

The Optimization of Efficiency in Grid-Connected PV Systems in Tropical Climates Using a Single-Axis Solar Tracker Based on Simulation

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ABSTRACT

The high potential for solar radiation in the tropics demands a Solar Power Plant (PLTS) system that can adapt to the sun's dynamic annual movements. Conventional fixed-tilt systems tend to be suboptimal at low latitudes due to the limited variation in solar radiation angle throughout the year. This study aims to evaluate and optimize the performance of on-grid solar power plants using a horizontal east-west single-axis solar tracker (SAT), as well as to analyze the effect of increased thermal losses on system efficiency in tropical climatic conditions. The case study was conducted on an on-grid solar power plant with a capacity of 50.4 kWp located in Mawang, Makassar (5.22° S), with a fixed-tilt system at a tilt angle of 17° as a comparison. The research methodology used a PVsyst software-based simulation approach with the activation of a backtracking scheme to mitigate inter-row shading at a ground coverage ratio of approximately 55.8%. The simulation results showed that the application of single-axis trackers increased the annual energy channeled to the grid (E_{Grid}) by 4.81%, equivalent to 3,149 kWh. However, the increase in the Performance Ratio (PR) was relatively limited, from 0.794 to 0.798, due to the increase in module thermal losses reaching 13.3%. These findings make a quantitative contribution regarding the trade-off between increased irradiation capture and thermal penalty in the application of single-axis trackers in the tropics, and confirm that the optimization of tracking systems depends not only on optical aspects but also on the thermal management of photovoltaic modules.

Keywords:

On-grid solar PV; single-axis solar tracker; tropical climate; performance ratio; thermal loss

INTRODUCTION

The increasing global demand for electrical energy, accompanied by the limitations of fossil energy sources and the environmental impact it causes, encourages the development of efficient and sustainable renewable energy technologies. Photovoltaic solar energy (PV) is one of the main solutions because it is clean, abundant, and flexible to be integrated into grid-connected systems (on-grid) (Tiwari, 2023; Xiao, 2023).

However, the performance of the PV system is greatly affected by the angle of arrival of solar radiation and the temperature of the module. Static PV systems are only able to reach the optimum incidence angle at a certain period, so the potential of daily solar energy cannot be utilized to its fullest, especially in tropical regions with dynamic solar trajectories and high radiation intensity (Qader & Ali, 2023; Thungsuk et al., 2023).

To increase the utilization of solar radiation, solar tracking system was developed to maintain the orientation of the PV module so that it is always close to perpendicular to the direction of sunlight. Studies have shown that solar tracking systems are the most effective method to increase PV energy production without changing the basic characteristics of solar

cells (Baouche et al., 2022; Kuttybay et al., 2024).

In general, solar tracking systems are classified into single-axis and two-axis trackers. Comparative studies show that although two-axis systems produce higher energy, the increase is relatively small when compared to the increase in cost, mechanical complexity, and maintenance requirements (Rafae et al., 2023; Thungsuk et al., 2023), (Wibowo & Marcel, 2023). Therefore, single-axis tracker solar systems are the most widely applied solution for medium to large-scale on-grid PV systems (Barbón et al., 2023; Manu et al., 2024).

The results of experimental and theoretical studies show that single-axis tracking systems can increase energy production by 15–40% compared to static systems, depending on the geographical location and tracking strategy used (Qader & Ali, 2023; Rafae et al., 2023), (Satria et al., 2023). The discrete tracking and timing approach has also been shown to reduce the energy consumption of the actuator without reducing the increase in energy obtained (Thungsuk et al., 2023; Wibowo & Marcel, 2023).

In addition to the increase in energy, the thermal aspect is an important factor in PV systems with solar trackers. The increase in radiation received by the module as a result of tracking can increase the temperature of the cell and decrease the conversion efficiency (Baouche et al., 2022; Chukwujindu et al., 2025; Manu et al., 2024; Qader & Ali, 2023). Therefore, the integration of the tracking system with thermal management techniques such as spray cooling has been proven to be able to increase the output power and efficiency of the system simultaneously (Sharaby et al., 2025).

Simulation-based approaches play a key role in the process of designing and optimizing solar tracker PV systems. Through simulation, parameters such as tracking angle, control algorithm, distance between module lines, shadow effect, and actuator energy consumption can be comprehensively analyzed before physical implementation is carried out (Baouche et al., 2022; Barbón et al., 2023; Kanu et al., 2024). Optimization studies show that this approach is able to lower the Levelized Cost of Energy (LCOE) and increase the economic viability of on-grid PV systems (Barbón et al., 2023).

