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ADVANCING SOLAR TECHNOLOGY: COMPARATIVE PERFORMANCE ASSESSMENT OF FIXED AND DUAL-AXIS TRACKING SYSTEMS

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Abstract
The increasing global demand for renewable energy has intensified interest in solar photovoltaic (PV) technologies. While fixed solar panels are widely used due to their simplicity and low cost, dual-axis solar tracking systems promise significantly improved energy capture by continuously aligning panels with the sun. This study presents an experimental comparison between a fixed PV system and a dual-axis solar tracking system under identical environmental conditions in Larkana, Pakistan. Data was collected hourly for voltage, current, power, temperature, and environmental effects. Results show that the dual-axis tracker produced between 25–40% more energy than the fixed system, with particularly large gains during morning and late-afternoon hours. The system also demonstrated improved adaptability under partially cloudy conditions. This research concludes that despite higher initial costs, dual-axis tracking offers superior performance and long-term energy benefits, making it a strong candidate for high-insolation regions.

INTRODUCTION

Over the past two decades, global reliance on fossil fuels has led to severe environmental degradation and accelerated resource depletion. As population growth and industrialization continue to rise, non-renewable energy reserves are being consumed at an unsustainable rate, prompting nations to seek cleaner and more reliable energy alternatives. In Bangladesh, the total electricity generation capacity is approximately 22,348 MW. According to data from the Bangladesh Power Development Board (BPDB), 52% of this electricity is generated from gas-powered plants, 27% from furnace oil, 5.86% from diesel, 8.03% from coal, 1% from hydroelectric sources, 0.5% from other renewable sources, and the remaining 5.27% is imported. Despite this capacity, the country produces only 12,000–13,000 MW of electricity daily against a demand of 14,000–14,500 MW (BPDB, 2023). This energy deficit highlights the urgent need to expand renewable energy utilization to meet increasing national demand.

Solar photovoltaic (PV) technology represents one of the most promising renewable energy solutions due to its sustainability, accessibility, and declining production costs. PV systems convert radiant energy from the sun into electrical energy through semiconductor-based cells. Optimal performance of these systems depends significantly on the angle at which panels face the sun. For instance, the ideal tilt angle is approximately 45° during spring and 20° during summer when solar elevation is high. However, fixed-tilt PV systems cannot continuously adjust to the sun's changing position, resulting in suboptimal energy capture throughout the day.

To address this limitation, dual-axis solar tracking systems have been developed to maintain optimal panel orientation by adjusting both tilt and azimuth angles. These systems improve solar radiation collection by continuously following the sun's trajectory, thereby increasing power output. The solar tracking mechanism used in this study operates autonomously, powered by an integrated rechargeable battery system. By employing dual-axis tracking, the proposed system aims to enhance the efficiency of PV panels and maximize energy production throughout the day.

As global interest in renewable energy grows, a comparative evaluation of fixed and dual-axis tracking solar panel systems becomes increasingly relevant. Fixed solar panels remain widely used due to their structural simplicity and lower installation costs. However, dual-axis systems promise significantly higher efficiency by maintaining direct alignment with sunlight. This research seeks to examine the advantages, limitations, and performance differences between fixed and dual-axis solar technologies, focusing on efficiency, economic viability, installation complexity, and practical applications. The goal is to provide evidence-based insight to support informed decision-making for renewable energy deployment.

1.2 Solar Energy

Solar energy is derived from the radiant light and heat emitted by the sun. This energy can be harnessed using a variety of technologies, including solar heating systems, photovoltaic (PV) panels, concentrated solar power (CSP), concentrator photovoltaic (CPV) systems, solar architecture, and artificial photosynthesis. The sun radiates more energy in a single day than the world consumes in an entire year, making solar energy one of the most abundant renewable resources available.

