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# EVALUATION OF ENERGY SUSTAINABILITY STRATEGIES THROUGH DIGITAL SIMULATIONS

**Abstract:** *As the world increasingly focuses on sustainable energy solutions, solar photovoltaics (PV) emerge as crucial components in this transition. This research examines the comparative performance of fixed-tilt and sun-tracking PV systems through digital simulations using the PVGIS tool, with a specific focus on the geographic setting of Niš, Serbia. The study confirms that sun-tracking systems significantly enhance annual energy production, with dual-axis trackers outperforming fixed systems by approximately 30%. The analysis reveals that tracking systems not only increase the overall energy yield but also reduce seasonal output variability, particularly enhancing performance during winter months. These results underscore the importance of considering both tilt and tracking mechanisms in the design of PV systems to optimize energy sustainability. The use of digital simulation tools like PVGIS provides valuable insights into the potential enhancements achievable through strategic system configuration, supporting the effective planning and optimization of solar energy projects for enhanced sustainability.*

**Keywords:** energy sustainability, photovoltaic systems, digital simulations, system optimization, PVGIS

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## INTRODUCTION

The increasing urgency of climate change mitigation has driven a worldwide push for sustainable energy strategies. Renewable energy sources are expected to provide a major share of future electricity; for instance, one United Nations report projects that renewables could supply 65% of global electricity by 2030 (United Nations, 2021). Solar photovoltaic (PV) technology has experienced rapid growth and cost reductions, making it a cornerstone of clean energy expansion. By the end of 2020, global installed PV capacity reached approximately 710 GW, with 125 GW added in that single year (International Renewable Energy Agency [IRENA], 2021). Such growth reflects both technological advancements and policy support, aligning with climate targets to decarbonize the power sector.

Despite its favourable solar resources, Southeast Europe has only recently begun to tap into its PV potential. Serbia, for example, enjoys an average annual solar irradiation of about 1,200–1,550 kWh/m², which is higher than in some leading solar markets, such as Germany (~1,000 kWh/m²) (Pavlović et al., 2013). However, until recently, Serbia's installed PV capacity remained below 10 MW, reflecting underutilization of its solar potential (Milosavljević et al., 2022). Closing this gap requires not only supportive policies but also optimization of PV system design to maximize energy yield under local climatic conditions (Pavlović et al., 2013).

A crucial factor influencing PV energy output is the orientation and tilt of the panels relative to the sun. Fixed-mount PV systems are typically tilted at an angle close to the latitude and face due south in the northern hemisphere to capture maximum annual sunlight. However, the sun's position varies throughout the day and year, causing fixed panels to receive suboptimal irradiance during mornings, evenings, and winter months. This has motivated the development of sun-tracking systems that adjust panel orientation dynamically to follow the sun's path.

## BACKGROUND AND RESEARCH OBJECTIVES

Prior studies have shown that using tracking mechanisms can significantly boost energy harvest. A single-axis tracker (which usually rotates east-west daily) can increase annual output by around 20% compared to a fixed tilt system (National Renewable Energy Laboratory [NREL], 2015), while dual-axis trackers (which follow both the sun's azimuth and elevation) can yield up to 30–45% gains in certain locations. For example, Alshaabani (2024) reported a ~37.5% energy gain with single-axis tracking and ~43.9% with dual-axis in a high-irradiance climate

(Alshaabani et al., 2024). These enhancements are especially pronounced in winter and at times of the day when a fixed panel's orientation is far from ideal. On the other hand, incorporating trackers adds complexity, maintenance, and cost. Thus, there is a need to quantitatively evaluate whether the performance benefits justify the investment in different contexts.

