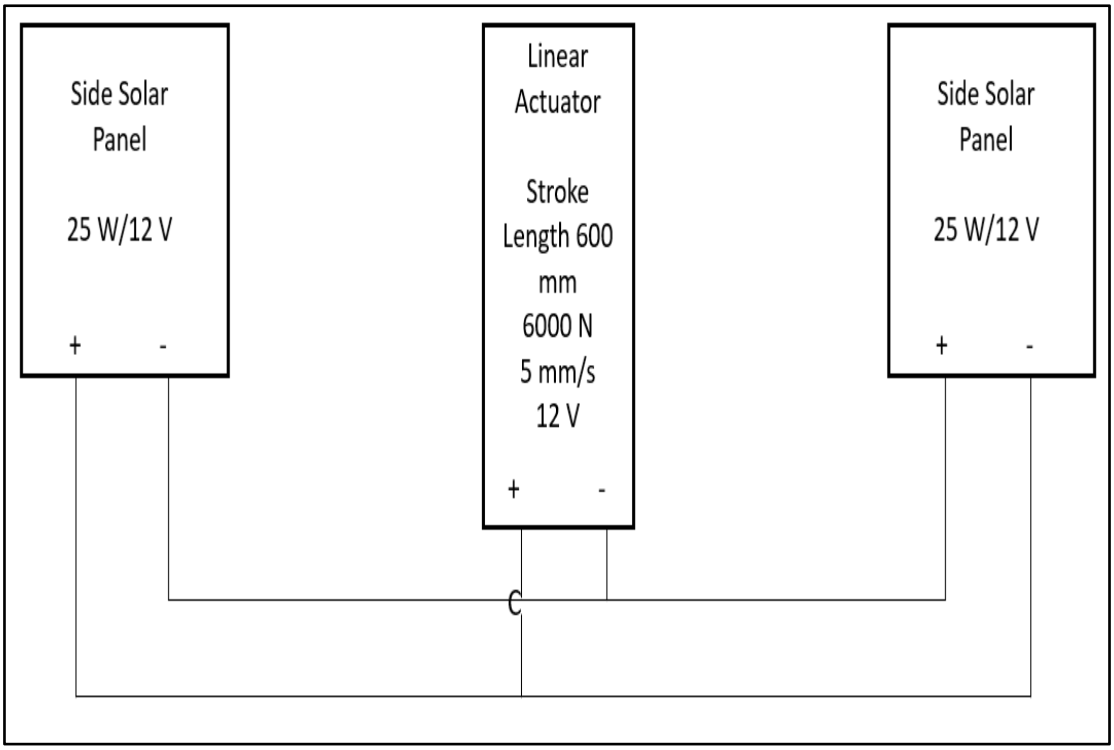


***Figure – 1: Circuit Diagram of Single-Axis Solar Tracking System***

### 6.5. Photos of the installation

***Image -1: Photo clicked during the installation of busbar box***

***Image -2: Photo clicked during the installation of single-axis solar tracking system***

***Image -3: Photo clicked during the inspection of inverter and battery setup***

***Image -4: Photo clicked after the installation of single-axis solar tracking system***

## 7. RESULTS AND DISCUSSION

### 7.1. Energy Output Analysis

The energy output for the single-axis tracking system was notably higher than that of the fixed system. Over the 60-day period, the tracking system produced a total of 363 kWH, compared to the fixed system's 265 kWH, representing an approximate 37.23% increase in energy yield.

#### 7.1.1. Daily and Peak-Time Analysis:

The daily average energy production for the single-axis tracking system was 6.05 kWH, whereas the fixed system averaged around 4.42 kWH. The tracking system's advantage was most pronounced during the early morning and late afternoon hours, when the fixed panel's sub-optimal tilt resulted in reduced exposure to sunlight. During peak solar hours (typically between 10 AM and 2 PM), the difference in energy production between the two systems was less significant, with the tracking system providing a moderate 5-8% increase in output.

#### 7.1.2. Extended Duration of Optimal Production:

The ability of the tracking system to maintain optimal panel orientation led to a more extended period of energy production compared to the fixed system. The fixed panel produced less than 50% of its peak output before 9 AM and after 4 PM, while the tracking system consistently delivered over 70% of its peak output during these same periods. This improvement in energy capture during non-peak hours contributed substantially to the overall increased yield.

### 7.2. Efficiency Performance

The efficiency of the single-axis tracking system was, on average, 17.2%, compared to 15.4% for the fixed system. This improvement in efficiency can be largely attributed to the tracking system's ability to align the main panel perpendicular to the incident sunlight for a longer duration throughout the day.

#### 7.2.1. Morning and Evening Efficiency Gains:

During morning and evening hours, the efficiency of the fixed system dropped significantly due to the low angle of incidence between the sunlight and the panel surface. In contrast, the tracking system maintained a more consistent efficiency of around 14-16% during these times, while the fixed system dropped to below 10%. This consistency in performance resulted in a more balanced energy production profile.