Solar technologies can be categorized as either passive or active. Passive systems—such as building orientation, thermal-mass materials, and natural ventilation designs—capture and distribute solar energy without mechanical mechanisms. In contrast, active systems utilize solar collectors, PV cells, or CSP units to convert sunlight into usable heat or electricity. Electricity generation through solar energy generally occurs via two methods: PV systems and solar thermal systems.

1.3 Solar Photovoltaic (PV) Cells

PV cells, commonly made from semiconductor materials like silicon, are the fundamental units of solar panels. When sunlight strikes a PV cell, photons energize the electrons within the semiconductor, causing them to move and generate an electric current. The efficiency of PV cells depends on material quality, cell architecture, and available sunlight. Modern PV technologies have significantly improved cell efficiency, enabling greater power output from smaller panel surfaces.

PV cells are assembled into modules or panels to enhance their overall electricity generation capacity. These panels can be installed on rooftops, in solar farms, or integrated into portable systems. Energy produced from PV panels may be used directly, supplied to the grid, or stored in batteries for later use.

1.4 Operation of Solar Photovoltaic (PV) Cells:

PV cells function by converting sunlight into direct current (DC) electricity through the photovoltaic effect. When photons strike the semiconducting material, electrons are excited and forced into motion, creating an electrical current. The energy conversion efficiency is influenced by factors such as semiconductor purity, panel orientation, temperature, and irradiance levels. PV modules are typically installed in arrays to increase output and are widely used to power residential, industrial, and commercial loads.

1.5 Environmental Impact:

Coal-fired power generation is associated with significant environmental and public health impacts. It releases large quantities of carbon dioxide (CO_2), contributing to global climate change, as well as harmful pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter. These emissions degrade air quality and pose health risks. Coal power plants also consume substantial water resources and generate pollutants that can contaminate waterways through runoff and coal ash disposal. Furthermore, coal mining leads to land degradation, habitat loss, and soil erosion. In contrast, solar energy offers a substantially cleaner alternative with minimal greenhouse gas emissions during operation. While large solar farms may require considerable land area, rooftop PV installations mitigate land-use concerns. The production of solar panels does involve raw material extraction, which can have environmental implications; however, overall impacts are significantly lower compared to fossil fuel-based systems. Effective recycling processes are essential to reduce waste and recover valuable materials at the end of a panel's lifecycle. Schuster (2010) investigated optimal tilt angles for solar panels and concluded that dual-axis tracking systems provide superior energy capture compared to fixed installations due to their ability to continuously adjust orientation. Similarly, Kostic and Pavlovic (2012) analyzed sun-tracking technologies and demonstrated that dual-axis systems significantly outperform fixed-angle collectors. Hassan and El-Shimy (2015) compared fixed, single-axis, and dual-axis systems, finding that dual-axis trackers produce the highest energy output across diverse climatic conditions.

Research by Stoyanov et al. (2017) and Bhuyan et al. (2018) further showed that dual-axis systems typically yield 15%–25% more energy than fixed systems and benefit from advancements in sensor and control algorithms. Kaddoura et al. (2013) reported that dual-axis trackers can increase efficiency by up to 40% in high-insolation regions. Bakirci (2011) emphasized the importance of seasonal tilt adjustments and demonstrated significant gains using dynamic tracking. Karakaya and Şahin (2019) highlighted increasing global adoption of dual-axis systems in utility-scale applications. Lave et al. (2010) explored variability in solar output and noted that dual-axis systems reduce fluctuations in energy generation. Bansal and Bhavsar (2014) examined mechanical and electronic components of dual-axis trackers, emphasizing the role of sensors, actuators, and microcontroller-based control systems. Chang and Lin (2012) found that dual-axis trackers consistently outperform single-axis and fixed systems across varying environmental conditions. Ali et al. (2020) evaluated economic feasibility in Pakistan and concluded that dual-axis systems offer substantial long-term financial benefits. Abdallah and Badran (2005) demonstrated practical improvements in energy capture using a fully functional dual-axis tracker. Sefa et al. (2009) showed notable performance gains during morning and late-afternoon hours. Shukla et al. (2015) observed reduced performance advantages under cloudy conditions but confirmed overall superiority over fixed systems.

