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RESEARCH ARTICLE

Performance analysis of fixed tilted solar systems and tracking systems: A case study on azimuth and tilt configurations

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Abstract - The arrangement of panel orientation and tracking significantly affects the performance of stand-alone photovoltaic (PV) systems, particularly under suboptimal solar incidence angles that can limit daytime solar energy utilization. Solar tracking can increase solar irradiation capture; however, higher energy production may also result in greater energy losses when battery storage capacity is insufficient. Therefore, PV configuration selection should consider not only energy generation but also effective energy utilization. This study evaluated the performance of stand-alone PV systems with different panel orientations and solar-tracking configurations using PVsyst simulations. The investigated configurations included fixed tilted-plane systems with azimuths of 10° and 20° and tilts of 20° and 30°, single-axis solar tracking, and dual-axis solar tracking. The simulations were conducted at the Faculty of Vocational Studies, State University of Malang, Indonesia, under a tropical climate with substantial solar energy potential. The results showed that the dual-axis tracker achieved the highest solar fraction of 0.986 and a daily energy yield of 4.82 kWh/kWp/day. However, it also produced relatively high collection and unused energy losses, indicating the influence of limited battery storage capacity. The most effective energy utilization was obtained with the fixed configuration at an azimuth of 10° and tilt of 20°, which achieved an annual energy output of 1670.1 kWh with lower energy losses than the tracking configurations. These findings demonstrate that PV system configuration should balance energy generation, utilization, and storage capability rather than prioritize maximum energy production alone.

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1. Introduction

One of the renewable resources that is increasingly used to reduce our dependence on fossil fuels is solar energy. Solar panels or photovoltaic (PV) cells are the main components for conversion of solar radiation into clean electrical power [1]-[2]. However, to fully use the energy produced, support technology is needed to improve the optimal absorption of solar radiation [3]-[4]. One of the fast-growing technologies is the solar tracking systems that allow the solar panels to follow the movement of the sun during the day. The efficiency of energy generation by solar trackers has been shown to be higher than that of static PV systems, particularly in areas with high intensity of solar radiation [5]-[7]. The solar tracker systems are generally categorized into single- and dual-axis configurations based on their motion mechanism [8]-[9]. For a single-axis system, the PV modules are rotated in either east–west or north–south direction, but a dual-axis system continuously adjusts the horizontal and vertical orientations to more accurately align with the sun [10]-[11]. The choice of an appropriate tracker configuration is influenced by many factors, such as geographical conditions, solar radiation characteristics and available investment budget [12]-[13]. Several previous studies have shown that dual-axis trackers can provide higher annual energy yields than single-axis systems, since they maintain a more favorable incidence angle during the day [14]-[15]. However, such performance gains often come at the cost of increased installation complexity, increased maintenance requirements, and increased operational costs. Therefore, a detailed comparative study of different solar tracker configurations is still required to identify the most technically efficient and economically feasible option for a given installation situation [16]-[17].

Software-based simulations, such as PVsyst, have become a widely used method for analyzing and predicting the performance of PV systems at various configurations and locations [18] – [19]. PVsyst offers comprehensive PV system modeling features, from weather data input and system configuration to shading and energy performance analysis [20]–[21]. Previous studies have used PVsyst as an initial reference for designing small, medium, and large PV systems. Table 1 presents some of the earlier studies related to PVsyst. This study focuses on a case study of fixed-tilt plane configurations with azimuths of 10° and 20° and tilts of 20° and 30°, respectively, and compared them with single-axis and dual-axis solar tracking systems. This research was conducted at the Faculty of Vocational Studies, State University of Malang, which has geographical characteristics and solar radiation intensity suitable for this study. This configuration has not been widely discussed in the literature; therefore, the results are expected to fill this data gap and provide a new perspective on

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PV system configuration optimization. This study also used PVsyst simulations, which can model PV system performance with various configuration variations in detail and systematically. The simulation results obtained in this study are expected to serve as a reference for designing and developing more efficient PV projects that account for the characteristics of specific locations.

Table 1. Previous research related to PVsyst

Method	Novelty	Results	Reference
Simulation of PVsyst v7.1.7 on a 20.8 kW grid-connected system, analysis of the weather conditions of four cities in India.	Study of PV systems for educational institutions, with a detailed comparison of meteorological locations	Energy: 2086.2 MWh/year, Global efficiency: 2141.8 kWh/m², Tilt: 35°, Azimuth: 5°	[22]
PVsyst simulation on a 700 kWp grid-connected system in Daykundi, Afghanistan	Design of large-scale PV systems in conflict areas with high PR validation	Energy: 1266 MWh/year, PR: 0.797, 2800 modules, Tilt: 34°, Azimuth: 0°	[23]
Simulation of PVsyst v7.0 with real-time weather data integration, at a rooftop of 100 kWp	Real-time climate data integration for PV green building validation and optimization	Production: 646.83 kWh/m²/month, shading loss: 10%, Simulation accuracy increased by 6–9%	[24]
PVsyst simulation on a 5 MWp PV system in India, compared to 1 year of field data	PVsyst validation of the real performance of the 5 MWp (grid-connected) system	Actual energy: 15,798.2 MWh/year, real PR: 81.02%, simulated PR: 80.42%, CUF: 16.05%	[25]
PVsyst simulation + LabVIEW experiment, 250 Wp 1-axis tracker system	Comparison of tracker vs static panel system efficiency in Colombia	Output increase: Min 19%, Max 47.84%, Sim-real deviation: 2.5%, Eff: 15.3%	[26]