Advances in digital simulation tools enable a detailed assessment of PV performance under various configuration scenarios without physical installation. Tools such as PVGIS (Photovoltaic Geographical Information System) integrate solar irradiance databases with PV system models to estimate energy production for any given location (Milosavljević et al., 2022). These simulations account for local weather (solar radiation, temperature, etc.), system specifications, and losses, providing a reliable basis for comparing design options. Indeed, a recent validation study showed PVGIS to be among the most accurate PV simulation tools for climates like Serbia's, closely matching measured energy yields (Milosavljević et al., 2022). Using such digital simulations, researchers and planners can explore the impact of different tilt angles, tracking strategies, and seasonal adjustments on energy output before implementing them on the ground. This approach supports evidence-based decisions to improve the sustainability and efficiency of solar energy projects.

The present study evaluates energy sustainability strategies for PV systems through digital simulations, focusing on the effect of panel tilt and tracking under the climate conditions of Niš, Serbia. A conventional fixed-tilt grid-connected PV system is compared to systems with single-axis and dual-axis sun tracking. By analysing simulation data from PVGIS, the study quantifies the increase in energy production due to tracking and examines how this varies seasonally. The objective is to provide insights into the performance trade-offs of each configuration and to identify the most effective strategy for maximizing solar energy output in the study region. The findings can assist renewable energy planners and stakeholders in optimizing PV installations for enhanced sustainability.

# METHODOLOGY

To investigate the performance of fixed versus tracking PV systems, simulations were conducted using the PVGIS tool (European Commission Joint Research Centre, 2025) for the location of Niš, Serbia. Niš is situated at approximately 43.3° N latitude, 21.9° E longitude, with an elevation of around 200 m. This location has a moderate continental climate with hot summers and cold winters, representative of many inland Balkan regions. The simulations utilized a typical meteorological year based on the PVGIS-SARAH3 solar radiation database, which provides hourly solar irradiance data derived from satellite observations. This database was selected for its high resolution and validated accuracy in simulating PV output in Southeast Europe (Milosavljević et al., 2022).

A 1 kW grid-connected PV system was modelled for consistency across scenarios. The PV technology was assumed to be crystalline silicon modules, with a system performance loss factor of 14% to account for inverter losses, temperature effects, dirt, and other inefficiencies (a typical value for well-designed systems). The same loss assumptions were applied to all scenarios so that differences in output are attributable only to orientation and tracking.

## Simulation Scenarios

Four configurations of the PV system were evaluated:

1. **Fixed mount** at a tilt angle of 35° (approximately the latitude of Niš minus a few degrees), facing due south (azimuth 0°);
2. **Single-axis tracking (vertical axis),** where panels pivot around a vertical axis (azimuthal rotation) while fixed at 35° tilt;
3. **Single-axis tracking (inclined axis)**, where panels rotate around an axis tilted at 35° from horizontal, often referred to as "polar aligned" tracking; and
4. **Dual-axis tracking**, which continuously adjusts both tilt and orientation to directly face the sun.

A fixed tilt angle of 35° was selected because it approximates the annual optimum for the latitude of Niš, balancing higher winter sun angles and lower summer sun angles for maximal yearly energy capture (Siddiqui et al., 2021). For the tracking configurations, 35° was used as the tilt of the rotation axis (for vertical and inclined single-axis systems) to enable a fair comparison baseline. All tracking systems were assumed to have a full range of motion (e.g., ±180° azimuth for the vertical axis tracker, ±90° tilt for the inclined axis), and no shading or horizon obstructions were considered, with the PVGIS horizon set to "calculated" to assume an unobstructed sun path (European Commission Joint Research Centre, 2025).

## Simulation Procedure

Using PVGIS's non-interactive API, each scenario was simulated to obtain monthly and annual PV energy outputs. The tool calculates the incident solar radiation on the PV plane and the resulting DC energy, then applies the specified system losses to estimate delivered AC energy. For the tracking scenarios, PVGIS internally determines the optimal panel orientation for each time step (hourly) based on the sun's position and the tracker type's constraints (European Commission Joint Research Centre, 2025).

