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Performance Evaluation of a 1.5 MW Ground-Mounted PV System at PLTGU Grati Using Measured Data and PVsyst Simulation with Consideration of Local Albedo Effects on Inverter Performance

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ABSTRACT

This study evaluates the performance of a 1.5 MW ground-mounted photovoltaic (PV) system installed at PLTGU Grati, Indonesia, using measured operational data and PVsyst simulation. Based on the 2025 dataset, the PV system achieved an annual energy production of approximately 2.32 GWh, slightly exceeding the simulated output of 2.28 GWh, with a positive deviation of about 1.7%, while monthly deviations range from approximately +18% to –24% due to environmental variability. The system demonstrated stable performance with an average performance ratio (PR) of approximately 80.6% and a capacity factor (CF) of around 17.7%, indicating efficient operation under tropical conditions. Furthermore, the influence of ground surface albedo on inverter performance is observed, where higher-reflectivity surfaces such as white gravel ($\approx 0.30\text{--}0.45$) provide greater reflected irradiance compared to soil ($\approx 0.12\text{--}0.18$) and vegetation ($\approx 0.20\text{--}0.25$), contributing to output variations of approximately 5–10% at the inverter level. These findings highlight the importance of incorporating local environmental factors, particularly albedo and surface characteristics, to improve the accuracy of PV system performance evaluation and modeling.

1. Introduction

Renewable energy has become a key strategy to meet the increasing global electricity demand while reducing greenhouse gas emissions and mitigating climate change impacts [1]. The growing concern over environmental sustainability and the depletion of fossil fuel resources has accelerated the global transition toward cleaner energy systems. Among various renewable technologies, solar energy is one of the most widely developed sources due to its abundant availability, scalability, and applicability across different geographical regions [2]. Solar energy can be harnessed through several technologies, with photovoltaic (PV) systems being the most widely implemented for direct electricity generation. PV modules operate based on the photoelectric effect, where photons striking semiconductor materials generate electron–hole pairs that produce direct current electricity [3].

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The Gas and Steam Power Plant (PLTGU) Grati, located in Pasuruan Regency, East Java, is an important combined-cycle power plant within the Java–Bali interconnected power system. A 1.5 MW ground-mounted photovoltaic system has been installed within the plant area to support the facility’s internal electricity demand as part of efforts to increase the contribution of renewable energy in conventional power generation environments [4]. The energy output of PV systems is influenced by several technical and environmental factors, including solar irradiance, module temperature, tilt angle, azimuth angle, shading conditions, and system configuration [5]. Variations in these parameters may lead to discrepancies between simulated results and actual energy production due to system losses and environmental dynamics.

In addition to technical factors, environmental conditions surrounding the installation site [6] also affect PV system performance, particularly through ground surface albedo, defined as the fraction of incident solar radiation reflected by a surface [7]. Surfaces such as gravel or rocky areas typically exhibit higher albedo than soil or grass, influencing the reflected irradiance received by PV modules [8]. Previous studies in Indonesia generally focus on performance indicators such as Performance Ratio (PR), Capacity Factor (CF), and specific yield, while studies examining the localized impact of ground surface albedo on inverter performance remain limited. Therefore, this study analyzes the performance of the 1.5 MW ground-mounted PV system at PLTGU Grati by comparing actual energy production data with simulation results obtained from PVsyst, and by evaluating the influence of ground surface albedo variations on inverter performance. The position of this study relative to previous research is summarized in Table 1.

Table 1

State of Art

Author (Year)	Location and PV Capacity	Research Focus	Key Findings	Ref.
Hutagalung et al. (2023)	Jakarta, Rooftop PV 463.25 kWp	Analysis of energy production and PV system performance	The annual energy production reached approximately 570,724 kWh, with a performance ratio (PR) of about 72% and a capacity utilization factor (CUF) of around 14%.	[9]
PV-TEG Study (2023)	Indonesia, Experimental PV system	Analysis of thermal effect on PV performance	The study shows that module temperature significantly affects PV efficiency, and cooling methods can improve energy output performance.	[10]
Bifacial PV Study (2025)	Bandung, Outdoor PV system	Analysis of solar irradiance and environmental effects	The results indicate that solar irradiance and environmental conditions strongly influence PV output under tropical outdoor conditions.	[11]
Orientation Study (2025)	Tropical region (Indonesia), PV system	Analysis of PV orientation and tilt configuration	The study demonstrates that panel orientation and tilt angle significantly affect energy yield and system performance.	[12]
This Study	PLTGU Grati, PV system 1.5 MWp	Analysis of energy production and albedo effect	Analysis of actual energy production and comparison of the albedo effect between rocky surfaces and soil/grass surfaces on PV system performance.	—

2. Methodology

This chapter describes the research methodology, including PVsyst modeling, data analysis, and comparison between simulated and measured results to evaluate the effect of albedo on PV system performance. The procedure is illustrated in Figure 1.