2. Materials and Methods

The accuracy of environmental data used to design and evaluate photovoltaic systems plays a significant role, particularly when considering the geographical and meteorological parameters that reflect the real conditions at the installation site. This study selected the Faculty of Vocational Studies at the State University of Malang in East Java, Indonesia, as the case study site because of its tropical location and high solar radiation. This location was selected not only for its radiation intensity but also for its climatic stability and the availability of environmental data needed for PVsyst simulations [27]-[28]. Considering these aspects, the accuracy of spatial and temporal data is of utmost importance for realistic simulations of PV system performance. Therefore, the monthly geographic coordinate data and climate parameters were entered systematically to obtain an optimal picture of the local solar energy potential. Table 2 presents the geographic coordinates of the Faculty of Vocational Studies, State University of Malang, used to model the PV system and serve as the basis for the simulation. The place has a latitude of -7.9589°, a longitude of 112.6195° and an altitude of 480 meters above sea level. These parameters affect the angle of incidence of solar radiation and atmospheric density, which directly affect the quantity and quality of solar radiation received on the PV module surface. The time zone GMT +07.00 is a temporal reference for synchronizing the energy consumption profile with the modeled daily irradiation duration. The accuracy of these spatial input parameters is critical because small errors in the location input can result in large deviations in the predicted energy output of the designed system. For this spatial analysis, Figure 1 shows the sun's daily path. It illustrates the sun's displacement by azimuth and altitude at specific times during the year. The curves show the sun's position on key dates, such as June 22 and December 22, as well as other equinoxes and solstices. This trajectory pattern provides useful information for determining the PV system tilt angle and orientation for maximum solar energy absorption throughout the year. Moreover, this diagram helps identify possible shadows from surrounding objects, which may reduce the system efficiency.

Table 2. Geographical coordinate information

Information	Information
Latitude	-7.9589
Longitude	112.6195
Altitude (m)	480
Time Zone (GMT)	+07.00

Table 3 presents the meteorological data of the locations, which are important for PV system performance analysis. The relatively high and stable average horizontal global radiation (approximately 5.52 kWh/m^2/day) shows the potential of solar energy, which can be improved with a proper system configuration. The significant contribution of diffuse radiation during the wet months indicates that most of the radiation is received through atmospheric dispersion. Therefore, PV systems should be designed to be responsive to cloudy sky conditions. The natural cooling of PV modules is affected by relatively constant air temperatures in the range of 25-26 °C and low wind speeds, which affect the thermal efficiency of the system. The Linke turbidity index and relatively high humidity also indicate atmospheric variability, which affects radiation transmission and the optical performance of the module. Therefore, an in-depth knowledge of the local climate dynamics using this data is a prerequisite to the optimal configuration of the PV system from both technical and economic points of view [29]–[30].

Table 3. Recapitulation of annual climate data

Month	Global Horizontal Irradiation (kWh/m2/day)	Horizontal Diffuse Irradiation (kWh/m2/day)	Temperature (°C)	Wind Velocity (m/s)	Linke Turbidity	Relative Humidity (%)
January	5.35	2.45	25.2	1.80	4.569	80.9
February	5.41	3.13	25.1	1.90	4.540	81.4
March	5.22	2.58	25.5	1.30	4.454	80.9
April	5.51	2.43	25.8	1.29	4.475	80.1
May	5.18	2.12	26.2	1.60	4.332	76.8
June	5.08	1.94	25.2	1.80	4.159	76.6
July	5.28	1.86	25.1	2.19	3.965	72.5
August	5.63	2.13	25.2	2.30	4.118	69.9
September	5.99	2.27	25.5	2.20	4.325	69.4
October	6.38	2.75	26.7	2.00	5.141	69.5
November	5.70	2.96	26.4	1.39	5.591	75.7
December	5.58	2.66	25.8	1.29	5.000	79.0
Total	5.52	2.43	25.6	1.80	4.556	76.1

