

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 has a significant effect on the performance of stand-alone photovoltaic (PV) systems, especially for the suboptimal solar incidence angle that can limit the use of solar energy during the daytime. Solar tracking systems can increase the capture of solar irradiation, but the higher energy production can also lead to additional losses in case the energy storage capacity is not enough. Therefore, the selection of a suitable PV configuration should take into account both energy generation and effective utilization of the energy. The aim of this paper is to evaluate the performance of stand-alone PV systems with different panel orientations and solar-tracking configurations using PVsyst simulation. The configurations studied were fixed tilted-plane systems with azimuths of 10° and 20° and tilts of 20° and 30°, single-axis solar tracking systems, and dual-axis solar tracking systems. The simulation was performed at the Faculty of Vocational Studies, State University of Malang, Indonesia which has a tropical climate and a large potential of solar energy. The results indicate that dual-axis solar tracker has the highest Solar Fraction (SF) of 0.986 and daily energy yield of 4.82 kWh/kWp/day. However, this configuration also showed high collection and unused-energy losses, which shows the effect of limited battery storage capacity. The best energy utilization was achieved for the fixed configurations at the combination of 10° azimuth and 20° tilt with an annual energy output of 1670.1 kWh and lower energy losses than the tracking systems. The results indicate that the PV configuration should consider a trade-off between energy generation, energy utilization and storage capability, instead of only the maximum energy production.

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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 in various configurations and locations [18]-[19]. PVsyst offers complete features in PV system modeling, from weather data input, system configuration, shading, to energy performance analysis [20]-[21]. Previous studies have used PVsyst as an initial reference for designing small, medium, and large PV systems worldwide. Table 1 presents some of the earlier studies related to PVsyst. The novelty of this study lies in its case-study focus on fixed-tilted plane configurations combining azimuths of 10° and 20° with tilts of 20° and 30°, respectively, compared against single-axis and dual-axis solar tracking systems. This research was carried out at the Faculty of Vocational Studies, State University of Malang, which has geographical characteristics and solar radiation intensity suitable for this study. The configuration tested in this study has not been widely discussed in the literature, so the results are expected to fill the

data gap and provide a new picture of PV system configuration optimization. This study also considers simulations using PVsyst software, which can model the performance of PV systems with various configuration variations in detail and systematically. With the simulation results obtained, this research is 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/m ² , 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/m ² /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 as input for the design and evaluation of photovoltaic systems plays a significant role, particularly when considering the geographical and meteorological parameters representing the real conditions on the installation site. This study selected the case study site of the Faculty of Vocational Studies at the State University of Malang in East Java, Indonesia, because of its tropical location and high solar radiation all year round. The selection of this location considers not only the intensity of the available radiation, but also the climatic stability and the availability of the environmental data needed for the simulation purposes of the PVsyst software [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 the climate parameters are entered systematically to obtain an optimal picture of the local solar energy potential.

The geographic coordinates of the Faculty of Vocational Studies, State University of Malang used to model the PV system are presented in Table 2 which is the basis in the simulation process. 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 the density of the atmosphere, which directly affect the quantity and the quality of solar radiation received on the surface of the PV module. The time zone GMT +07.00 is a temporal reference to synchronize the energy consumption profile with the modeled daily irradiation duration. The accuracy of these spatial input parameters is critical, since 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 2 shows the daily path of the sun. It illustrates the displacement of the sun according to its azimuth and altitude at specific times of the year. The curves in this diagram show the position of the sun on important dates such as June 22 and December 22 and other equinoxes and solstices. This trajectory pattern gives useful information in the determination of the PV system tilt angle and orientation for maximum absorption of solar energy during the year. Moreover, this diagram also allows to recognize possible shadows of surrounding objects which may reduce system efficiency.