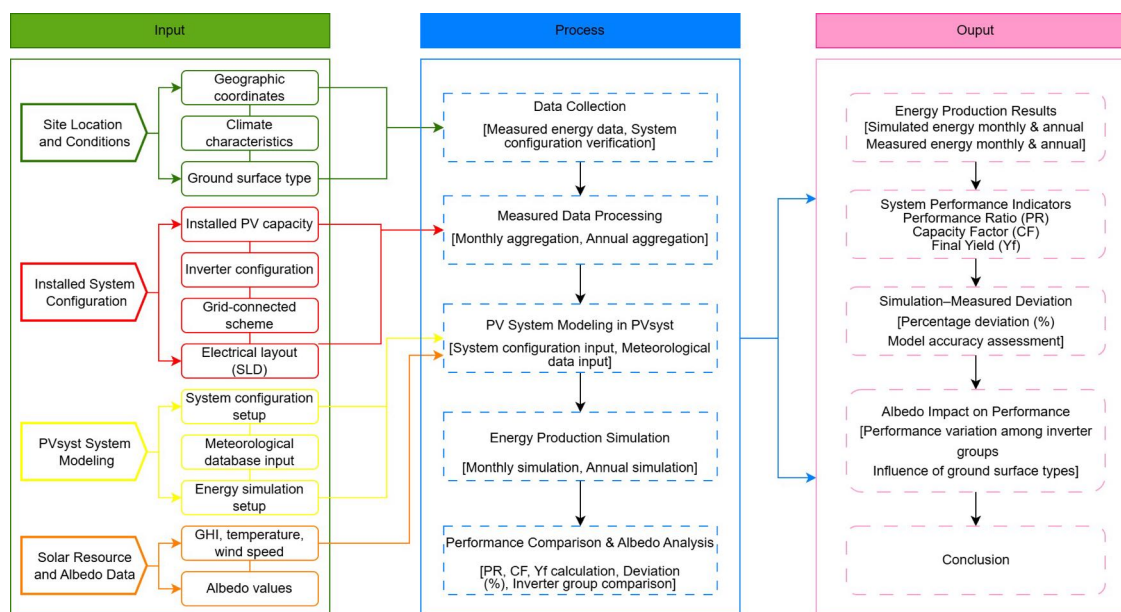


Fig. 1. Flowchart Diagram

2.1 Site Description of PLTS Landbase at PLTGU Grati

The study was conducted at the PLTS Landbase within the PLTGU Grati complex in Pasuruan Regency, East Java, Indonesia. PLTGU Grati is part of the Java–Bali interconnected power system supplying electricity to Indonesia’s most densely populated regions. The site is located at approximately 7°38′54.21″ S latitude and 113°27′ E longitude in a tropical coastal region with high solar irradiance and low seasonal variability, making it suitable for photovoltaic (PV) generation. The PV system is installed on open land within the power plant complex to minimize shading and ensure optimal solar exposure. The dominant surface types around the PV arrays include white stone (gravel), soil, and grass, which are relevant for albedo analysis due to their different reflectance characteristics. The site layout is shown in Figure 2, while the main characteristics are summarized in Table 2.



Fig. 2. Geographic location of the PLTS Landbase

Table 2
General Site Characteristics

Parameter	Description
Location	PLTGU Grati, Pasuruan Regency, East Java, Indonesia
Geographic Coordinates	7°38'54.21" S; 113°27' E
Elevation	± 0–50 m above sea level
Climate Type	Tropical
Average Solar Irradiance	High annual irradiance (typical tropical region)
Installation Area Condition	Open land within power plant complex
Dominant Surface Types	White stone, soil, and grass

2.2 Electrical Configuration Based on the Single Line Diagram

The electrical configuration of the PV system installed at PLTS Landbase within the PLTGU Grati complex is illustrated in the Single Line Diagram (SLD) shown in Figure 3. The diagram presents the main components and the overall power flow of the system. Electrical energy generated by the photovoltaic (PV) modules in the form of direct current (DC) is first delivered to the string inverters, where it is converted into alternating current (AC) at a voltage level of 0.4 kV. The AC output from multiple inverters is then aggregated through the low-voltage distribution system and transmitted to a step-up transformer rated at 0.4/6.3 kV. This transformer increases the voltage level to match the medium-voltage distribution network within the power plant, allowing the PV system to be synchronized with the existing grid infrastructure and ensuring stable power delivery.

The main technical specifications of the PLTS Landbase system are summarized in Table 3. The photovoltaic system has an installed capacity of 1.5 MWp and operates as a grid-connected system without energy storage. The system utilizes twelve string inverters rated at 100 kW each, resulting in a total inverter capacity of 1.2 MW. The difference between the installed PV capacity and the inverter capacity indicates the implementation of a DC/AC ratio greater than one, which is a common design approach in photovoltaic systems. This strategy allows the inverter to operate closer to its optimal efficiency range for longer periods during the day. As a result, the system can capture more solar energy during low and moderate irradiance conditions, thereby improving inverter utilization and increasing the overall annual energy yield of the PV plant.

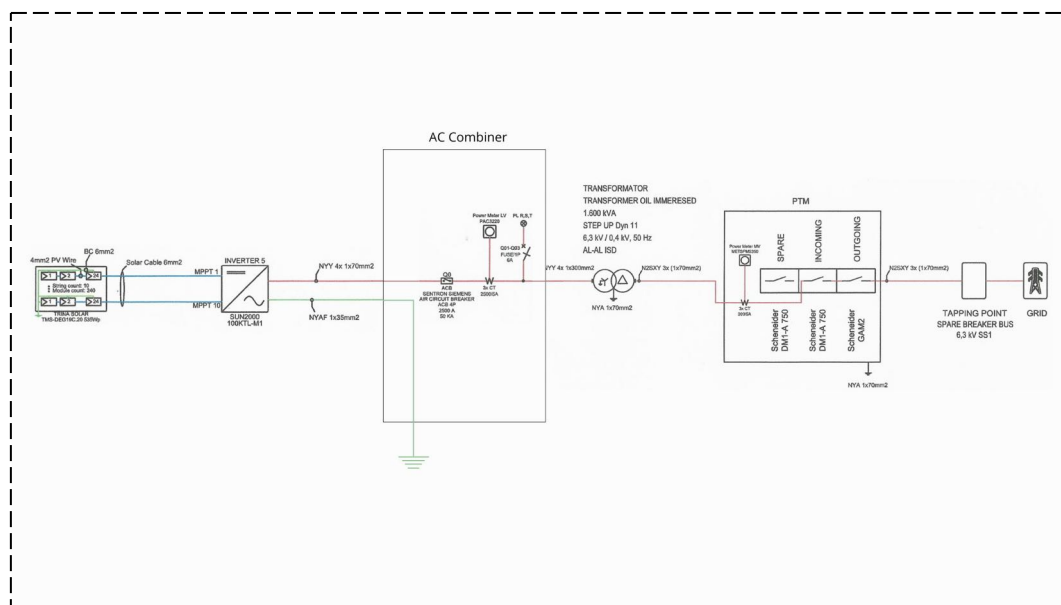


Fig. 3. Single Line Diagram (SLD) of the grid-connected PV system at PLTS Landbase

Table 3

Main technical specifications of the PLTS Landbase photovoltaic system

Parameter	Specification	Parameter	Specification
Installed PV Capacity	1.5 MWp	DC/AC Ratio	1.25
Total Inverter Capacity	1.2 MW	Inverter Type	String inverter
Number of Inverters	12 units	Inverter Output Voltage	0.4 kV
Inverter Rating	100 kW per unit	Nominal Frequency	50 Hz
System Type	Grid-connected (On-grid)	Transformer Type	Step-up
Transformer Rating	0.4 / 6.3 kV	Grid Connection Level	6.3 kV (MV)
Grid Integration	Plant Internal Grid	Energy Storage	Not installed

2.2 Basic Theory of Surface Albedo

Solar radiation received by a photovoltaic (PV) system consists of several components, mainly direct radiation and diffuse radiation. Direct radiation refers to solar energy that travels directly from the sun to the PV module without atmospheric scattering and generally represents the largest contribution to total irradiance under clear-sky conditions. In contrast, diffuse radiation results from the scattering of solar radiation by atmospheric particles such as clouds, water vapor, and aerosols. As illustrated in Figure 4, both direct and diffuse radiation contribute to the total solar energy received by the PV module.

