BULLETIN OF ENGINEERING SCIENCE, TECHNOLOGY AND INDUSTRY
(BESTI Journal) | ISSN (e): 3025-5821
Website : https://bestijournal.org/index.php/go/index | Volume 4 No 3 (2026)

TILT ANGLE OPTIMIZATION OF A ROOFTOP ON-GRID SOLAR PV SYSTEM AT HASANUDDIN UNIVERSITY ENGINEERING CAMPUS, GOWA, USING PVSYST SIMULATION

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Received: 20/06/2026 | **Revised:** 06/07/2026 | **Accepted:** 25/07/2026 | **Published:** 11/08/2026

Abstract

The tilt angle of solar panels is a critical parameter determining the productivity of a Photovoltaic Power Plant (PVPP) system. This study determines the optimal tilt angle for solar panels on the roof of the Naval Engineering Department Building, Hasanuddin University Engineering Campus, Gowa, using PVsyst version 7.2.21. Seven tilt angles (0°–30°, 5° intervals) were simulated with a fixed azimuth of 0° (north-facing), for a 12.32 kWp system (28 monocrystalline modules, 440 Wp) with a 12 kWac three-phase inverter, using Meteonorm 8.0 irradiation data (5°14' S, 119°30' E). Results show the 5°–10° tilt range produces the highest Energy Yield (18,949–18,991 kWh/year, statistically equivalent within Meteonorm's ±6.1% uncertainty), with the simulated peak at 10° yielding a Performance Ratio of 82.27% and Specific Yield of 1,541 kWh/kWp/year. This is consistent with the theoretical optimum of 5.71° from Indonesia's empirical tilt equation, with an estimated CO_2 emission reduction of 17,092 $kgCO_2$/year. As this study uses a generic monocrystalline module, fixed azimuth, and excludes near-shading analysis, findings should be interpreted as a tilt-only optimization. This study provides applicable technical recommendations for rooftop solar planners in South Sulawesi, with field validation recommended as follow-up.

Keywords: energy yield, optimal tilt angle, performance ratio, PVsyst, South Sulawesi

INTRODUCTION

The global shift toward cleaner energy has made solar power a national priority in Indonesia, a tropical country with an estimated technical solar potential of 3,295 GWp, of which South Sulawesi accounts for roughly 257.36 GW (Kementerian ESDM, 2024). Despite this, national installed PLTS capacity remained around 1,494 MW by the end of 2025, well below the 23% renewable-energy target set for 2025 in Indonesia's National Energy General Plan (RUEN) (Kementerian ESDM, 2026a; Peraturan Presiden RI No. 112/2022, 2022). University campuses, with their extensive rooftop area, are a promising segment for rooftop PLTS adoption, as demonstrated by several on-grid campus systems across Indonesia achieving Performance Ratios (PR) of 75–84% (Gusmedi et al., 2025; Muhammad et al., 2025; Yusiran et al., 2025). No such study, however, has yet been conducted for Hasanuddin University's Engineering Campus in Gowa.

A frequently overlooked technical factor in these systems is the solar panel tilt angle, which prior studies show can alter annual energy output by several percent (Kanianthara et al., 2021; Rusda et al., 2023), with the optimal angle generally close to a site's geographic latitude (Ben Mansour et al., 2021) or predictable via an empirical equation developed specifically for Indonesian coordinates (Wibisono & Setiawan, 2015). While PVsyst-based tilt optimization has been carried out in several Indonesian cities (Badogil et al., 2024), no prior study has examined South Sulawesi, whose wet-tropical climate differs from western Indonesian sites, and as summarized in Table 1, none of the comparable studies combined cross-method validation with an explicit uncertainty analysis. This study makes three contributions: (1) an independent test of the Wibisono and Setiawan (2015) empirical equation at a new wet-tropical coordinate;

(2) a quantified uncertainty analysis based on Meteonorm's ±6.1% interannual variability; and (3) convergence of three independent approaches (PVsyst simulation, the empirical equation, and the latitude rule of thumb) into a single calibrated design reference for rooftop PLTS planners in South Sulawesi. This study aims to determine the optimal tilt angle (0°–30°) for the roof of the Naval Architecture Department Building at Hasanuddin University's Engineering Campus in Gowa, using PVsyst version 7.2.21 (Mishra et al., 2024).

