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Performance, Economic, and Operational Perspectives Assessment of Fixed Tilt Versus Adjustable Tilt Solar Photovoltaic Systems

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ABSTRACT: This paper presents a comprehensive analysis of fixed-tilt and adjustable-tilt solar photovoltaic (PV) systems. And evaluating their technical performance, economic viability, and operational characteristics. The study synthesises findings from publications to assess how tilt adjustment strategies—from fixed optimal angles to seasonal and continuous tracking—affect energy yield, levelised cost of electricity (LCOE), and system complexity. The analysis between adjustable-tiltand fixed-tilt systems shows that the adjustable-tilt increased annual energy yield by 10-45%. The magnitude of improvement basically dependent on geographical location, local climate conditions and adjustment frequency. However, economic analysis demonstrates that the incremental energy gain must be weighed against increased capital costs, maintenance requirements, and system complexity. The paper proposes a decision framework incorporating technical, economic, and operational factors to guide system selection, emphasising that optimal solutions are highly context-dependent rather than universally applicable.

Keywords: Photovoltaic systems, tilt optimisation, solar tracking, economic assessment, performance comparison.

INTRODUCTION

The global transition toward renewable energy has positioned solar photovoltaic (PV) systems as critical components of sustainable energy portfolios [1]. As solar installations boom worldwide, economic return has become increasingly important so optimising PV system configurations for maximum energy yield more important. Among the most significant design decisions facing PV system planners is the selection of mounting configurations: fixed-tilt systems with optimised but unchanging angles versus adjustable-tilt systems that modify panel orientation either seasonally or continuously.

In Fixed-tilt systems PV panels mounted at an angle optimised for annual. This system simplest and most economical installation approach. In contrast, adjustable-tilt systems—encompassing seasonal manual adjustments, single-axis tracking, and dual-axis tracking—actively modify panel orientation to better align with the sun's position throughout the day and year [2]. While in adjustable-tilt systems PV panels mounted on mechanical components that control systems and maintenance to yield available potentially more energy from sun required additional costs. This paper conducts a comparative analysis of fixed-tilt versus adjustable-tilt PV systems, synthesising findings from recent research to evaluate three key perspectives:

Performance: How much additional energy can adjustable-tilt systems capture compared to fixed-tilt configurations?

Economic: What are the cost implications of adjustable-tilt systems, and under what conditions do they provide economic justification?

Operational: What are the practical implications for installation, maintenance and reliability of adjustable-tilt systems?

The analysis draws upon publications that collectively provide global perspectives, methodological approaches, and empirical data on tilt optimisation and tracking systems. This paper aims to provide a balanced assessment to guide system engineers, designers, installers, and policymakers in selecting appropriate mounting configurations for specific applications and locations.

MOUNTING TILT ANGLE OPTIMISATION

Mathematical Foundations

The optimal mounting tilt angle for fixed PV systems depends on multiple factors like primarily latitude, season and local climate conditions [3] provided a comprehensive global analysis comparing three solar radiation models (Hotel and Woertz, Isotropic diffuse, and HDKR). And establishing fundamental relationships between latitude, declination angle, and optimal tilt. Their work demonstrated that for many locations, the simple formula $\beta\_opt = \varphi - \delta$ (where φ is latitude and δ is declination) provides a reasonable approximation for tilt optimisation [4] conducted an extensive review of tilt and azimuth angle optimisation for various solar applications. And confirming that optimal angles are lowest during summer months that approaching solar panel are horizontal and highest during winter approaching solar panel vertical. Their synthesis revealed numerous location-specific correlations developed for different geographical regions, highlighting the importance of localised optimisation.

Geographical Considerations

Geographical factors significantly influence optimal tilt angles and the potential benefits of adjustable systems. [5] developed location-specific models for Tabass, Iran, their finding that yearly optimum tilt was approximately 32° (close to the local latitude of 33.36°). They also find that monthly optimum tilt was variations ranging from 0° in summer to 64° in winter. Their work demonstrated that semi-yearly adjustment (10° for April-September, 55° for October-March) could capture most of the benefits of monthly adjustment with significantly reduced complexity. [6] evaluated 50 empirical models for predicting diffuse solar radiation across five climate zones, emphasising that accurate diffuse radiation estimation is crucial for determining the benefits of tilt adjustment. Regions with high diffuse radiation fractions benefit less from precise solar alignment, as diffuse radiation arrives isotropically from the entire sky dome. The optimal tilt angle characteristics are summarised in Table 1.

