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Maximizing Solar Harvest: A Review of Tracking System Viability

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ABSTRACT: This review synthesizes recent research work on solar tracking systems and tilt angle optimization for photovoltaic arrays. The reviewed work find that the systems can enhance energy produce by 10–45% relative to fixed-tilt installations with dual-axis trackers. This enhance typically providing a 5–15% performance advantage over single-axis designs. The economic feasibility is highly contingent on local factors that include geographic location, available solar capitals, and capital costs. The emerging trends emphasize cost-effective designs such as position tracking and intelligent control algorithms. Analysis further identifies substantial regional differences in optimal system configuration areas with significant diffuse radiation. For instance, see reduced returns from tracking. Main outstanding research needs include standardized evaluation frameworks, longitudinal reliability studies and holistic designs that incorporate energy storage. This summary is intended to help academics, engineers, and policy-makers choose and use solar tracking technologies effectively.

Keywords: Solar tracking, Photovoltaic systems, Tilt angle optimization, Maximum power point tracking, Economic feasibility

I. INTRODUCTION

The global transition toward renewable energy has accelerated the adoption of photovoltaic (PV) systems. Solar tracking (ST) technology is vital for maximising their energy yields. It actively adjusts panel angles to follow the sun's daily and seasonal path, significantly boosting power output over fixed installations. Thereby significantly improving energy capture compared to fixed installations. This research synthesises recent investigations into ST devices, focusing on technical performance, economic viability, geographical considerations and future advancements. The importance of ST System has increased along with the decreasing cost of photovoltaic modules and making system efficiency increasingly critical for economic justification. Initially, research was well-known for its foundational concepts, but recent studies have focused on refining tracking strategies, reducing costs, and adapting PV systems to specific local conditions. The first objective of this review is to identify the performance differentials between fixed, single-axis and dual-axis tracking systems. The second objective is to find the role of geographic and environmental factors in determining system suitability. The third objective is to examine the economic variables that impact the cost-benefit analysis of tracking implementations, and the last aim is to determine the trajectory of recent technological advancements in STS.

II. METHODOLOGY

The methodology for this review study is based on a selection of various recent publications. that give suggestion expressive insights into ST systems. The selected literature represents a wide range of geographic contexts like Africa, Asia, Europe, and the Americas and also examines various system types for example from fixed and single-axis to dual-axis trackers. These studies were evaluated using theoretical modelling, experimental data, and economic assessments. The review is structured around five main areas these are as follows (1) Tracking technology configurations and their performance outcomes (2) Strategies for optimizing panel tilt angles (3) The impact of geographic and climatic conditions (4) Control systems used and maximum power point tracking (MPPT) methods adopted (5) Methodologies for economic evaluation Through comparative evaluation this review work highlights prevailing trends, points of inconsistency and notable gaps in the existing research.

III. ST TECHNOLOGIES AND PERFORMANCE

A. Technology Classification and Energy Gains

Solar tracking systems are broadly classified into fixed-tilt, single-axis, and dual-axis configurations. Single-axis trackers are again categorised by orientation: East-West, North-South, Vertical Axis, and Inclined East-West trackers. However, the dual-axis systems provide complete sun path following capability.

Bahrami *et al.* (2017, 2018) [1], [2] conducted comprehensive assessments across multiple latitudes. And their finding shows that dual-axis tracking increases annual energy gain by 12.52-29.58% in low-latitude countries compared to optimally fixed panels. While it is 5-40% in northern hemisphere locations. The improvements achieved by single-axis systems typically achieve 10-30% compared to optimally fixed panels. Hoffmann *et al.* [3] reported average monthly gains of 17.20-31.1% for dual-axis systems in southern Brazil, while Batayneh *et al*. [4] demonstrated that discrete single-axis tracking (three daily actuations) achieved 91-94% of the energy collection of continuous tracking.

B. Tracking System Innovations

The advancement of solar tracking technology is currently focused on simplifying mechanical designs that minimise expenses and also maintain effective efficiency. The studies are broadly classified into three categories: step tracking, cost-effective implementations and hybrid-intelligent systems.

Step Tracking: Batayneh *et al.* [4] study that three-position daily tracking attains near-continuous performance while decidedly decreasing mechanical complexity and energy consumption. Zhu *et al*. [5] introduced an innovative tilted-rotating axis configuration demonstrating a commendable performance of 96.40% in dual-axis radiation while maintaining single-axis simplicity.