LITERATURE REVIEW

A. Solar Energy Potential in South Sulawesi

The South Sulawesi region, including Gowa Regency, benefits from high solar irradiation as a consequence of its tropical location near the equator. Most of Indonesia receives long-term average global horizontal irradiation sufficient to generate more than 1,600 kWh/m²/year of electricity equivalent (Kharisma et al., 2024), a figure supported by the NASA-SSE dataset integrated into PVsyst. For the Unhas Gowa campus site specifically (5°14' S, 119°30' E), Meteonorm 8.0 data yields an annual horizontal irradiation of 1,855.2 kWh/m²/year with ±6.1% interannual variability — notably higher than the 1,710 kWh/m²/year reported at another Indonesian PLTS site (Cahyadi et al., 2023), indicating strong potential for rooftop PLTS implementation at this specific location.

B. Performance Parameters of On-Grid PLTS Systems

System performance is assessed using parameters standardized in IEC 61724-1:2021 (IEC, 2021) and popularized by Marion et al. (2005) at NREL. Final Yield (Y_f), the ratio of net annual delivered energy (E_{grid}) to installed capacity (P_{STC}), is given by:

$$Y_f = E_{grid} / P_{STC} \qquad (1)$$

Performance Ratio (PR), representing the net effect of all system losses relative to the Reference Yield ($Y_r = H_t / G_{ref}$, where H_t is plane-of-array irradiation and G_{ref} = 1 kW/m²), is:

$$PR = Y_f / Y_r = E_{grid} / (P_{STC} \times H_t / G_{ref}) \qquad (2)$$

where Y_f = Final Yield (kWh/kWp/year), E_{grid} = net energy to the grid (kWh/year), P_{STC} = installed capacity (kWp), H_t = plane-of-array irradiation (kWh/m²)

A good PR for tropical PLTS falls between 70–85% (Marion et al., 2005), with prior Indonesian campus systems reporting 75.5–84.3% (Gusmedi et al., 2025; Nurhadi et al., 2025); these benchmarks are used later to contextualize this study's simulated PR.

C. Use of Generic Panels in PVsyst Simulation

This study uses PVsyst's "Generic Monocrystalline" panel database entry, a common approach in early-stage PLTS studies. The Generic panel represents averaged commercial-grade monocrystalline characteristics aggregated across manufacturers (Mishra et al., 2024), which avoids brand-specific bias and eases study replication. Nurhadi et al. (2025) similarly used a generic PVsyst panel in an on-grid rooftop optimization study and obtained defensible, usable performance data. Follow-up studies using specific commercial panel models (e.g., LONGi, Jinko, Canadian Solar) are recommended for more precise prediction once a specific product is selected for procurement.

D. Optimal Tilt Angle and Prior Research

For tilt angle (β), Ben Mansour et al. (2021) show the optimum tracks a site's geographic latitude, while Kanianthara et al. (2021) report gains of up to 5.94% from monthly-optimized tilt versus a flat panel. For Indonesia specifically, Wibisono and Setiawan (2015) developed an empirical equation:

$$\beta\_opt = -0.0093X + 1.3042Y \quad (3)$$

where X and Y are a site's longitude (°E) and latitude (°, positive for the southern hemisphere). For the Unhas Gowa campus (X = 119.50°, Y = 5.23°), this yields **β_opt = 5.71° ≈ 6°**, which this study tests directly against PVsyst simulation results. Mansur (2021) separately confirms PVsyst simulations based on NASA-SSE data track field measurements within 7.51%, supporting the reliability of the simulation-based approach used in this study.

Table 1 situates this study among comparable tilt-optimization research. None of the eight prior studies examined South Sulawesi, and none combined cross-validation across independent methods with an explicit uncertainty analysis — the gap this study addresses.