Table 1: Optimal Tilt Angle Characteristics by Region Type.

Region Type	Annual Optimal Tilt	Seasonal Variation	Diffuse Fraction	Tracking Benefit Potential	Region Type
Low Latitude (0-15°)	φ ± 5°	Minimal (10-20°)	Variable	Moderate (10-25%)	Low Latitude (0-15°)
Mid Latitude (15-45°)	φ ± 10°	Significant (30-50°)	Medium-High	High (15-35%)	Mid Latitude (15-45°)
High Latitude (45-70°)	φ ± 15°	Extreme (40-60°)	High	Limited (5-20%)	High Latitude (45-70°)
High Altitude	φ - 5° to φ	Moderate	Low	High (20-40%)	High Altitude

PERFORMANCE COMPARISON OF DIFFERENT MOUNTING

Energy Yield

As expected, adjustable-tilt systems consistently demonstrate higher energy yields compared to fixed-tilt mounting. However, the magnitude of improvement varies significantly based on adjustment frequency and geographical factors. While comparing low and high latitude locations [7] found that in low-latitude countries latitude 0-15°N, dual-axis tracking increased annual energy gain by 12.52-29.58% compared to optimally fixed panels [8] extended this analysis to northern hemisphere locations latitude 20-70°N, demonstrating that performance rankings of different tracking systems varied significantly based on local irradiation characteristics. Their work highlighted that cities at similar latitudes but with different climate conditions e.g., Cairo, Egypt vs. Chongqing, China) shownsignificantlydissimilar optimal configurations. This emphasising the importance of localised analysis.

Discrete vs. Continuous Adjustment

Recent research has investigated the performance tradeoffs between continuous tracking and discrete adjustment strategies [9] demonstrated that a discrete single-axis system with only three daily actuations achieved 91-94% of the energy collection of continuous tracking while significantly reducing mechanical complexity and energy consumption. This finding suggests that for many applications, discrete adjustment strategies may offer favourable performance-cost tradeoffs. [10] proposed a novel tilted-rotating axis single-axis structure that achieved 96.40% of the solar radiation capture of dual-axis systems. Their work represents ongoing innovation in tracking mechanisms aimed at maximising performance while minimising complexity and cost.

Climate-Specific Performance

Climate conditions significantly influence the relative benefits of adjustable tilt systems. Regions marked by elevated diffuse radiation fractions, such as those with frequent cloud cover, exhibit diminished advantages from the implementation of precise solar tracking [11]. Research, as cited by [12], indicated that tracking systems yielded a 39% energy gain in Berlin, a temperate climate, whereas the energy gain was only 8% in Aswan, Egypt, a location with a hot and clear climate; furthermore, the energy consumption of tracking systems could potentially offset the benefits in hot regions.

The performance comparison of tilt adjustment strategies is shown in Table 2.

Table 2: Performance Comparison of Tilt Adjustment Strategies.

Adjustment Strategy	Typical Energy Gain vs. Fixed	Adjustment frequency	Mechanical Complexity	Control System	Best Suited For
Fixed Optimal Tilt	0% (Baseline)	None	Low	None	Large pant, rooftops with limited space
Seasonal Manual	5-15%	2-4 times/year	Low	Manual	Commercial/industrial, moderate budgets
Seasonal Automated	10-20%	2-12 times/year	Medium	Simple	Remote locations, moderate maintenance
Single-Axis Discrete	15-30%	2-6 times/day	Medium	Moderate controller	High-value applications, good maintenance
Single-Axis Continuous	20-35%	Continuous	High	Advanced controller	High-insolation regions, premium installations
Dual-Axis	25-45%	Continuous	Very High	Advanced controller	Research, maximum yield applications

