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Impact of Ground Albedo on Monofacial and Bifacial PV Modules: A PVsyst-Based Performance Evaluation under South Indian Climate

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ABSTRACT

This investigation evaluates the influence of rooftop reflectance on the performance of mono- and bifacial photovoltaic systems using a PVsyst-based simulation of a 125 kWp rooftop installation under tropical climatic conditions in southern India. Both photovoltaic technologies were analysed using identical electrical and geometric configurations so that rooftop albedo remained the only varying parameter. A reference albedo of 0.30 was considered for both technologies, while enhanced albedo scenarios of 0.50, 0.60, and 0.85 were evaluated for bifacial modules. Simulation results show that the monofacial system operating at an albedo of 0.30 generated 188.45 MWh/year with a performance ratio (PR) of 83.76%, whereas the bifacial configuration under identical conditions produced 187.11 MWh/year. As the rooftop albedo increased, the annual energy yield of the bifacial system increased to 187.86, 188.23, and 189.16 MWh/year for albedo values of 0.50, 0.60, and 0.85, respectively. This improvement was accompanied by a marginal reduction in PR from 83.17% to 82.83%, primarily due to higher operating temperatures associated with increased rear-side irradiance. The analysis further identifies an albedo-dependent performance transition threshold between 0.60 and 0.85, beyond which bifacial modules provide superior annual energy performance compared with monofacial modules.

