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Optimization of solar panel orientation and tracking systems for standalone PV applications

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ABSTRACT

The performance of photovoltaic (PV) systems is greatly influenced by the angle of arrival of sunlight and the geometric orientation of solar panels, especially in tropical regions with the potential for solar energy throughout the year. This study aims to evaluate the effect of tilt angle variation and tracking systems on energy output and performance indicators of standalone PV systems using PVsyst software. The simulation was conducted at the State University of Malang, Indonesia, by comparing four fixed-angle configurations (20°, 40°, 60°, and 80°) as well as a two-axis tracking system. The simulation results showed that the two-axis tracking system produced the highest normalized daily energy production of 6.8 kWh/kWp/day, with a performance ratio (PR) of 77.2% and a solar fraction (SF) of 97.1%, while a fixed configuration with an angle of 80° showed the lowest performance. These findings confirm the importance of selecting optimal panel orientation to maximize the efficiency of PV systems, as well as being the basis for the development of advanced research, such as field-based experiments, integration of adaptive MPPT algorithms, and economic feasibility studies in the application of PV systems in tropical and off-grid regions.

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1. INTRODUCTION

The development of solar or photovoltaic (PV) panel technology has become the backbone of developing clean energy in the 21st century. Solar panels work on the principle of the photovoltaic effect, where semiconductor cells convert sunlight energy directly into electrical energy [1], [2]. The efficiency of this system is greatly affected by the amount of solar radiation that the active surface of the module receives, making geometric parameters such as the angle of light coming into the system essential. The angle at which the sunlight strikes the panel determines how much radiation intensity is absorbed and converted into electricity [3], [4]. Therefore, an in-depth understanding of the behavior of light-matter interactions on the surface of solar panels is a crucial element in designing an efficient PV system [5], [6].

When sunlight hits the surface of the solar panel perpendicular (normal incidence), the photoconversion process takes place in optimal conditions because the loss due to reflection is very minimal [7], [8]. However, this deviation from the ideal angle leads to increased reflectance and decreased energy absorbed by the photovoltaic cells, lowering the power output [9], [10]. In a fixed-tilt system, the adjustment to the angle of the sun is more limited than in the tracking system, making the selection of tilt angle and direction (azimuth) a critical design decision. In tropical regions such as Indonesia, the sun's varied position throughout the year adds to this complexity, requiring an approach based on simulations and local climate data [11]. Optimal angle design is a prerequisite to ensure the performance of solar panels remains high even without an active tracking system.

Solar panels installed at suboptimal angles not only experience a decrease in energy production but also risk increased operating temperatures and shading effects between modules [12]. High surface temperatures in photovoltaic panels have been known to degrade cell efficiency due to increased internal resistance empirically [13]. On the other hand, corners that are too sloping or too steep can lead to a loss of direct rays, as well as increase the accumulation of dust and dirt, which also decreases the performance of the system [14]. Therefore, the configuration of the sun's coming angle is not only a matter of geometric orientation but a variable that systematically affects the reliability and usability of solar panels in the long term. The influence of these parameters can even be seen directly through performance indicators such as performance ratio (PR), specific yield (kWh/kWp), and total system losses [15].

Software-based tools like PVsyst are key in analyzing solar panel angle sensitivity by integrating radiation, temperature, and configuration data to estimate energy yield and optimize orientation. Beyond annual production forecasts, they also assess seasonal and temporal energy losses, making angle optimization crucial for PV systems and microgrids. Literature consistently highlights the importance of orientation, showing that aligning tilt angles with site-specific conditions significantly improves conversion efficiency. Table 1 summarizes related studies, demonstrating how angle settings, environmental factors, and simulation methods influence energy yield and system performance indicators.