Table 3 complements the above information with the meteorological data of the location which is important for the performance analysis of the PV system. The relatively high and stable average value of the horizontal global radiation (around 5.52 kWh/m²/day) shows the potential of solar energy, which can be improved by proper system configuration. The significant contribution of diffuse radiation during the wet months shows that most of the radiation is received through atmospheric dispersion. PV systems should therefore be designed to be responsive to cloudy-sky conditions. 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 the transmission of radiation 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 point of view [29]–[30].

Table 2. Geographical coordinate information

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

Table 3. Recapitulation of annual climate data

Month	Global Horizontal Irradiation (kWh/m ² /day)	Horizontal Diffuse Irradiation (kWh/m ² /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	1.8	4.556	76.1

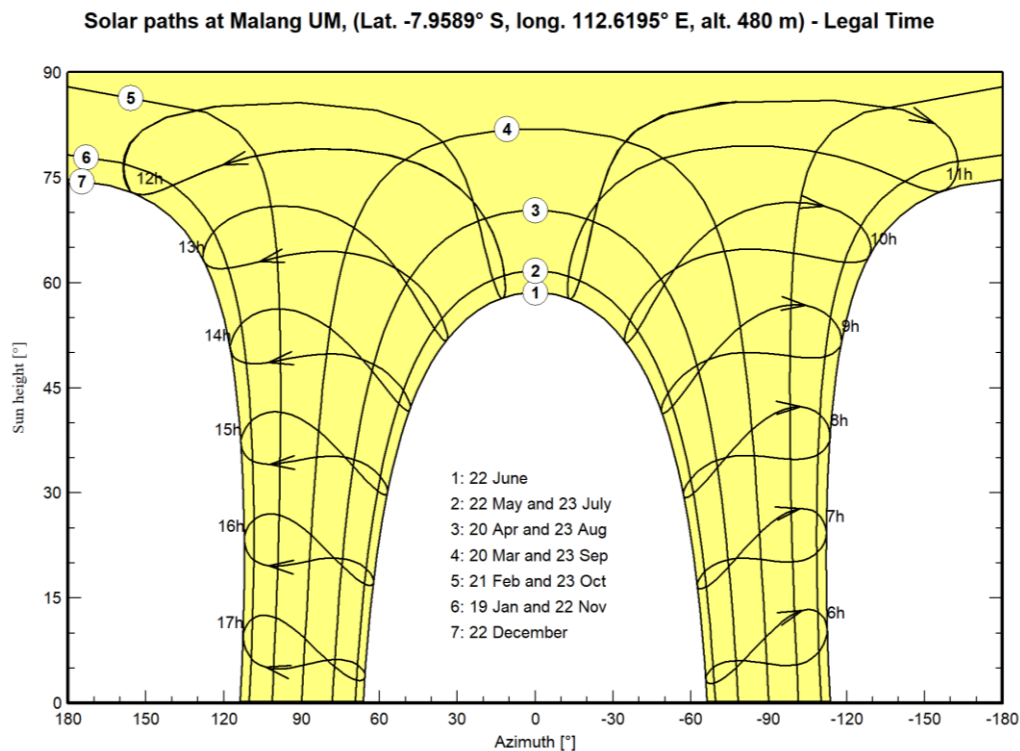


Figure 2. Sun path diagram

2.1 Planning

2.1.1 PV System Architecture

The architecture of the PV system built in this research is 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 consists of four computers which are favorite and actively used by the students, four lights which are turned on during the nite for room lighting and two printer units as supporting facilities. The total energy requirement based on estimated daily usage is projected at 4404 Wh per day or approximately 132.1kWh per month (see Table 4 and estimated Electrical Energy Consumption). This estimation is important since it provides a baseline for the capacity and configuration of each PV system component to provide energy continuously and reliably.