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1. Introduction

In recent solar energy research, the interaction between albedo, panel tilt angle, and bifacial photovoltaic (PV) performance became a central research focus [1]. Earlier investigations consistently indicated that ground reflectance was one of the most important factors affecting bifacial PV system performance. Demir et al [2] investigated the trade-offs between energy generation and agricultural productivity due to panel height, tilting angle, and shading effects. Their results showed an energy yield improvement of approximately 19.46% under favorable albedo conditions. Almohsen et al. [3] performed a comparative simulation of photovoltaic technologies under Saudi climatic conditions and reported that bifacial modules achieved improved energy production when the surrounding surface exhibited higher reflectivity. Their results confirmed that rooftop albedo is an important parameter influencing bifacial system performance. The reported findings indicated that increasing surface reflectance enhances the additional energy captured from the rear side of bifacial modules, Haroun et al. [4] examined the combined influence of rooftop reflectivity and module inclination, showing that optimisation of both parameters can substantially increase rear-side energy collection in bifacial photovoltaic systems. Similarly, Diwan et al. [5] reported that variations in albedo and optimal panel tilt indicated that tilt angles derived from monofacial systems were insufficient for bifacial configurations. Instead of treating albedo and tilt as independent variables, these findings highlighted the need for coupled modelling. Despite compelling evidence that albedo–tilt interactions have a major impact on bifacial energy output, models at the time did not include time-varying albedo or adaptive tilt techniques. Ernst et al [6] provided a methodologically comprehensive comparison using view factor (VF) and ray-tracing (RT) models, carrying out rigorous performance validation in experimental investigations and demonstrating that simpler VF techniques could diverge substantially under various ground reflection situations. This result was consistent with the findings of Lopes et al. [7] who indicated that short-term albedo dynamics could be obscured by long-term irradiation measurements, impacting model accuracy. Urdiroz et al. [8] showed that PERC bifacial cells could increase output through improved light reception and radiative cooling techniques, underscoring the significance of precisely simulating rear-side diffuse irradiance. Despite these developments, there was still no consensus on a rear-side irradiance model that accounts for spectral effects, thermal behaviour, VF/RT inconsistencies, and abrupt changes in surface reflectance. Hashemian et al. [9] proposed a solar wind-based multigeneration system. The proposed system achieved an energy efficiency of 83.65% and an exergy efficiency of 17.97% under optimal operating conditions. With an ideal ambient temperature of 35°C, the system's primary source of energy loss was the parabolic trough collector. Yin et al. [10] suggested adding sky condition clustering and sophisticated hourly diffuse fraction calculation to classical models frequently used in PV software. This enhanced the work of Türkdoğru and Kutay [11] who showed that rear-side energy yield was highly sensitive to small variations in albedo using PVsyst to assess various ground types. In order to approximate RT models at a lower computing cost-a crucial component for large-scale system simulations-Durusoy et al. [12] developed foundational models featuring a simpler back-irradiance technique. Pelaez et al. [13] presented a single-axis bifacial solar tracking model and showed that albedo increased bifacial advantages in tracking systems more than in fixed setups. Similarly, Bhakta and Mukherjee [14] assessed the techno-economic trade-offs between fixed and two-axis tracking systems for Indian climates and concluded that tracking was only financially feasible when surface reflectance and irradiance circumstances warranted the extra expense. Nevertheless, comprehensive optimization studies combining albedo effects with tracking geometry, module elevation, and seasonal tilt adjustments remained lacking [15]. Moreover, the effect of albedo augmentation in bifacial tracking systems was frequently overlooked by previous techno-economic models. Improvements in system-level performance were also influenced by material-level research. In their review of SiO_2 /SiN_x antireflection coatings, Zhou et al. [16] showed enhanced efficiency and mitigation of potential-induced degradation (PID), which through spectral response optimization indirectly increased bifacial gain. In order to increase the precision of measurements of photovoltaic devices under diffuse irradiation conditions, Plag et al. [17] suggested a multidimensional model. To assess the impact of spectral-angular mismatch, the investigation took into account anisotropic sky radiation, ground-reflected irradiance, and the angular response of PV devices. The authors indicated that ignoring angular effects could result in calibration errors greater than 1% using radiative transfer calculations and experimental measurements. The suggested corrective method greatly increased the precision of outdoor PV performance evaluations and offered useful assistance for bifacial solar system analysis and calibration. Furthermore, spectral albedo modelling was improved by Brennan et al. [18] highlighting the significance of wavelength-dependent reflectance in bifacial simulations. By enhancing reflectance assumptions in energy simulation tools, Yusufoglu et al. [19] improved ground reflection modelling and had an impact on later PVsyst and bifacial models. Additionally, Zaragoza Ramírez and Bartolomé Muñoz [20] examined albedo in urban settings, showing how anthropogenic surface differences affected bifacial PV system design and local energy flux. In contemporary research, traditional analytical frameworks remained applicable. Krenzinger and Lorenzo [21] developed analytical models that supported subsequent bifacial PV research. The commonly used diffuse radiation models developed by Erbs et al. [22] were crucial for estimating bifacial irradiance, especially for rear-side diffuse components. Notwithstanding these advances, the capabilities of conventional analytical and diffuse radiation models have been surpassed by contemporary bifacial module materials and environmental heterogeneity. Therefore, to handle the spectral, geometric, and environmental complexity of next-generation bifacial PV systems, advanced theoretical formulations are required [23]. Although previous investigations have examined bifacial photovoltaics under different environmental conditions, very limited attention has been given to identifying the practical albedo level at which bifacial modules become more beneficial than conventional monofacial systems in tropical rooftop applications. Existing studies generally report performance improvements without defining an engineering decision criterion for technology selection. To address this gap, the present study develops a systematic PVsyst-based evaluation using identical system configurations while varying rooftop reflectivity. The investigation aims to identify the albedo transition threshold governing energy yield, performance ratio and economic indicators, thereby providing engineering recommendations for rooftop photovoltaic deployment in tropical climates.

Table 1. Previous study and problems identified

Ref. No.	Author & Year	Problem Identified	Identified Research Gap
[2]	Demir et al. 2026	energy production is strongly influenced on module height and albedo	Lacks dynamic optimization of system parameters.
[3]	Almohsen et al. 2026	energy production is strongly influenced on site-specific albedo	Lacks time-varying and adaptive optimization strategies.
[4]	Haroun et al., 2025	Analyzed how albedo and tilt affect bifacial PV performance.	No real-time or climatic variation analysis of albedo; no field validation.
[5]	Diwan et al., 2024	investigated the impact of increasing albedo in the ideal tilt position	Only covers a case study; lacks dynamic tilt/adaptive modelling.
[6]	Ernst et al., 2024	View-factor and ray-tracing models for bifacial irradiance were compared.	Limited validation environments; no broad terrain/albedo diversity.
[7]	Lopes et al., 2024	PV performance simulation using ongoing monthly radiation data	Monthly resolution is insufficient for bifacial hourly/rear modelling.
[8]	Urdiroz et al., 2023	Evaluated radiative cooling + light trapping for bifacial PERC cells.	Does not assess outdoor/large-scale module performance.