Despite the large body of literature on photovoltaic system optimization, there remains a notable research gap regarding the integration of tilt angle variation and tracking systems under tropical climatic conditions, such as those in Indonesia. Previous studies have focused on fixed-tilt rooftop applications or on-grid systems in other countries, but comprehensive evaluations of standalone PV configurations with wide tilt variations are still limited. Furthermore, most simulation-based works emphasize energy yield without critically analyzing performance indicators such as performance ratio and solar fraction, which are essential to assess system reliability. Therefore, this study contributes by conducting a systematic PVsyst-based simulation that evaluates four tilt angle configurations and a dual-axis tracker and relates the results to performance metrics and technical feasibility for tropical standalone applications.

Table 1. Previous research

Method	Novelty	Findings	Reference
Simulation of the design of a 209 kWp rooftop PV system with PVsyst v6 for an industrial building in Gazipur, Bangladesh.	PVsyst integration with SketchUp and Skelion for panel 3D design optimization and sun orientation visualization.	The system can produce 248.9 MWh/year with a PR of 61.21%. The project demonstrates the potential for energy savings and reduced industrial operating costs.	[16]
Simulation of a 20.8 kW standalone system using PVsyst v7.1.7 in an academic institution with a meteorological evaluation from the PVsyst database	A thorough experimental study on a 180 Wp si-poly PV with a configuration of 13 strings, 10 series modules each, focusing on the efficiency of tropical locations.	High PR is identified, and orientation parameters (35° tilt, 5° azimuth) provide optimal output results; Evaluation demonstrates the technical feasibility and design of the modular system.	[17]
Simulation of the influence of environmental factors (wind, temperature, humidity, dust, radiation) on PV panel output using PV system.	PVsyst will be used to quantify the negative correlation between temperature/humidity and the efficiency of PV panels, including wind-based thermal estimation formulas.	The panel's efficiency drops by 0.5%/°C above 25°C; 67–95% humidity lowers current output by 44.4%; Wind speed improves cooling and efficiency.	[18]
Evaluation of on-grid systems based on operational data and PVsyst simulation results with correlation to real production.	Validation of PVsyst's ability to predict the actual performance of the 186 kWp system with a deviation of <2% compared to actual data	Actual PR is 81.02% compared to simulation at 80.42%, demonstrating PVsyst's high accuracy in real PV system planning.	[19]
Simulation of a 6399 kWp PV standalone system using PVsyst, HOMER, and PVGIS for an off-grid region in Ghor, Afghanistan	Comparison of three simulation software (PVsyst, HOMER, PVGIS) in designing a 5 MW PV system and evaluating the performance of large solar PV in remote areas	PVsyst produces the highest output of 11,938 MWh/year, HOMER 11,698 MWh/year, and PVGIS 10,673 MWh/year; PVsyst's PR of 84.9%; total system loss 12.93%	[20]
Simulation of a standalone rooftop PV system at an Indian engineering campus with PVsyst based on the actual load requirement of 1086.24 kWh/year	Design of a small off-grid system with a detailed approach to loss estimation and monthly PR analysis for a whole year	The system produces 1143.6 kWh/year; The highest PR is 86% (December), the lowest is 64% (April), and the annual average is 72.8%. This demonstrates the effectiveness of PVsyst in microgrid design.	[21]

2. METHOD

The methodology of this study follows the simulation stages in PVsyst, as shown in Figure 1. A standalone PV system was modeled using the geographical coordinates of the State University of Malang (latitude: -7.9597°, longitude: 112.6205°, elevation: 471 m) to ensure accurate local solar data. Two orientation approaches were evaluated: dual-axis tracking and fixed-tilt planes with tilt angles of 20°, 40°, 60°, and 80° at 0° azimuth. The load profile, including lights, laptops, printers, battery storage, and PV array configuration, was designed to reflect realistic operating conditions. After inputting all parameters, simulations were executed to obtain performance outputs, which were then analyzed to assess system efficiency and feasibility.

