IJIRMET ISSN (Online): 2456-0448
International Journal Of Innovative Research In Management, Engineering And Technology
Vol. 10, Issue 10, October 2025

Dual-Axis Solar Panels: Enhancing Solar Energy Harvesting Efficiency

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Abstract: ***With regards to the straightforwardness of making an installment while settling down anyplace on the planet, online installments have been a wellspring of engaging quality. Throughout the course of recent many years, there has been an expansion in web-based installments. E-installments empower organizations bring in a ton of cash notwithstanding buyers. Nonetheless, on the grounds that electronic installments are so straightforward, there is likewise a gamble of misrepresentation related with them. A customer needs to make sure that the money he or she spends only goes to the right service provider. Online extortion opens clients to the chance of their information being compromised, as well as the burden of announcing the misrepresentation, block their installment strategy, and different things. At the point when organizations are involved, it causes a few issues; every so often, they should give discounts to keep clients. As a result, consumers and businesses alike must be aware of these online scams. This study proposes a model for determining whether an online payment is fraudulent. To decide whether a specific Internet based installment is false or not, a few elements like the sort of installment, the beneficiary's personality, and so on. would be taken into consideration.***

Keywords—Online payment, Fraud detection, Credit card Fraud, Machine Learning, Supervised Learning, Digital Transactions and Data Preprocessing.

I. INTRODUCTION

1.1 Global Energy Context and the Role of PV

The twenty-first century is defined by an urgent global transition from fossil fuels to sustainable, renewable energy sources. Central to this transition is Photovoltaic (PV) technology, which converts solar radiation directly into electricity. However, the efficiency of PV modules is fundamentally dependent on the angle of incidence between the incoming solar rays and the panel surface. The maximum power output of a PV module occurs when the angle of incidence is zero, meaning the panel is perfectly perpendicular to the sun's rays. Any deviation from this optimal angle leads to a reduction in output proportional to the cosine of that angle, a phenomenon defined by the law of irradiance: is the direct normal irradiance. This inherent geometric limitation necessitates the use of dynamic orientation systems, or solar trackers, to maximize energy capture. Dual-axis trackers, which are the focus of this report, represent the pinnacle of this technology, achieving the highest possible energy yield by continuously minimizing

1.2 Limitations of Fixed and Single-Axis Systems

Traditional fixed-tilt PV systems are the simplest and most cost-effective solution, but they sacrifice significant energy potential. A fixed panel is optimized for only one moment in time (typically solar noon on the equinoxes) and remains suboptimal for the vast majority of the year, leading to annual energy losses of 25–40% compared to ideal tracking.
Single-Axis Trackers (SATs), primarily employed in large utility-scale settings, adjust the panel along a single axis (usually following the sun East-West, known as the azimuth). While SATs offer substantial improvements over fixed systems (typically 15–25% gain), they fail to compensate for the significant seasonal variation in the sun's vertical position (solar altitude). Dual-Axis Trackers (DATs) overcome both these limitations by integrating two independent axes of rotation, ensuring the panel face remains normal (perpendicular) to the sun's rays throughout all daylight hours, year-round. This geometric advantage is what unlocks the documented energy yield increases of 35–45% relative to fixed systems.

1.3 Report Objectives and Scope

The primary objective of this report is to provide an exhaustive technical and economic analysis of dual-axis solar tracking technology. Specifically, this work will:
1. Detail the principles of solar geometry and the mathematical models used for precise solar tracking.
2. Analyze the distinct control system architectures (active, chronological, and hybrid) employed in DATs.
3. Examine the crucial mechanical engineering challenges, including load analysis, structural design, and component selection (actuators and drives).
4. Quantify the performance advantages through comparative energy yield analysis and a rigorous Levelized Cost of Energy (LCOE) assessment.
5. Discuss operational reliability, maintenance protocols, and the integration of AI/Machine Learning for future optimization.

2. Theoretical Foundations and Solar Geometry

The precise operation of a dual-axis solar tracker is entirely dependent on accurately calculating and following the geometric position of the sun. This involves understanding fundamental solar angles relative to the Earth and the tracker's location.

2.1 Solar Path Definition (Azimuth and Zenith/Altitude)

The sun's position at any given time and location is defined by two primary angles:

1.Solar Azimuth Angle (gamma): This is the angular deviation of the sun's projection on the horizontal plane, measured clockwise from due North (or due South, depending on convention). A tracker's horizontal movement (East-West) corresponds to this axis.

2. Solar Zenith Angle : This is the angle between the sun's rays and the vertical (zenith) direction. Its complement is the Solar Altitude Angle , which is the angle between the sun's rays and the horizontal plane. A tracker's vertical movement (North-South tilt) corresponds to this axis. Variation: This angle varies seasonally due to the Earth's axial tilt with the highest altitude occurring at summer solstice and the lowest at winter solstice.