[9]	Hashemian et al., 2023	Significant exergy losses limited overall system efficiency.	Existing work lacks advanced optimization strategies
[10]	Yin et al., 2023	Proposed hourly diffuse-fraction model using sky clustering.	Not integrated into bifacial POA or rear-irradiance modelling.
[11]	Türkdoğru & Kutay, 2022	Used PVsyst to study albedo effect on 30-kW bifacial system.	PVsyst assumptions are not experimentally validated for different surfaces.
[12]	Durusoy et al., 2020	Developed a rear-side irradiance model for bifacial PV modules.	Model does not include seasonal albedo and complex shading effects.
[13]	Pelaez et al., 2019	Single-axis trailing model and validation for bifacial photovoltaics	Limited to certain tracker types and specific site conditions.
[14]	Bhakta & Mukherjee, 2017	Compared techno-economic performance of fixed vs tracking PV.	No bifacial modules included; reflects older PV technology.
[16]	Zhou et al., 2015	Developed PID-resistant antireflection coating.	Does not analyze rear-surface optical effects for bifacial modules.
[17]	Plag et al.,2018	Inaccurate PV measurements due to diffuse irradiation effects.	Limited focus on albedo and bifacial PV energy performance under different operating conditions
[18]	Brennan et al., 2014	Investigated spectral albedo effects on PV.	Does not incorporate spectral effects into bifacial rear modelling.
[19]	Yusufoglu et al., 2014	Simulated bifacial module energy with improved ground reflection.	No integration of 3D shading or modern module structures.
[20]	Zaragoza & Bartolomé, 2012	Studied albedo effect on urban energy efficiency.	No analysis of bifacial PV performance in urban high-albedo areas.
[21]	Krenzinger & Lorenzo, 1986	Early analytical model for bifacial irradiance estimation.	Outdated for modern bifacial geometry, reflectivity and materials.
[22]	Erbs et al., 1982	Developed diffuse radiation fraction estimation model.	Not optimized for tilted or rear-surface irradiance in bifacial PV.
Present Study	This Investigation	Evaluates rooftop monofacial and bifacial PV systems under identical configurations while varying rooftop albedo using PVsyst.	Identifies an albedo-dependent transition threshold for rooftop PV technology selection and integrates energy yield, performance ratio and techno-economic assessment to provide engineering design guidance for tropical rooftop installations.