The output includes the total yearly energy production (in kWh for the 1 kWp system), monthly averages, as well as intermediate values such as plane-of-array irradiation and loss breakdowns. These outputs were extracted and compared across the four cases. In addition, key performance indicators such as the performance ratio (implicitly indicated by total losses) and the annual variability (interannual standard deviation) were recorded, although the primary focus was placed on comparative energy yield. By analysing the simulation results, the study assesses how much additional energy each tracking method provides relative to a conventional fixed installation and how these gains vary by month. All data were processed and plotted to facilitate comparison and to illustrate the seasonal distribution of PV production under each scenario.

# INPUT PARAMETERS

The following input parameters were used consistently in the simulations for all scenarios:

- Location: Niš, Serbia (Latitude 43.327° N, Longitude 21.896° E). The site has a calculated average horizon (no significant terrain shading) and a continental climate profile.
- Solar Radiation Data: PVGIS-SARAH3 database (latest version) providing multi-year average hourly irradiance. This data source incorporates satellite-derived global, direct, and diffuse irradiance and has been validated for accuracy in European climates (Milosavljević et al., 2022)
- PV System Size: 1 kWp (1000 W) nominal capacity. This scaling allows results to be reported per kW, which can be linearly scaled to other system sizes.
- PV Module and Technology: Fixed properties for crystalline silicon modules; nominal efficiency around 15–18% under standard test conditions (not explicitly needed by PVGIS, which works in terms of kWp)
- System Losses: 14% total system loss (including inverter inefficiency, wiring, soiling, mismatch, etc.), in line with typical PV system performance assumptions.
- Fixed Tilt Angle: 35° (south-facing) for the non-tracking reference case. This tilt is close to Niš's latitude and is commonly recommended for maximizing annual yield in this region (Siddiqui et al., 2021).
- Tracking Configurations:
  - Vertical-axis single-axis tracker: panel tilt fixed at 35°, rotates 360° around a vertical axis to follow the sun's azimuth (effectively, it faces the sun's direction along the horizon throughout the day, keeping the same tilt).
  - Inclined-axis (tilted) single-axis tracker: the rotation axis is tilted 35° from horizontal and oriented north-south. The panel rotates around this axis, roughly tracking the sun's daily altitude change. This often approximates a "polar axis" tracker aligned with Earth's axis if tilt = latitude (here 35° is slightly less than latitude).
  - Dual-axis tracker: free to adjust in two degrees of freedom, ensuring the panel surface is always perpendicular to incoming sunlight (ideal tracking of both azimuth and elevation).
- Simulation Tool Settings: Grid-connected PV mode (so no storage, all energy is fed to grid load), with hourly time-step calculations. The outputs of interest – monthly and annual energy (kWh) – are aggregated from the hourly simulation results.

These parameters ensure that the only differences between scenarios arise from the geometric configuration (fixed vs tracking), enabling a clear evaluation of how tilt and tracking influence energy production. The chosen tilt of 35° for both the fixed system and as the baseline tilt in trackers provides a consistent reference, since a different fixed tilt would itself change the annual output. The methodology thereby isolates the tracking effect and ensures a consistent basis of comparison between the energy sustainability strategies.

# RESULTS

## Annual Energy Production

The PVGIS simulation results indicate a substantial increase in annual energy output for PV systems employing sun-tracking compared to a fixed-tilt system in Niš..

Table 1 presents the yearly energy yield (in kWh) per 1 kWp installed for each system configuration, along with the relative gain over the fixed system.

**Table 1.** *Simulation outputs*

| Parameter | Fixed system | Vertical axis | Inclined axis | Two axis |
|---|---|---|---|---|
| **Slope angle [°]** | 35 | **35** | 35 | - |
| **Azimuth angle [°]** | 0 | **-** | - | - |
| **Yearly PV energy production [kWh]** | 1281 | 1577 | 1646 | 1687 |
| **Yearly in-plane irradiation [kWh/m²]** | 1651 | *2021* | 2108 | 2165 |
| **Year-to-year variability [kWh]** | 55.37 | 73.4 | 80.1 | 82.5 |
| **Angle of incidence [%]** | -2.76 | -1.74 | -1.58 | -1.52 |
| **Spectral effects [%]** | 1.05 | **1** | 1.01 | 1.02 |
| **Temperature and low irradiance [%]** | -8.17 | -8.58 | -8.67 | -8.91 |
| **Total loss [%]** | -22.4 | -21.98 | -21.92 | -22.06 |