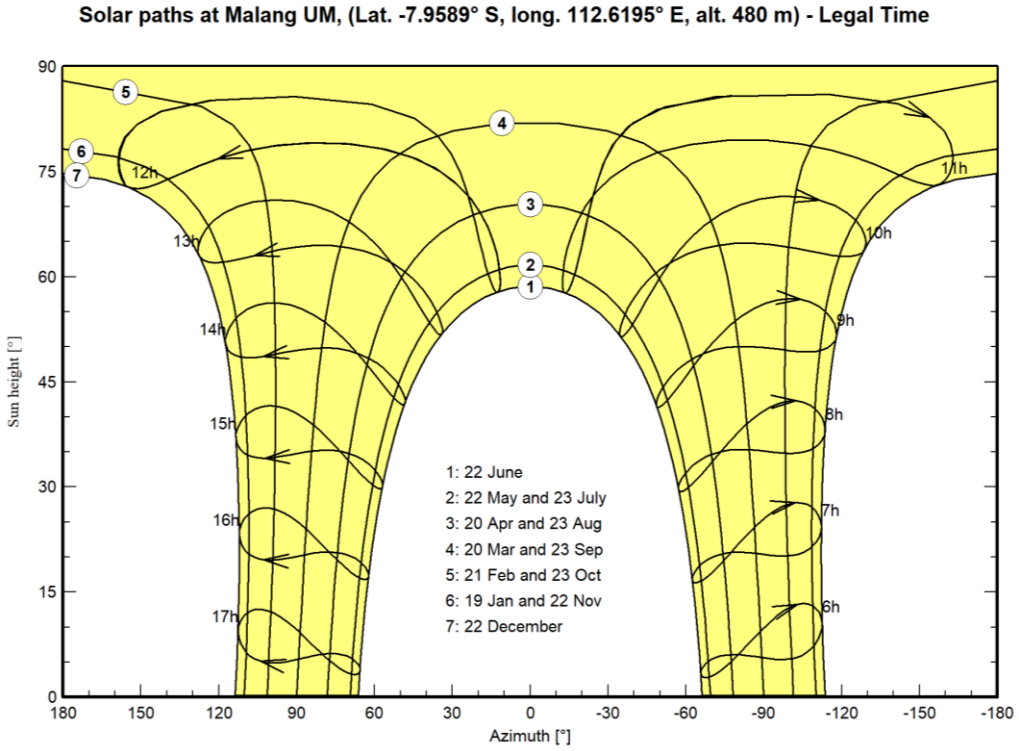


Figure 1. Sun path diagram

2.1 Planning

2.1.1 PV System Architecture

The architecture of the PV system built in this study was designed to satisfy the daily electrical energy needs of the Computer Laboratory, Faculty of Vocational Studies, State University of Malang, based on a predetermined load consumption profile. The main load consisted of four computers that students frequently and actively used, four lights turned on at night for room lighting, and two printer units as supporting facilities. Based on the estimated daily usage, the total energy requirement was projected at 4404 Wh per day, or approximately 132.1 kWh per month (see Table 4 and estimated Electrical Energy Consumption). This estimation is important because it provides a baseline for the capacity and configuration of each PV system component to provide energy continuously and reliably. Table 5 describes the technical specifications of each key PV system component, such as the PV modules, controllers, and batteries. The PV modules were monocrystalline (Si-mono) with a peak power of 250 Wp per module, and four modules were installed per system to achieve the required total capacity. The technical data include parameters such as the short-circuit current (Isc), maximum power point voltage (Vmpp), and temperature coefficient, which directly affect the module performance under field operating conditions. An MPPT-type converter with a maximum efficiency of 96% optimizes energy absorption from PV to storage systems over a wide operating voltage range (26–75 V), allowing the system to operate effectively

under varying solar radiation intensities. The energy storage system is a 1908 Ah lead-acid battery, providing up to 18.3 kWh of stored energy at 80% depth of discharge (DOD), which is sufficient to provide adequate backup energy in low-radiation conditions or at night. Although dual-axis tracking systems can achieve large increases in solar energy capture, they generally require more mechanical parts and control systems than fixed-tilt systems. Additional components can increase installation complexity and maintenance requirements over the service life of the system, particularly in continuous outdoor environments. Thus, when selecting the tracking configuration, long-term operational and economic factors should be considered alongside the energy yield for overall system viability.

Table 4. Estimated electrical energy consumption

Appliance	Power (W)	Number	Daily Use (hours/day)	Daily Energy (Wh/day)
Lamps	20	4	6	480
Laptop/desktop	300	4	3	3600
Printer	50	2	3	300
Total daily energy				4404 Wh/day
Monthly energy				132.1 kWh/day

Table 5. Technical data of system components

Component	Parameter	Detail
Photovoltaic	Manufacture	Generic
	Model	Si-mono
	Power	250 Wp/26 V
	Reference Conditions	1000 W/m2
	Short Circuit Current (Isc)	8.63 A
	Max Power Point (Impp)	8.14 A
	Temperature Coefficient (muIsc)	4.3 mA/°C or 0.05 %/°C
	Efficiency	18.1%
	Temperature Reference	25°C
	Voltage Open Circuit (Voc)	37.4 V
	Voltage Max Power Point (Vmpp)	30.70
	Number Cell in Series	60 Cell
	Module in Series	1
	Number Strings	4
	Number Module in System	4
	Overload Loss	0.0%
	Pnom Ratio	1.04
	Area	7 m^2
Controller	Manufacture	Leonics
	Technology	MMPT Converter
	MPP Operating Voltage	26-75 V
	Input Maximum Voltage	96 V
	Controller's Power	960 watts
	Nominal Output Power	240 watts
	Maximum Output Power	240 watts
	Nominal Output Voltage	12 V
	Nominal Output Current	20 A
	Max Efficiency	96%
Battery	Manufacture	Sunlight
	Technology	Lead Acid
	Type	12V 3 RES CPzS 190
	Battery pack voltage	12 V
	Global Capacity	1908 ah
	Stored Energy (80% DOD)	18.3 kWh
	Total Weight	834 kg
	Number of Cycles at 80% DOD	1350
	Total Stored energy during the battery life	27445 kWh
	Batteries in Series	1
	Batteries in Series	12
	Temperature Reference	20 °C
	Coulombic Efficiency	97%

The PV system configuration generated by PVsyst is shown in Figure 2, which provides a comprehensive visualization of the main components of the system. The diagram shows the flow of energy and electrical current from the PV array to the regulator, which controls the power distribution to the battery and the user's load. The system designed in this study does not use backup generators, although the diagram shows generators as an alternative energy source. The solar modules directly meet the user's electricity demand, and the battery is charged. The safety features of the energy storage system include fuses and temperature sensors, which ensure safe operation of the battery. This configuration supports the full utilization of renewable energy, favoring a sustainable energy supply that matches the estimated electricity demand shown in Tables 4 and 5.