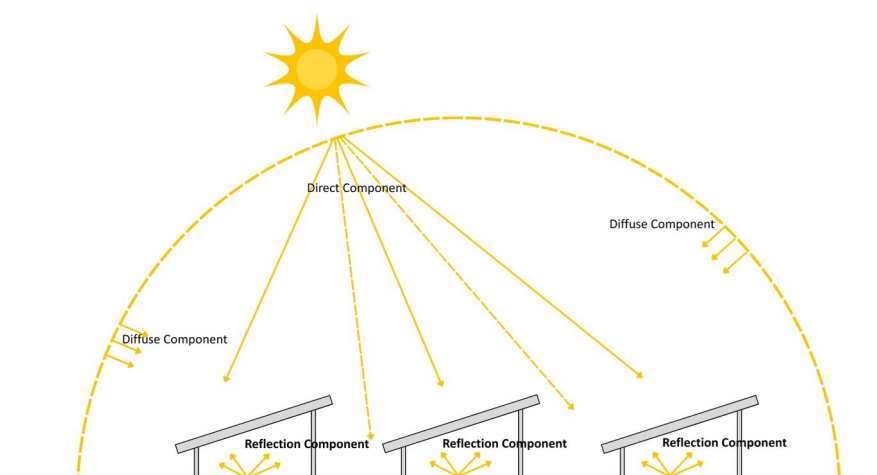


Fig. 4. Illustration of solar radiation components on a photovoltaic module

In addition to these components, PV modules may also receive radiation reflected from the surrounding ground surface, known as ground-reflected radiation. As shown in Figure 4, a portion of the solar radiation reaching the ground is reflected back toward the PV module depending on the reflectivity characteristics of the surface. The ability of a surface to reflect solar radiation is described by the albedo parameter. Mathematically, the albedo value can be expressed as follows eq (1).

$$\alpha = \frac{I_{reflected}}{I_{incident}} \quad (1)$$

where α represents the surface albedo (dimensionless), $I_{reflected}$ is the intensity of solar radiation reflected by the ground surface (W/m^2), and $I_{incident}$ is the intensity of solar radiation incident on the surface (W/m^2). Albedo values range from 0 to 1, where higher values indicate greater surface reflectivity.

2.3 Inverter Grouping and Ground Surface Conditions

The photovoltaic (PV) installation is divided into twelve inverter groups distributed across several ground surface types within the project site. These surfaces include vegetated areas, white gravel, bare soil, and heterogeneous ground conditions, indicating that the PV system is installed on non-uniform terrain. Variations in ground surface characteristics can influence the local albedo and thermal behavior of the surrounding environment, which may affect PV module operating temperature and electrical performance [13]. As illustrated in Figure 5, the layout shows the spatial distribution of Inverter 01 to Inverter 12 using boundary markings and color differentiation, indicating how each inverter group corresponds to specific ground surface zones across the site.

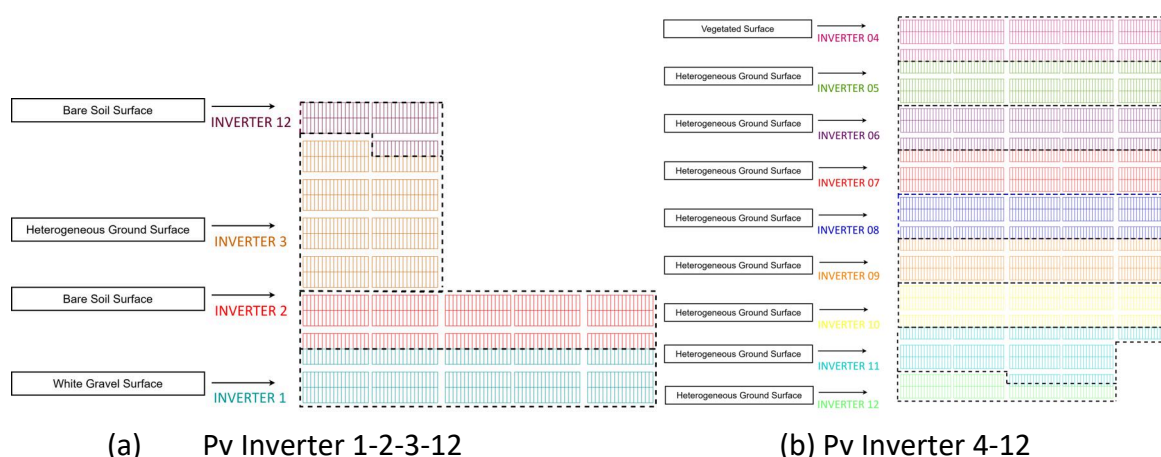


Fig. 5. Layout inverter grouping and surface conditions

The actual ground surface conditions are presented in Figure 6, which shows photographic documentation of several representative inverter locations. The white gravel surface appears bright and highly reflective, while the vegetated surface is covered with grass that provides natural shading and cooling effects. In contrast, the bare soil area exhibits darker tones indicating higher heat absorption, whereas the heterogeneous surface displays mixed textures consisting of soil, sparse vegetation, and compacted ground. These visual differences confirm the presence of distinct surface characteristics that may contribute to variations in reflected irradiance and localized thermal conditions around the PV arrays, which can influence photovoltaic system performance [14].



(a) White gravel



(b) Bare soil



(c) Vegetated surface



(d) Heterogeneous surface

Fig. 6. Ground surface conditions at the PLTS Landbase site

2.4 Albedo Characteristics and Multi-Level Analysis of Photovoltaic Systems

Variations in ground surface characteristics across the photovoltaic (PV) plant result in different reflectivity levels that may influence PV system performance [15]. In this study, the analysis focuses on four selected inverters—Inverter 01, Inverter 02, Inverter 04, and Inverter 05—each representing distinct ground surface conditions with different albedo characteristics. Differences in ground reflectivity affect the amount of reflected irradiance received by the PV modules and may consequently influence the electrical output of the PV array. Each inverter is connected to ten PV strings, with 24 modules per string. It should be noted that surface albedo is not constant and can vary depending on environmental conditions. Under clear and dry conditions, bare soil tends to exhibit higher reflectivity due to reduced moisture content, whereas vegetated surfaces generally absorb more radiation due to canopy characteristics [16]. The classification of ground surface types, albedo ranges, and PV configuration associated with each inverter are summarized in Table 4.

Table 4

Ground Surface and PV Configuration

Inverter	Strings	Modules	Surface Type	Nominal Albedo	Dry Condition	Category
INV-01	10	24	White gravel	0.30–0.45	—	High
INV-02	10	24	Bare soil	0.12–0.18	0.20–0.30	Moderate
INV-04	10	24	Vegetated	0.20–0.25	0.15–0.25	Moderate
INV-05	10	24	Mixed surface	0.15–0.30	0.15–0.35	Mixed

In addition to evaluating inverter-level energy production, this study also performs a detailed electrical analysis at the PV string level to observe the response of PV modules under different ground surface conditions. Therefore, this study applies two complementary analytical approaches to evaluate the effect of ground surface albedo, namely inverter-level analysis based on AC energy production and string-level analysis based on DC electrical parameters. For consistency in the comparison, one representative string containing 24 PV modules is selected from each inverter. Both inverter output data and PV string electrical parameters, including DC voltage and current, are analyzed to assess the influence of ground albedo on system performance. The DC power of each selected PV string is calculated using the basic electrical relationship between voltage and current as follows eq (2):

$$P = V \times I \quad (2)$$

where P represents the DC power (W), V is the DC voltage (V), and I is the DC current (A). The detailed observation scheme, including the selected PV string, data level, and observation time for each inverter, is presented in Table 5. As shown in Table 5, both inverter-level and string-level data are collected simultaneously from each selected inverter, and all observations are conducted at three representative daytime periods, approximately at 10:00, 12:00, and 14:00 local time, to ensure comparable solar irradiation conditions.