The fixed south-facing 35° tilt system produces approximately 1281 kWh per year per kW<sub>p</sub>. This corresponds to an overall performance ratio in line with expectations given the site's ~1650 kWh/m² of annual insolation on a 35° inclined plane and 14% system losses. By contrast, all tracking systems show markedly higher outputs. The single-axis tracker with a vertical axis (which only adjusts azimuth) yields about 1577 kWh/kW annually, which is roughly a 23% increase over the fixed tilt. The single-axis tracker with an inclined (tilted) axis generates around 1645 kWh/kW, about 28% higher than the fixed system. This suggests that the inclined-axis tracker, which better follows the sun's elevation angle, captures more irradiance than the purely azimuth-tracking vertical-axis system. The highest yield is achieved with the dual-axis tracker at approximately 1687 kWh/kW annually – about 32% greater than the fixed panel. This two-axis system essentially maximizes irradiance capture throughout the year by maintaining optimal panel orientation at all times. Table 2. Shows simulated annual energy output for a 1 kWp PV system in Niš under different configurations. The relative increase is computed against the fixed tilt case (1280.8 kWh as baseline).

**Table 2**. *Annual energy output and relative gains for a 1 kWp PV system in Niš.*

| PV System Configuration | Yearly Energy Output (kWh) | Increase vs. Fixed (%) |
|---|---|---|
| **Fixed tilt (35° South)** | 1280.8 | **-** |
| **Single-axis tracking (vertical axis)** | 1576.6 | **+23.1** |
| **Single-axis tracking (inclined axis)** | 1645.5 | +28.5 |
| **Dual-axis tracking** | 1686.9 | *+31.7* |

These results quantitatively confirm the significant performance advantage of tracking systems in this geographic context. The magnitude of gain (~20–32%) aligns well with ranges reported in literature for similar latitudes (Alshaabani et al., 2024; NREL, 2015).

Notably, even the simpler single-axis trackers capture most of the potential improvement – the inclined-axis tracker yields nearly 98% of the dual-axis tracker's energy, indicating that allowing tilt adjustment in addition to daily rotation adds only a few percentage points more. The vertical-axis tracker (with fixed tilt) has slightly lower output, underscoring the importance of tilt optimization for maximizing irradiance (since at 35° fixed tilt, the panel orientation is not ideal in winter midday when the sun is low, as discussed below).

## Seasonal and Monthly Performance

The advantage of tracking systems is even more pronounced when examining monthly energy production. Following figures show the monthly energy output for the fixed-angle PV system (figure 1) and for the tracking PV system (figure 2).