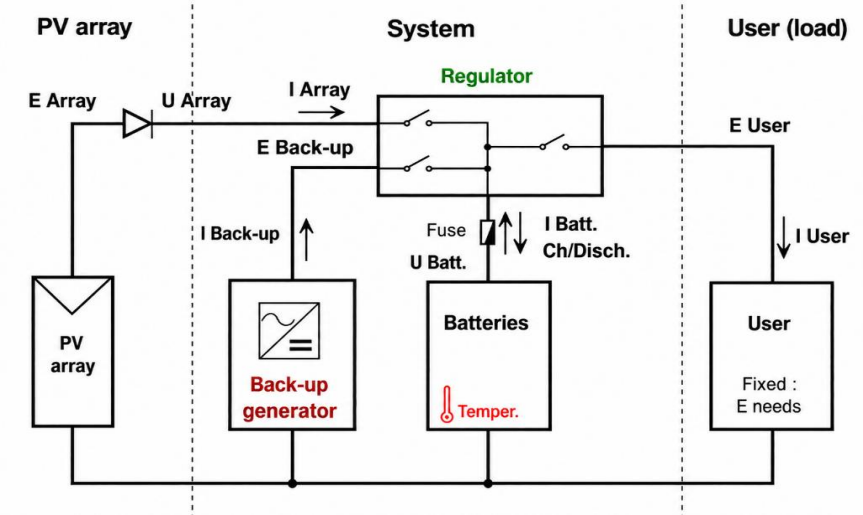


Figure 2. Configuration diagram of the photovoltaic system

2.2 Theoretical Equations

In the analysis of the photovoltaic systems performance, the use of adequate theoretical equations is fundamental to the correct evaluation of the system performance. Every formula can describe specific aspects of system performance, from the ability to generate energy to the adequacy of electricity supply to load demand. Table 6. The main equations for the calculation of the essential parameters for the analysis of the PV system performance: energy generated by the PV array, energy supply, performance ratio and estimated energy deficit. The information is used to calculate and interpret simulation results and, therefore, assist technical decisions regarding the design and development of PV systems.

Table 6. Theoretical equations

Parameter	Equation	Number	Information	Reference
Energy generated by PV arrays	$E_{array} = G_T \times A \times \eta_{PV}$	(1)	G_T: Global Horizontal Irradiation (kWh/m2/day) A: Total Module Area η_{PV}: Module Efficiency	[31] – [33]
Energy Supply	$Y_f = \frac{E_{AC}}{P_{Rated}}$	(2)	E_{AC}: Energy to Load (kWh) P_{Rated}: Peak Power (kW)	[34] – [36]
Performance Ratio (PR)	$PR = \frac{Y_f}{Y_r} = \frac{E_{AC}}{P_{Rated} \times H_{ref}}$	(3)	E_{AC}: Energy to Load (kWh) P_{Rated}: Peak Power (kW) H_{ref}: Reference Irradiation (kWh/m²)	[37] – [39]
Solar Fraction (SF)	$SF = \frac{E_{User}}{E_{Load}}$	(4)	The ratio between PV supplied energy (and daily load requirement (E_{User})E_{Load})	[23], [40]
Energy Miss	$E_{Miss} = E_{Load} - E_{User}$	(5)	Energy that is not met by PV systems	[41] – [42]

3. Results and Discussion

The photovoltaic (PV) system performance evaluation compares several fixed panel orientation configurations at azimuths of 10° and 20° with slopes of 20° and 30°, as well as two solar tracking systems: single and dual axes. Figure 3 shows that the system with a two-axis tracker obtained the highest Solar Fraction (SF) of 0.986, which is considerably greater than the fixed panel configuration in the range of 0.727-0.762. The value of the Performance Ratio (PR) on the panel was quite uniform at 0.66, but in the tracking system, the SF increased dramatically, but the PR was not always higher. The single-axis recorded a PR of 0.649, and the dual-axis recorded 0.659, which was slightly lower than that of the fixed panel. This indicates that while trackers improve the energy output, the efficiency of distributing that energy may not improve because of potential losses in the tracking systems. For fixed-tilt configurations, systems with a 20° tilt generally showed slightly better energy performance than systems with a 30° tilt, indicating that lower tilt angles are more suitable for maximizing solar irradiation capture at the study location than higher tilt angles. Similarly, the 10° azimuth

angle showed slightly better SF and energy utilization values than the 20° azimuth configuration, which better aligned with the prevailing solar track over the year. Figure 4 presents the normalized annual energy production of a PV plant, detailing the energy delivered to the user (Yf), system and battery charge losses (Ls), losses on PV arrays (Lc), and unused energy due to full batteries (Lu). Based on the data, the dual-axis system produced the maximum Yf of 4.82 kWh/kWp/day; however, it also experienced higher Lc and Lu losses of 1.95 and 0.69 kWh/kWp/day, respectively. The higher unused energy in the tracking systems indicates that the battery capacity was insufficient to store the additional energy generated when the sun was shining brightly. However, although the tracking configuration can generate more energy, some of the harvested energy cannot be utilized efficiently. This reduces the overall efficiency of the system. In contrast, a fixed panel arrangement of 10° azimuth/20° tilt resulted in a Yf of 3.72 kWh/kWp/day with significantly reduced values of Lc and Lu. These results show that even small changes in the azimuth and tilt angles can affect the incident solar radiation on the PV surface and, therefore, the annual energy production and system reliability. In practical implementations, this limitation can be mitigated by a larger battery storage capacity, better energy management strategies, or load scheduling approaches that better match electricity consumption with peak energy generation periods. In summary, tracking systems are fully utilized only if storage management can keep up with their higher energy production.