Table 5

Inverter and PV String Observation Scheme

Inverter	Data Level	Selected String	Modules/String	Observation Time (LT)
INV-01	Inverter & String	String 01	24	10:00, 12:00, 14:00
INV-02	Inverter & String	String 01	24	10:00, 12:00, 14:00
INV-04	Inverter & String	String 01	24	10:00, 12:00, 14:00
INV-05	Inverter & String	String 01	24	10:00, 12:00, 14:00

2.5 Technical Specifications of System Components

The technical specifications of the photovoltaic modules and grid-connected string inverters define the system configuration and serve as key input parameters for PV system modeling in PVsyst.

2.5.1 Photovoltaic Module Specifications

The land-based PV system at PLTGU Grati has a total installed DC capacity of 1.5 MWp, consisting of approximately 2,804 monocrystalline photovoltaic modules of type Trina Solar TSM-535DE19C.20 with a nominal power rating of 535 Wp per module. The technical specifications of the photovoltaic modules used in this system are presented in Table 5. Each module has a voltage at maximum power (V_{mp}) of approximately 37.16 V and a current at maximum power (I_{mp}) of about 14.4 A, with an open-circuit voltage (V_{oc}) ranging from 44–49 V and a short-circuit current (I_{sc}) of approximately 15–18 A. The maximum system voltage of 1500 VDC enables high-efficiency string configurations and reduces DC-side power losses. These parameters form the basis for array configuration design and were used as input data in PVsyst software for energy production modeling and system performance evaluation.

Table 5

Photovoltaic Module Specifications

Parameter	Value
Brand / Type	Trina Solar TSM-535DE19C.20
Maximum Power (P_{max})	535 Wp
Voltage at Maximum Power (V_{mp})	±37.16 V
Current at Maximum Power (I_{mp})	±14.4 A
Open Circuit Voltage (V_{oc})	±44–49 V
Short Circuit Current (I_{sc})	±15–18 A
Maximum System Voltage	1500 VDC
Cell Type	Monocrystalline
Installed Quantity	±2,804 modules
Total Installed Capacity (DC)	1.5 MWp

2.5.2 Inverter Specifications

The DC-to-AC energy conversion process is carried out using Huawei SUN2000-100KTL-M1 inverters with a nominal power rating of 100 kW per unit. The technical specifications of the inverter are summarized in Table 6. A total of 12 inverter units are installed in the system, resulting in a total AC installed capacity of 1.2 MW. The inverter features an MPPT voltage range of 200–1000 VDC and a maximum input voltage of 1100 VDC, ensuring compatibility with the module string voltage characteristics. The system operates on a three-phase 380/400 V network at a frequency of 50 Hz in accordance with national electrical standards. The ratio between the DC installed capacity (1.5 MWp) and the AC installed capacity (1.2 MW) indicates a DC/AC ratio of approximately 1.25, which is commonly applied in PV system design to optimize annual energy production and improve inverter utilization.

Table 6

Inverter Specifications

Parameter	Value
Brand / Type	Huawei SUN2000-100KTL-M1
Nominal Output Power	100 kW
Maximum Apparent Power	110 kVA
Maximum Input Voltage	1100 VDC
MPPT Voltage Range	200 – 1000 VDC
AC Output Voltage	380/400 V (3-phase)
Operating Frequency	50/60 Hz
Maximum Output Current	±168 A (380 V)
Protection Rating	IP66
Installed Quantity	12 units
Total Installed Capacity (AC)	1.2 MW

2.6 Solar Energy Resources

In this study, two different sets of solar radiation data were utilized based on the specific objectives of the analysis. The 2025 dataset was used to evaluate the annual energy production of the 1.5 MWp PV system, as complete monthly operational data were available at the plant level. This dataset represents the overall performance of the PV system during one full year of operation. Meanwhile, the 2026 dataset was used specifically for inverter-level albedo analysis because detailed irradiation and energy production data were available for several inverters installed over different ground surface types during that period. The separation of these data periods ensures methodological consistency, allowing both the annual energy performance assessment and the albedo impact analysis to be conducted using the most relevant and technically appropriate datasets.

2.6.1 Annual Solar Radiation Characteristics in 2025

The annual solar radiation characteristics were analyzed using on-site monitoring data recorded from January to December 2025. This dataset serves as the basis for evaluating the overall annual energy production of the 1.5 MWp PV system. The analyzed parameters include global horizontal irradiation (GlobHor), diffuse horizontal irradiation (DiffHor), plane-of-array irradiation (GlobInc), effective irradiation (GlobEff), ambient temperature, array energy output, energy injected into the grid, and performance ratio (PR). The total annual global horizontal irradiation reached 1908.5

kWh/m²/year, with an average ambient temperature of 28.10°C and an annual performance ratio of 0.779, indicating stable and consistent system performance throughout 2025.

Table 7

Annual Solar Radiation and Energy Production Data in 2025 (On-Site Monitoring)

Month	GlobHor (kWh/m ²)	DiffHor (kWh/m ²)	T_Amb (°C)	GlobInc (kWh/m ²)	GlobEff (kWh/m ²)	EArray (MWh)	E_Grid (MWh)	PR
Jan	126.0	83.61	27.70	120.7	109.1	147.9	142.2	0.782
Feb	124.9	82.43	27.45	121.9	110.5	149.4	143.7	0.783
Mar	145.1	93.58	27.83	145.4	131.9	178.0	171.2	0.782
Apr	145.8	75.05	28.24	150.7	137.3	183.9	176.7	0.778
May	162.4	69.53	28.64	175.2	159.4	213.4	205.2	0.778
Jun	159.8	58.43	27.59	176.1	160.1	215.2	207.0	0.780
Jul	168.5	60.44	27.60	184.1	167.6	224.9	216.2	0.779
Aug	175.8	74.30	27.59	186.1	170.1	227.9	219.1	0.781
Sep	174.0	78.81	28.08	177.6	162.4	216.4	208.0	0.777
Oct	183.5	95.13	29.22	180.8	165.1	219.7	211.2	0.775
Nov	198.8	85.84	28.83	189.7	173.5	230.9	221.9	0.777
Dec	143.7	87.37	28.32	136.5	123.6	166.8	160.5	0.780
Annual	1908.5	944.51	28.10	1944.7	1770.7	2374.4	2282.8	0.779

2.6.2 2026 Irradiation Data for Inverter-Level Albedo Analysis

The inverter-level albedo analysis was conducted using irradiation data from 2026, as detailed energy production data were available for selected inverters installed over different ground surface types during that period. To ensure consistent radiation conditions during the comparative evaluation, a representative month was selected as the analysis basis, namely March 2026. This month was chosen due to its relatively high irradiation level and stable performance ratio, thereby minimizing seasonal bias in assessing the influence of ground reflectance on inverter energy production.