Studies by García et al. (2016) highlighted durability considerations and maintenance requirements, particularly in harsh climates. Zahra et al. (2018) recorded a 35% performance improvement for dual-axis systems in Middle Eastern solar farms. Kane and Verma (2017) analyzed utility-scale applications in India and found dual-axis systems advantageous in areas with high solar variability.

Recent advancements include integrating dual-axis trackers with bifacial solar panels and smart grid technologies (Al-Mohamad, 2018), as well as pairing tracking systems with battery storage for improved reliability (Rodriguez & Contreras, 2019). Finally, Nafeh (2011) concluded that despite higher initial costs—typically 20%–25% above fixed systems—dual-axis tracking often results in faster payback periods in high-irradiance regions.

2. METHODOLOGY

2.1 Introduction

This study compares the performance of a fixed solar panel system and a dual-axis solar tracking system. The research design uses experimental, comparative, and analytical approaches to measure efficiency, system performance, cost-effectiveness, operational ease, and environmental interactions.

2.2 Parameters Evaluated

1. **Energy Efficiency:**

Voltage and current were recorded using a clamp meter to calculate total energy output for both systems over identical time intervals.

2. **System Performance:**

3. Panel surface temperature was measured using an infrared thermometer, while ambient temperature was recorded using an alcohol thermometer. The accuracy of real-time tracking adjustments was also evaluated.

4. **Cost-Effectiveness:**

Costs of materials, installation, maintenance, and energy output per financial investment were compared.

5. **Ease of Operation:**

6.

The level of automation, set-up complexity, and user interaction required for each system were documented.

7. **Environmental Interaction:**

The effect of cloudy and sunny conditions on both systems was analysed, with emphasis on the tracking system's ability to adapt to light variations.

2.3 Project Planning and Fabrication

A market survey was conducted to source components locally and internationally. Solar tracker controllers and actuators were purchased from a Chinese supplier. Fabrication took place in the Mechanical Engineering Workshop of the University of Larkana.

2.3.1 Frame Construction

- Fixed Frame: A rigid frame set at a latitude-based angle and anchored for stability.
- Dual-Axis Frame: Constructed using a central pole, slotted metal strips, and bolted joints to allow rotation along both horizontal (X) and vertical (Y) axes.

2.3.2 Solar PV System Fabrication

Components were assembled, including panels, actuators, controller, and sunlight sensor. Wiring and mechanical integration ensured smooth tracking motion

Figure: 2.1: Solar panel.

Table: 2.1 Specification of solar panel.

Sr. No	Description	Dimensions
01	Length of panel	58 Inches
02	Height of panel	26 Inches
03	Width of panel	35 mm
04	Power of panel	150 watts
05	Voltage of panel	24 Volts

2.4 Materials and Equipment Used

- Solar Panel (150W MG Mono): Selected based on performance rating and expert guidance.
- Solar Tracker Controller + LDR Sensor: Provided real-time sun-position feedback.

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- DC Linear Actuators: Two actuators (150mm & 300mm stroke) controlled dual-axis movement.
- Clamp Meter: Measured voltage and current output.
- Infrared Thermometer: Monitored panel surface temperature.
- Alcohol Thermometer: Recorded ambient temperature

2.5 Fabrication Process

2.5.1 Fixed System Assembly

The 150W solar panel was mounted on a fixed, tilted frame aligned with the geographic latitude. Electrical connections were established for power monitoring.

2.5.2 Dual-Axis System Assembly

A stable base was built to support moving components. Two actuators enabled vertical and horizontal movement. The tracker controller and LDR sensor regulated motion automatically.

Figure: 2.2: Dual axis frame mechanism

2.5.3 Tracking Mechanism

- Actuators: Converted controller signals into mechanical motion.
- LDR Array: Detected light intensity differences.
- Controller: Processed sensor data and commanded actuator movement.
- Mechanical Linkages: Translated linear motion into rotational movement.