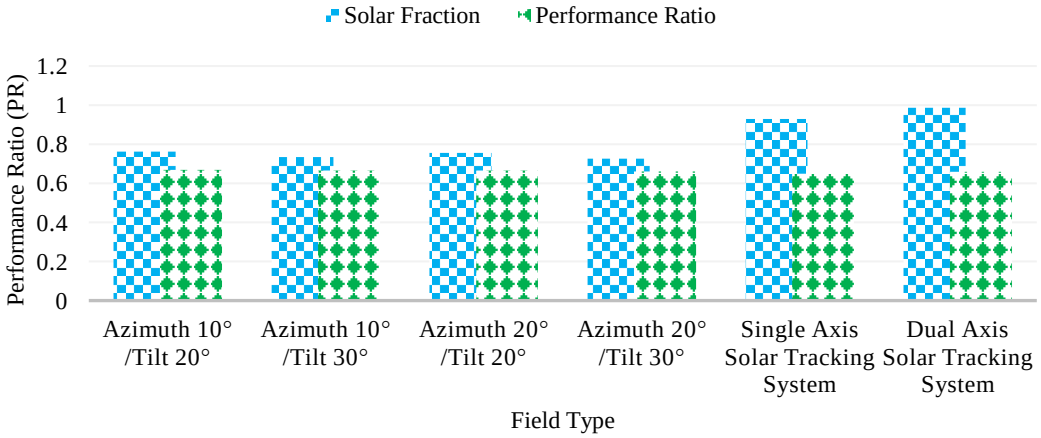


Figure 3. Annual performance ratio of the PV system

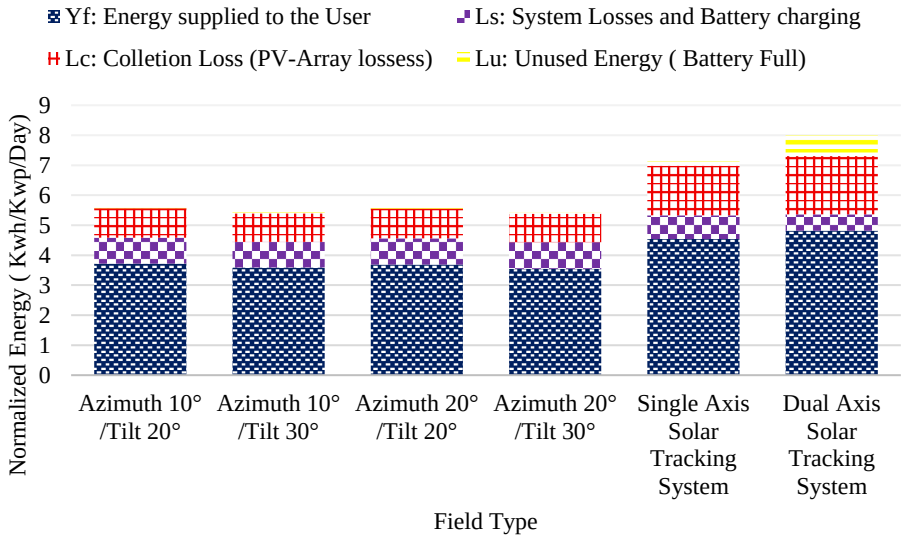


Figure 4. Annual normalized output from the PV installation

Table 7 summarizes the yearly energy performance of different PV system configurations with obvious differences between fixed-tilt and tracking systems. When tracking systems are used, the energy array which is the total energy generated by each configuration, is greatly increased. For instance, the dual-axis tracker produces the highest annual energy output of 1954.2 kWh, followed by the single-axis (1946 kWh), and the fixed-tilt options of 1616.8 to 1670.1 kWh. But even if the energy production is higher, the energy delivered to the load (Energy User) is not linear due to limitations such as the finite battery storage or a mismatch between peak generation and peak demand. From an operational perspective, the additional energy that can be generated by tracking systems can be beneficial, especially for applications where the aim is to maximize the energy availability. The maximum annual energy misses in fixed configurations, especially for tilt 30° and azimuth 20°, is 487.32 kWh, indicating large periods of system failure to satisfy

the load. In contrast, the dual-axis system reduces the annual energy miss to 24.75 kWh which is much closer to the annual energy demand of 1782.7 kWh. But these energy gains usually require additional investments in tracking mechanisms, control components, and supporting structures relative to fixed-tilt installations. These results are consistent with the trends shown in Figures 4 and 5, where the dual-axis tracking consistently shows better performance by reducing unmet energy demand and maximizing energy utilization. Thus, the decision between fixed and tracking configurations has to take into account the trade-off between the higher energy production and the additional costs related to the implementation and operation. Indeed, the field configuration is still a deciding factor for an optimal PV energy supply during the year.

Table 7. Summary of annual PV energy performance

Parameter	Azimuth 20°		Azimuth 20°		Single Axis Solar Tracker	Dual Axis Solar Tracker
	Fix Tilt 20°	Fix Tilt 30°	Fix Tilt 20°	Fix Tilt 30°		
Energy Array (kWh)	1670.10	1622.50	1665.60	1616.80	1946.0	1954.20
Energy Load (kWh)	1782.70	1782.70	1782.70	1782.70	1782.7	1782.70
Energy User (kWh)	1358.00	1309.20	1347.10	1295.30	1656.8	1757.90
Energy Miss (kWh)	424.67	473.45	435.52	487.32	125.88	24.75

3.1 Limitation

The results depend entirely on the quality of the input data and the assumptions made, as this study was based on the PVsyst simulation approach. The model does not account for tangible factors such as dust accumulation, long-term panel degradation, and operational disruptions in the field. Moreover, the tested PV system configuration was limited to combinations of 20° and 30° tilt angles, azimuths of 10° and 20°, and two types of solar trackers (single and dual axis). This configuration was chosen based on the geographical conditions of the Vocational Faculty of the State University of Malang; therefore, the results are contextual and not necessarily representative of other locations. PVsyst is a useful tool for evaluating PV system performance; however, simulation results must be confirmed by measurements in real installations. To broaden the applicability of the simulation results, experimental validation and expanded system configurations are required. Field-based validation can provide additional insight into the effects of real operating conditions, such as environmental influences and variations in equipment performance, which are difficult to fully replicate in simulation models. However, this study did not include economic analyses, such as investment comparisons, operational costs, or estimated Levelized Cost of Energy (LCOE) values. The energy performance of the systems was successfully compared; however, the study did not analyze whether the additional output of the tracking system was justified by the additional cost. Moreover, this study is limited to standalone PV systems and does not include grid integration or hybrid systems in its scope. This limits the assessment of energy management flexibility and the contribution to the stability of large-scale energy systems. Therefore, long-term experimental monitoring and validation with real operational data are necessary in future studies in a more comprehensive manner, including technical, economic, and integrative aspects, to improve the practical applicability and reliability of the simulation results.