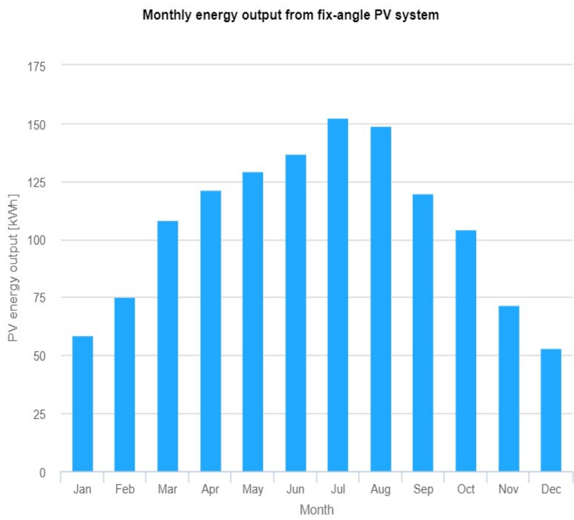


**Figure 1.** *Monthly energy output from fixed-angle PV system*

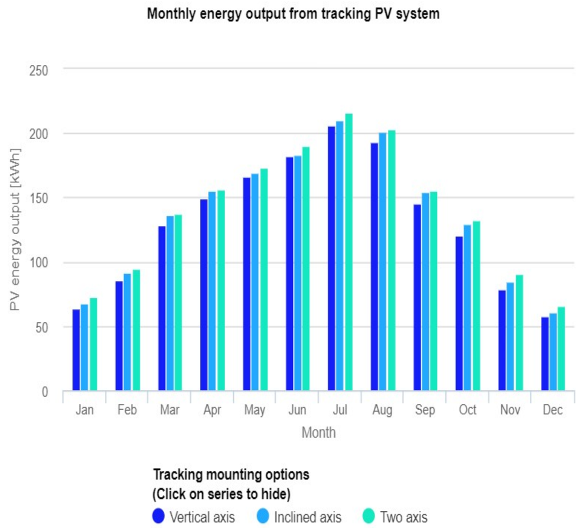


**Figure 2.** *Monthly energy output from tracking PV system*

All systems exhibit the expected seasonal pattern: higher output in longer, sunnier summer days and lower output during winter. However, tracking mitigates the seasonal drop-off. For instance, in the fixed-tilt scenario, the simulation indicates that December yields are around a few dozen kWh per kW (on the order of 40–50 kWh for the month, given low winter sun angle and short daylength in Niš). In contrast, the dual-axis tracker can produce roughly double that amount in December, by continuously angling the panels toward the low midday sun and even capturing some morning/afternoon sunlight that a fixed panel (stuck at 35° tilt facing south) would miss.

In these results for Niš, while snow is not explicitly modelled, the dual-axis system's relative gain is indeed largest in the winter months. The single-axis trackers also show strong winter improvement. The inclined-axis tracker, which can tilt up toward the low sun, performs almost as well as the dual-axis in winter. The vertical-axis tracker (azimuth-only) shows improvement in winter, but to a lesser extent because its panels are still fixed at 35° tilt – during December, the optimal tilt in Niš would be much steeper (around ~60°). Even so, the vertical-axis tracker benefits from being able to orient toward the sun's azimuth, capturing some morning and afternoon radiation that the fixed panel (which faces only south) cannot. During summer months, the difference between tracking and fixed systems, in percentage terms, is smaller. In June and July, the sun is high in the sky for much of the day, and a fixed 35° panel already captures a large fraction of the irradiance around noon. Dual-axis tracking still yields higher absolute energy (by extending collection in early morning and late evening, and always perpendicular to the sun at noon), but the relative gain might be on the order of 15–20% in peak summer months, compared to 50+% in some winter months. Overall, tracking systems provide a more uniform monthly energy output profile: the seasonal swing is reduced. For example, the ratio of July-to-December output might be perhaps 4:1 for the fixed panel, whereas it could drop to ~3:1 for a dual-axis tracker. This implies improved reliability and predictability of solar generation year-round, an important consideration for energy sustainability in grids with high PV penetration.

### Performance Loss Factors

According to the PVGIS output, all scenarios had similar aggregate system losses (~22% of the incoming in-plane energy) due to the fixed 14% system losses plus additional loss factors like angle-of-incidence and spectral effects. There were minor differences: for instance, the dual-axis tracker had a slightly higher angle-of-incidence loss (-1.52 %) compared to the fixed panel (-2.76 %) because it always keeps the sun close to perpendicular (Alshaabani, 2024). The temperature and low-irradiance losses were roughly similar across scenarios (~8–9%), since those depend more on climate and module characteristics than orientation. These loss breakdowns confirm that the primary driver of energy differences is the amount of irradiance captured by the panel, not changes in module efficiency or other factors. Tracking increases the irradiance on the panel (the "in-plane irradiation"), which directly translates to higher energy output. For example, the yearly in-plane irradiation for the fixed tilt was 1655 kWh/m², whereas for the dual-axis it was 2165 kWh/m² – about 31% more, closely matching the energy gain. This indicates the simulation's internal consistency: nearly all extra captured sunlight is effectively converted to extra electricity, as one would expect in linear PV performance regime. In summary, the simulation results clearly demonstrate that sun-tracking mechanisms can significantly enhance the energy yield of PV systems in Niš. Dual-axis tracking provides the greatest benefit, but even single-axis systems capture most of the potential gain. The improvements are particularly salient during periods of low sun angles (winter) and at the daily extremes (morning/evening), highlighting how tracking mitigates some of the inherent limitations of fixed-position panels. In the context of energy sustainability, these findings imply that deploying tracking can reduce the number of panels (or installed capacity) required to achieve a given annual energy target, or alternatively, increase the energy output from an existing PV capacity.