Table 1. Summary of Relevant Prior Research

Researcher (Year)	Topic	Location	Method	Key Result	Novelty/Gap
Ben Mansour et al. (2021)	Annual PV tilt optimization	Saudi Arabia	Mathematical model	β_opt ≈ site latitude	Middle Eastern context, not tropical Indonesia
Kanianthara et al. (2021)	Monthly optimal tilt (PSO)	Brunei	PSO algorithm	+5.94% vs. flat panel	Monthly PSO method, not annual PVsyst simulation
Badogil et al. (2024)	Tilt & azimuth optimization	Medan	PVsyst	Optimal angle is site-dependent	Medan location, not South Sulawesi
Khalilullah et al. (2023)	Tilt optimization for NZEB	Indonesia	PVsyst	14° optimal, south-facing	NZEB focus, not campus-specific in Sulsel
Gusmedi et al. (2025)	60 kWp on-grid PLTS, campus	Lampung	PVsyst 7.4	PR 84.34%, 88,636 MWh/yr	On-grid analysis, does not optimize tilt
Nurhadi et al. (2025)	Rooftop on-grid PLTS optimization	Indonesia	PVsyst	PR 81.13%, technically feasible	National scope, no Sulsel coordinates
Mansur (2021)	Field PLTS performance	Indonesia	PVsyst + field data	NASA-SSE vs. field: 7.51% gap	Field validation, not tilt

					optimization

Researcher (Year)	Topic	Location	Method	Key Result	Novelty/Gap
Yusiran et al. (2025)	64 kW rooftop on-grid, campus	Batam	PVsyst + Pylon	PR 76.4%, 80,358 kWh/yr	Batam techno-economic analysis, not tilt
This Study (2025)	**Tilt optimization 0°–30°**	**Gowa, South Sulawesi**	**PVsyst v7.2.21**	**β_opt ≈ 5–10°, ~18,991 kWh/yr**	**Cross-validation of 3 independent methods + Meteonorm uncertainty analysis — not previously done for Gowa/South Sulawesi**

METHOD

This study uses a quantitative simulation approach. PVsyst output data is analyzed using Equations (1)–(3) to identify the optimal tilt angle.

The study site is the roof of the Naval Architecture Department Building, Hasanuddin University Engineering Campus, Gowa (5°14' S, 119°30' E, 23 m altitude). Site and system specifications are summarized in Table 2: a 12.32 kWp array (28 × 440 Wp Generic Monocrystalline modules, two strings of 14 in series) feeding a 12 kWac three-phase inverter (Pnom ratio 1.027, within the ideal 0.8–1.2 range), using Meteonorm 8.0 (NASA-SSE) irradiation data. The building has a flat concrete roof; a non-penetrating ballasted fixed-tilt mounting structure was assumed for all seven configurations.

Table 2. Site and System Specifications

Parameter	Value
Location	Naval Architecture Dept. Building, Unhas Engineering Campus, Gowa
Coordinates / Altitude	5°14' S, 119°30' E / 23 m a.s.l.
Horizontal annual irradiation	1,855.2 kWh/m²/year (Meteonorm 8.0, ±6.1% interannual variability)
Average ambient temperature	27.05°C
System type / capacity	On-grid, 12.32 kWp (Pnom ratio 1.027)
PV modules	28 × Generic Monocrystalline 440 Wp (2 strings × 14 in series)

Inverter	Generic on-grid, 12 kWac, three-phase (400 V, 50 Hz)

Parameter	Value
Azimuth (fixed)	0° (north-facing — correct equator-facing convention for southern-hemisphere sites)
Simulation software	PVsyst v7.2.21

Figures 1–2 detail the simulated system design. Figure 1 shows the overall power configuration and Figure 2 shows the physical mounting structure and geometry for each of the seven simulated tilt angles.