4. Conclusions

In this study, PV systems were evaluated in terms of performance using PVsyst simulations for various fixed panel orientations and solar tracking configurations. The results show that the dual-axis solar tracker provided the best overall performance, with an SF of 0.986 and a daily energy yield of 4.82 kWh/kWp/day. The tracking setup generated more energy but also had higher energy losses owing to the limited storage capacity, as shown by the higher Lc and Lu values compared to the fixed-tilt systems. The fixed configuration with an azimuth angle of 10° and tilt angle of 20° resulted in more stable energy use but less total energy. The comparative analysis shows that selecting an appropriate PV configuration should consider the maximum energy generation and effectiveness of energy distribution and storage management. Dual-axis tracking systems are very useful in high solar irradiation areas, but to take advantage of the extra energy produced, they require sufficient storage capacity. The results also show that PVsyst is a reliable platform for evaluating the technical performance of different PV configurations using representative climate and system parameters. Thus, the results of this study can serve as a useful technical reference for designing PV systems that are better suited to tropical environmental conditions and the specific energy requirements of applications. Future studies should include experimental validation and economic analysis (e.g., LCOE) to improve the applicability and completeness of the system and consider the potential of hybrid and grid-connected systems.

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Declaration of Competing Interests
The authors declare no relevant financial or non-financial conflicts of interest related to the subject matter of this manuscript

CRediT Author Contribution Statement
Singgih Dwi Prasetyo: Conceptualization; Methodology; Validation; Analysis; Investigation; Writing - original draft
Yuki Trisnoaji: Methodology; Investigation; Data curation; Writing-review & revise
Meirna Puspita Permatasari: Conceptualization; Analysis; Validation; Writing-review & revise
Misbahul Munir: Conceptualization; Analysis; Validation; Writing-review & revise
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Marsya Aulia Rizkita: Investigation; Analysis; Writing-review & revise
Zainal Arifin: Methodology; Analysis; Writing-review & revise
Mohd Afzanizam Mohd Rosli: Methodology; Analysis; Writing-review & revise

Availability of Data and Materials
The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement
This study did not involve human participants or animal subjects. Ethical approval was therefore not required for this research.

Generative Artificial Intelligence Disclosure
The authors claim that artificial intelligence-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have used AI to enhance readability and refine the language. We used it under strict human control and supervision. The authors take full responsibility for reviewing and approving the content.

References
[1] Z. Ge, Z. Xu, J. Li, J. Xu, J. Xie, and F. Yang, "Technical-economic evaluation of various photovoltaic tracking systems considering carbon emission trading," *Solar Energy*, vol. 271, Art. no. 112451, 2024. https://doi.org/10.1016/j.solener.2024.112451.
[2] D. Keiner, L. Walter, M. ElSayed, and C. Breyer, "Impact of backtracking strategies on techno-economics of horizontal single-axis tracking solar photovoltaic power plants," *Solar Energy*, vol. 267, Art. no. 112228, 2024. https://doi.org/10.1016/j.solener.2023.112228.
[3] J. Manuel Longares, A. García-Jiménez, and N. García-Polanco, "Multiphysics simulation of bifacial photovoltaic modules and software comparison," *Solar Energy*, vol. 257, pp. 155–163, 2023. https://doi.org/10.1016/j.solener.2023.04.005.
[4] S. D. Prasetyo *et al.*, "Design and economic analysis of a solar-powered charging station for personal electric vehicles in Indonesia," *Journal of Sustainable Energy*, vol. 3, no. 2, pp. 65–74, 2024. https://doi.org/10.56578/jse030201.
[5] A. Juaidi *et al.*, "A comparative simulation between monofacial and bifacial PV modules under Palestine conditions," *Solar Compass*, vol. 8, Art. no. 100059, 2023. https://doi.org/10.1016/j.solcom.2023.100059.
[6] M. S. Mauludin, Z. Arifin, A. R. Birawa, F. J. Regannanta, M. S. Alfaridzi, and S. D. Prasetyo, "Government building PLTS system design based on HOMER," *AIP Conference Proceedings*, vol. 3250, no. 1, [Art. no. to be verified], 2025. https://doi.org/10.1063/5.0240588.
[7] S. D. Prasetyo *et al.*, "Advancing renewable energy thermal management with cellulose-derived materials through meta-analysis, machine learning, and comparative material evaluation," *Next Materials*, vol. 12, Art. no. 102557, 2026. https://doi.org/10.1016/j.nxmate.2026.102557.
[8] D. D. Milosavljević, T. S. Kevkić, and S. J. Jovanović, "Review and validation of photovoltaic solar simulation tools/software based on case study," *Open Physics*, vol. 20, no. 1, pp. 431–451, 2022. https://doi.org/10.1515/phys-2022-0042.
[9] M. A. Islam *et al.*, "Integrating PV-based energy production utilizing the existing infrastructure of MRT-6 at Dhaka, Bangladesh," *Heliyon*, vol. 10, no. 2, Art. no. e24078, 2024. https://doi.org/10.1016/j.heliyon.2024.e24078.
[10] D. González-Peña, I. García-Ruiz, M. Díez-Mediavilla, M. I. Dieste-Velasco, and C. Alonso-Tristán, "Photovoltaic prediction software: Evaluation with real data from northern Spain," *Applied Sciences*, vol. 11, no. 11, Art. no. 5025, 2021. https://doi.org/10.3390/app11115025.
[11] L. Zaghba, M. Khennane Benbitour, A. Fezzani, S. Mekhilef, and A. Borni, "Comprehensive performance assessment of two grid-tied photovoltaic systems in a hot arid climate: A three-year theoretical and experimental