In the latest development, a single-axis tracking system is also applied in the agrivoltaics concept, which is the integration of PV plants with agricultural activities. Research shows that the single-axis tracking system is able to improve the efficiency of land use, although the design of the system must be optimized so as not to reduce crop productivity, especially for plants that are intolerant to shade (Berrian et al., 2025; Willockx et al., 2023).

As technology develops, the integration of artificial intelligence and physics-based models is beginning to be applied to improve the accuracy of predicting the performance of PV systems with solar trackers, especially in the face of climate variability and long-term climate change (Chukwujindu et al., 2025; Kanu et al., 2024).

Although various studies have examined the improvement of the performance of PV systems using single-axis solar trackers through experimental approaches, simulations, and economic analysis, there are still some research gaps that need to be studied further. Most studies focus on evaluating energy increases or comparisons between static, single-axis, and dual-axis systems separately (Qader & Ali, 2023; Rafae et al., 2023; Thungsuk et al., 2023). On the other hand, design and cost optimization research has been extensively done for single-axis tracking systems, but they are generally oriented towards non-tropical climatic conditions

or mid-latitude case studies (Barbón et al., 2023; Willockx et al., 2023). In addition, studies that integrate energy, thermal, economic, and mechanical aspects simultaneously in grid-connected PV systems in tropical climates are still relatively limited.

Furthermore, although a simulation-based approach has been used to optimize the configuration and operation strategy of the single-axis tracker (Baouche et al., 2022; Barbón et al., 2023), most studies have not specifically evaluated the implications of such optimization on the efficiency of on-grid PV systems in tropical climatic conditions characterized by high radiation intensity, relatively high ambient temperatures, as well as significant weather variability. In addition, the integration of tracking strategies with energy-efficient control approaches and consideration of the feasibility of implementation in grid-connected PV systems is still an aspect that has not been discussed comprehensively. Therefore, a study is needed that systematically optimizes the efficiency of single-axis solar tracker-based on-grid PV systems by taking into account tropical climate characteristics through an integrated simulation approach.

This study aims to evaluate and optimize the performance of on-grid solar power plants utilizing horizontal east-west single-axis solar trackers (SAT) and analyze the impact of thermal losses on the system's efficiency in tropical climates. It specifically investigates the effect of SAT on energy production, compares it with fixed-tilt systems, and quantifies the trade-off between increased irradiation capture and thermal losses.

METHOD

This study uses a comparison-based simulation method to analyze the impact of the application of *Single-Axis Solar Tracker* (SAT) on the performance of on-grid solar PV systems in tropical climates. The fixed-tilt system is used as the reference system, while the East–West Direction horizontal single-axis tracker (SATT) system is used as the comparison system.

The evaluation focused on the annual increase in energy channeled to the grid (E_{Grid}), changes in Performance Ratio (PR), and analysis of system loss mechanisms, especially thermal and optical losses, which became the basis for discussion in the results and discussion section.

The study was conducted at UPDL Makassar on-grid solar power plants, located in Mawang, Makassar (5.22° LS). This location was chosen because it has a high potential for solar irradiation with extreme annual solar movements, which causes fixed-tilt systems to be unable to capture energy optimally throughout the year.

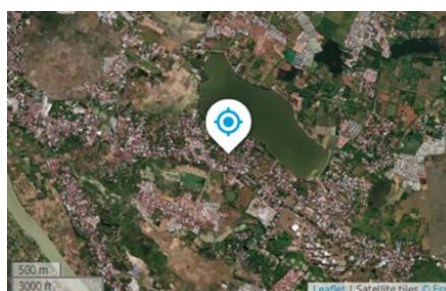


Figure 1. Location of UPDL Makassar On-grid PV
Data Source: Research document, UPDL Makassar, 2026

These characteristics of the tropical climate are the basis for the analysis of the variability of monthly energy gain, which in the results is shown to have a significant range between the moon with the extreme solar trajectory and the transition moon.

The solar PV system analyzed has the following specifications:

- DC Capacity: 50.4 kWp
- AC Capacity: 50.0 kWac
- DC/AC Ratio: 1.01

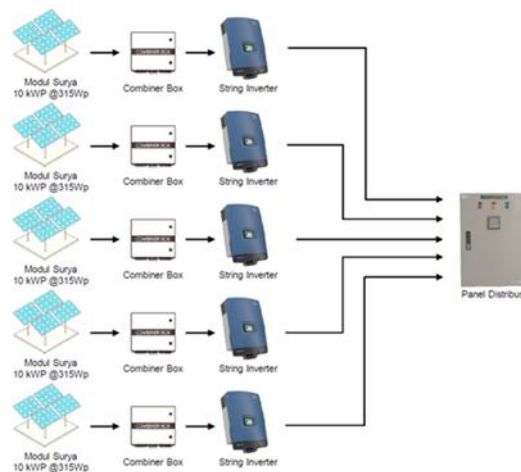


Figure 2. Configuration of UPDL Makassar On-grid PV PV
Data Source: Research document, UPDL Makassar, 2026

Two modeled configurations:

1. Fixed-Tilt (Reference)
 - Tilt: 17°
 - Azimuth: 0°
2. Single-Axis Solar Tracker (SATT)
 - Horizontal single axis
 - Tracking direction: East–West
 - Backtracking: enabled
 - GCR: ±55.8%

This configuration allows for a direct evaluation of the effective irradiation increase, IAM loss reduction, as well as the thermal consequences discussed in the results section.

