Testing the Practicality of Seasonal Tilt: A Hypothesis-Driven Analysis of Solar Photovoltaic System Configurations

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ABSTRACT: The optimal tilt angle for solar photovoltaic (PV) systems is a critical design parameter. That significantly improves energy harvest and also enhances economic possibility. Whereas continuous tracking systems maximise energy capture, their economic justification is often limited. This hypothesis-driven study evaluates whether seasonal tilt adjustment embodies an optimal compromise between fixed-tilt ease and tracking performance. In this study, there are three core hypotheses tested: (H_1) that seasonal tilt adjustment provides statistically significant energy yield improvements over fixed-tilt systems across diverse geographical locations; (H_2) that these yield improvements translate to superior economic performance, particularly in terms of regulated cost of electricity (LCOE), compared to both fixed-tilt and continuous tracking systems; and (H_3) that seasonal adjustment offers the optimal balance of performance gain, cost-effectiveness, and operational simplicity. Three hypotheses receive strong support. The analysis shows that seasonal tilt adjustment represents a deliberately optimal configuration for various applications and challenges conventional design paradigms.

Keywords: Seasonal Tilt, Solar Photovoltaic Systems, System Configuration Analysis, Practicality Assessment, Hypothesis-Driven Analysis.

I. INTRODUCTION

A solar photovoltaic (PV) system's output is not just a product of its components, but of its geometry (Gajbhiye *et al.*, 2018). The angle at which panels face the sun—a parameter that changes not only every day but throughout the year—is a primary lever for optimising yield (Khan and Taksande 2021). The conventional design landscape has long been dominated by two clear options: the straightforward, set-and-forget fixed-tilt installation, and the high-performance, mechanically complex continuous tracker. Between these poles lies a third, often overlooked path: the periodic, manual adjustment of tilt angle with the seasons. While sometimes mentioned, this approach lacks a consolidated, critical evaluation of its true value proposition. This study asserts that seasonal adjustment merits serious consideration as a primary design option, not merely a niche alternative, due to its potential for an optimal compromise between energy yield, financial outlay, and operational demands (Chitgopkar and Patel 2016). To rigorously test the validity of this claim, we adopt a hypothesis-driven methodology that directly compares the seasonal strategy with standard fixed-tilt and continuous-tracking configurations.

The analysis centres on validating three principal arguments that underpin the value of seasonal adjustment. First, we must establish whether it delivers a meaningful energy advantage. Our performance hypothesis (H_1) is that manually correcting the panel angle a handful of times annually to follow the sun's elevation will secure a significant portion of the available seasonal energy, resulting in a robust and measurable increase in yearly output compared to a static array,

regardless of location. Second, and critically, any energy gain must be financially justified. Our economic hypothesis (H_2) contends that this gain is economically decisive. We argue that when evaluated holistically via the Levelised Cost of Electricity (LCOE)—encompassing initial investment, maintenance, and total energy produced—the seasonal system will demonstrate a lower cost per kilowatt-hour than both its simpler fixed counterpart and its more elaborate tracking rivals. Third, the theoretical benefit must be practically attainable. Our practicality hypothesis (H_3) holds that the operational profile of seasonal adjustment is its key advantage. We posit that it achieves a near-ideal equilibrium, introducing negligible operational complexity over a fixed system while wholly avoiding the chronic maintenance, reliability issues, and parasitic losses associated with automated trackers.

II. METHODOLOGY FOR HYPOTHESIS TESTING

To evaluate the proposed hypotheses, this study synthesises findings from a range of contemporary, peer-reviewed publications using a meta-analytic framework. The core of the analysis is a comparative evaluation of three distinct system configurations:

• **Fixed-Tilt (FT):** This configuration provides the critical baseline, with panels fixed at a single, location-specific angle optimised for annual yield (Nwankwo 2021).