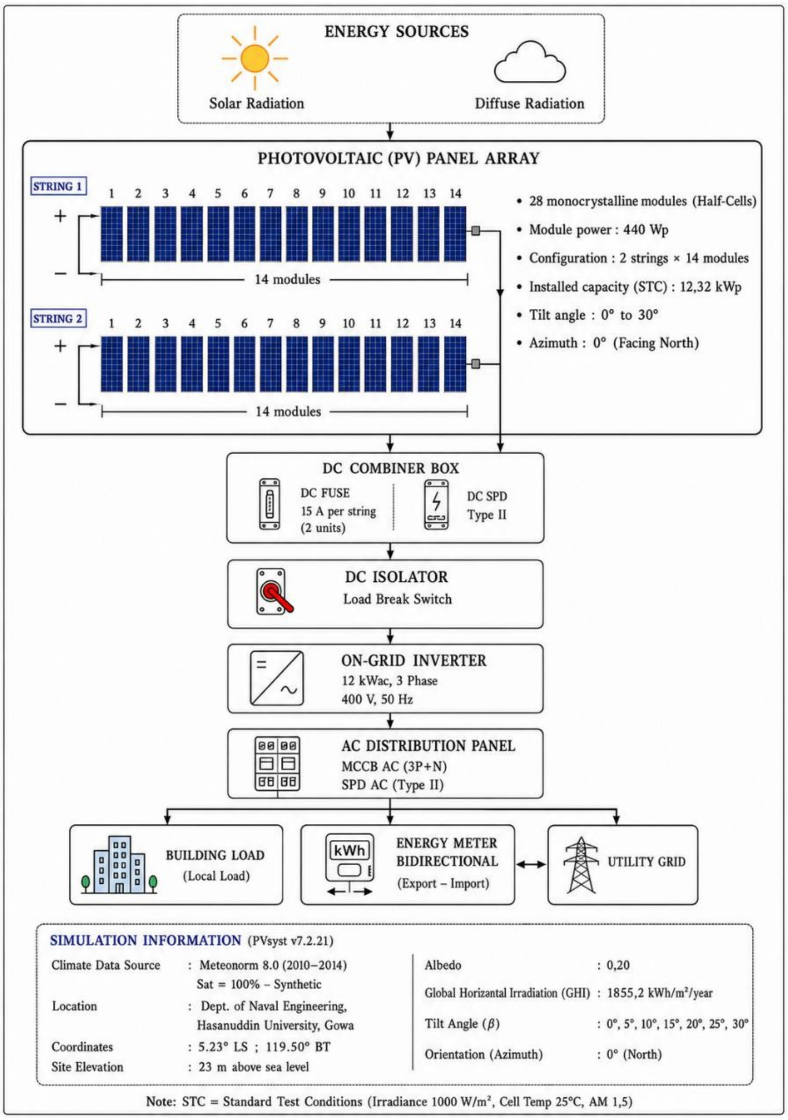

Figure 1. Overall Configuration of the Simulated 12.32 kWp Rooftop On-Grid PLTS

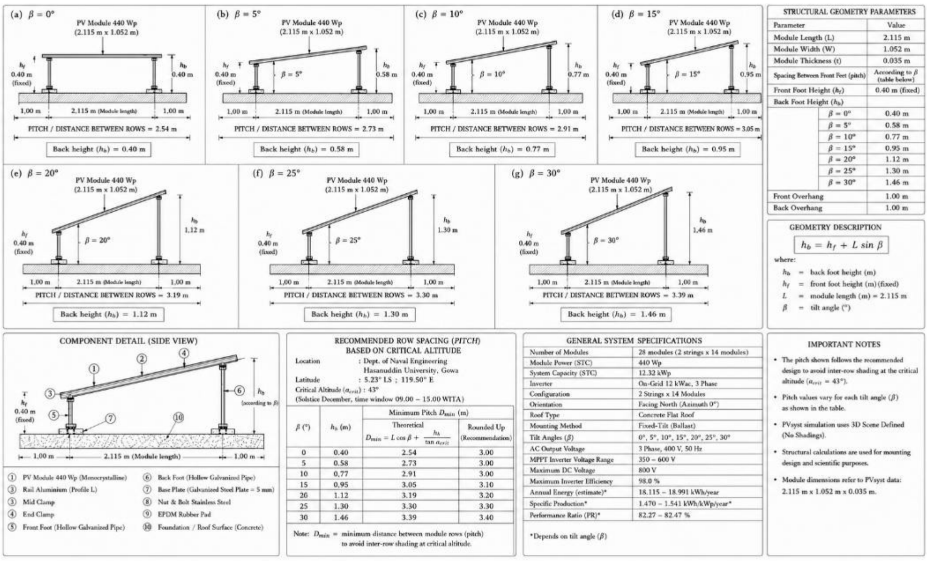

Figure 2. Fixed-Tilt PV Mounting Structure for the Seven Simulated Tilt Angles (β = 0°, 5°, 10°, 15°, 20°, 25°, and 30°)