Table 8

Representative Irradiation Conditions for Albedo Analysis (March 2026)

Parameter	Value	Unit
Global Horizontal Irradiation (GlobHor)	145.1	kWh/m ²
Diffuse Horizontal Irradiation (DiffHor)	93.58	kWh/m ²
Plane-of-Array Irradiation (GlobInc)	145.4	kWh/m ²
Effective Irradiation (GlobEff)	131.9	kWh/m ²
Ambient Temperature (T_Amb)	27.83	°C
Performance Ratio (PR)	0.782	–

2.7 Performance Ratio (PR) and Capacity Factor (CF)

The performance evaluation of grid-connected photovoltaic (PV) systems requires standardized and size-independent indicators to ensure objective comparison under different environmental conditions. Performance Ratio (PR) and Capacity Factor (CF) are widely adopted metrics to quantify system efficiency and utilization level. The combined assessment of these indicators provides a comprehensive representation of technical performance and operational effectiveness.

2.7.1 Performance Ratio (PR)

Performance Ratio (PR) is a dimensionless indicator that represents the ratio between the actual AC energy output and the theoretical energy yield based on available solar irradiation under standard reference conditions. This parameter inherently accounts for aggregated system losses, including thermal losses, inverter conversion losses, mismatch effects, wiring losses, and soiling. As a location-independent metric, PR is commonly used to evaluate the overall quality of PV system performance[17].

$$PR = \frac{Y_f}{Y_r} \quad (3)$$

where Y_f denotes the final yield and Y_r represents the reference yield derived from plane-of-array irradiation under standard test conditions.

2.7.2 Capacity Factor (CF)

Capacity Factor (CF) quantifies the extent to which the installed generation capacity is effectively utilized over a specified operational period. Unlike PR, CF is influenced by both system efficiency and local solar resource availability, thereby reflecting actual annual productivity. This indicator is particularly useful for comparing energy generation performance with other power generation technologies[18].

$$CF = \frac{E_{AC}}{P_{rated} \times T} \quad (5)$$

where E_{AC} is the total AC energy output, P_{rated} is the rated system capacity, and T is the total operating hours within the evaluation period.

2.8 PVsyst Modeling and Energy Production Analysis

The energy production modeling of the 1.5 MW ground-mounted photovoltaic (PV) system was conducted using PVsyst to estimate the expected monthly and annual AC energy output under site-specific conditions [19]. The simulation model was configured based on the actual system specifications, including 1.5 MWp installed DC capacity, 1.2 MW total inverter capacity, a DC/AC ratio of 1.25, and a grid-connected operational scheme without energy storage. Meteorological input data were obtained from the Meteonorm 8.2 database to represent the local solar irradiation and ambient temperature characteristics of the PLTGU Grati site [20]. The array orientation was defined with an approximate tilt angle of 10° and azimuth of 0° (north-facing in PVsyst convention), which is suitable for the southern hemisphere location. The simulation outputs, including AC energy production and specific yield (kWh/kWp), were used as baseline references for subsequent comparison with measured operational data [21]. The key PVsyst simulation input parameters used in this study are summarized in Table 9.

Table 9
Key PVsyst Simulation Input Parameters

Parameter	Value	Description / Source
Installed DC Capacity	1.5 MWp	Actual system specification
Total AC Capacity	1.2 MW	12 × 100 kW inverters
DC/AC Ratio	1.25	System design configuration
Inverter Type	Huawei SUN2000-100KTL-M1	Section 2.4.2
Module Type	Trina Solar TSM-535DE19C.20	Section 2.4.1
Tilt Angle	10° (approx.)	Site observation
Azimuth	0° (North-facing)	Southern hemisphere orientation
Meteo Data Source	Meteonorm 8.2	PVsyst database
System Type	Grid-connected	No energy storage

2.9 Comparative Analysis and Model Validation

This study applies a quantitative comparative approach to evaluate both annual plant-level performance and inverter-level performance under varying ground surface conditions. Two operational datasets are used: the 2025 dataset for annual plant-level energy performance evaluation and the 2026 dataset for inverter-level albedo assessment. Simulated energy production generated using PVsyst under identical system configuration parameters is used as the reference model [22]. Measured AC energy output is obtained from the inverter monitoring system accessed through the plant’s web-based operational monitoring platform.

Comparative analysis is conducted by evaluating measured AC energy against simulated AC energy to assess model accuracy and identify performance deviations potentially associated with ground surface reflectance differences [23]. Four representative inverters are selected based on distinct surface characteristics: Inverter 01 (white gravel), Inverter 02 (bare soil), Inverter 04 (vegetated surface), and Inverter 05 (heterogeneous surface). Key performance indicators—including Performance Ratio (PR), Capacity Factor (CF), and Yield Factor (YF)—are calculated and compared [24]. Model validation is performed using percentage deviation analysis between simulated and measured AC energy. The core comparative and validation framework applied in this study is summarized in Table 10.

Table 10
Core Comparative and Validation Framework

Component	Description
Research Approach	Quantitative comparative analysis
Dataset (2025)	Annual plant-level performance evaluation
Dataset (2026)	Inverter-level albedo assessment
Simulation Tool	PVsyst
Measured Data Source	Web-based inverter monitoring system
Selected Inverters	Inv-01, Inv-02, Inv-04, Inv-05
Performance Indicators	PR, CF, YF
Validation Method	Percentage deviation (%)

3. Results

3.1 Realized Energy Production

The realized AC energy production of the 1.5 MWp ground-mounted photovoltaic system at the PLTGU Grati during 2025 is illustrated in Figure 3.1. The figure shows a clear seasonal production pattern, with energy generation gradually increasing from the beginning of the year toward the third

quarter before declining toward the end of the year. The system achieved a total annual output of 2.32 GWh, with monthly production consistently remaining above 160 MWh. Peak generation occurred during late dry-season months, particularly in September, while the lowest output was recorded in November. The overall variation between maximum and minimum monthly production reached approximately 57 MWh, indicating moderate seasonal fluctuation typical of tropical irradiation conditions.

As observed in Figure 7, the production curve exhibits a relatively smooth profile without abrupt drops, suggesting high system availability and stable operational performance throughout the monitoring period. The increasing trend toward mid-year reflects improved irradiation conditions, whereas the decline toward year-end corresponds to seasonal climatic transitions. Despite monthly variability, the system maintained consistent energy delivery across all twelve months. This behavior confirms that the PV installation operated reliably under real operating conditions and contributed stable renewable energy to the plant's internal electrical network.