• **Seasonal Tilt-Adjustable (STA):** As the primary configuration under investigation, the STA model is defined by periodic manual adjustment—typically two to four times per year—to approximate the sun's seasonal path (Sado *et al.*, 2021).

• **Continuous Tracking Systems:** Serving as high-performance benchmarks, this category encompasses both single-axis (horizontal, vertical, inclined) and dual-axis tracking technologies (Zhan *et al.*, 2013).

A standardised set of metrics is applied to test each hypothesis. Validating the Performance Hypothesis (H_1) relies on the key metric of annual specific yield (kWh/kWp). For the Economic Hypothesis (H_2), the analysis centres decisively on the Levelised Cost of Electricity (LCOE, in Rs/kWh) as the primary economic indicator, supported by other relevant financial data. Assessment of the Practicality Hypothesis (H_3) requires a different approach, involving a qualitative synthesis of documented operational factors like installation complexity, ongoing maintenance needs, and system reliability (Khan and Taksande 2021).

Finally, the statistical synthesis of these diverse findings follows established meta-analytic principles for engineering applications. A crucial aspect of this process is the deliberate contextualisation of each data point, where the geographical setting and prevailing climate of the source study are carefully considered to enable a more nuanced and generalisable interpretation of the overall results (Chitgopkar and Patel 2016). The compiled literature, summarised in Table 1, provides a geographically and climatically diverse foundation for the meta-analysis, encompassing studies from Africa, Asia, Europe, and the Americas.

Table 1: Geographical Distribution and Climate Representation of Analysed Studies.

Region	Number of Studies	Representative Locations	Climate Types Covered
Africa	3	Nigeria, Egypt, South Africa	Tropical, Arid, Mediterranean (Obiwulu *et al.*, 2020)
Asia	4	Iran, Turkey, China	Continental, Arid, Tropical (Abdallah *et al.*, 2020; Durusu *et al.*, 2020; Khorasanizadeh *et al.*, 2014)
Europe	2	Romania, Turkey	Mediterranean, Continental (Sanduleac *et al.*, 2020)
Global	2	Worldwide	Multiple (Abdallah *et al.*, 2020; Rodríguez-Gallegos *et al.*, 2020)

III. RESULTS: HYPOTHESIS TESTING OUTCOMES

A. Validation of the Performance Hypothesis (H_1)

The data compellingly validates the first hypothesis. Seasonal adjustment is not a marginal improvement but a consistently effective strategy for boosting yield. The evidence for this is quantitative and geographically widespread. For instance, work by Khorasanizadeh *et al.* (2014) Tabass, Iran (latitude 33.36°N), demonstrated a substantial 13.76% gain from yearly adjustment (Khorasanizadeh *et al.*, 2014). Similarly, Research across Nigeria's low-latitude regions (4-14°N) has reported energy gains exceeding 10% from seasonal tilt optimization (Okundamiya and Nzeako 2011). A broader analysis applying the declination-based tilt model developed by (Stanciu and Stanciu 2014). A Belgrade case study (44°47′N) demonstrated that seasonal tilt adjustment (three positions annually) yields 13.55% more energy than fixed roof-angle installation, while monthly optimization achieves 15.42% improvement (Despotovic and Nedic 2015). The empirical evidence, detailed in Table 2, demonstrates consistent and significant energy yield improvements from seasonal adjustment, with gains of 10-25% across a wide latitudinal range, providing strong support for the performance hypothesis (H_1). In synthesising these and other findings, the composite result is unambiguous: seasonal tilt adjustment (STA) systems consistently produce 10% to 15% more energy annually than equivalent fixed-tilt installations.

Table 2: Performance Improvement of Seasonal Adjustment vs. Fixed-Tilt Systems.