2.5.4 Testing & Calibration

Both systems were tested for alignment accuracy, actuator response time, and sunlight detection. Movements were calibrated under identical conditions.

2.6 Experimental Set-Up

Both systems were installed at the University of Larkana, a region with high solar irradiance. Panels were oriented at 180° azimuth. A data logger recorded voltage, current, temperature, and irradiance.

2.7 Night Returning System

An automatic mechanism reset the dual-axis tracker to the east at sunset using low-light detection signals from the sensor. This ensured maximum morning energy capture without manual adjustment.

2.8 Data Collection Procedure

Measurements were taken hourly for:

- Surface Temperature: Using infrared thermometer
- Ambient Temperature: Using alcohol thermometer
- Voltage & Current: Using clamp meter
- Energy Output: Using V×I and integrated over time

Efficiency Calculation:

$P = V \times I$

Where:

- P is the power output (in watts),
- V is the voltage (in volts),
- I is the current (in amperes).

The total energy produced over a given period was calculated by integrating the power output over time, typically in kilowatt-hours (kWh), using the formula:

$E = P \times t$

Where:

- E is the energy produced (in kWh),
- P is the instantaneous power output (in watts),
- t is the time interval over which the energy is measured (in hours).

Next, the theoretical maximum energy available from the sun was calculated based on the solar irradiance measurements, using the formula:

$$E_{max} = G \times A$$

3. RESULTS AND DISCUSSIONS

3.1 VOLTAGE COMPARISON BETWEEN FIXED & DUAL AXIS SOLAR PANEL

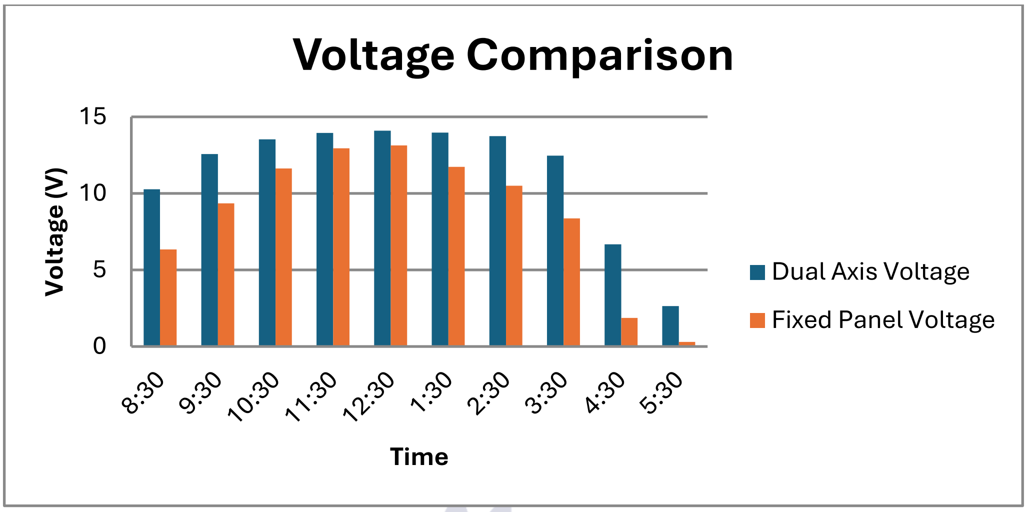

Figure 3.1: Voltage comparison

In this figure illustrates the voltage output of two solar panel configurations—fixed and dual-axis—measured throughout the day from 8:30 AM to 5:30 PM. The dual-axis solar panel, shown by the green line, consistently delivers higher voltage than the fixed panel, represented by the blue line, at every recorded time interval. This consistent advantage highlights the ability of the dual-axis system to continuously track the sun's movement, thereby maximizing solar exposure and energy capture.