2. Methodology

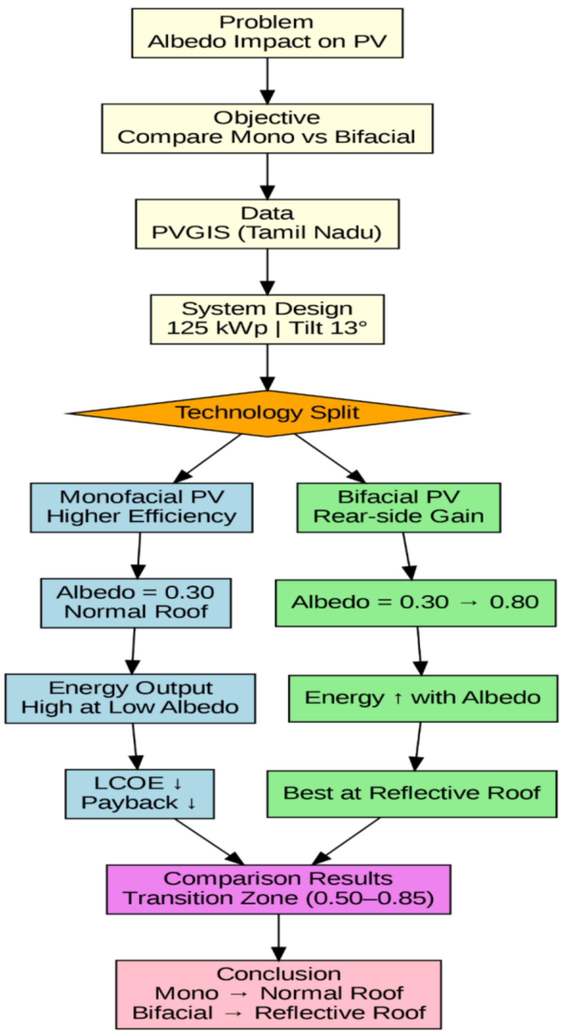

Figure 1. Flowchart for methodology procedure

The flowchart in Figure 1 represents the entire system workflow. Initially, the problem is identified regarding albedo impact on solar panels. The objective is to compare monofacial and bifacial panel modules. Prior to simulation, meteorological and PVGIS data were collected for the specific location using latitude and longitude coordinates, along with solar meteorological data and climatic characteristics. The PV system was configured as a 125 kWp rooftop installation with a fixed tilt angle of 13° for both monofacial and bifacial module technologies. All simulation scenarios were developed using identical electrical and geometric configurations while varying only the rooftop albedo. The resulting datasets were evaluated to determine how changes in surface reflectivity influence annual energy generation, performance ratio and the comparative operating behaviour of the two photovoltaic technologies.

2.1 Proposed Evaluation Framework

Unlike conventional comparative studies that evaluate only annual energy production, the present investigation adopts an albedo-driven assessment framework in which identical PV system configurations are maintained while rooftop reflectivity is systematically varied. This approach enables the direct isolation of rear-side irradiance effects without interference from changes in inverter sizing, module orientation or array geometry. The proposed framework further combines electrical performance, thermal behaviour, performance ratio and economic indicators to determine the practical operating region of bifacial modules. Consequently, the methodology identifies an engineering transition threshold rather than simply reporting energy differences between module technologies.

2.2 Meteorological Data Source and Climate Characteristics

Meteorological information required for the simulation was obtained from the PVGIS Typical Meteorological Year (TMY) database. The imported climatic dataset provides the environmental inputs necessary for assessing photovoltaic system performance at the selected location. Based on this assessment, Sankarapuram, Tamil Nadu, India, a tropical region, was selected as the study location. PVGIS, a widely accepted database, was used in PVsyst simulations to guarantee precise evaluation of solar resources. Monthly records of ambient temperature, wind speed, relative humidity, global horizontal irradiance and diffuse irradiance obtained from PVGIS were incorporated into the simulation environment. The meteorological data indicate elevated humidity during the monsoon season (July–November), which may alter rooftop surface conditions and consequently influence albedo. The average GHI value of 5.28 kWh/m²/day reflects strong solar potential at the site, while the average diffuse irradiance of 1.84 kWh/m²/day contributes significantly to bifacial rear-side energy gain under tropical conditions. The annual average temperature of approximately 27.8°C indicates potential thermal stress, which may reduce panel efficiency. Additionally, a moderate wind speed of about 2.4 metres per second suggests adequate natural cooling and airflow around the tilted solar panels, supporting stable system operation. Adequate airflow beneath the PV modules enhances convective heat dissipation, thereby reducing operating temperature and mitigating thermal efficiency losses.