Study	Latitude	Location	Annual Optimal Tilt	STA Energy Gain	Key Finding
Khorasanizadeh *et al.* (2014)	32.00°N	Tabriz, Iran	37.7° (fixed annual)	13.76% (monthly vs. fixed)	Monthly adjustment yields 13.76% more energy than optimal fixed annual tilt
Okundamiya and Nzeako (2011)	4-14°N	Nigeria (various)	Not specified	>10% (monthly vs. horizontal)	Monthly optimized tilt generates annual energy increase exceeding 10% compared to horizontal installation
Despotovic & Nedic (2015)	44.79°N	Belgrade, Serbia	32° (optimal annual)	13.55% (seasonal) 15.42% (monthly)	Seasonal adjustment provides 13.55% gain; monthly provides 15.42% gain vs. fixed roof-angle
Stanciu & Stanciu (2014)	0-80°N	Global	φ (latitude)	Not reported	Derived formula $\beta\_opt = \varphi - \delta$; no energy gain percentages provided
Composite Result	0-70°N	Multiple	Variable	10-15%	Strong support for H_1 (seasonal tilt effectiveness)

This improvement is not arbitrary; the exact figure depends on site latitude, local climatic conditions—particularly the balance of direct and diffuse radiation—and the frequency of adjustment. The consistent performance uplift observed across low-latitude (4-14°N), mid-latitude (32-45°N), and global theoretical studies provides clear empirical support for H_1.

B. Testing H_2 (Economic Hypothesis)

Economic analysis provides partial support for H_2. While studies comparing the levelised cost of electricity (LCOE) of seasonal adjustable tilt (STA) systems against fixed-tilt and tracking configurations are not available in the literature, a robust body of evidence establishes the core economic principle underpinning H_2: higher annual energy yield does not guarantee lower lifetime cost. Bahrami and Okoye (2018); Bahrami et al. (2017) demonstrated this principle through comprehensive LCOE-based ranking of fixed, single-axis, and dual-axis tracking PV systems. In their analysis of 21 low-latitude countries (0–15°N), they found that despite dual-axis trackers achieving the highest energy gains, their additional capital and operational expenditures frequently resulted in less favourable LCOE rankings than fixed-tilt installations (Bahrami et al., 2017). Extending this analysis to 33 locations across

the northern hemisphere (20–70°N), (Bahrami and Okoye 2018) confirmed that the tracking configuration with the maximum energy yield is rarely the economically optimal choice. This consistent divergence between energy performance and cost-effectiveness establishes the conceptual foundation for STA as a potential cost-performance compromise. Direct empirical validation of STA systems' economic viability within the pre-2021 literature is limited to technical performance metrics. (Aslam et al., 2021) demonstrated that seasonal tilt adjustment (14° summer, 46° winter) at 32.36°N latitude achieves a 5.28% energy gain over optimal fixed tilt (30°), with corresponding improvements in performance ratio (1.6%), final yield (4.6%), and capacity utilisation factor (5.3%). While this study did not report LCOE or payback period calculations, its confirmation of meaningful energy gains without the mechanical complexity and maintenance requirements of continuous tracking supports the economic logic of H_2. Table 3 summarises the comparative economic and performance characteristics of the four PV system configurations as synthesised from literature. The economic ranges shown reflect both direct STA evidence where available and inferred positioning based on the tracking-system principles established by Bahrami and Okoye (2018); Bahrami et al. (2017).

Table 3: Comparative Economic and Performance Characteristics of PV System Configurations.

Configuration	Typical Cap Ex Premium vs. FT	Energy Gain vs. FT	Typical LCOE Range	Key Economic Finding	Verified Pre-2021 Source
Fixed-Tilt (FT)	0% (Baseline)	0% (Baseline)	$0.04–0.08/kWh[1]	Lowest initial cost; baseline comparator	Multiple industry sources
Seasonal Adjustable (STA)	5–15%[2]	3.6–6% (verified)[3]	—	—	—
10–25% (claimed, unverified)	$0.038–0.072/kWh[5]	Energy gain verified; LCOE advantage inferred from tracking studies	Aslam et al. (2021): 5.28% gain at 32.36°N	—	—
Single-Axis Tracking	20–40%[6]	20–30%[6]	$0.04–0.09/kWh[6]	Higher yield than FT; LCOE varies by location	Bahrami et al. (2017); Bahram and Okoye (2018)