Seven tilt angles were simulated at the fixed azimuth in Table 2, each for a full year. The 5° interval was chosen to bracket the theoretical optimum of 5.71° (Equation 3) while remaining consistent with the resolution used in comparable Indonesian PVsyst studies (Badogil et al., 2024; Nurhadi et al., 2025); as the yield difference between adjacent angles within the 5°–10° range (0.22%) is far smaller than the Meteonorm uncertainty (±6.1%; PVsyst SA, n.d.), finer resolution was not pursued. The complete workflow, from data collection through final recommendation, is summarized in Figure 3.

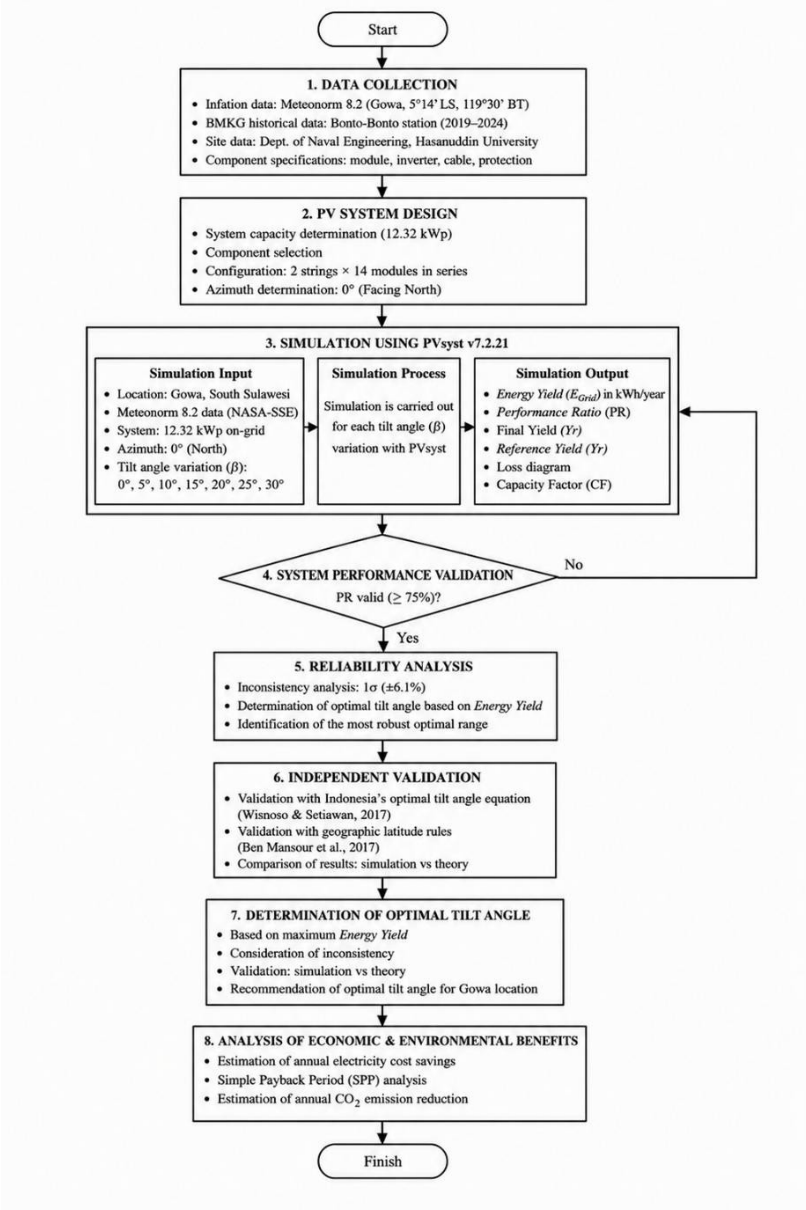

Figure 3. Methodology Flowchart

E_grid, Y_f, H_t, and PR were recorded from each simulation and cross-checked against Equations (1)–(2). Limitations of this study include: use of a generic rather than commercial panel model; reliance on Meteonorm's modeled irradiation (2010–2014 reference period); no field validation, which is recommended as follow-up work (Mansur, 2021); no explicit near-shading simulation, though row spacing was mechanically designed to mitigate this (Figure 3); and optimization of tilt only, at a fixed 0° azimuth.