The technical specifications of each key component of the PV system such as the PV modules, controllers and batteries are also described in Table 5. The PV modules are monocrystalline (Si-mono) with a peak power of 250 Wp per module and four modules are installed per system to achieve the required total capacity. Technical data comprises parameters like short circuit current (I_{sc}), maximum power point voltage (V_{mpp}) and temperature coefficient which have direct impact on the module performance under field operating conditions. An MPPT-type converter with the maximum efficiency of 96% optimizes the absorption of energy from PV to storage systems over a wide operating voltage range (26–75 V), so

the system can work effectively under variations of solar radiation intensity. 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 enough to provide adequate backup energy in the low radiation conditions or during the nite. Dual-axis tracking systems can achieve large increases in the capture of solar energy, but generally require more mechanical parts and control systems than fixed-tilt systems. Additional components can add to the complexity of the installation and the maintenance requirements of the system during its service life, especially for continuous outdoor environments. Thus, in selection of tracking configuration, long-term operational and economic aspects should be taken into account besides 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/m ²
	Short Circuit Current (Isc)	8.63 A
	Max Power Point (Imp)	8.14 A
	Temperature Coefficient (μI_{sc})	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 3 which is 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 distribution of power to the battery and the user's load. The system designed in this study does not use backup generators, although generators are shown as an alternative energy source in the diagram. The energy generated by the solar modules will directly meet the user's electricity demand and the battery will be charged. The safety features of the energy storage system include fuses and temperature sensors, which ensure the battery is operating in a safe condition. This configuration presents an approach based on the full utilization of renewable energy, thus favoring the sustainability of the energy supply to match the estimated electricity demand shown in Tables 4 and 5.

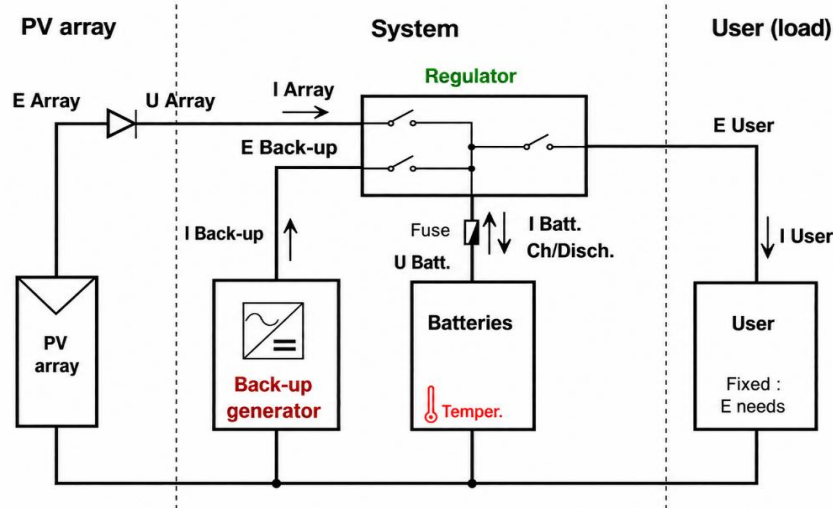


Figure 3. Configuration diagram of the photovoltaic system

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/m ² /day) A : Total Module Area η_{PV} : Module Efficiency	[31], [32], [33]
Energy Supply	$Y_f = \frac{E_{AC}}{P_{Rated}}$	(2)	E_{AC} : Energy to Load (kWh) P_{Rated} : Peak Power (kW)	[34], [35], [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/m ²)	[37], [38], [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 is carried out by comparing a number of fixed panel orientation configurations at azimuths of 10° and 20° with slopes of 20° and 30°, and two solar tracking systems, single-axis and dual-axis. Figure 4 shows that the system with two-axis tracker obtains the highest Solar Fraction (SF) of 0.986, which is considerably greater than the fixed panel configuration that is 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 is a little bit less than the fixed panel. This indicates that, while trackers improve the amount of energy produced, the efficiency of distributing that energy might not improve because of potential losses in the tracking systems. For fixed-tilt configurations, systems with a tilt of 20° generally showed slightly better energy performance than systems with a tilt of 30°, indicating that lower tilt angles are more suitable for maximizing solar irradiation capture under the study location.