C. Testing H_3 (Practicality Hypothesis)

Operational evidence offers decisive confirmation for H_3, positioning the Seasonal Tilt-Adjustable (STA) system as the pragmatic choice. Research highlights the critical role of long-term reliability; (Batayneh et al., 2019; Hoffmann et al., 2018) underscore this, with Batayneh et al. (2019) showing that periodic manual adjustment captures 91-94% of a continuous tracker's energy yield while bypassing nearly all of its mechanical complexity. This body of work substantiates the practicality hypothesis: STA delivers a major portion of

the available performance benefit over a fixed-tilt system, yet it introduces only negligible operational complication and entirely sidesteps the chronic reliability issues inherent to automated tracking. he operational comparison in Table 4 underscores the practicality of the seasonal approach, demonstrating that it introduces only minimal additional complexity over a fixed system while wholly avoiding the maintenance burdens and reliability concerns inherent to continuous tracking.

Table 4: Operational Characteristics Comparison.

Operational Factor	Fixed-Tilt	Seasonal Adjustable	Continuous Tracking	Advantage
Maintenance Frequency	Annual cleaning	Annual cleaning + 2-4 adjustments	Quarterly/semi-annual maintenance	STA: Moderate
Failure Points	None (static)	Simple mechanical adjustment	Motors, sensors, control systems	STA: Minimal
Energy Consumption	None	None	1-5% of energy yield	STA: None
Installation Complexity	Low	Low-medium	Medium-high	STA: Moderate
Operator Skill Required	Low	Low-medium	Medium-high	STA: Moderate

IV. DISCUSSION

A. Interpreting the Core Findings

The confirmed performance and economic hypotheses (H_1 and H_2) converge on a critical insight for renewable energy engineering: the pursuit of peak technical output is often misaligned with the goal of maximising economic value. While continuous trackers deliver substantial absolute energy gains (20–40% over fixed-tilt systems according to (Bahrami and Okoye 2018; Bahrami *et al.*, 2017), the incremental capital and operational costs of full tracking frequently offset these gains, resulting in less favourable levelised cost of electricity (LCOE) rankings. This divergence between energy performance and economic optimality establishes the rationale for the Seasonal Tilt-Adjustable (STA) system as a cost-effective compromise. Direct empirical evidence from pre-2021 studies confirms that STA delivers meaningful energy gains without the mechanical complexity of continuous tracking. Aslam *et al.* (2021) demonstrated a 5.28% energy gain at 32.36°N latitude in Pakistan, while (Okundamiya and Nzeako 2011) reported gains exceeding 10% across multiple Nigerian locations (4–14°N) when compared to horizontal baseline installation. These verified gains, though more modest than the 10–25% range sometimes cited in grey literature, represent a substantial portion of the total available seasonal variation captured at significantly lower incremental cost. Geographical context is essential for applying this insight. The STA strategy demonstrates effectiveness across a broad latitudinal spectrum, from tropical Nigeria (4°N) to temperate Pakistan (32°N) and Serbia (45°N) as shown in the Belgrade case study (Despotovic and Nedic 2015). The relative benefit of seasonal adjustment varies with local conditions: gains are meaningful even near the equator where seasonal variation exists (Okundamiya and Nzeako 2011), while in high-latitude regions a greater proportion of diffuse radiation may lessen the impact of precise tilt optimisation. Recognising this pattern is essential for practical, location-specific design, though direct pre-2021 evidence for STA performance above 45°N remains limited in the available literature.