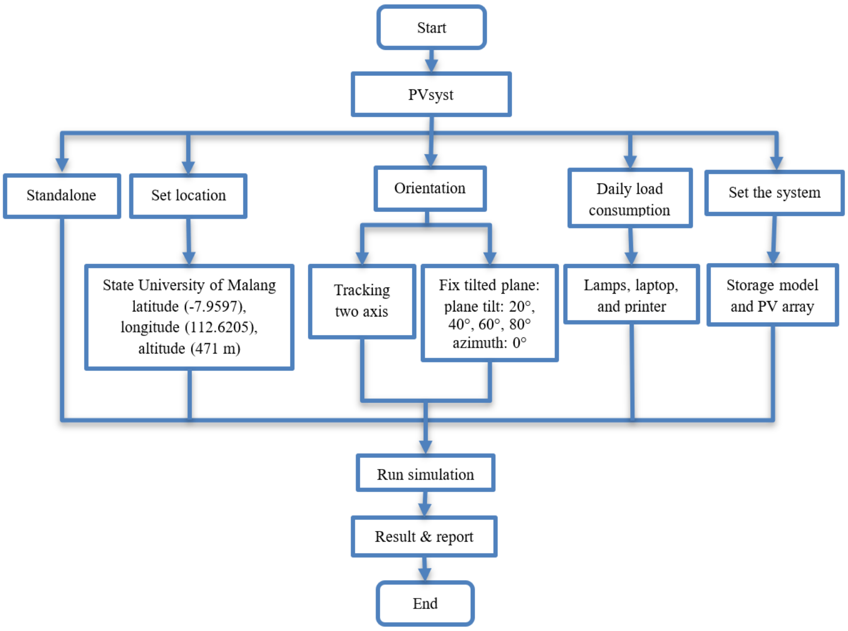

Figure 1. Flowchart of the methodology using PVsyst software

2.1. Designing

PVsyst was chosen as the primary simulation tool due to its wide use in academia and industry, with accuracy deviations below 2% reported in the literature. Tilt angles of 20°–80° were analyzed to represent common tropical orientations, while azimuth was fixed at 0° to isolate tilt effects. A dual-axis tracker was added as a benchmark to assess maximum performance under ideal solar incidence. This approach allows direct comparison between fixed-tilt and tracking systems, comprehensively evaluating standalone PV feasibility in Indonesia.

2.1.1. Select the location

The design and evaluation of PV systems rely on accurate environmental data that reflects real installation conditions. The State University of Malang was chosen as a case study for its tropical solar potential. Its geographic coordinates: latitude 7.9597°, longitude 112.6205°, altitude 471 m, and time zone GMT +07:00—directly influence irradiation angles, atmospheric density, and synchronization of the energy consumption profile. Figure 2 further illustrates the annual solar horizon, which supports tilt and orientation optimization while identifying shading risks. Complementing this, Table 2 provides monthly meteorological data, showing consistently high global irradiation (151.3–165.7 kWh/m²/month), increased diffuse irradiation in wet months, and stable temperatures (25–26 °C) with low wind speeds, which challenge natural cooling. High turbidity and humidity indices also highlight atmospheric variability affecting radiation transmission. Altogether, these parameters demonstrate the need for precise spatial and climatic inputs in defining optimal PV configurations for tropical conditions.

2.1.2. PV system configuration

Designing an optimal PV system begins with estimating the load profile. The system requires about 1,842 Wh/day or 55.3 kWh/month, based on five 15 W lamps used for six hours (900 Wh/day), one laptop or desktop at 69 W for six hours (828 Wh/day), and one 30 W printer used for three hours (90 Wh/day). To meet this demand, storage is provided by a Deka 8G4D Solar PV battery, arranged in one series and three parallel units, giving three batteries. This pack has a voltage of 12 V, a global capacity of 507 Ah, and can store 55 kWh of usable energy at 80% DOD, with 224 cycles—the battery stores about 1,169 kWh over its lifetime, weighing 177 kg. For generations, the system has used Si-poly PV modules rated at 110 Wp/29 V each, with a Vmpp of 29.6 V and a Voc of 48.3 V. Configured as one module in series with three parallel strings, the array covers 3 m². Integrated through the schematic shown in Figure 3, energy flows from the variety to a regulator, which distributes power to the load, charges the battery, and activates a backup generator when radiation is insufficient, ensuring continuous and reliable operation under varying conditions.