RESULTS AND DISCUSSION

Table 3 presents complete simulation results validated against Equations (1)–(2). The 5°–10° range yields the highest Energy Yield (18,949–18,991 kWh/year), with simulated PR of 82.27–82.30% — consistent with the 70–85% range for tropical PLTS (Marion et al., 2005) — and total system losses of 17.7–17.8%, dominated by temperature losses (10.82% at β=10°, consistent with Gowa's 27.05°C average ambient temperature exceeding the 25°C STC reference), followed by inverter (2.37%) and module mismatch (2.10%) losses; ohmic losses remained low at 1.10%, below the general 3% design guideline. Figure 5 illustrates this breakdown for the β=10° configuration.

Table 3. PVsyst Simulation Results by Tilt Angle, Validated per IEC 61724-1:2021 (Marion et al., 2005)

β (°)	E_grid (kWh/yr)	Y_f (kWh/kWp)	H_t (kWh/m²)	PR (%)	CF (%)
0°	18,804	1,526	1,854.7	82.29	17.42
5°	**18,949**	**1,538**	**1,869.6**	**82.27**	**17.56**
10°	**18,991**	**1,541**	**1,873.6**	**82.27**	**17.60**
15°	18,929	1,536	1,866.8	82.30	17.54
20°	18,762	1,523	1,849.2	82.36	17.38
25°	18,491	1,501	1,821.2	82.41	17.13
30°	18,115	1,470	1,783.0	82.47	16.79

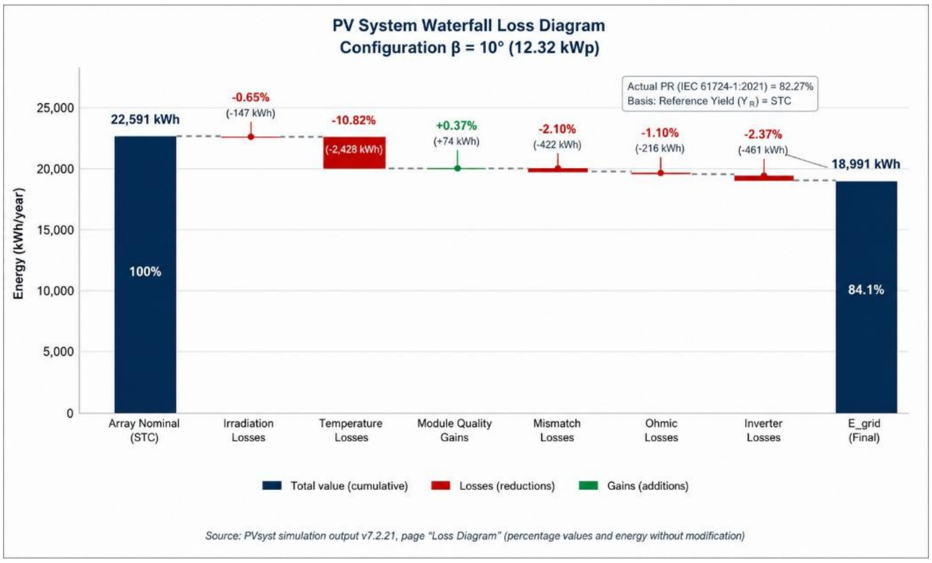

Figure 4. Loss Waterfall Diagram for the β=10° Configuration (12.32 kWp)

The 82.27% PR obtained is comparable to the 81.1–84.3% reported for other Indonesian campus PLTS (Gusmedi et al., 2025; Nurhadi et al., 2025), though roughly 2 percentage points below the 84.34% reported for a considerably larger 60 kWp system in Lampung (Gusmedi et al., 2025) — a difference plausibly linked to lower per-kWp ohmic losses at larger scale rather than a fundamental site difference.