During the morning hours (8:30 AM to 10:30 AM), the dual-axis panel shows a significantly stronger performance, beginning at 10.27 V compared to the fixed panel's 6.35 V. Although both systems show increased voltage output as sunlight intensifies, the dual-axis panel maintains a clear lead. In the peak sunlight period (11:30 AM to 1:30 PM), both panels reach their maximum output. The dual-axis system peaks at 14.10 V at 12:30 PM, while the fixed panel reaches a slightly lower maximum of 13.13 V. This difference demonstrates the enhanced ability of the tracking system to maintain optimal orientation during the most productive hours of the day.

As the afternoon progresses (3:30 PM to 5:30 PM), voltage output declines for both systems due to decreasing sunlight intensity. However, the dual-axis panel continues to perform more efficiently, generating 6.68 V at 4:30 PM compared to just 1.86 V from the fixed panel. By 5:30 PM, the fixed panel's output drops to nearly zero (0.30 V), whereas the dual-axis panel still produces a usable 2.65 V.

3.2 AMPERE COMPARISON BETWEEN FIXED & DUAL AXIS SOLAR PANEL

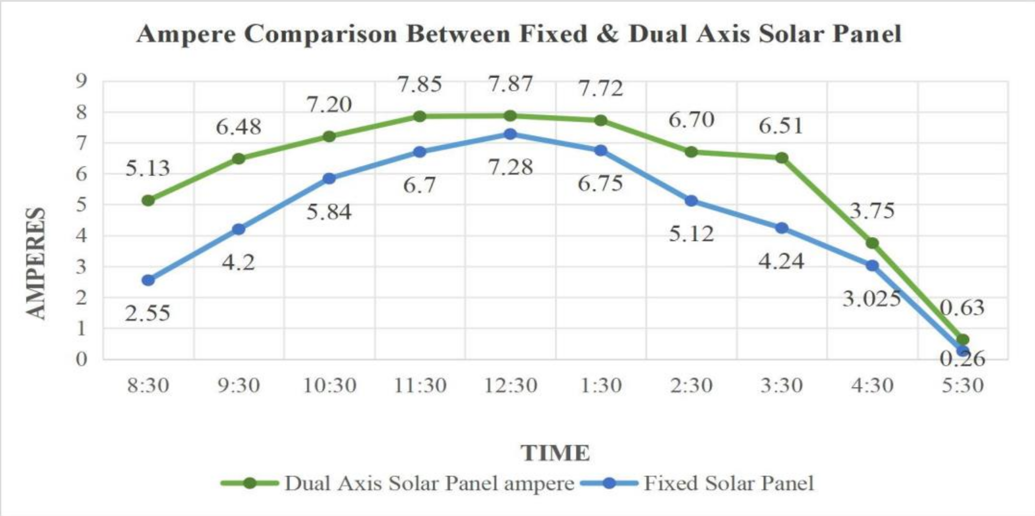

Figure 3.2: Ampere comparison

Morning and Afternoon Performance: In the morning hours, from 8:30 AM to 10:30 AM, the dual-axis solar panel consistently produces higher current than the fixed panel. At 8:30 AM, the dual-axis panel generates 5.13 amperes, which is significantly higher than the fixed panel's 2.55 amperes. As sunlight intensity increases, both systems see a rise in current, but the dual-axis system benefits more from its ability to track the sun's position, reaching 7.20 amperes by 10:30 AM, compared to the fixed panel's 5.84 amperes.

Peak Efficiency: During peak sunlight hours, from 11:30 AM to 1:30 PM, both panels perform at their best, achieving their maximum current outputs. The dual-axis panel reaches its peak at 7.87 amperes at 12:30 PM and maintains a stable output during this time. The fixed panel also performs well, peaking at 7.28 amperes at the same time. During this period, the performance gap between the two systems narrows as both benefit from optimal sunlight conditions. Decline in Efficiency: In the afternoon, as sunlight intensity begins to decrease, the current output of both panels declines. The dual-axis panel maintains a better performance, generating 6.51 amperes at 3:30 PM, compared to the fixed panel's 4.24 amperes. By 4:30 PM, the fixed panel's current drops significantly to 3.75 amperes, while the dual-axis panel still manages to produce the same amount of current. Toward the end of the day, at 5:30 PM, the fixed panel's output diminishes to a negligible 0.26 amperes, whereas the dual-axis panel continues to generate a modest but notable 0.63 amperes.