Table 2. PVGIS Typical Meteorological Year (TMY) meteorological data used in the PVsyst simulation

Month	GHI (kWh/m²/day)	Diffuse (kWh/m²/day)	Temperature (°C)	Wind Speed (m/s)	Relative Humidity (%)
January	4.95	1.56	24.5	2.35	70.9
February	5.42	1.53	25.2	1.98	78.9
March	6.31	1.68	26.2	1.97	78.0
April	6.57	1.74	29.4	2.49	72.7
May	6.34	1.81	31.5	2.61	65.5
June	5.44	1.88	31.0	2.60	63.4
July	4.46	2.44	28.8	2.57	70.7
August	5.34	2.15	30.2	2.74	62.3
September	5.12	2.28	28.6	2.39	73.7
October	4.78	1.77	27.7	2.04	76.5
November	4.46	1.46	26.2	2.35	84.0
December	4.24	1.49	24.4	2.99	76.7
Annual Average	**5.28**	**1.84**	**27.8**	**2.40**	**72.8**

2.3 Rooftop PV System and Grid-Connected Configuration

The rooftop photovoltaic system is located on the main block building of Adhi College of Engineering and Technology campus rooftop, which is located in the tropical region of Sankarapuram, India. The site is located at latitude 12.7987° N and longitude 79.8619° E, with an altitude of 51 m above sea level and a time zone UTC +5.5h. The required weather data of monthly TMY for this location were obtained from PVGIS-TMY and imported to the PVsyst simulation software for integrating the geographic configuration and the climatic resource used for the simulation. The investigation considers a nominal rooftop photovoltaic installation rated at 125 kWp and connected to the utility grid. Two PV module technologies, namely monofacial and bifacial modules, each rated at 540 Wp, were evaluated under identical system configurations. A total of 234 modules were installed to achieve a nominal DC capacity of 125 kWp. The modules were arranged in optimally spaced arrays on the available rooftop area of the main building to maximise solar energy capture while facilitating efficient cable routing and maintenance access. The orientation was configured in PVsyst using a fixed-tilt system with an optimized tilt angle of 13° and azimuth of 180° in front of true south. The selected tilt angle is consistent with previous investigations on building-integrated rooftop photovoltaic systems, which indicated that appropriate array orientation and tilt optimisation improve annual solar energy capture while maintaining structural feasibility [15].

The transposition factor is about 0.93 with 10% loss compared with the theoretical optimum to make it suitable for a tropical region. The modules are mounted in an elevated structure providing a ventilation gap of roughly 0.6–0.8 m between the module back-sheet and the rooftop surface. Increasing the mounting height improves natural air circulation beneath the modules, thereby reducing operating temperature, facilitating roof drainage and providing maintenance access. Similar observations regarding the importance of natural ventilation and rooftop design for improving solar energy utilisation in buildings have also been reported in previous investigations [24]. The panel self-shading is avoided by aligning in constant rows with suitable inter-row spacing and with a chosen tilt angle during critical solar hours. At the other end of the electrical system, the modules are formed into multiple series strings and are combined in rooftop DC combiner boxes. The DC power output from the panels is fed to a three-phase grid-tied inverter to match the 125 kWp DC array. The inverter can be configured as a single central inverter or as two parallel string inverters, depending on the manufacturer selection.

Figure 2 presents the monthly variation of the principal meteorological parameters obtained from the PVGIS Typical Meteorological Year (TMY) database for the selected study location. These climatic inputs, including solar irradiance and ambient temperature, were used as the basis for the PVsyst simulations and subsequent performance evaluation of the rooftop photovoltaic systems.

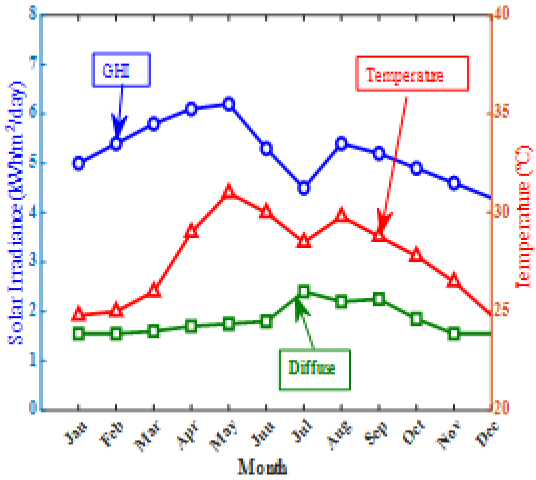

Figure 2. Monthly Solar Radiation & Climate Profile -Sankarapuram (PVGIS TMY)