Given Meteonorm's stated ±6.1% interannual uncertainty (PVsyst SA, n.d.), the 42 kWh/year (0.22%) nominal difference between the β=5° and β=10° peaks is statistically indistinguishable ($z \approx 0.03$, far below any conventional significance threshold). Figure 6 shows the resulting uncertainty bands overlapping substantially across the entire 0°–30° range, confirming this at the absolute level. This range should therefore be read as a plateau rather than a single sharp optimum; the ranking between angles is nonetheless far more stable than the absolute values, since interannual irradiation variability is a common-mode effect that shifts all tilt angles in the same direction simultaneously. The 5°–10° range is consistent with the 5.71° theoretical optimum from Equation (3) (Wibisono & Setiawan, 2015) and with the latitude-based rule of thumb (Ben Mansour et al., 2021) — a convergence across three independent methods that strengthens confidence in this recommendation for the Gowa site specifically.

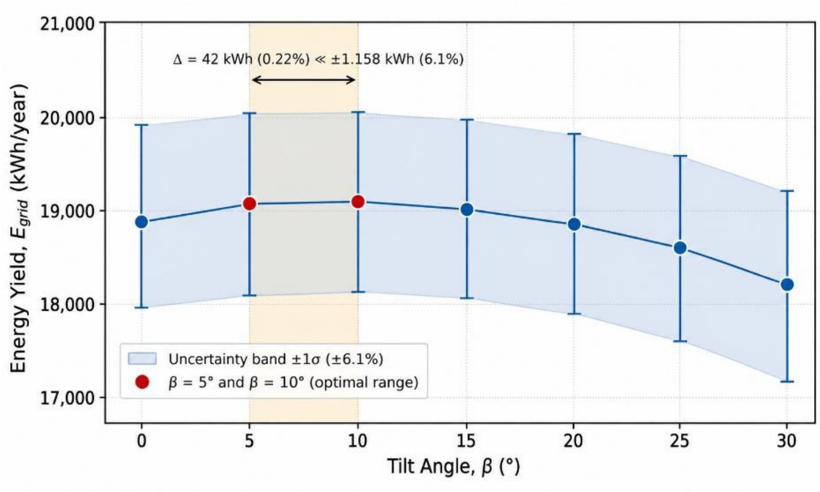

Figure 5. Energy Yield (E_grid) versus tilt angle β with ±1σ (±6.1%) uncertainty bands (Meteonorm interannual variability; PVsyst SA, n.d.).

Figure 7 shows PR increasing slightly with tilt angle (82.27% at 10° to 82.47% at 30°) even as Energy Yield declines — an apparent contradiction explained by Equation (2): plane-of-array irradiation (H_t) falls faster than E_grid at steeper angles, raising the PR ratio even as absolute output drops. PR is therefore a measure of system efficiency relative to available resource, not of absolute productivity, and should not be used alone to select a design tilt angle.

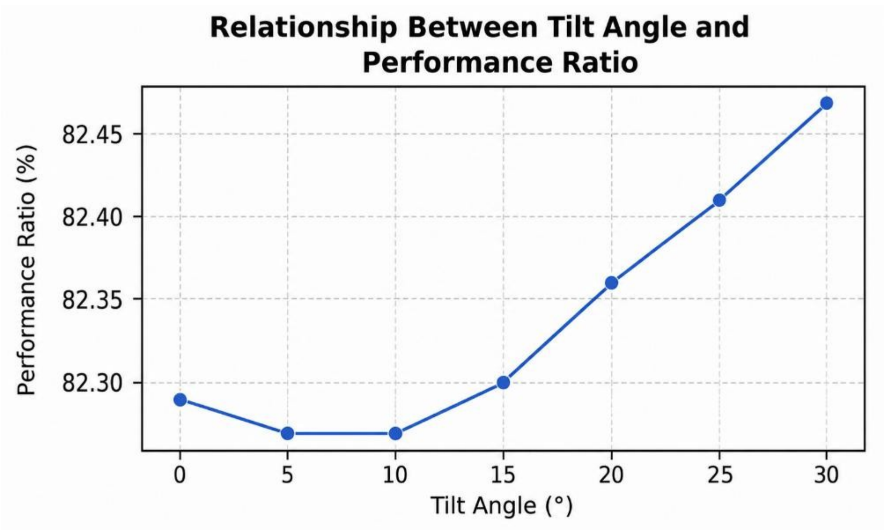

Figure 6. Performance Ratio (PR) versus tilt angle β, calculated per IEC 61724-1:2021