Cost-Effective Implementations: Jamroen *et al*. [6] created a Light Dependent Resistor (LDR)-based digital logic dual-axis system, which they show results in a 44.89% enhancement in efficiency compared to fixed systems at a reduced cost. Abdollahpour *et al.* [7] developed a machine vision system employing shadow image processing with an accuracy of ±2°, therefore obviating the necessity for astronomical computations.

Hybrid-Intelligent Systems: The integration of diverse control strategies, including sensor-based methods and temporal computations. This is employed to improve reliability under variable weather conditions. Chen *et al.* [8] demonstrated hybrid methodologies that maintain functionality during periods of cloud cover. Recent advancements emphasise the optimisation of mechanisms and cost reduction, all while preserving performance levels.

IV. TILT ANGLE OPTIMIZATION

A. Optimization Models and Formulas

Optimal tilt angles vary by location, season, and application. Stanciu *et al.* [9] compared three radiation models (Hottel and Woertz, isotropic diffuse, and HDKR) globally, proposing the simple formula latitude minus declination when using the Hottel and Woertz model. For fixed installations, seasonal adjustments of latitude ± 10-15° are commonly recommended. Khorasanizadeh *et al.* [10] established location-specific correlations for Tabass, Iran. Their finding for yearly optimum tilt of 32°. This optimum tilt angle is close to the local latitude of 33.36° with monthly variations from 0° (June-July) to 64° (December). Semi-yearly adjustment: 10° for April-September, 55° for October-March. This provided near-optimal performance with reduced complexity.

B. Geographical Considerations

Hafez *et al.* [11] comprehensively reviewed tilt and azimuth angle optimization across applications PV, water heating, cooking, building integration. Their analysis confirmed that optimal angles are lower in summer (approaching horizontal in some regions) and higher in winter, with significant regional variations requiring localized optimization. Bahrami *et al.* [2] demonstrated that solar irradiation levels significantly affect tracker ranking patterns in northern hemisphere locations. Cities at similar latitudes but different irradiation characteristics e.g., Cairo, Egypt vs. Chongqing, China require different optimal configurations.

V. GEOGRAPHICAL AND CLIMATIC INFLUENCES

Tracking system performance varies significantly with latitude. Bahrami *et al*. [1] found that the countries at latitude 0-15°N, i.e., low-latitude countries, with specific tracking strategies outperformed others, with rankings changing based on local conditions. In contrast, Bahrami and Okoye [2] showed that the counties at latitude 20-70°N, i.e., medium and high latitudes, found different patterns emerged. This illustrates the importance of latitude-specific design guidelines.

Regions with high diffuse radiation due to cloudy climates benefit less from tracking systems. Eldin *et al*., [12], studies in the cold climate country of Berlin and found tracking provided a 39% energy gain. Whereas their studies in hot climate counties in Aswan, Egypt, found tracking provided only 8% energy gain. This shows that energy gain potentially negates benefits in hot regions by tracking. Despotovic *et al*. [13] evaluated 50 empirical models for predicting diffuse solar radiation across five climate zones. They incorporated clearness index, relative sunshine duration and ambient temperature. These three-variable models performed best for forecasting globally. Accurate diffuse radiation prediction is crucial for determining tracking system viability in different regions.

VI. CONTROL SYSTEMS AND MPPT TECHNIQUES

Solar tracking employs mainly sensor-based or time-date control approaches. Sensor-based systems use sun position detected by LDRs, photodiodes, or image processing. Abdollahpour *et al*. [7] achieved ±2° accuracy with machine vision. Jamroen, et al. [6] implemented digital logic control with LDR sensors. However, time-date-based systems use astronomical algorithms to compute sun position. The GPS with pyranometer data combined for hybrid control [7].

Maximum Power Point Tracking plays a vital role for PV efficiency, especially with tracking systems. There are various algorithms used in MPPT. Ali *et al*. [14] proposed a variable step P&O algorithm dividing the operational region into four sectors. They achieve faster convergence with reduced oscillation compared to conventional P&O. For rapidly changing irradiance, the fuzzy logic MPPT technique achieves >99.6% efficiency under EN 50530 standard testing [15]. Their approach combined fuzzy logic advantages with P&O simplicity. While comparing performance between the above two concepts, variable-step P&O outperformed conventional techniques under rapidly changing insolation. This is crucial for tracking systems following sun movement throughout the day.