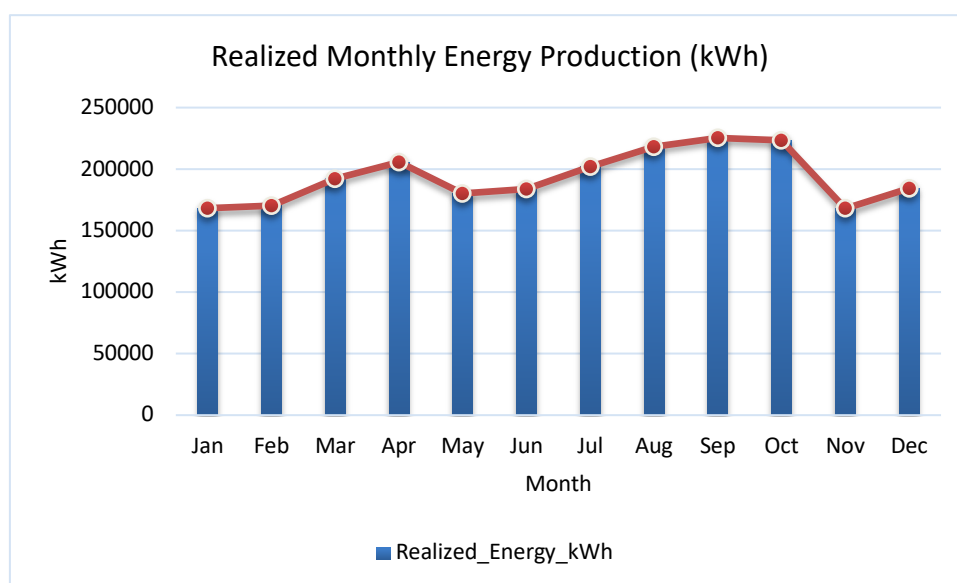


Fig. 7. Monthly Realized AC Energy Production of the 1.5 MWp PV System

3.2 Simulated Energy Production

The simulated energy production of the 1.5 MWp ground-mounted PV system obtained from PVsyst modeling is presented in Figure 8. The model estimated a total annual AC energy output of 2.28 GWh, with monthly production ranging between approximately 142 MWh and 222 MWh. The simulated profile demonstrates a gradual increase in energy generation from the first quarter toward mid-year, followed by moderate fluctuations in the remaining months. The highest simulated production was predicted in November, while the lowest value occurred in January, reflecting seasonal irradiation assumptions embedded in the meteorological database.

As illustrated in Figure 8, the simulated production curve appears smoother compared to typical measured operational data, as it is derived from long-term averaged meteorological inputs rather than site-specific short-term variability. The model predicts relatively stable generation during mid-year months, particularly from May to November, corresponding to higher irradiation levels in the simulation dataset. No extreme monthly deviations are observed in the simulated profile, indicating

consistent system performance under standard design conditions. Overall, the PVsyst results provide a baseline estimation of expected energy production for the installed configuration.

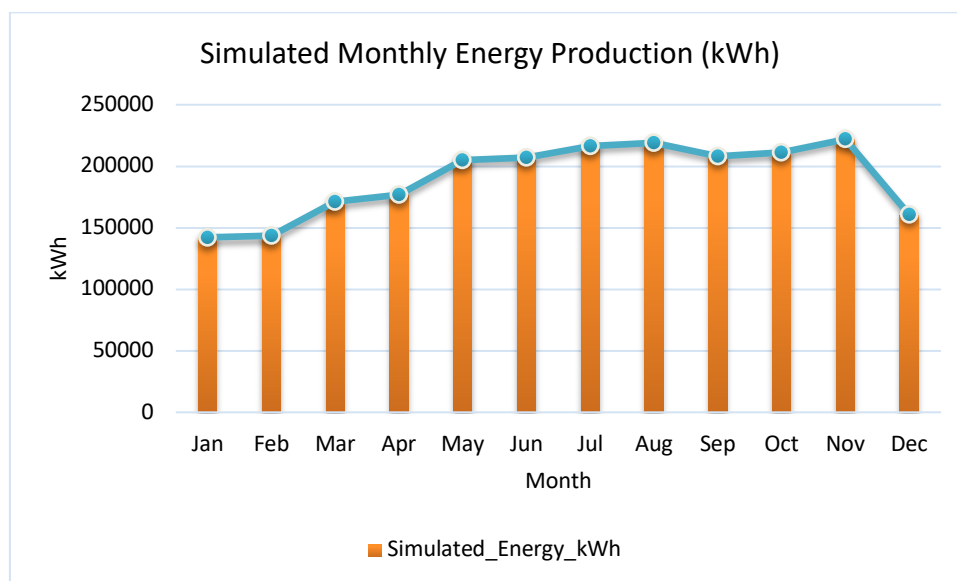


Fig. 8. Monthly Simulated AC Energy Production of the 1.5 MWp PV System

3.3 Comparative Analysis of Realized and Simulated Energy Production

The comparison between measured and simulated monthly AC energy production is presented in Table 11. Overall, the realized annual energy output (2.32 GWh) exceeded the simulated value (2.28 GWh), resulting in a positive deviation of approximately 39 MWh, equivalent to about 1.7% higher than the predicted output. This indicates that the PV system performed slightly better than the design expectation. During the first four months (January–April), measured production consistently surpassed simulation results, suggesting favorable irradiation conditions or lower-than-expected system losses during this period.

Table 11

Comparison of Simulated and Realized Monthly Energy Production

Month	Simulated (kWh)	Realized (kWh)	Deviation (kWh)	Deviation (%)
January	142,200	168,171.64	25,971.64	18.26
February	143,700	170,204.27	26,504.27	18.44
March	171,200	192,188.68	20,988.68	12.26
April	176,700	205,553.61	28,853.61	16.33
May	205,200	180,333.54	-24,866.46	-12.12
June	207,000	183,846.71	-23,153.29	-11.19
July	216,200	202,110.79	-14,089.21	-6.52
August	219,100	218,430.25	-669.75	-0.31
September	208,000	225,342.10	17,342.10	8.34
October	211,200	223,631.06	12,431.06	5.89
November	221,900	167,975.95	-53,924.05	-24.30
December	160,500	184,143.14	23,643.14	14.73
Total	2,282,900	2,321,931.74	39,031.74	1.71

However, deviations are not uniform throughout the year. In May, June, and November, realized production fell below the simulated values, with November showing the most significant negative deviation. Conversely, September and October demonstrated strong positive deviations,

contributing substantially to the annual surplus. As illustrated in Figure 9, the measured curve exhibits greater fluctuation compared to the smoother simulated profile, reflecting real climatic variability and operational factors not fully captured in long-term meteorological modeling. Despite monthly discrepancies, the overall annual agreement between measured and simulated energy confirms the reliability of the PVsyst model for performance estimation of the 1.5 MWp installation.