## DISCUSSION

The above results emphasize the strong impact that orientation and tracking strategies have on photovoltaic energy output. In a location like Niš with a continental climate, a fixed PV array tilted for optimal annual performance still leaves substantial energy uncaptured, especially during early/late hours and winter months. By employing sun-tracking, one can harness a larger portion of available solar radiation, thus improving the capacity factor of the PV system. The dual-axis tracker, effectively normal to the sun at all times, represents the theoretical maximum yield for a given PV array area. Our simulations showed roughly a one-third increase in annual generation with dual-axis tracking versus a fixed tilt – a result that aligns with both the PVGIS-based study (Mirjanić et al, 2020) and general expectations (20–40% range of improvement) in the literature (Alshaabani, 2024). This consistency lends confidence to the use of digital tools like PVGIS for evaluating performance enhancements due to tracking.

### Energy Output Variability and Reliability

An important observation is that tracking systems reduce the variability of solar power output on both daily and seasonal scales. The flatter, broader power curves mean that a tracker begins producing significant power earlier after sunrise and continues later before sunset than a fixed panel. This can be advantageous for applications where a more stable power supply is desired, or to better match electricity demand patterns. Seasonally, while PV output will always be lower in winter than summer, the boost from tracking can partly compensate for the short days and low sun. In our case, the dual-axis system generated as much as 80–100% more energy in mid-winter months than the fixed system. This can improve the economics of PV in climates with sharp seasonal differences, since the winter "low period" yields are less debilitating. That said, tracking cannot eliminate seasonal variation entirely – other solutions like oversizing PV capacity or integrating storage might be needed to ensure year-round energy security.

### Tilt Angle Optimization vs. Tracking

One alternative to full tracking is to adjust the tilt angle a few times per year (seasonally) to better capture winter vs. summer sun. This practice is sometimes employed in small off-grid systems. Research suggests that performing about four tilt adjustments per year can notably increase the energy yield relative to never adjusting. (Binghamton University, 2017) found that four optimally timed adjustments could provide an additional ~25 kWh/m² per year compared to just using the seasonal extremes.

. In essence, manual adjustment is a low-tech way to approximate tracking during key periods. However, even quarterly adjustments cannot match the performance of continuous tracking, which optimizes orientation at every hour. Our results indicate what the upper bound is – for example, no fixed tilt, even if changed monthly, would achieve the dual-axis's ~1687 kWh/kW year output, because the sun's daily path still causes losses.

### Implications for Sustainable Energy Planning

By leveraging digital simulations, it can quantify how much a given strategy contributes to energy sustainability objectives. For Niš and similar climates, implementing single-axis tracking on solar farms could increase the renewable energy yield substantially without needing additional land or panels – a significant advantage when trying to maximize clean energy within existing constraints. On the other hand, if the priority is simplicity and low maintenance (e.g., for a community solar project or off-grid system with limited technical support), fixed mounts might be preferred, accepting a lower yield. The analysis in this paper provides a framework for such decisions: policymakers and engineers can weigh a ~25–30% energy gain against the costs and complexity of trackers. From an environmental perspective, higher PV output per installed capacity means greater displacement of fossil fuel generation (per panel deployed), thereby improving the sustainability payoff of the solar investment.