3.3 POWER COMPARISON BETWEEN FIXED & DUAL AXIS SOLAR PANEL

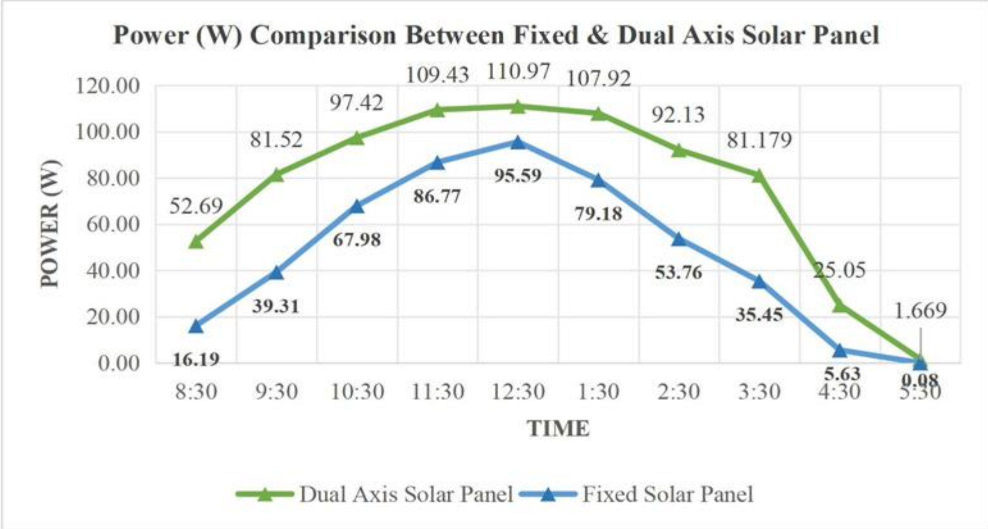

Figure 3.3: Power comparison

During both the morning and afternoon periods, the dual-axis solar panel consistently outperforms the fixed solar panel, with the difference being most notable in the early hours. At 8:30 AM, the dual-axis system delivers 52.69 watts, far exceeding the fixed panel's 16.19 watts. This advantage continues as sunlight increases throughout the morning: by 10:30 AM, the dual-axis panel reaches 97.42 watts, while the fixed panel produces only 67.98 watts

In the afternoon, starting around 3:30 PM, the dual-axis panel maintains stronger performance, generating 81.17 watts, compared to the fixed panel's sharp decline to 35.45 watts. During the peak efficiency period (11:30 AM to 1:30 PM), both systems achieve their highest power outputs. The dual-axis panel peaks at 110.97 watts at 12:30 PM, while the fixed panel reaches its maximum of 95.59 watts at the same time. Although the performance gap narrows during these optimal sunlight conditions, the dual-axis system still demonstrates superior efficiency. As sunlight intensity decreases later in the day, both systems show a reduction in power output. However, the dual-axis panel continues to operate more effectively than the fixed panel. At 4:30 PM, the dual-axis panel still produces 25.05 watts, whereas the fixed panel's output drops to 5.63 watts. By 5:30 PM, the dual-axis panel generates 1.67 watts, while the fixed panel's output becomes nearly negligible at 0.08 watts.