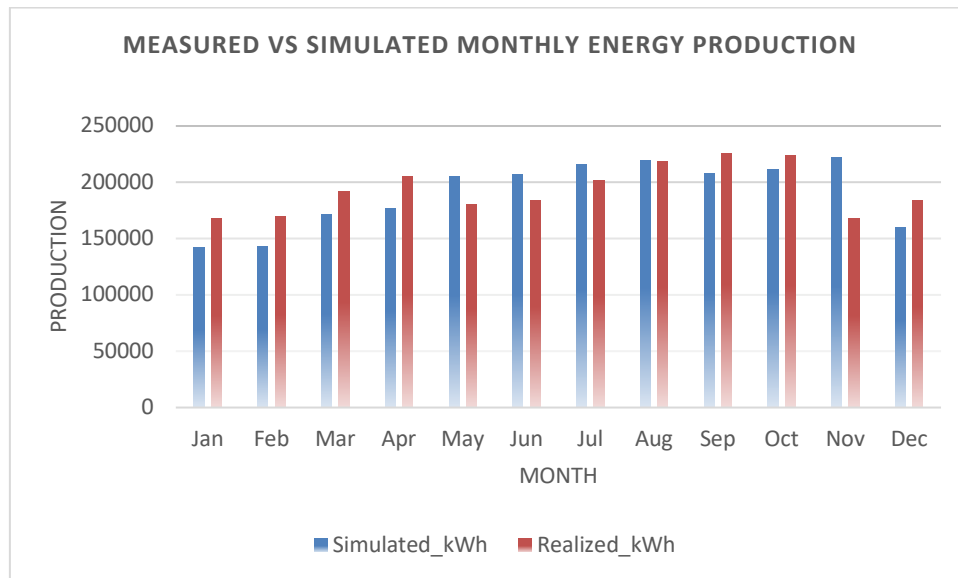


Fig. 9. Grafik Measured vs Simulated Monthly Energy Production

3.4 Factors Affecting Energy Production Variability

The slight difference between the actual energy production and the simulation results is influenced by several field conditions that are not fully represented in the PVsyst model. Based on the annual comparison, the measured energy output of 2.32 GWh is slightly higher than the simulated value of 2.28 GWh, resulting in a positive deviation of approximately 1.71%. As shown in Figure 10(a), the northern-side view indicates that the PV system is installed in an open area, with surrounding trees located outside the boundary fence and at a safe distance from the array rows, resulting in negligible shading losses. Meanwhile, Figure 10(b), which presents the southern-side view, shows that the surrounding area is relatively open with no nearby tall buildings or major obstructions close to the modules, allowing the system to receive optimal solar radiation throughout the day. These field conditions support the slightly higher measured energy production compared to the simulation results.



Fig. 10. Actual field condition of the PV system: (a) northern-side view, (b) southern-side view, showing open-site installation with minimal shading from surrounding trees and nearby structures

As summarized in Table 12, several key factors affecting system performance include the north-facing array orientation with an approximate tilt angle of 10° , minimal shading conditions, adequate airflow beneath the modules, ground surface variation, and module cleaning practices. The wide clearance beneath the modules allows sufficient natural airflow, which helps maintain lower module operating temperatures and stable conversion efficiency. In addition, variations in surface types such as white gravel, soil, and vegetation may produce different albedo values, particularly in the white gravel area, which can increase the reflected irradiance received by the modules. The cleaning practice, which is carried out periodically during prolonged dry periods and naturally assisted by rainfall during cloudy or rainy conditions, also contributes to maintaining stable system performance. The combination of these factors is considered to be the main reason why the measured energy production is slightly higher than the simulation results.

Table 12

Factors Affecting Energy Production Variability

Parameter	Actual Field Condition	Effect on Performance
Array orientation	North-facing, tilt $\pm 10^\circ$	Optimal solar capture
Shading	Minimal, trees at safe distance	Negligible losses
Air circulation	Wide clearance below modules	Lower module temperature
Ground surface	White gravel, soil, vegetation	Albedo variation
Cleaning practice	Periodic in dry periods; rainfall-assisted in wet periods	Stable efficiency

3.5 Capacity Factor and Performance Ratio Analysis

The performance of the 1.5 MWp ground-mounted PV system was evaluated by comparing expected and realized Capacity Factor (CF) as summarized in Table 13. The expected CF varied monthly according to projected irradiation levels, while the realized CF exceeded expectations during the first four months, indicating favorable solar conditions. The highest realized CF occurred in September at 25.24%, surpassing the expected 23.30%, whereas May, June, and November showed lower values of 18.81% compared to 24.85%, reflecting seasonal climatic effects.

A similar trend was observed for the Performance Ratio (PR), which was expected to be constant at 78% based on PVsyst simulation. The realized PR exceeded this assumption in several months,

reaching 92% in January and 93% in February, indicating efficient system operation, but decreased to 59–69% in May, June, and November, consistent with negative production deviations. On an annual basis, the system achieved an average PR of 80.6% and a capacity factor of 17.7%, demonstrating stable, reliable, and efficient performance throughout the year despite monthly environmental and operational variability.

Table 13
Monthly Comparison of Expected and Realized CF and PR

Month	Expected CF (%)	Realized CF (%)	Expected PR (%)	Realized PR (%)
January	15.93	18.84	78	92
February	17.82	21.11	78	93
March	19.18	21.53	78	88
April	20.45	23.79	78	91
May	22.98	20.20	78	68
June	23.96	21.28	78	69
July	24.22	22.64	78	73
August	24.54	24.47	78	78
September	23.30	25.24	78	84
October	23.66	25.05	78	82
November	24.85	18.81	78	59
December	17.98	20.63	78	90

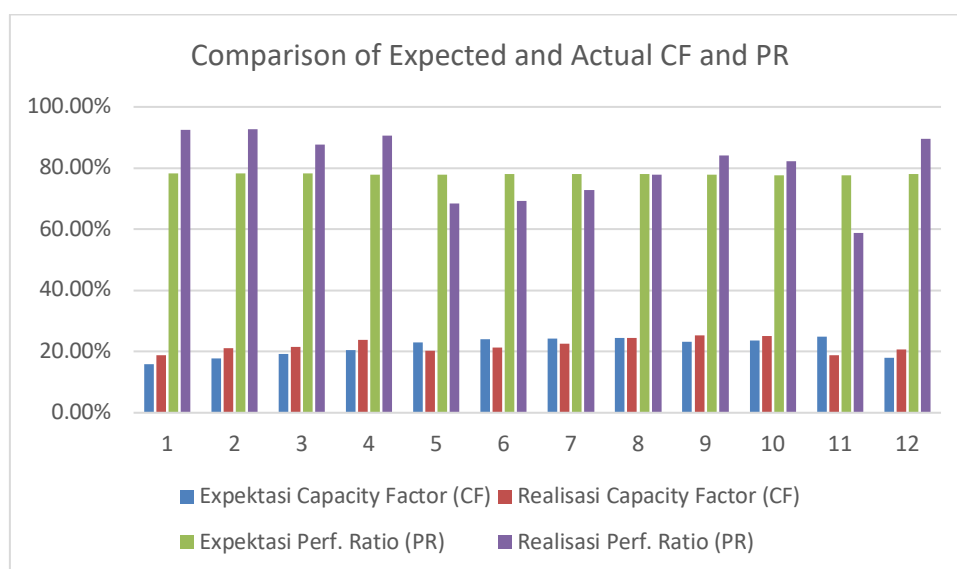


Fig. 10. Comparison of expected and actual Capacity Factor (CF) and Performance Ratio (PR)