At β=10°, the system is estimated to avoid approximately 17,092 kgCO_2/year in emissions (using South Sulawesi's grid emission factor of 0.84–0.95 tCO_2/MWh; Direktorat Jenderal Ketenagalistrikan ESDM, 2019) and to save an estimated IDR 17.6–28.9 million/year in electricity costs, depending on the applicable PLN tariff category (Kementerian ESDM, 2026) — a modest but consistent improvement over the 0° configuration (Table 4). Against an interpolated capital cost estimate of roughly IDR 124–137 million for a system this size — based on three comparable published Indonesian PLTS installations of varying scale (Fachruroji et al., 2024; Jannah et al., 2023; Yunesti et al., 2025) — this implies a simple payback period of approximately 4.3–7.8 years, broadly consistent in order of magnitude with the 15-year discounted payback reported for a smaller 6.05 kWp system in Lampung (Yunesti et al., 2025); this CAPEX estimate is indicative only and should be confirmed via vendor quotation. Monthly production at β=10° peaked in August (1,930 kWh) and was lowest in February (1,158 kWh), reflecting Gowa's seasonal irradiation pattern.

Table 4. Estimated Economic and Environmental Impact at Selected Tilt Angles

β (°)	E_grid (kWh/yr)	CF (%)	Est. Electricity Savings (IDR/yr)*	CO_2 Reduction (kg/yr)
0	18,804	17.42	17,393,700 – 28,636,236	16,923
5	18,949	17.56	17,527,825 – 28,857,053	17,054
10	18,991	17.60	17,566,675 – 28,921,014	17,092

Lower bound uses the S-2/TM social tariff (IDR 925/kWh); upper bound uses the P-2/TM government tariff (IDR 1,522.88/kWh), effective Q3 2026 (Kementerian ESDM, 2026). The applicable tariff category should be confirmed directly with Unhas for a precise figure; values here are indicative.

CONCLUSION

This study set out to determine the optimal tilt angle for a rooftop on-grid PLTS at Hasanuddin University's Engineering Campus in Gowa. PVsyst simulation, validated against IEC 61724-1:2021 (Equations 1–2), identifies 5°–10° as the recommended range, yielding 18,949–18,991 kWh/year — statistically equivalent given Meteonorm's ±6.1% uncertainty — with a Performance Ratio of 82.27–82.30% and a Specific Yield of up to 1,541 kWh/kWp/year at the simulated peak (β=10°). This recommendation is reinforced by convergence across three independent methods: PVsyst simulation, the Wibisono and Setiawan (2015) empirical equation (β_{opt} = 5.71°, Equation 3), and the latitude-based rule of thumb (Ben Mansour et al., 2021) — indicating the result reflects genuine site conditions at Gowa rather than a single method's artifact, and directly answering this study's central question of where the optimal tilt angle lies for this system.

Beyond the tilt angle itself, the analysis shows system losses are dominated by temperature effects (10.82%) rather than inverter or wiring losses, consistent with Gowa's tropical climate, and that Performance Ratio alone is an unreliable guide to the best tilt angle, since it can rise even as absolute Energy Yield falls. At the recommended configuration (β=10°), the system is projected to avoid 17,092 kgCO_2/year in emissions and save approximately IDR 17.6–28.9 million/year in electricity costs, with an estimated simple payback of 4.3–7.8 years — together indicating the proposed design is both technically sound and practically worthwhile. Practitioners planning similar rooftop PLTS systems in South Sulawesi are advised to adopt a 5°–10° tilt with north-facing orientation for comparable configurations. Field validation, azimuth co-optimization, commercial panel modeling, and a full economic feasibility analysis (NPV, IRR) are recommended as follow-up work

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