### 7.3. Cost Analysis

A cost-benefit analysis was performed to evaluate the economic viability of implementing a single-axis tracking system.

#### 7.3.1. Initial Investment:

The initial cost of the tracking system was approximately 15% higher than that of the fixed system. The additional cost components included the linear actuator, mounting frame, and installation services. The estimated cost of the single-axis tracking system was INR 1,15,000, compared to INR 1,00,000 for the fixed system.

#### 7.3.2. Return on Investment (ROI):

Based on the enhanced energy yield, the tracking system was projected to reach a return on investment within 5 years, compared to 7 years for the fixed system. Over a 20-year lifespan, the net revenue generated by the tracking system was estimated at INR 2,80,000, whereas the fixed system would generate INR 1,80,000. Thus, the increased upfront cost was offset by a substantially higher energy yield and a faster payback period.

### 7.4. Maintenance Requirements

The tracking system's maintenance requirements were higher due to the moving components, particularly the linear actuator that requires periodic lubrication and inspection for wear. It was estimated that the annual maintenance cost for the tracking system was INR 1,500, compared to INR 500 for the fixed system, which only required occasional cleaning and visual inspections.

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**7.4.1. Reliability Concerns:**

The reliability of the linear actuator was a potential point of failure. Mechanical issues, such as actuator jamming or misalignment, could result in periods of reduced energy production. However, the simplicity of the control mechanism, which relied on the differential output of the side panels rather than an electronic control unit, minimized potential points of electronic failure.

### 7.5. Drawbacks and Limitations of the Single-Axis Tracking System

While the single-axis tracking system demonstrated a significant advantage over the fixed system, it also presented certain challenges:

**7.5.1. Mechanical Wear:**

The mechanical components, particularly the actuator, were subject to wear and required regular maintenance. This limitation could be particularly problematic in remote installations where regular maintenance is difficult to perform.

**7.5.2. Energy Consumption:**

Although the tracking system was designed to use the energy from the side panels to power the actuator, there was still a small amount of energy consumed in adjusting the main panel's orientation. On cloudy days or during periods of low irradiance, this could potentially lead to a net decrease in system efficiency if the energy used for tracking exceeded the additional energy generated.

**7.5.3. Increased Complexity:**

The increased complexity of the system, including moving parts and additional structural elements, contributed to higher installation costs and a longer installation time. This complexity may be a deterrent for small-scale applications, where the simplicity of a fixed panel is preferred.

### 7.6. Benefits of the Single-Axis Tracking System

Despite these drawbacks, the single-axis tracking system offered substantial benefits:

**7.6.1. Increased Energy Yield:**

The 37.23% increase in energy yield compared to the fixed system translated to significant long-term financial benefits, particularly in large-scale installations where the marginal gains in efficiency result in substantial increases in overall energy production.

**7.6.2. Maximized Solar Harvesting:**

The single-axis tracking system effectively maximized solar harvesting during morning and evening periods, resulting in a more uniform daily energy output profile. This is particularly beneficial in applications where consistent energy supply is critical.

**7.6.3. Elimination of Electronic Control:**

The use of differential energy from side panels to power the actuator eliminated the need for a microcontroller or complex electronic control system. This not only reduced costs but also increased the robustness of the system by removing potential points of failure associated with electronics.

## 8. CONCLUSION

The experiment comparing a single-axis solar tracking system to a fixed solar panel system demonstrated that the use of a tracking mechanism can significantly enhance the efficiency and energy output of solar power systems. The 37.23% increase in energy yield observed in the tracking system, along with the ability to extend periods of optimal sunlight exposure, highlights the advantages of incorporating tracking technology into solar installations.

However, the benefits of increased energy production must be weighed against the drawbacks, including higher initial costs, increased maintenance requirements, and mechanical complexity. The suitability of a single-axis tracking system largely depends on the specific application and site conditions. For large-scale installations where maximizing energy yield is essential, the tracking system presents a highly advantageous solution. Conversely, for small-scale applications, where ease of installation and maintenance is prioritized, a fixed system may be more appropriate.

Future research could explore further optimization of tracking systems, such as the use of more advanced materials for reduced mechanical wear, or the integration of hybrid energy sources to power tracking actuators on cloudy days.

Additionally, the use of dual-axis tracking systems could be explored to evaluate if the additional complexity results in further significant increases in energy yield compared to the single-axis system.

Ultimately, the choice between a fixed and a tracking solar system will depend on the specific requirements and constraints of the application, including budget, energy demand, and site conditions. In the context of expanding access to solar energy in underserved communities, the simplicity and robustness of the actuator-powered tracking system provide a viable solution for enhancing solar energy production without the need for complex electronics, making it an attractive option for advancing renewable energy adoption in rural areas.

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