3.3.1 ENERGY OUTPUT COMPARISON

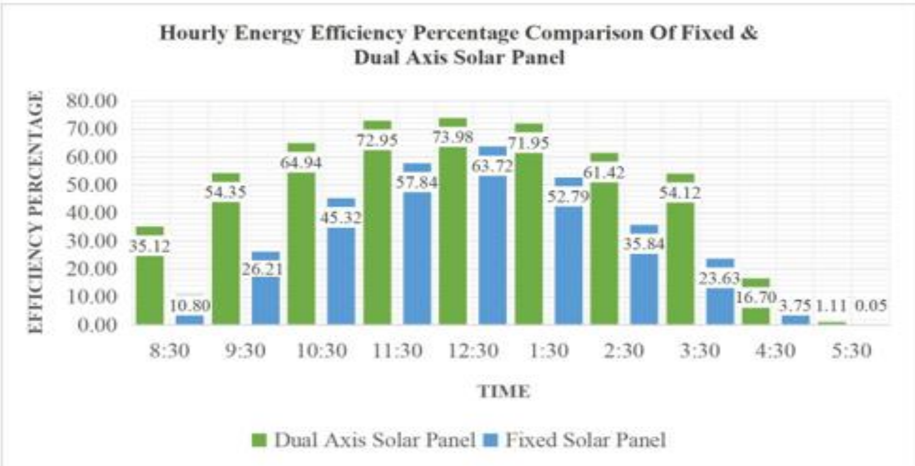

Figure 3.4: Hourly energy efficiency comparison

Morning and Afternoon Performance:
The figure clearly shows that during both the morning and late afternoon hours, the rotating panels outperform the fixed panels. At 8:30 AM, the rotating panels demonstrate much higher efficiency compared to the fixed system. A similar pattern appears at 3:30 PM, where the rotating panels continue to capture more energy while the fixed panels show a noticeable decline in performance.

Peak Efficiency:
During the midday period, especially between 12:30 PM and 1:30 PM, both systems reach their maximum efficiency. However, the rotating panels consistently achieve higher output throughout this peak window. This advantage comes from their ability to track the sun's movement and maintain an optimal angle for energy absorption.

Decline in Efficiency:
As the day progresses beyond 3:30 PM, both systems begin to lose efficiency due to decreasing sunlight. However, the decline is more pronounced in the fixed panels, which cannot adjust their orientation and therefore struggle to capture sunlight effectively when the sun is lower in the sky.

3.4 Energy Efficiency Performance Between Fixed & Dual Axis Solar Panel

In this pie chart that provides a visual representation of the energy efficiency contribution of dual-axis and fixed solar panels. It divides the total energy performance into two distinct portions: the green segment represents the efficiency of the dual-axis solar panel, while the blue segment represents the efficiency of the fixed solar panel. The numerical values in the chart quantify the respective contributions, with the dual-axis solar panel accounting for 50.04% of the total efficiency and the fixed solar panel contributing 31.20%.