2.2 The Fundamental Irradiance Equation

The core goal of the dual-axis tracker is to make the angle of incidence (θ) between the solar ray and the panel surface equal to zero. This angle is calculated using a complex spherical trigonometry equation that relates the sun's position to the panel's orientation

2.3 Comparative Energy Yield Potential

The performance gain of a DAT system can be quantified by comparing the total energy collected over a period against a fixed system and a single-axis system

3. Working Principle and Control Systems

The control system is the brain of the dual-axis tracker, responsible for calculating the sun's position and translating that calculation into precise mechanical movement. Control systems are broadly categorized into active (sensor-based) and chronological (model-based) approaches.

3.1 Active Tracking Systems (Closed-Loop)

Active tracking utilizes optical sensors to directly measure the intensity of sunlight and determine the direction of maximum irradiance. This is a closed-loop control system, meaning the input (sunlight) drives the output (motor movement) until the error (angular misalignment) is minimized.

3.1.1 Sensor Array Design

The most common setup involves a simple array of four Light Dependent Resistors (LDRs) or photodiodes mounted on a central column, separated by opaque baffles. The baffles create a shadow on one or more sensors if the sun is not directly overhead.

3.1.2 Limitations of Active Tracking

Active systems are inherently simple but face significant practical challenges:
1. Cloud Sensitivity: Under overcast conditions or when partially shaded, the system can hunt erratically, wasting energy and potentially leading to component wear.
2. Calibration: Requires initial, precise calibration of sensor thresholds and motor control parameters.
3. Dust/Dirt Accumulation: Debris on the sensor array can lead to false readings and misalignment.
3.2 Chronological/Algorithmic Tracking (Open-Loop)
Chronological tracking, often termed Open-Loop or Heliocentric tracking, relies on mathematical equations to calculate the precise position of the sun at the tracker's exact geographical location (latitude, longitude) and specific time (date, time).

3.2.1 The Solar Positioning Algorithm (SPA)
Advanced chronological systems often utilize sophisticated algorithms like the Solar Positioning Algorithm (SPA) developed by the National Renewable Energy Laboratory (NREL). The SPA takes the following inputs:
• Latitude and Longitude
• Time Zone
• Date and Time
It then outputs the calculated Solar Azimuth and Solar Zenith angles. These angles are fed directly to the motor controllers as the target positions.

3.2.2 Advantages of Chronological Tracking
1. Robustness: Immune to weather conditions (clouds, fog) and sensor contamination. The tracker will always move to the geometrically correct position.
2. Predictive Capability: Allows for optimization of movement schedules, such as only moving every 15 minutes to conserve actuator energy.
3. Low Power Consumption: Eliminates the need for continuous sensor monitoring and real-time processing.

3.3 Hybrid Control Architectures
The most robust and high-performing commercial DATs employ Hybrid Control Architectures. This strategy leverages the strengths of both active and chronological methods:
• Primary Mode (Chronological): The system defaults to the accurate, energy-efficient chronological model to calculate the sun's position.
• Correction Mode (Active): A minimal sensor array is used periodically (e.g., at solar noon) to verify the panel's actual position against the model's prediction. If a significant discrepancy exists (due to structural settling, unexpected mechanical slippage, or data drift), the active system provides a momentary correction signal.
• Stow/Safety Mode: Based on astronomical data, the system predicts high-wind events and automatically commands the tracker to a stow position (horizontal or angled for minimum wind profile) to protect the structure.

3.4 Key System Components and Specifications

The control system integrates several essential hardware components:

Component	Function	Technical Requirement
Microcontroller	Executes the SPA/PID algorithm and manages motor control.	High processing speed, sufficient I/O pins, low power consumption (e.g., dedicated Industrial PLC or high-end Arduino/ESP32).
Actuators/Motors	Provides the mechanical force for rotation (Azimuth) and tilt (Elevation).	**High torque capacity** to overcome panel weight and potential wind loading. Must have built-in encoders or position feedback.
Position Sensors	Provide feedback on the actual angular position of the panel.	**Absolute rotary encoders** (preferred for persistence) or potentiometers for high precision.
Anemometer	Measures wind speed to trigger emergency **stow protocols**.	Rugged, industrial-grade sensor with fast response time.
Power Supply	Powers the control board and motors.	Must be independent and battery-backed to ensure **stow function** during grid outages.

4. Detailed Mechanical Design and Structural Integrity

The mechanical structure of a dual-axis tracker must reconcile two conflicting requirements: the need for free movement in two planes and the capacity to withstand extreme environmental loads. The structural design is paramount to the system's longevity and safety.

4.1 Load Analysis and Wind Resistance (Stow Protocols)

A major design challenge for DATs is resisting wind load. Unlike fixed panels, which are statically mounted, DATs present a large surface area (the PV array) that acts like a sail. The forces exerted on the panel must be thoroughly analysed

Stow Protocols

To prevent catastrophic structural failure, all DATs incorporate sophisticated **stow protocols**.

- **Trigger:** An anemometer detects wind speeds exceeding a critical threshold
- **Action:** The control system overrides the tracking algorithm and commands the actuators to move the panel to a **Stow Position**. This is typically a near-horizontal position or a low-angle tilt, which presents the smallest cross-sectional area to the wind and minimizes the drag coefficient
- **Emergency Power:** The system must be capable of executing the stow protocol using battery backup power in the event of grid failure during a storm.