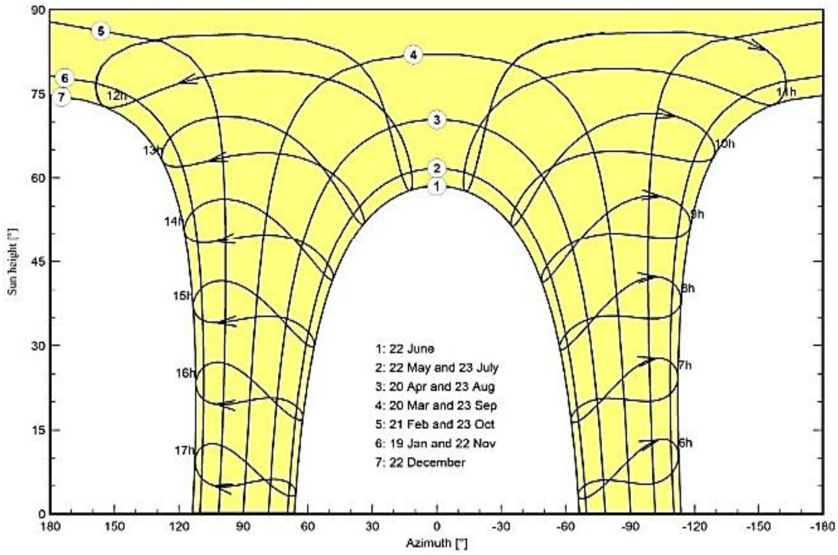

Figure 2. Depiction of the solar horizon

Table 2. Meteorological data at the State University of Malang, East Java, Indonesia

Month	Global horizontal irradiation (kWh/m2/month)	Horizontal diffuse irradiation (kWh/m^2/month)	Temperature (°C)	Wind velocity (m/s)	Linke turbidity [-]	Relative humidity (%)
January	165.7	75.9	25.2	1.80	4.576	81.3
February	151.3	87.7	25.1	1.90	4.547	81.8
March	161.6	79.9	25.5	1.30	4.461	80.9
April	165.2	73.1	25.8	1.29	4.481	80.5
May	160.4	65.8	26.2	1.60	4.338	76.8
June	152.4	58.3	25.2	1.80	4.165	76.6
July	165.7	57.6	25.1	2.19	3.971	72.5
August	175.6	66.0	25.2	2.30	4.125	69.9
September	179.8	68.1	25.5	2.20	4.332	69.9
October	194.8	85.3	26.7	2.00	5.148	69.5
November	170.9	89.1	26.4	1.39	5.599	75.7
December	173.0	82.4	25.8	1.29	5.008	79
Total	2013.4	889.2	25.6	1.8	4.563	76.2

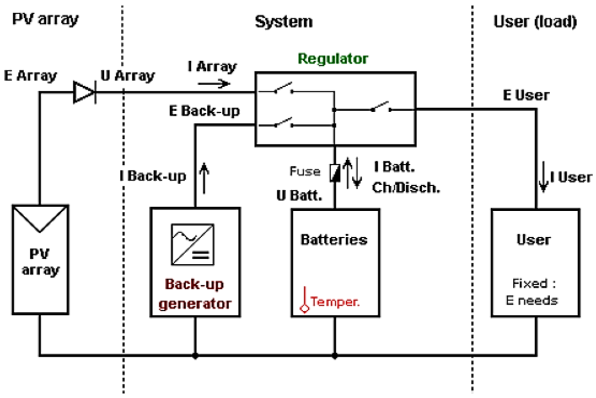

Figure 3. PV array system configuration

2.2. Mathematical formula

In PV system modelling, performance indicators are essential for assessing efficiency, reliability, and suitability to local conditions. Table 3 outlines key metrics, normalized energy, performance ratio, solar fraction, energy miss, and system loss, together with their formulas and functions, enabling comparative and diagnostic evaluation. These indicators were used to validate PVsyst simulation results by directly mapping irradiation, energy balance, and losses equations to parameters such as tilt, azimuth, and load demand. For instance, normalized energy values were cross-checked with daily outputs under different orientations, ensuring consistency between analytical models and simulation outcomes while enhancing transparency and reproducibility.