The simulation was carried out using PVsyst software, with representative annual meteorological data (TMY) input for the Makassar region. The simulation was conducted at hourly time resolution for an entire year.

This approach allows for the analysis:

- Annual energy,
- annual homework, as well as
- monthly performance variations,

which is further used to explain the fluctuations in energy gain in the Results & Discussion section.

In order for the simulation results to be directly compared, all electrical and environmental parameters are kept identical, except for the module orientation mechanism. The simulation stages include:

1. Simulate a fixed-tilt system as a baseline.
2. Simulation of the SATT system with identical specifications.
3. Activation of backtracking to reduce shadows between lines.
4. Calculation of effective irradiation, output energy, and system loss components.
5. Extraction of annual and monthly results for gain and loss analysis.

PVsyst's built-in module temperature model is used to calculate the increase in thermal loss due to increased effective irradiation in the tracker system.

RESULTS AND DISCUSSION

3.1 System Annual Performance Simulation Results

Simulation of the performance of the 50.4 kWp on-grid solar system was carried out to compare the fixed-tilt configuration as a reference system and the east-west horizontal single-axis tracker (SATT) with an active backtracking scheme. The study location is in Mawang, Makassar at a latitude of 5.22° LS which has a high potential for solar radiation with significant variations in the sun's angle throughout the year

Table 1. Annual Performance Comparison (*Fixed Tilt vs. Single-Axis Tracker*)

Parameter	Fixed Tilt	Single-Axis Tracker	Percentage Increase (%)
Annual Energy to Grid (kWh/year)	65523	68672	4.81
Specific Production (kWh/kWp/year)	1300	1363	4.85
Performance Ratio (PR)	0.794	0.798	0.50

Data Source: Simulation results using PVsyst software, 2026.

The simulation results showed that the use of a single-axis tracker system resulted in an increase in annual energy delivered to the grid (E_{Grid}) by 4.81% compared to fixed-tilt systems. In absolute terms, this increase is equivalent to an additional energy production of 3,149 kWh per year. These findings confirm that single-axis tracking systems are capable of improving effective irradiation capture in tropical regions with extreme annual solar movements.

Despite the significant increase in energy, the system's Performance Ratio (PR) only experienced a marginal increase from 0.794 in the fixed-tilt system to 0.798 in the single-axis tracker system. This indicates that the increase in energy is not entirely followed by an increase in the overall efficiency of the system, but rather is influenced by the internal loss factor of the system.

3.2 Optical Performance Analysis and Seasonal Variation

In terms of optical performance, the single-axis tracker system showed an improvement in Incidence Angle Modifier (IAM) losses, which decreased from -2.3% in the fixed-tilt system to -2.0% in the tracker system. This decrease in optical losses is one of the main factors contributing to the annual increase in system energy.

Table 2. Comparison of Optical Performance (Fixed vs. Tracker)

Metrics	Fixed Tilt	Single-Axis Tracker
Global Radiation Coming (GlobInc) (kWh/m²/year)	1637,4	1708,4
Effective Global Radiation (GlobEff) (kWh/m²/year)	1589,1	1673,6
IAM Factor Loss (%)	-2,3	-2,0
Near Shading Loss (%)	-0,7	-0,5

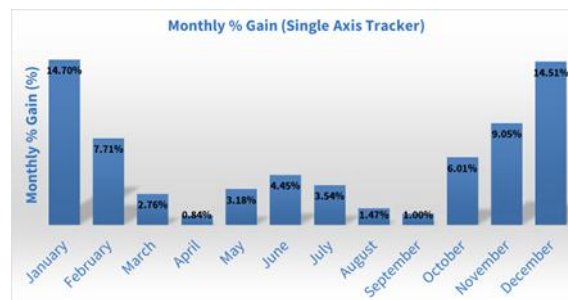


Figure 3. Monthly % gain percentage

Data Source: Simulation results using PVsyst software, 2026

Monthly results provide a crucial geographic context to system performance. As shown in the Fixed Tilt and Single-Axis Tracker comparison chart, the highest percentage increase in energy which reached nearly 14.7% occurred in January and December.