4.2 Drive Mechanisms: Slew Drives vs. Linear Actuators

The choice of drive mechanism dictates the overall precision, maintenance profile, and cost of the DAT In most utility-scale dual-axis trackers, **slewing drives** are the preferred choice for the azimuth

(horizontal) axis due to their robustness and high torque density. Linear actuators are often sufficient for the elevation (tilt) axis on smaller, residential-scale DATs.

4.3 Foundation Design and Site Preparation

The foundation must securely anchor the entire structure against overturning moments caused by wind loading.

- **Piers and Piles:** Deep foundations (driven piles or helical piers) are common, especially in large-scale applications, to transfer wind uplift forces deep into the ground.
- **Ballast:** For sites where drilling is prohibited, a ballasted concrete foundation may be used, relying on mass to counteract the overturning moment.
- **Soil Analysis:** Site-specific geotechnical studies are mandatory to determine soil bearing capacity and ensure the foundation design can safely accommodate the calculated wind and snow loads. The stability of the foundation is directly related to the tracker's long-term accuracy.

5. Performance Analysis and Economic Viability

The ultimate justification for the higher complexity and cost of a dual-axis tracking system lies in its superior energy output and subsequent economic returns.

5.1 Quantifying the Energy Gain

The **Annual Energy Production (AEP)** of a DAT is determined not only by the direct normal irradiance but also by the tracker's ability to utilize diffuse radiation. While direct sunlight is maximized by tracking, diffuse light (scattered by clouds or atmosphere) is received regardless of orientation.

Empirical studies consistently show that the maximum gain of math 35% to 45% is achieved in clear-sky conditions at mid-to-high latitudes 30^ to 50^ where the seasonal variation in solar altitude is most pronounced. In equatorial regions, the gain is marginally lower but still substantial (approx. 25% - 30%.

5.2 Levelized Cost of Energy (LCOE) Assessment

LCOE is the primary metric for comparing energy generation technologies. It represents the net present value of the unit-cost of electricity over the lifetime of the asset:

DAT systems have higher initial capital costs due to the motors, drives, and complex control systems. They also have slightly higher **Operation and Maintenance (O&M)** costs due to moving parts.

However, the significant increase in energy yield acts as a powerful denominator multiplier in the LCOE equation. In high-insolation environments with favourable electricity tariffs, the reduction in LCOE due to higher output often outweighs the increased costs, making DAT a cost-competitive solution. For smaller, space-constrained installations, the high energy density of DATs is invaluable, even if the LCOE is not the absolute lowest.

5.3 Return on Investment (ROI) and Payback Period

The payback period is the time required for the cumulative net savings generated by the system to equal the initial investment cost

In regions with high electricity prices (high dollar value per kWh), the substantial math f 35% to 45% increase in annual cash flow provided by a DAT system dramatically shortens the payback period compared to a fixed system.

Metric	**Fixed System**	**Dual-Axis Tracker**
Installed Cost (per kWp)	$1,500	$2,000
Annual Output (kWh/kWp)	$1,500	$2,100
Energy Price (per kWh)	$0.20	$0.20
Annual Revenue (per kWp)	$300	$420
Payback Period (Years)	**5.0**	**4.76**

Despite the 33% higher initial cost, the DAT achieves a shorter payback period due to the 40% increase in energy generation, proving its long-term financial superiority in high-performance applications.

6. Design Considerations

Designing a dual-axis tracker involves multiple engineering disciplines:

- **Mechanical Design**: Must support panel weight and withstand wind loads.
- **Control Systems**: Algorithms like PID or fuzzy logic enhance tracking precision.
- **Power Supply**: Often powered by a small PV panel or battery.
- **Material Selection**: Corrosion-resistant materials like aluminium or galvanized steel are preferred.

Innovations such as AI-based tracking and IoT integration are also being explored to improve performance and remote monitoring[3].

7. Challenges and Limitations

Despite their benefits, dual-axis trackers face several challenges:

- **Cost**: Higher capital and maintenance costs than fixed systems.
- **Complexity**: Requires precise calibration and robust control systems.
- **Maintenance**: Moving parts are prone to wear and require regular servicing.
- **Space Requirements**: Larger footprint due to movement range. These factors must be weighed against the expected energy gains and site-specific conditions.

8. Applications and Case Studies Dual-axis

The future of dual-axis solar tracking lies in:

- **AI and Machine Learning**: For predictive tracking and fault detection.
- **Smart Grids**: Integration with energy storage and demand response systems.
- **Modular Designs**: Easier installation and scalability.
- **Hybrid Systems**: Combining solar tracking with wind or thermal energy. As technology matures and costs decline, dual-axis systems are expected to play a pivotal role in global solar adoption.

9.References

1. JETIR: Dual-Axis Intensity-Based Solar Tracking System[1]
2. MDPI: Hardware-Implemented Dual-Axis Solar Tracking System[2]

JEST: Innovative Approaches to Dual Axis Solar Tracking[3]