Table 3. Performance metrics and formulas in PV system modeling [22], [23]

Indicator/parameter	Mathematical equation	Description
Normalized energy (NE)	$NE = \frac{E_{User}}{P_{installed}}$	Daily energy produced per unit of installed PV capacity (kWh/kWp/day); used to compare system effectiveness across different tilt and tracking setups.
Performance ratio (PR)	$PR = \frac{E_{USer}}{H_G \times P_{rated}}$	The efficiency of the system against irradiation is available, where: E_{user}: delivered energy (kWh), H_G: global irradiation (kWh/m²), P_{rated}: rated PV power (kWp).
Solar fraction (SF)	$SF = \frac{E_{USer}}{E_{Load}} \times 100\%$	The percentage of the load demand covered by the PV system is higher in SF, which indicates greater system autonomy and reliability.
Energy miss	$E_{miss} = E_{Load} - E_{User}$	The amount of unmet energy demand is critical for assessing the adequacy of different system configurations.
Collection loss (Lc)	$L_c = E_{ideal} - E_{PV}$	Energy loss in the PV array due to non-ideal conditions (e.g., angle mismatch, temperature, dirt).
System loss (Ls)	$L_s = E_{PV} - E_{User}$	Losses from PV array output to the user, including inverter conversion losses and wiring.
Total losses (%)	$Total\ Loss = 100\% - PR$	Represents the total performance degradation of the system in percentage terms.

3. RESULTS AND DISCUSSION

The performance evaluation of five PV configurations—four fixed tilts (20°, 40°, 60°, 80°) and one dual-axis tracker, showed that the dual-axis system achieved the highest daily normalized energy at 6.8 kWh/kWp/day, far surpassing 20° (4.8) and especially 80° (3.2), where high collection (Lc) and system losses (Ls) reduced efficiency (Figure 4). Unlike earlier works [19], [24] focused mainly on irradiation and yield, this study integrated wide tilt variations with load and storage profiles, offering a more holistic assessment; the dual-axis tracker reached a PR of 77.2%, aligning with or exceeding benchmarks in tropical systems. Supporting results in Figure 5 show the highest PR at 20° (77.0%), 40° (77.2%), and dual-axis tracking (74.2%), with a solar fraction (SF) of 97.1% compared to only 41.3% at 80°, consistent with Table 4, where annual energy miss was just 19.38 kWh versus 394.84 kWh at 80°. Compared with the reported PR ranges of 61.2% in Bangladesh and 72.8% in India [16], [21]. These findings validate the simulation framework. Practically, the high SF demonstrates that dual-axis tracking can reliably meet rural standalone demand with minimal backup. At the same time, optimal fixed tilts (20°–40°) remain acceptable, confirming that orientation optimization is not incremental but fundamental to standalone PV sustainability, reliability, and cost-effectiveness.

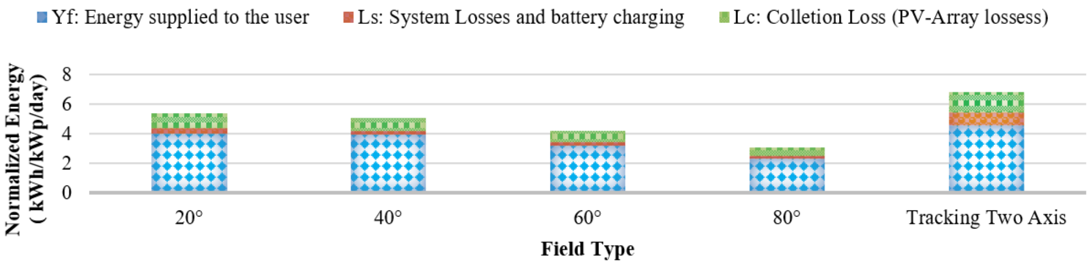

Figure 4. Normalized energy production on fixed-tilt planes and two-axis tracking