This period coincides with the conditions when the sun's trajectory is at its most extreme due to the influence of the latitude of the research site of -5.22° . During these months, the fixed-tilt configuration experienced limitations in capturing radiation optimally due to the angle of the sun coming that deviated significantly from the orientation of the fixed module. In contrast, the Single-Axis Tracker (SAT) system is able to dynamically adjust the orientation of the module, resulting in a substantial improvement in optical performance.

The high percentage gain in these critical months proves that the implementation of the SAT is indispensable to compensate for the complex annual trajectory of the sun in the equatorial region. Thus, the main advantage of the tracking system lies not only in the

aggregate annual energy increase, but also in its ability to maintain system performance in periods when conventional fixed-tilt systems are at their least optimal condition.

3.3 Discussion of Thermal Loss and Its Impact on PR

The simulation results also identified that the biggest loss to the system was thermal loss, with the maximum value reaching 13.3% in the single-axis tracker system. This increase in thermal losses is due to the increased effective irradiation received by the module, which directly increases the operating temperature of the solar module.

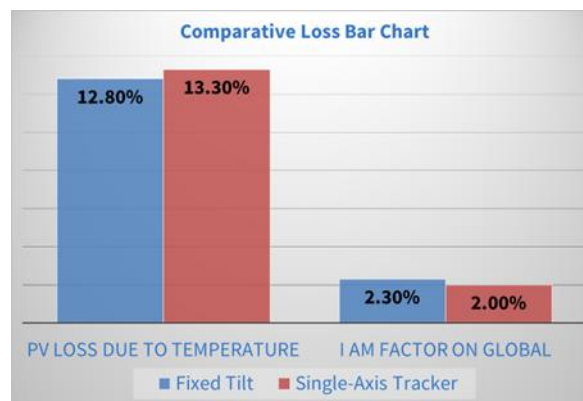


Figure 4. Loss Comparison

Data Source: Simulation results using PVsyst software, 2026

The results of the analysis showed that the largest losses in the system came from PV Loss due to temperature, with a peak value of 13.3% in the tracker system. The increase in effective irradiation received by the module on the SAT system causes an increase in the operating temperature of the module, which ultimately decreases the power conversion efficiency. This phenomenon explains why a relatively large annual increase in energy is not followed by a comparable increase in Performance Ratio (PR).

This analysis is focused only on thermal losses and radiation loss angles (IAM losses). Other losses such as inverter efficiency, module mismatch, and ohmic losses on cables are system constants, as the hardware configurations used in fixed-tilt and tracker scenarios are identical. Thus, only losses affected by system geometry and climatic conditions are analyzed in depth, since it is these factors that directly explain the difference in PR values between the two configurations.

The simulation results confirmed that the Single-Axis Tracker system experienced an additional thermal penalty of about 0.5 percentage points compared to the fixed-tilt system. These findings confirm that thermal trade-offs are the dominant factor limiting the overall PR increase, as well as being a major challenge in optimizing tracking systems in the tropics. Therefore, the successful implementation of SAT in tropical climates depends heavily on the system design's ability to manage the rise in module temperatures, rather than solely on increased irradiation capture.

3.3 Technical Implications for Deployment in Tropical Climates

These findings indicate that the application of single-axis tracker systems in low-latitude tropical regions, such as Makassar (−5.22°), is highly effective in compensating for the annual movement of the sun, especially in the extreme months. However, such an increase in energy

performance must be considered in conjunction with the impact of increased module temperatures contributing to thermal losses.

Therefore, the optimization of tracker systems in tropical climates should not only be focused on aspects of geometry and irradiation capture, but also need to be combined with thermal mitigation strategies, such as increasing the natural ventilation of modules or selecting modules with lower temperature coefficients.

CONCLUSION

The study assessed the performance of a 50.4 kWp on-grid solar power plant in Makassar's tropical climate, comparing fixed-tilt and single-axis solar tracker configurations. Results indicated that single-axis trackers increased the electrical energy distributed to the grid by 4.81%, or 3,149 kWh annually, primarily due to enhanced optical performance and reduced Incidence Angle Modifier loss. Although the Performance Ratio saw a slight increase from 0.794 to 0.798, thermal losses in the tracking system, peaking at 13.3%, limited this gain due to higher effective irradiation and operating temperatures. Monthly energy gains varied, with the highest at 14.7% in extreme months and the lowest at 0.8% in some periods. The study concludes that while single-axis trackers effectively enhance annual energy production at latitudes -5.22° LS, thermal management is crucial for optimising tracker-based systems in tropical climates. Future research could focus on developing advanced thermal management solutions to mitigate these losses and further improve system efficiency. The author would like to thank UPDL Makassar for the support of operational data and technical discussions that support this research.

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