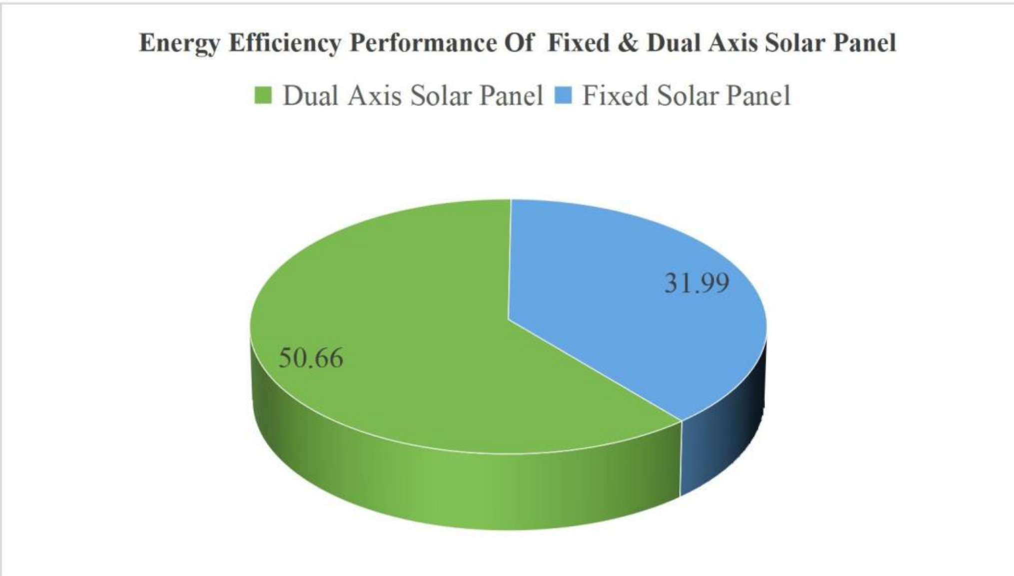

Figure 3.5: Energy efficiency percentage comparison pie chart

3.5 COST-EFFECTIVENESS OF FIXED AND DUAL-AXIS SOLAR TRACKING SYSTEMS

When comparing the cost-effectiveness of fixed and dual-axis solar tracking systems, it is essential to evaluate their initial investment costs, maintenance expenses, operational efficiency, and long-term benefits. Fixed solar panels are typically more affordable to install and maintain, as they do not require any mechanical or electronic systems for movement. However, they are limited in their energy generation capabilities because they remain stationary and cannot adjust their orientation to maximize sunlight exposure throughout the day. On the other hand, dual-axis solar tracking systems involve higher initial costs due to their advanced tracking mechanisms, sensors, and motors. Despite this, the increased energy output of dual- axis systems often justifies these additional expenses, making them more cost-effective over time.

The dual-axis solar tracking system used in our experimental set-up demonstrates the practicality and value of investing in this technology. By continuously adjusting its orientation to follow the sun's position, the dual-axis system ensures maximum energy absorption throughout the day. This capability leads to a significant increase in energy generation compared to the fixed system, especially in environments with clear skies or varying sunlight angles. The energy efficiency of the dual-axis system, as observed in the experiment, was consistently higher, which directly translates into more power generation for a given area of solar panels. This enhanced performance reduces the payback period of the system, as the increased energy output compensates for the initial higher costs within a reasonable time-frame. From a maintenance perspective, it is often argued that dual-axis systems require more attention due to their moving parts. While this is partially true, modern dual- axis systems are designed with durable materials and efficient tracking mechanisms that minimize the frequency and cost of maintenance. Additionally, the incremental cost of maintaining the system is outweighed by the additional energy generated, ensuring that the system remains financially viable in the long term.

4.1 conclusions

I. This research compared fixed solar panels with dual-axis solar tracking systems in terms of efficiency, adaptability, cost, and maintenance.
II. The experiment used two 150-watt panels—one fixed and one dual-axis—tested over three days.
III. The fixed panel achieved **31.99% efficiency**, while the dual-axis system reached **51.66%**.
IV. Results show the dual-axis tracker consistently produced higher voltage, current, and power output.
V. Its ability to follow the sun improved energy capture, especially during morning and evening low-sunlight periods.
VI. The fixed panel's static orientation limited its performance during non-optimal sun angles.
VII. The dual-axis system's automation and night-returning mechanism improved reliability and reduced manual intervention.
VIII. These features also minimized mechanical wear and extended operational lifespan.
IX. Although more expensive, dual-axis systems offer faster payback and greater long-term returns in high-irradiance regions.
X. The study concludes that dual-axis trackers are ideal for high-demand or variable-sunlight environments, while fixed panels suit simpler, low-budget applications.

4.2 SUGGESTIONS

i. Integration with Energy Storage: Consider integrating energy storage solutions, such as batteries or grid connection, with the solar tracking systems. This will enable you to assess not only the energy output but also the energy storage capabilities, making the systems more practical for real-world use.

ii. Use of Automation for System Calibration: Suggest automating the calibration of the dual-axis solar tracking systems using sensor feedback loops to continuously adjust the system for optimal solar panel orientation without manual intervention.

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