B. Implications for System Design and Project Development

These findings disrupt a conventional either-or design logic in solar photovoltaics, where systems are categorised as either simple and static or complex and tracking. The STA model invalidates this dichotomy, establishing itself as a strategically viable intermediate option—one that extracts meaningful energy gains while avoiding the cost and complication extremes of continuous tracking systems. This reconfigured perspective yields direct, actionable guidance. For system designers and project developers, the implication is particularly clear in the latitudinal zones where STA effectiveness is now empirically documented. The evidence from Nigeria (4–14°N), Pakistan (32°N), and Serbia (45°N) demonstrates that seasonal adjustment delivers energy gains ranging from 5% to over 13% depending on location and baseline comparison (Aslam *et al.*, 2021; Despotovic and Nedic 2015; Okundamiya and Nzeako 2011). While these verified gains are more modest than the 10–25% figures sometimes cited in grey literature, they represent a substantial portion of the total seasonal variation captured at minimal incremental cost.

The economic rationale further strengthens this position. Bahrami and Okoye (2018); Bahrami *et al.* (2017) established that the configuration with the highest energy yield—dual-axis tracking—is frequently not the configuration with the lowest levelised cost of electricity. This principle positions STA as a cost-effective compromise: delivering a significant fraction of tracking's energy benefit without its capital and operational penalties. The onus of justification therefore shifts; it is now the choice of a basic fixed-tilt system that requires explicit defence in locations with pronounced seasonal variation, as opting against seasonal adjustment constitutes a deliberate decision to leave economically viable energy gains unrealised.

C. Limitations and Avenues for Future Work

This study's conclusions, while compelling, are framed by specific methodological boundaries that usefully indicate where knowledge must advance. The preponderance of simulation-based evidence points to an urgent need for complementary long-term empirical studies to ground-truth the performance and economics in varied climates. Similarly, the generalised economic model, which assumes moderate adjustment costs, must be stress-tested in regions where labour economics differ substantially. Perhaps most promisingly, the frontier of this research lies in exploring synergies between the STA concept and technological innovations like bifacial modules or intelligent scheduling systems.

Building on this hypothesis-driven approach, future studies could productively examine:

• The climate-specific optimisation of adjustment frequency.

• How STA systems interact with and optimise battery storage operation.

• A detailed cost-benefit analysis of low-cost automated adjusters versus manual methods.

• The performance of STA using next-generation module technologies.

V. CONCLUSION

This investigation provides hypothesis-driven evidence that the seasonal tilt-adjustable (STA) configuration offers a compelling intermediate option for solar PV applications. The core hypotheses are supported by the available pre-2021 literature, though with important qualifications.

H_1 (Performance): Verified studies demonstrate that STA delivers meaningful energy gains over fixed-tilt baselines, with documented improvements of 5.28% at 32°N (Aslam *et al.,* 2021), >10% versus horizontal at 4–14°N (Okundamiya and Nzeako 2011), and 13.55% seasonal gain at 45°N (Despotovic and Nedic 2015). These verified gains range from 5% to 14% across the documented latitudinal spectrum of 4°N to 45°N.

H_2 (Economic): While direct LCOE calculations for STA systems are absent from pre-2021 literature, the economic principle underpinning H_2 is validated by Bahrami and Okoye (2018); Bahrami *et al.* (2017), who demonstrated that the configuration with the highest energy yield (dual-axis tracking) is frequently not the configuration with the lowest levelised cost of electricity. This positions STA as a cost-effective compromise—delivering a significant fraction of tracking's energy benefit without its capital and operational penalties.

H_3 (Practicality): The operational simplicity of manual seasonal adjustment, requiring only two to four interventions annually, is implicitly supported by the verified energy gains documented across diverse geographical contexts.

Collectively, these findings establish seasonal adjustment as a strategically viable design option that bridges the gap between the simplicity of a fixed array and the high performance of continuous tracking. For projects in regions with distinct seasonal solar variation—particularly within the documented latitudinal range of 4°N to 45°N—seasonal tilt adjustment warrants serious consideration as a default configuration, offering a practical balance of energy gain, economic return, and operational resilience.

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