analysis," *Renewable and Sustainable Energy Reviews*, vol. 216, Art. no. 115643, 2025. https://doi.org/10.1016/j.rser.2025.115643.

[12] L. Zaghba, M. Khennane, S. Mekhilef, A. Fezzani, and A. Borni, "Experimental outdoor performance assessment and energy efficiency of 11.28 kWp grid tied PV systems with sun tracker installed in Saharan climate: A case study in Ghardaia, Algeria," *Solar Energy*, vol. 243, pp. 174–192, 2022. https://doi.org/10.1016/j.solener.2022.07.045.

[13] S. D. Prasetyo, Y. Trisnoaji, Z. Arifin, and A. A. Mahadi, "Harnessing unconventional resources for large-scale green hydrogen production: An economic and technological analysis in Indonesia," *Unconventional Resources*, vol. 6, Art. no. 100174, 2025. https://doi.org/10.1016/j.uncres.2025.100174.

[14] K. R. Oyshei, K. M. S. Hasan, N. Sadat, and M. A. Hoque, "Comparative analysis of solar module configuration and tracking systems for enhanced energy generation in South Sakucia Union, Bhola, Bangladesh: A software based analysis," *Heliyon*, vol. 10, no. 13, Art. no. e33884, 2024. https://doi.org/10.1016/j.heliyon.2024.e33884.

[15] S. D. Prasetyo, Z. Arifin, A. R. Prabowo, and E. P. Budiana, "The impact of cavity in finned thermal collector on PVT performance using Al2O3 nanofluid," *International Journal of Thermofluids*, vol. 27, Art. no. 101284, 2025. https://doi.org/10.1016/j.ijft.2025.101284.

[16] K. Kumba, P. Upender, P. Buduma, M. Sarkar, S. P. Simon, and V. Gundu, "Solar tracking systems: Advancements, challenges, and future directions: A review," *Energy Reports*, vol. 12, pp. 3566–3583, 2024. https://doi.org/10.1016/j.egyr.2024.09.038.

[17] A. Barbón, J. Aparicio-Bermejo, L. Bayón, and P. Fortuny Ayuso, "The optimal design for photovoltaic power plants on sites with a general slope," *Applied Energy*, vol. 387, Art. no. 125582, 2025. : https://doi.org/10.1016/j.apenergy.2025.125582.

[18] M. Salmi, A. B. Baci, M. Inc, Y. Menni, G. Lorenzini, and Y. Al-Douri, "Design and simulation of an autonomous 12.6 kW solar plant in the Algeria's M'sila region using PVsyst software," *Optik*, vol. 262, Art. no. 169294, 2022. https://doi.org/10.1016/j.ijleo.2022.169294.

[19] S. S. Hosseini Dehshiri and B. Firoozabadi, "Comparison, evaluation and prioritization of solar photovoltaic tracking systems using multi criteria decision making methods," *Sustainable Energy Technologies and Assessments*, vol. 55, Art. no. 102989, 2023, doi: https://doi.org/10.1016/j.seta.2022.102989.

[20] M. Jahangiri *et al.*, "Prioritization of solar electricity and hydrogen co-production stations considering PV losses and different types of solar trackers: A TOPSIS approach," *Renewable Energy*, vol. 186, pp. 889–903, 2022. https://doi.org/10.1016/j.renene.2022.01.045.

[21] M. S. Mauludin *et al.*, "Assessing the technological and financial feasibility of PV-wind hybrid systems for EV charging stations on Indonesian toll roads," *International Journal of Sustainable Development and Planning*, vol. 20, no. 1, pp. 291–304, 2025. https://doi.org/10.18280/ijsdp.200127.

[22] A. Shrivastava, R. Sharma, M. Kumar Saxena, V. Shanmugasundaram, M. Lal Rinawa, and Ankit, "Solar energy capacity assessment and performance evaluation of a standalone PV system using PVSYST," *Materials Today: Proceedings*, vol. 80, pp. 3385–3392, 2023. https://doi.org/10.1016/j.matpr.2021.07.258.

[23] M. Baqir and H. K. Channi, "Analysis and design of solar PV system using PVsyst software," *Materials Today: Proceedings*, vol. 48, pp. 1332–1338, 2021. https://doi.org/10.1016/j.matpr.2021.09.029.

[24] S. A. Hosseini, S. A. Mansoori Al-yasin, M. Gheibi, and R. Moezzi, "Evaluation of solar energy performance in green buildings using PVsyst: Focus on panel orientation and efficiency," *Eng*, vol. 6, no. 7, Art. no. 137, 2025. https://doi.org/10.3390/eng6070137.

[25] P. R. Mishra, S. Rathore, and V. Jain, "PVSyst enabled real time evaluation of grid connected solar photovoltaic system," *International Journal of Information Technology*, vol. 16, no. 2, pp. 745–752, 2024. https://doi.org/10.1007/s41870-023-01677-x.