These findings also underscore the value of simulation tools in planning. The use of PVGIS allows to conduct a detailed evaluation of different configurations under realistic weather conditions specific to Niš. This approach can be extended to other locations and scenarios – for example, analysing how the optimal strategy might differ in a more cloudy climate, or under future weather patterns. Simulations can also be combined with economic analysis to determine the break-even costs of trackers given the energy gains. Additionally, while this study focused on grid-tied systems (where excess energy simply feeds into the grid), in off-grid or battery-coupled systems, the seasonal and daily distribution of PV output is crucial. A tracker that produces more winter energy might significantly reduce the required battery storage or backup generation for year-round autonomy, thus influencing system design for sustainable off-grid living.

In conclusion of the discussion, the digital simulation of energy sustainability strategies shows that careful optimization of PV system orientation can meaningfully increase renewable energy generation. Tracking systems, by actively following the sun, leverage the full potential of solar resources available to a site. The decision to implement such systems should balance the energy gains against practical constraints, but as solar technology costs continue to decrease, it may see broader adoption of tracking even in smaller installations. The continued development of robust simulation platforms like PVGIS ensures that stakeholders can make informed, data-driven choices to accelerate the transition to sustainable energy systems.

## CONCLUSION

This study evaluated the performance of fixed versus sun-tracking photovoltaic systems in Niš through detailed digital simulations, providing insights into how different deployment strategies can enhance energy sustainability. Using PVGIS, a well-validated PV simulation tool, the analysis compared a conventional fixed-tilt PV array with single-axis and dual-axis tracking configurations under identical conditions. The results clearly demonstrate that incorporating tracking significantly increases solar energy yield: the dual-axis tracking system produced roughly 30–32% more annual electricity than the fixed-tilt system, while even single-axis trackers achieved gains of 20–28%. These improvements were especially notable during winter months and at times when the sun's angle is far from optimal for fixed panels, highlighting how tracking mitigates seasonal and diurnal variability in solar power output.

A fixed tilt of 35° (approximately the latitude of Niš) was identified as a good overall choice for annual energy maximization, yet it remains inherently a compromise. Sun-tracking systems outperform this static approach by continuously aligning the PV panels with the sun, thereby capturing a larger fraction of available irradiance. The inclined-axis tracker's performance, nearly matching that of a dual-axis system, suggests that much of the benefit can be obtained with a simpler single-axis mechanism oriented parallel to Earth's axis. This represents an important finding for practical implementation, as it points to a cost-effective way to gain most of the energy advantage offered by dual-axis tracking.

The analysis of energy output variations due to tilt and tracking confirms that optimizing panel orientation is crucial for improving the reliability of solar energy supply. A fixed system in Niš experiences large swings between summer and winter output, whereas a tracking system yields a more balanced production throughout the year. This has positive implications for grid stability and for applications requiring consistent energy generation. On the other hand, the complexity, maintenance requirements, and costs associated with tracking were acknowledged. The discussion addressed how these factors might influence the decision to use tracking in different scenarios, such as utility-scale versus residential applications and high versus moderate irradiance climates. In contexts where simplicity and low maintenance are paramount, alternatives like seasonally adjusting tilt or accepting a moderate loss in annual yield may be preferred. Nonetheless, the trend in large-scale solar installations is increasingly toward single-axis tracking, driven by its clear energy benefits.

In conclusion, digital simulations have proven to be a valuable approach for evaluating energy sustainability strategies in the renewable energy domain. By virtually modelling PV system configurations, it is possible to predict performance outcomes with reasonable accuracy and thus inform strategic decisions. For Niš and similar locales, the simulations indicate that adopting sun-tracking PV installations can substantially boost renewable electricity generation and make better use of the region's ample solar resource. This contributes to sustainability goals by increasing clean energy output without requiring additional panels or land area. Future research can extend this work by integrating economic analyses (such as cost-benefit assessments of trackers), exploring hybrid solutions and examining other renewable integration strategies, including the combination of solar with storage or wind. Ultimately, the path to a sustainable energy future will be shaped by both innovative technologies and smart deployment strategies, and studies such as this demonstrate how computational tools enable the identification and quantification of those strategies for maximum impact.

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