VII. ECONOMIC ASSESSMENT AND VIABILITY

Economic viability assessment has been done on simple payback periods to comprehensive metrics analysis. Levelized Cost of Electricity (LCOE) plays a vital role when choosing a tracking system. [1] and [2] used LCOE to compare tracking systems across various locations and found that tracker preferences change when considering economics rather than just energy gain. However, several studies highlighted the importance of including maintenance, repair, and operational expenses beyond the initial installation of the system. Furthermore, studies in developing regions have emphasised affordability and local manufacturing potential. This model is specifically designed as a low-cost system for rural electrification [16].

The research consistently shows that economic viability depends on specific local conditions. Tracking systems are usually a better economic choice in areas with high sunshine because they generate more energy. Simpler systems like fixed or single-axis often prove more economically viable despite lower energy yield, specifically in high-cost installation areas. Economic considerations differ significantly with off-grid systems, sometimes justifying trackers due to high energy storage costs. The tracker selection depends on some other aspects, considering various installation costs, including battery storage for off-grid systems [1]. It is found that simpler systems became preferable despite lower energy production.

VIII. EMERGING TRENDS AND INNOVATIONS

Technological trends moved toward simpler mechanisms with reduced actuation frequency while maintaining performance. Further, intelligence integration is increasing the use of predictive algorithms, weather forecasting, and learning systems to optimise tracking. Additionally, exploration of material innovation for tracking mechanisms to reduce cost and maintenance. Furthermore, there is growing interest in combining tracking with bifacial panels for additional energy gain.

The system integration trend moved toward hybrid renewable systems, smart grid compatibility and energy storage integration. The integration of tracking PV with other renewable energy systems, mostly wind and biomass, is used. These hybrid renewable systems give a more consistent energy supply. In addition, the development of tracking systems with advanced grid support capabilities which improve grid stability. The energy storage integration is another aspect of the combined optimisation of tracking with storage system charging/discharging cycles.

IX. RESEARCH GAPS AND FUTURE DIRECTIONS

This study identified the following research gaps. Generally, studies are based on short-term data. Insufficient long-term operational and maintenance data, along with a lack of standardised methodologies for comparing tracking systems across studies, constrain reliability-orientated assessments. Furthermore, there is limited research on optimal integration of tracking with storage, converters, and building systems. Additionally, lifecycle sustainability's exhaustive environmental influence assessments include manufacturing and operation. More context-specific designs are required for developing regions, but most research originates from developed countries.

Future research on solar tracking systems should focus on developing internationally accepted standardised testing instead of local needs. This ensures accurate beater evaluation and comparison across different technologies. It is also essential for predictive maintenance algorithms that can anticipate failures and increase system reliability while reducing downtime and maintenance expenses. Additionally, advanced material applications are used in the investigation of composites, smart materials, and novel manufacturing techniques. It is important to come up with designs for tracking systems that will make the climate more resilient. That withstand extreme environmental conditions such as high wind speeds, dust accumulation and temperature variations. Furthermore, social and economic studies are needed to assess local manufacturing potential and overall societal acceptance to support large-scale adoption of solar tracking technologies.

X. CONCLUSION

This comprehensive review shows significant developments in solar tracking systems. Through clear trends toward cost reduction, performance optimisation and intelligent control. The key findings of this study include the following:

Performance Gains: Typically increases energy yield by 10-45% with dual-axis tracking systems, and it generally outperforms single-axis tracking systems by 5-15%. However, paybacks vary significantly by location, climate and other local factors.

Economic Viability: As the tracking system economics severely depend on local conditions. In some cases, simple fixed or single-axis systems prove more viable results with lower energy production.

Geographical Considerations: The optimal system design requires localised optimisation constraints. These include latitude, climate, diffuse radiation fraction and economic factors.

Innovation Directions: Step tracking is an emerging trend in tracking systems. This is due to low-cost implementations, smart control systems and improved reliability.

This study also found that there are some shortcomings in the research, emphasising standard evaluation procedures, long-term reliability data, integrated system design, and developing areas. For academics, prolonged innovation in materials, control algorithms and system integration is suggested. For installers, it is crucial to consider local conditions and calculate the total cost of ownership over the entire lifecycle. For policymakers, supporting context-appropriate technologies, local manufacturing, and standardised testing protocols will accelerate sustainability adoption. As solar energy expands globally, tracking technology will play an increasingly crucial role in maximising energy yield and economic benefits. The research presented here provides a foundation for future innovation and informed decision-making in this vital renewable energy sector.

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