FINANCIAL ANALYSIS

Financial Structures and LCOE Comparison

The financial feasibility of adjustable-tilt systems hinges on the optimal balance between enhanced energy output and the associated capital and operational expenditures. [7] utilised Levelised Cost of Electricity (LCOE) analysis to evaluate tracking systems across nations situated in low-latitude zones, revealing instances where economic rankings diverged from performance assessments. In certain scenarios, less complex fixed or single-axis systems demonstrated superior economic viability, notwithstanding their reduced energy generation. [8] illustrated that economic preferences exhibited considerable variation across locations in the northern hemisphere; specifically, regions with high irradiation levels typically presented more favourable economics for tracking systems, attributable to their superior absolute energy gains. Their research underscored the necessity of incorporating local energy prices, financing costs, and policy incentives, alongside technical performance, into economic evaluations.

Capital and Operational Costs

Adjustable-tilt systems incur additional costs in several categories:

Hardware Costs: Mechanical components (motors, gears, structural supports), control systems, and sensors

Installation Costs: More complex installation procedures and potential need for specialised labour

Operational Costs: Energy consumption of tracking mechanisms, maintenance, and potential repairs

Financing Costs: Potentially higher interest rates for more complex systems

[10] developed a low-cost dual-axis tracking system using digital logic design with LDR sensors, demonstrating that cost-effective solutions are possible with careful design. Their system achieved a 44.89% efficiency improvement over fixed systems while maintaining reasonable costs.

Economic Decision Framework

Economic justification for adjustable-tilt systems (as summarised in Table 3) depends on multiple factors:

Energy Price: Higher electricity prices increase the value of additional energy generation.

System Scale: Increasing electricity prices hike the value of producing more energy.

Larger networks can more easily divide out the fixed costs of tracking mechanisms.

Locations with a lot of sunlight provide greater energy production. Financial factors, such as discount rates, tax breaks, and financing options, greatly affect the economic side of things.

Sites with limited maintenance access are better suited for simpler systems.

Table 3: Economic Comparison Metrics.

Economic Metric	Fixed-Tilt	Seasonal Adjustable	Continuous Tracking	Primary Influencing Factors
Capital Cost ($/W)	0.8-1.2	1.0-1.5	1.2-2.0+	Scale, local manufacturing, design complexity
LCOE ($/kWh)	0.03-0.08	0.035-0.09	0.04-0.12	Location, financing, O&M, energy yield
Simple Payback (years)	5-10	6-12	7-15+	Energy prices, incentives, installation costs
O&M Costs (% of capital/year)	0.5-1.5%	1-3%	2-5%+	Environment, maintenance quality, design
Energy Value Increase	Baseline	+5-20%	+15-45%	Location, climate, system optimization

OPERATIONAL PERSPECTIVES

Maintenance and Reliability

Operational considerations represent essential advantages between fixed- and adjustable-tilt systems. Fixed-tilt systems offer greater reliability with minimal maintenance needs mainly occasional cleaning. In contrast, adjustable-tilt systems introduce moving parts, control electronics, and sensors that require regular maintenance and are subject to potential failures [14] monitored a dual-axis tracking system over 152 days in southern Brazil, noting the importance of robust design and control algorithms to minimise maintenance requirements. Their system incorporated features to ration motor usage during low-irradiation periods, extending component life and reducing energy consumption [15] developed a machine vision-based dual-axis tracker with ±2° accuracy, emphasising the importance of reliable sensor systems for maintaining performance. Their image processing approach eliminated the need for astronomical calculations and was independent of topographical location.

Control Systems and Intelligence

Modern adjustable-tilt systems increasingly incorporate intelligent control strategies to optimise performance and reliability. [16, 17] developed advanced maximum power point tracking (MPPT) algorithms that are particularly beneficial for tracking systems. Ali *et al.* proposed variable-step perturb and observe algorithm and Al-Majidi *et al.* fuzzy logic approach both addressed the "drift problem" during rapidly changing irradiance conditions, which is especially relevant for tracking systems following the sun's movement. [12] provided an inclusive evaluation of tracking knowledges, remarking trends toward hybrid control systems that combine sensor-based and time/date calculation approaches for better reliability under flexible weather conditions.