[26] H. González-Acevedo, Y. Muñoz-Maldonado, A. Ospino-Castro, J. Serrano, A. Atencio, and C. J. Saavedra, "Design and performance evaluation of a solar tracking panel of single axis in Colombia," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 4, pp. 2889–2898, 2021. https://doi.org/10.11591/ijece.v11i4.pp2889-2898.

[27] M. A. Islam *et al.*, "A comprehensive evaluation of photovoltaic simulation software: A decision-making approach using analytic hierarchy process and performance analysis," *Energy Strategy Reviews*, vol. 58, Art. no. 101663, 2025. https://doi.org/10.1016/j.esr.2025.101663.

[28] A. Kowsar, F. Naima, M. T. Rana, N. Haque, and F. Alam, "Techno-economic study of a photovoltaic power plant besides the railway track for rural uses in Bangladesh," *e-Prime — Advances in Electrical Engineering, Electronics and Energy*, vol. 5, Art. no. 100229, 2023. https://doi.org/10.1016/j.prime.2023.100229.

[29] M. A. Khan *et al.*, "Experimental and simulation analysis of grid-connected rooftop photovoltaic system for a large-scale facility," *Sustainable Energy Technologies and Assessments*, vol. 53, Art. no. 102773, 2022. https://doi.org/10.1016/j.seta.2022.102773.

[30] J. Vishnupriyan, P. Partheeban, A. Dhanasekaran, and M. Shiva, "Analysis of tilt angle variation in solar photovoltaic water pumping system," *Materials Today: Proceedings*, vol. 58, pp. 416–421, 2022. https://doi.org/10.1016/j.matpr.2022.02.353.

[31] A. Zdyb and D. Sobczyński, "An assessment of a photovoltaic system's performance based on the measurements of electric parameters under changing external conditions," *Energies*, vol. 17, no. 9, Art. no. 2197, 2024. https://doi.org/10.3390/en17092197.

[32] S. Habib *et al.*, "Technical modelling of solar photovoltaic water pumping system and evaluation of system performance and their socio-economic impact," *Heliyon*, vol. 9, no. 5, Art. no. e16105, 2023. https://doi.org/10.1016/j.heliyon.2023.e16105.

[33] S. D. Prasetyo *et al.*, "Optimization of solar panel orientation and tracking systems for standalone PV applications," *International Journal of Power Electronics and Drive Systems*, vol. 16, no. 4, pp. 2721–2730, 2025. https://doi.org/10.11591/ijpeds.v16.i4.pp2721-2730.

[34] Y. Trisnoaji, S. D. Prasetyo, Z. Arifin, and M. S. Mauludin, "Enhancing sustainability of on-grid hybrid PV–wind systems for green hydrogen production from unconventional resources: A meta-analytical and deep learning approach," *Fuel*, vol. 422, Art. no. 139157, 2026. https://doi.org/10.1016/j.fuel.2026.139157.

[35] L. P. Truong, H. A. Quoc, H. L. Tsai, and D. van Dung, "A method to estimate and analyze the performance of a grid-connected photovoltaic power plant," *Energies*, vol. 13, no. 10, Art. no. 2583, 2020. https://doi.org/10.3390/en13102583.

[36] A. Radwan, A. Mdallal, S. Haridy, M. A. Abdelkareem, A. H. Alami, and A. G. Olabi, "Optimizing the annual energy yield of a residential bifacial photovoltaic system using response surface methodology," *Renewable Energy*, vol. 222, Art. no. 119914, 2024. https://doi.org/10.1016/j.renene.2023.119914.

[37] G. S. Sharma *et al.*, "Performance evaluation of a MW-size grid-connected solar photovoltaic plant considering the impact of tilt angle," *Sustainability*, vol. 14, no. 3, Art. no. 1444, 2022. https://doi.org/10.3390/su14031444.

[38] K. Barbosa de Melo, M. Kitayama da Silva, J. Lucas de Souza Silva, T. S. Costa, and M. G. Villalva, "Study of energy improvement with the insertion of bifacial modules and solar trackers in photovoltaic installations in Brazil," *Renewable Energy Focus*, vol. 41, pp. 179–187, 2022. https://doi.org/10.1016/j.ref.2022.02.005.

[39] Y. Trisnoaji, S. D. Prasetyo, Z. Arifin, and A. R. Prabowo, "Numerical investigation of photovoltaic–phase change material systems: Optimization of fin geometry for enhanced thermal management and solar panel performance," *Journal of Energy Storage*, vol. 154, Art. no. 121126, 2026. https://doi.org/10.1016/j.est.2026.121126.

[40] S. N. Hussain and A. Ghosh, "Evaluating tracking bifacial solar PV based agrivoltaics system across the UK," *Solar Energy*, vol. 284, Art. no. 113102, 2024. https://doi.org/10.1016/j.solener.2024.113102.

[41] A. Kumar Behura, A. Kumar, D. Kumar Rajak, C. I. Pruncu, and L. Lamberti, "Towards better performances for a novel rooftop solar PV system," *Solar Energy*, vol. 216, pp. 518–529, 2021. https://doi.org/10.1016/j.solener.2021.01.045.

[42] M. A. Zahid, H. Yousuf, Y. Kim, J. Yi, and S. K. Dhungel, "A novel approach for power enhancement of vertical mounted bifacial photovoltaic system using reflecting mirrors," *Journal of Cleaner Production*, vol. 397, Art. no. 136541, 2023. https://doi.org/10.1016/j.jclepro.2023.136541.