Similarly, the 10° azimuth angle showed slightly better SF and energy utilization values compared to the 20° azimuth configuration which shows a better alignment to the prevailing solar track over the year. Moreover, Figure 5 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 kWh/kWp/day and 0.69 kWh/kWp/day respectively. The higher unused energy in the tracking systems indicates that the battery capacity was not sufficient to store the additional energy generated when the sun was shining bright. However, the tracking configuration can generate more energy, but some part of the harvested energy cannot be utilized efficiently. This reduces the overall system efficiency. In contrast, a fixed panel arrangement of 10° azimuth/20° tilt results in a Yf of 3.72 kWh/kWp/day with much reduced values of Lc and Lu. These results demonstrate that even small changes in azimuth and tilt angles can influence the amount of incident solar radiation on the PV surface and therefore the annual energy production and the system reliability. In practical implementations, this limitation can be mitigated by larger battery storage capacity, better energy management strategies or load scheduling approaches that better match the electricity consumption with peak energy generation periods. To summarize, tracking systems are only fully utilized if the storage management is able to catch up with their higher energy production.

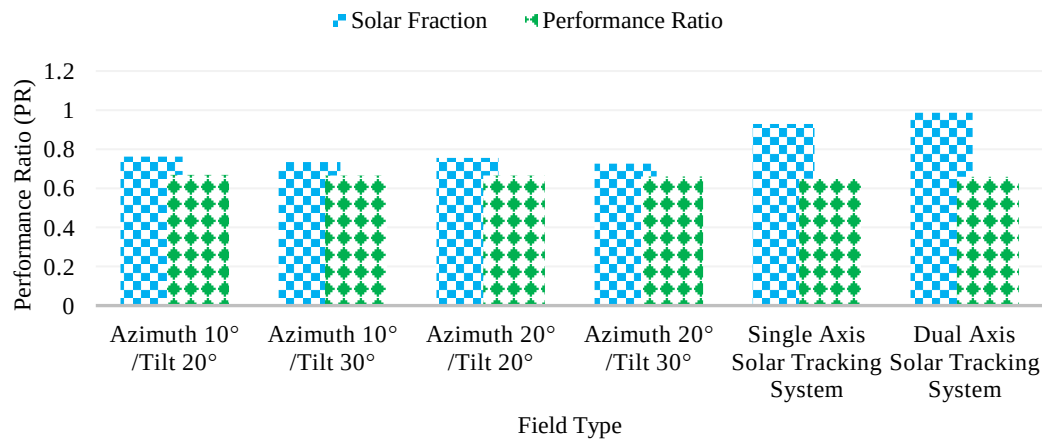


Figure 4. Annual performance ratio of the PV system

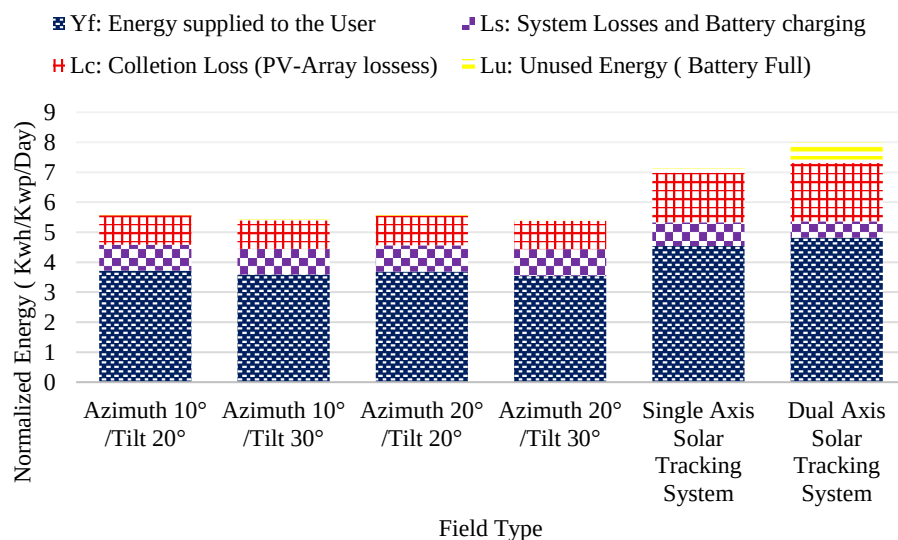


Figure 5. Annual normalized output from the PV installation

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. Research Limitation

The results are totally dependent on the quality of input data and assumptions made, as this study is based on the PVsyst-simulation approach. The model did not account for the tangible factors such as dust accumulation, long-term degradation of panels, and operational disruptions in the field. Moreover, the tested PV system configuration was limited to a combination of 20° and 30° tilt angles and azimuths of 10° and 20° and two types of solar trackers (single axis and dual axis). This configuration was chosen considering the suitability of the geographical conditions of the Vocational Faculty of the State University of Malang, so that the results are contextual and not necessarily representative of other locations. PVsyst is a good tool to evaluate the performance of PV systems but the results of the simulations have to be confirmed by measurements in real installations. More general applicability of the simulation results requires experimental validation and expansion of system configuration. Field-based validation can give 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, economic analysis such as investment comparison, operational costs and estimated Levelized Cost of Energy (LCOE) values were not included in this study. The energy performance of the systems was successfully compared, but it has not been analyzed whether the additional output of the tracking system is justified by the additional cost. Moreover, this study is limited to standalone PV systems and does not include integration with the grid or hybrid systems. This limits the assessment of the flexibility of energy management or the contribution