3.6 Comparative Analysis of PV Output Based on Ground Surface Type

The inverter active power generated over different ground surface types was analyzed at several observation times, namely 10:00, 12:00, and 14:00 on March 27 and March 30. As presented in Table 14, the results show that the power output generally increases from 10:00 to 12:00 and decreases at 14:00, following the typical daily pattern of solar irradiance. On 27 March, the highest output occurs at 12:00 with 99.432 kW on the gravel surface, followed by soil (97.215 kW), grass (94.604 kW), and mixed surfaces (93.851 kW). A similar trend is observed on 30 March, where the maximum output again occurs at 12:00 with 99.410 kW on the gravel surface, while the other surfaces produce slightly lower values. At 10:00 on both observation days, the power output ranges between approximately

87–93 kW depending on the surface type. By 14:00 on 30 March, the output decreases to around 80–84 kW as solar irradiance gradually declines in the afternoon. These results indicate that the gravel surface consistently produces the highest inverter active power compared to the other surface types.

Table 14

Inverter Active Power at Different Observation Times

Date	Time	Gravel (kW)	Soil (kW)	Grass (kW)	Mixed (kW)
27 Mar	10:00	92.850	90.680	88.120	87.399
27 Mar	12:00	99.432	97.215	94.604	93.851
30 Mar	10:00	93.284	90.932	89.174	88.742
30 Mar	12:00	99.410	97.271	95.261	94.786
30 Mar	14:00	84.340	82.470	81.331	80.752

To further evaluate the influence of surface characteristics, the relative power output of each surface was calculated using the gravel surface as the reference (100%). As shown in Table 15, the soil surface produces approximately 97–98% of the gravel output, while the grass surface ranges between about 95–96%, and the mixed surface between about 94–96%. The results also show that the differences between surfaces remain relatively consistent at different observation times. For example, at 12:00 on both dates, the soil surface reaches around 97–98% of the gravel output, while the grass and mixed surfaces remain below 96%. These findings indicate that although the variations are relatively small, the gravel surface consistently provides slightly higher power output. Overall, the variation in power generation among the surfaces ranges between approximately 2% and 6%, suggesting that surfaces with higher reflectivity may enhance the effective irradiance received by the photovoltaic modules through reflected radiation.

Table 15

Relative Power Output Compared to Gravel Surface

Date	Time	Gravel (%)	Soil (%)	Grass (%)	Mixed (%)
27 Mar	10:00	100%	97.66%	94.91%	94.13%
27 Mar	12:00	100%	97.77%	95.14%	94.39%
30 Mar	10:00	100%	97.48%	95.60%	95.13%
30 Mar	12:00	100%	97.85%	95.83%	95.35%
30 Mar	14:00	100%	97.78%	96.43%	95.75%

3.6 String-Level Analysis of PV Performance under Different Ground Surface Albedo

On 30 March, String 1 of the 1.5 MWp ground-mounted PV system was evaluated across Inverters 1, 2, 4, and 5 at 12:00 and 14:00 to assess the effect of ground surface albedo on voltage and current. As shown in Table 16, at 12:00, Inverter 1 recorded the highest voltage and current (656.3 V, 14.79 A), while Inverter 5 showed lower values (637.5 V, 12.50 A), reflecting realistic variations among inverters due to positioning and resistive losses. By 14:00, voltages and currents decreased across all inverters (Inverter 1: 644.6 V, 13.51 A; Inverter 5: 618.1 V, 13.17 A) as solar irradiance declined, with ΔV ranging from 1.79% to 5.95% and ΔI from 8.63% to 15.52% relative to Inverter 1 at 12:00. These results indicate that higher-albedo surfaces like gravel consistently enhance string-level PV output, while small variations among inverters remain realistic, highlighting the combined influence of surface reflectivity, irradiance fluctuations, and electrical configuration on system performance throughout the afternoon.

Table 16

String-Level Voltage and Current Comparison under Different Ground Surface Conditions (30 March, 12:00–14:00)

Inverter	String	Time	Voltage (V)	Current (A)	V (%)	I (%)
1	1	12:00	656.3	14.79	0	0
1	1	14:00	644.6	13.51	1.79	8.63
2	1	12:00	645.8	13.95	1.61	5.68
2	1	14:00	628.3	13.37	4.46	9.60
4	1	12:00	639.2	12.85	2.61	13.12
4	1	14:00	628.1	13.40	4.38	9.29
5	1	12:00	637.5	12.50	2.86	15.52
5	1	14:00	618.1	13.17	5.95	10.78

4. Conclusions

This study evaluates the performance of a 1.5 MW ground-mounted photovoltaic (PV) system at PLTGU Grati using measured data and PVsyst simulation. The system achieved an annual energy production of 2.32 GWh, slightly exceeding the simulated output of 2.28 GWh, resulting in a positive deviation of approximately 1.7%. This relatively small deviation indicates a strong agreement between the simulation model and actual operating conditions, confirming the reliability of the PVsyst approach for performance estimation. However, monthly deviations ranging from +18% to –24% highlight the significant influence of short-term environmental variability, including fluctuations in solar irradiation, cloud cover, and ambient temperature, which are not fully captured by the model. Overall, the system demonstrated stable and reliable performance with an average performance ratio (PR) of 80.6% and a capacity factor (CF) of 17.7%, confirming efficient operation under tropical climatic conditions and consistent energy delivery throughout the year.

Furthermore, this study identifies that ground surface albedo contributes to variations in inverter-level performance across different installation zones. Surfaces with higher reflectivity, such as white gravel, provide greater reflected irradiance compared to soil and vegetated surfaces, thereby enhancing the effective solar input received by PV modules. This difference in reflectivity results in output variations estimated at approximately 5–10% between inverter groups under comparable irradiation conditions. These findings indicate that local surface characteristics and environmental heterogeneity play a significant role in modifying irradiance distribution and system performance. Therefore, incorporating albedo effects and detailed site-specific environmental parameters into PV system modeling is essential to improve prediction accuracy, reduce uncertainty, and support more optimal PV system design and operation.

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