Installation and Site Considerations

The installation and site considerations are following factors significantly determine the possibility of adjustable-tilt systems.

Space Requirements: Space systems, particularly those designed for classical applications, necessitate increased the spacing to minimise shading effects.

Wind Loading: Adjustable tilt systems often demand more resilient structural designs to endure wind loads across various orientations.

Foundation Requirements: Continuous tracking systems may necessitate more substantial foundations.

Grid Integration: Systems with variable output might require supplementary power electronics to ensure grid compatibility.

Environmental Factors: Dust accumulation, snowfall, and extreme temperatures all impact the selection of the system.

INTEGRATED DECISION FRAMEWORK

This framework integrates technical performance considered technical factors, economic feasibility and operational constraints to support systematic and application-oriented decision-making for MPPT technique selection.

Multi-Criteria Analysis

Selecting between fixed and adjustable-tilt systems requires consider technical, economic, and operational factors. The optimal choice depends on project-specific circumstances rather than universal rules. In this main decision factors include:

Technical Factors: Location (latitude, climate), available space, grid connection, and performance requirements

Economic Factors: Budget constraints, energy prices, incentives, and financing options

Operational Factors: Maintenance capabilities, site accessibility, and required system lifetime

Project-Specific Factors: Aesthetic considerations, regulatory requirements, and stakeholder preferences

Context-Specific Recommendations

The following context-specific recommendations arise after analysis:

For Utility-Scale Projects in High-Insolation Regions: The single-axis tracking often gives the best balance of performance improvement and economic viability. Due to this typically increasing energy yield by 20-30% with reasonable additional costs.

For Commercial/Industrial Rooftops: With the frequency 2 to 4 times/year of seasonal manual adjustment often represents the optimal compromise. This providing meaningful 10 to 20 % energy gains without significant complexity and also minimum maintenance requirements.

*For Residential Applications:It is difficult to adjust tilt angle and f*ixed-tilt systems at optimal angles generally provide the best value, as the incremental costs of adjustable systems are difficult to justify at small scales.

For Remote/Off-Grid Applications: For additional energy generation is higher potentially justifying more appropriate tracking systems.

For High-Latitude Regions:For high latitude regions benefits of tracking are often limited due to high diffuse radiation therefore fixed and seasonally adjusted systems are much better.

For Research and Demonstration Projects: Dual-axis systems may be justified to maximize energy capture or demonstrate advanced technologies.

Future Trends and Innovations

The research indicates several emerging trends in tilt optimisation:

Discrete Tracking Strategies: Increased focus on systems with reduced actuation frequency to balance performance and reliability

Intelligent Control Systems: Integration of weather prediction, learning algorithms, and adaptive control

Bifacial Panel Integration: Tracking systems optimised for bifacial panels to capture additional rear-side irradiation

Hybrid Approaches: Combining fixed and tracking systems within the same installation to optimise overall economics

Standardisation and Certification: Development of standardised testing protocols and performance metrics

CONCLUSIONS

This comparative analysis of fixed-tilt and adjustable-tilt photovoltaic systems highlights that adjustable-tilt system mostly achieve higher energy yields that improving performance by about 10–45%. This is depending on location, latitude, and adjustment rate. However, these energy gains arise with some drawback like increased capital costs, higher maintenance requirements, and greater system complexity. As a result, when evaluated using metrics such as energy level costs, their overall economic attractiveness is often reduced.

From an operational perspective this is observed that fixed-tilt systems are more reliable and require less maintenance, making them ideal for harsh environments or locations with limited access. Thus, any one type of system is not best for every situation. Therefore, finest choice depends on factors specific based on the project such as budget, scale, site conditions and maintenance capabilities. In many cases studies, this is found that systems with limited seasonal adjustments offer a balanced compromise between better performance and manageable complexity. Future research is focusing on reducing costs, increasing reliability, enhance efficiency and developing intelligent control strategies. This indicating that both fixed and adjustable-tilt systems will continue to play a significant role in future solar PV installations.