These meteorological inputs form the basis of the comparative analysis presented in the subsequent sections. The DC output from the panels is fed to the inverter, which converts it into 415 V, 50 Hz AC output, and this is interconnected to the main LT distribution panel of the block. On the other end, the system is connected to a utility transformer for a bidirectional grid connection system under the net metering concept, enabling the surplus power produced to be exported to the electricity grid. The configuration includes a fixed tilting angle with base albedo with south-facing azimuth for the mono-facial panels, along with a properly ventilated array system. A grid-connected system connects the electrical output from the interconnected panels to the utility grid. These parameters are considered for simulating both performance evaluation and comparative analysis under different albedo and operating scenarios. From March to July, sunshine is higher in this tropical region.

2.4 Module Orientation and Geometric Configuration

The module orientation, position, and basic meteorological data are programmed via the PVsyst software. For rooftop installations, the panel fixed tilt mounting system is chosen because of its affordability and ease of use. While the azimuth and tilt angle are set according to solar geometrical features, the project site's geographic location is specified. The ideal tilting angle for optimal energy yield and structural viability at tropical latitudes, where the sun path is high all year round, is 13°. The module plane and global irradiance are strongly aligned, as indicated by the transposition factor of 0.93. Compared to the ideal tilt determined for maximum annual yield, the energy loss is only around 9.6%, which is still acceptable for rooftop limits. In order to maximise the yearly global irradiance on the collector surface in places located in the northern hemisphere, the panel's azimuth is fixed to 180°, aligned to the south. A base tilt angle of 13° is maintained consistently with the module layout, and the system setup area is 556 m².

The modules are organised in a series array. The optimum direction for tropical rooftop deployment is confirmed by the yearly worldwide irradiation of 1802 kWh/m² on the panel surface. For both monofacial and bifacial panels, the comparison analysis considers a base albedo value of 0.30, which represents typical rooftop circumstances. Albedo is the fraction of incident solar radiation reflected by a surface. Higher rooftop albedo increases the rear-side irradiance received by bifacial photovoltaic modules. In tropical regions, most concrete surfaces are non-reflective; therefore, rooftops generally have low reflectivity, resulting in reduced gain for bifacial panels. The investigation also evaluates different albedo values corresponding to various reflective surfaces, which influence the bifacial panel performance. For both monofacial and bifacial panels, the simulation is run with a base albedo value of 0.30. The typical albedo range obtained in the simulation varies from 0.25 to 0.35, indicating low reflectivity for standard urban rooftops.

Table 3. Representative rooftop surface materials and corresponding albedo values adopted in the PVsyst simulation

S. No	Surface Material / Condition	Typical Albedo Value (ρ)
1	Fresh lawn	0.26
2	Dry lawn	0.28
3	Wet lawn	0.25

4	Urban concrete rooftop	0.20 – 0.25
5	Fresh concrete	0.30 – 0.35
6	Asphalt (dry)	0.12 – 0.18
7	Asphalt (wet / monsoon season)	0.10 – 0.15
8	Red clay tiles	0.30 – 0.35
9	Aluminum sheet roofing	0.55 – 0.85
10	Oxidized galvanized steel	0.08
11	New galvanized steel sheet	0.35
12	Reflective white coating (painted concrete)	0.55 – 0.75
13	Fresh snow	0.70 – 0.82
14	Wet snow	0.55 – 0.75
15	Desert sand	0.30 – 0.45

Fresh concrete has an albedo range of 0.30 to 0.35, red clay tiles vary from 0.30 to 0.35, aluminium sheet roofing runs from 0.55 to 0.85, and cooling tiles range from 0.55 to 0.75, according to the rooftop surface analysis.

2.5 PV Module

In the PVsyst simulation, the monofacial solar panel Longi Solar LR7-66HTH-540M and the bifacial panel Longi LR5-72HBD-540M are used. The inverter configuration, Sungrow SG125CX-P2 three-phase grid-tied string inverter, is selected for the proposed 125 kWp rooftop PV system at Adhi College of Engineering and Technology and is configured in the simulation software.