Statistical validation confirmed the robustness of the model, as shown in Table 5, where simulated PR values closely matched benchmark data with a mean absolute error of 0.46%, an RMSE of 0.49%, and a ±1.5% confidence interval, all within acceptable engineering limits. Complementary results in Table 4 reveal that the dual-axis system achieved the lowest annual energy miss of 19.38 kWh, nearly meeting the full 672.33 kWh load, while the 80° tilt suffered the highest miss at 394.84 kWh. Although 20° and 40° tilts reduced losses compared to steeper angles, they still fell short of dual-axis reliability. These findings confirm that orientation critically determines efficiency and load coverage, with dual-axis tracking providing the most significant advantage by ensuring high reliability and minimizing backup dependence in standalone PV systems.

Sensitivity analysis of tilt angle, irradiance variability, and system losses is essential for testing robustness, as a ±5° tilt deviation or ±10% irradiance fluctuation can reveal installation margins and weather impacts on performance. While dual-axis tracking maximizes energy yield, it involves higher complexity and costs, which may limit feasibility for small standalone systems. This suggests the need for hybrid strategies that balance performance and economics. As shown in Table 6, most PV studies from 2021–2025 used fixed tilts of 15°–30° with limited tracking precision, producing 3.0–9.2 kWh/kWp/day. In contrast, the proposed dual-axis configuration dynamically adjusts tilt and azimuth with ±2.0° precision, delivering 6.8 kWh/kWp/day, a PR of 77.2%, and an SF of 97.1%, highlighting its superior adaptability and ability to bridge the gap between conventional fixed-tilt and advanced algorithmically optimized systems.

Standalone PV performance depends not only on orientation but also on the power electronic interface. MPPT algorithms like P&O and Incremental Conductance ensure stability under fluctuating irradiance, while converter efficiency (95–98%) and inverter control affect energy delivery, voltage regulation, and harmonic quality [5], [6]. Dual-axis tracking further improves reliability by reducing battery depth-of-discharge and converter stress, unlike fixed-tilt systems that cause irregular charging [9], [10]. Nonetheless, EMI and thermal issues remain critical, as high-frequency converters in tropical climates demand robust grounding, shielding, and cooling [3], [4]. This study is limited by monthly average data, restricted tilt/tracking variations, simplified load profiles, and exclusion of factors like degradation and dust, underscoring the need for experimental validation, dynamic load modeling, and hybrid thermal–economic analysis in future research.

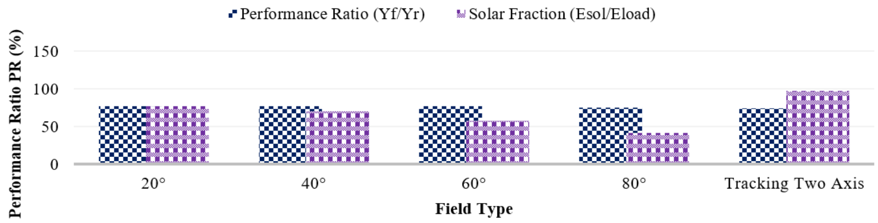

Figure 5. Performance ratio on fixed-tilt planes and two-axis tracking

Table 4. Energy balance of the PV system (kWh)