REFERENCES

[1]. Gajbhiye, P., Jain, T. and Shukla, P. N. (2018). Environmental Impact of Electricity Generation on Indian Ecosystem. *International Journal of Electrical,*

Electronics and Computer Engineering, **7**(2), pp. 11–17.
[2]. Chitgopkar, R. and Patel, I. (2016). Solar Power Generation Based on Mechatronics System. *International Journal on Emerging Technologies*. Special Issue on ICRIET-2016, **7**(2), 34–40.
[3]. Stanciu, C. and Stanciu, D. (2014). Optimum tilt angle for flat plate collectors all over the World–A declination dependence formula and comparisons of three solar radiation models. *Energy conversion and management*, **81**, 133-143.
[4]. Hafez, A. Z., Soliman, A., El-Metwally, K. A. and Ismail, I. M. (2017). Tilt and azimuth angles in solar energy applications–A review. *Renewable and sustainable energy reviews*, **77**, 147-168.
[5]. Khorasanizadeh, H., Mohammadi, K. and Mostafaeipour, A. (2014). Establishing a diffuse solar radiation model for determining the optimum tilt angle of solar surfaces in Tabass, Iran. *Energy conversion and management*, **78,** 805-814.
[6]. Despotovic, M., Nedic, V., Despotovic, D. and Cvetanovic, S. (2016). Evaluation of empirical models for predicting monthly mean horizontal diffuse solar radiation. *Renewable and Sustainable Energy Reviews***, 56,** 246-260.
[7]. Bahrami, A., Okoye, C. O. and Atikol, U. (2017). Technical and economic assessment of fixed, single and dual-axis tracking PV panels in low latitude countries. *Renewable Energy*, **113,** 563-579.
[8]. Bahrami, A., & Okoye, C. O. (2018). The performance and ranking pattern of PV systems incorporated with solar trackers in the northern hemisphere. *Renewable and Sustainable Energy Reviews*, **97,** 138-151.
[9]. Batayneh, W., Bataineh, A., Soliman, I. and Hafees, S. A. (2019). Investigation of a single-axis discrete solar tracking system for reduced actuations and maximum energy collection. *Automation in Construction*, **98**, 102-109.
[10]. Zhu, Y., Liu, J. and Yang, X. (2020). Design and performance analysis of a solar tracking system with a novel single-axis tracking structure to maximize energy collection. *Applied Energy*, **264,** 114647.
[11]. Gupta, N. and Khatri, M. (2017). An Experimental Analysis of Shading on Solar Photovoltaic System. *International Journal on Emerging Technologies*, Special Issue NCETST-2017, **8**(1), pp. 226–228.
[12]. Awasthi, A., Shukla, A. K., SR, M. M., Dondariya, C., Shukla, K. N., Porwal, D. and Richhariya, G. (2020). Review on sun tracking technology in solar PV system. *Energy Reports*, **6**, 392-405.
[13]. Jamroen, C., Komkum, P., Kohsri, S., Himananto, W., Panupintu, S. and Unkat, S. (2020). A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation. *Sustainable Energy Technologies and Assessments*, **37,** 100618.
[14]. Hoffmann, F. M., Molz, R. F., Kothe, J. V., Nara, E. O. B. and Tedesco, L. P. C. (2018). Monthly profile analysis based on a two-axis solar tracker proposal for photovoltaic panels. *Renewable energy*, **115,** 750-759.
[15]. Abdollahpour, M., Golzarian, M. R., Rohani, A. and Zarchi, H. A. (2018). Development of a machine vision dual-axis solar tracking system. *solar energy*, *169*, 136-143.
[16]. Ali, A. I., Sayed, M. A. and Mohamed, E. E. (2018). Modified efficient perturb and observe maximum power point tracking technique for grid-tied PV system. *International Journal of Electrical Power & Energy Systems*, **99,** 192-202.
[17]. Al-Majidi, S. D., Abbod, M. F. and Al-Raweshidy, H. S. (2018). A novel maximum power point tracking technique based on fuzzy logic for photovoltaic systems. *International Journal of Hydrogen Energy*, **43**(31), 14158-14171.