to the stability of large-scale energy systems. Therefore, long-term experimental monitoring and validation with real operational data are also 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 the study, PV systems were evaluated in terms of their performance by PVsyst simulations under various fixed panel orientations and solar tracking configurations. The results obtained show that the best overall performance is obtained by the dual-axis solar tracker 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 due to the limited storage capacity, as evidenced by higher Lc and Lu values compared to fixed-tilt systems. The fixed configuration with azimuth angle of 10° and tilt angle of 20° however resulted in a more stable use of energy, but less energy in total. The comparative analysis shows that the selection of a proper PV configuration should take into account the possibility of maximum energy generation and the effectiveness of energy distribution and storage management. Dual-axis tracking systems are very useful in high solar irradiation areas but for them to take advantage of the extra energy produced, they need to be supported with enough storage capacity. The results also show that PVsyst is a reliable platform to evaluate the technical performance of different PV configurations with representative climatic and system parameters. Thus, the results of this work can be a useful technical reference for designing PV systems more suitable for tropical environmental conditions and specific energy requirements of the applications. Future studies should include experimental validation and economic analysis (e.g. LCOE) to improve the applicability and completeness of the system and should 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; Software; Validation; Formal analysis; Investigation; Resources; Data Curation; Writing - Original Draft; Writing - Review & Editing; Visualization; Supervision; Project administration; Funding acquisition.

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Meirna Puspita Permatasari: Conceptualization; Software; Validation; Investigation; Resources; Writing - Review & Editing; Visualization; Project administration; Funding acquisition.

Misbahul Munir: Conceptualization; Formal analysis; Investigation; Data Curation; Writing - Review & Editing.

Mochamad Subchan Maulidin: Methodology; Formal analysis; Resources; Writing - Review & Editing; Supervision; Funding acquisition.

Marsya Aulia Rizkita: Methodology; Software; Formal analysis; Investigation; Writing - Review & Editing.

Zainal Arifin: Methodology; Formal analysis; Data Curation; Writing - Review & Editing; Supervision; Project administration; Funding acquisition.

Mohd Afzanizam Mohd Rosli: Methodology; Formal analysis; Data Curation; Writing - Review & Editing; Supervision; Project administration; Funding acquisition.

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

Grammarly was used solely for language editing, grammar correction, and improvement of English language clarity. No AI tools were used to generate scientific content, simulation data, data analysis, scientific interpretation, or conclusions. All scientific content and intellectual contributions are original and remain the responsibility of the authors.

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