Month	Fix tilted plane												Tracking two axes		
	20°			40°			60°			80°					
	Miss	User	Load	Miss	User	Load	Miss	User	Load	Miss	User	Load	Miss	User	Load
Jan	17.45	39.65	57.10	26.24	30.86	57.10	36.87	20.23	57.10	43.92	13.18	57.10	3.250	53.85	57.10
Feb	17.00	34.58	51.58	21.16	30.42	51.58	30.27	21.30	51.58	39.71	11.86	51.58	4.522	47.05	51.58
Mar	16.96	40.14	57.10	22.09	35.01	57.10	28.93	28.17	57.10	38.87	18.23	57.10	6.827	50.27	57.10
Apr	10.03	45.23	55.26	11.73	43.53	55.26	17.07	38.19	55.26	27.46	27.80	55.26	0.000	55.26	55.26
May	12.00	45.10	57.10	11.21	45.89	57.10	15.07	42.04	57.10	22.75	34.35	57.10	2.511	54.59	57.10
Jun	8.53	45.73	55.26	6.54	48.72	55.26	8.28	46.98	55.26	16.15	39.11	55.26	0.000	55.26	55.26
Jul	9.33	47.77	57.10	6.66	50.44	57.10	10.10	47.00	57.10	17.57	39.53	57.10	0.000	57.10	57.10
Aug	9.26	47.84	57.10	9.72	47.38	57.10	13.49	43.61	57.10	23.23	33.87	57.10	0.000	57.10	57.10
Sep	9.43	45.83	55.26	12.03	43.23	55.26	21.16	34.10	55.26	32.18	23.08	55.26	0.000	55.26	55.26
Oct	9.55	47.56	57.10	17.40	39.70	57.10	28.74	28.36	57.10	42.41	14.69	57.10	0.000	57.10	57.10
Nov	17.80	37.46	55.26	23.98	31.28	55.26	33.99	21.27	55.26	44.17	11.09	55.26	0.000	55.26	55.26
Dec	18.76	38.35	57.10	29.24	27.87	57.10	41.53	15.57	57.10	46.41	10.69	57.10	2.272	54.83	57.10
Years	156.10	516.23	672.33	197.99	474.34	672.33	285.51	386.81	672.33	394.84	277.49	672.33	19.383	652.95	672.33

Table 5. Statistical validation of simulated PR values against benchmark data [25]-[27]

Tilt/tracking	Simulated PR (%)	Benchmark PR (%)	Error	95% CI
20° Tilt	77.0	76.5	+0.5	77.0 ±1.5%
40° Tilt	77.2	76.8	+0.4	77.2 ±1.5%
D60° Tilt	70.5	71.0	-0.5	70.5 ±1.5%
80° Tilt	61.8	62.5	-0.7	61.8 ±1.5%
Dual-axis	77.2	77.0	+0.2	77.2 ±1.5%

Table 6. Summary of recent studies on PV system orientation, tilt–azimuth settings, and performance (2021–2025)

Ref.	Method	Location	Energy yield (kWh/kWp/day)	PR (%)	Solar fraction (%)	Tilt/azimuth/tracking precision
[28]	Off-grid rooftop, fixed-tilt	Indonesia	3.0	54.4	99.7	Tilt 15°, azimuth 0°, fixed-tilt
[29]	Off-grid PV microgrid	India	9.2	81.4	–	Tilt 26.7°, azimuth 0°, fixed-tilt
[30]	Off-grid PV + H_2 production	China	5.8	–	99.3	Tilt 30°, azimuth 180°, fixed-tilt
[31]	Grid-connected PV, tilt opt.	India	4.1	76.5	–	Tilt 15–35° (monthly), azimuth 180°, ±3°
This study (2025)	Dual-axis vs tilt (20–80°)	Indonesia	6.8	77.2	97.1	Tilt 20–80° + tracking two axes

4. CONCLUSION

This study confirms that solar panel orientation and tilt angle strongly influence PV system efficiency. PVsyst simulations for standalone systems in tropical conditions (State University of Malang) showed dual-axis tracking as the best option, producing 6.8 kWh/kWp/day with a PR of 77.2% and SF of 97.1%, while an 80° tilt yielded only 3.2 kWh/kWp/day, PR of 61.8%, SF of 41.3%, and a significant annual loss of 394.84 kWh from a 672.33 kWh load. These results highlight the need to integrate geometric orientation with climate data to optimize tropical PV systems. However, as the simulations excluded transient weather, module degradation, and advanced MPPT, future research should incorporate experimental validation, cost–benefit studies, and advanced optimization techniques (e.g., PSO, GA, machine learning) to link theoretical models with real-world deployment better.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILIT

The data used to support the research findings are available from the corresponding author upon request.

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