2.5.1 PV Module – Longi LR7-66HTH-540M Monofacial panel

The panel array structure consists of 234 monocrystalline PERC modules, each rated at 540 Wp, 34 V Si mono, Longi model LR7-66HTH-540M. The DC output of the system is 125 kWp. The panels are arranged in 13 strings, each containing 18 modules connected in series, under standard testing conditions and within the allowable MPPT voltage window of the selected inverter. This configuration provides an increased module efficiency of 21% with a compact module area, accommodating 125 kWp within the available 556 m² rooftop area. The panels are sourced from a Tier-1 manufacturer, ensuring high reliability. The system runs at a standard voltage of 1500 VDC, and the chosen module's acceptable temperature coefficient makes it appropriate for tropical rooftop operation.

2.5.2 Bifacial Module LR5-72HBD-540M G2 Configuration and Array Design

The proposed 125 kWp rooftop photovoltaic system configuration makes use of the bifacial panel module Longi Solar LR5-72HBD-540M G2. These modules may capture energy from both the front and rear surfaces. This module improves performance in an open rooftop setting in a tropical climate when both diffuse and reflected irradiance are present. The proposed system is configured as a nominal 125 kWp rooftop photovoltaic installation comprising 234 modules rated at 540 Wp each. For maximum sun exposure, the bifacial panels are installed with a south-facing azimuth orientation at a fixed tilt angle of about 13°. The modules are organized into 13 strings, each of which has 18 modules connected in series. With Vmp (at 25°C) ≈ 754 V and Voc (at −10°C) ≈ 979 V, the system is set up to function inside the inverter's permitted MPPT voltage window. Safe operation conditions are guaranteed by the inverter's maximum input voltage limit of 1100 V. During bifacial gain events, sufficient current margins are maintained to account for increased rear-side irradiance. Because of the increased frame spacing and ventilation clearance that enable effective rear-side illumination, the installed bifacial system requires a slightly larger area of 604 m².

2.5.3 Inverter – Sungrow SG125CX-P2

The operating DC input voltage of the inverter ranges from approximately 180–1000 V, which is compatible with the string design of 18 modules connected in series. The inverter, Sungrow SG125CX-P2, is a grid-connected system rated at 125 kWac, 400 V, 50 Hz, with 12 MPPT inputs to receive DC power from the PV array. The PVsyst configuration shows a nominal PV power of 125 kWp, nominal AC power of 125 kWac, and a Pnom ratio of approximately 1.01, which falls within the recommended range of 1.0–1.2 for grid-tied systems. This inverter configuration ensures proper sizing and optimal loading under typical irradiance conditions, thereby limiting clipping losses to a minimal level. Additionally, the selected inverter offers suitable features for protection, monitoring, and ease of maintenance, making it an appropriate choice for the system.

Table 4. Comparison parameters of two different Modules

Parameter	Monofacial PV System	Bifacial PV System
Module Type	Longi LR7-66HTH-540M	Longi LR5-72HBD-540M G2
Modules Used	234	234
Total DC Capacity	125 kWp	125 kWp
Rear-Side Generation	Not available	Available
Tilt / Orientation	13° / 180° (South)	13° / 180° (South)
Required Roof Area	556 m²	604 m²
Expected Annual Yield*	5–8% lower	5–20% higher (depends on albedo)
Operating Voltage	Similar	Similar
Performance Ratio	~75–77%	~78–82%

2.5.4 Indicative Costing of Monofacial PV Modules and Inverter

Table 5 indicates the cost of the monofacial PV module based on the typical 2024–25 Indian market range for Tier-1 PERC modules, which is approximately INR19–21/Wp for 500–540 Wp modules. The string inverter cost is approximately ₹6–9 lakh for a 100–125 kW unit. The module and inverter are the two main parts that make up the majority of the system's cost. The total estimated cost for these components is approximately ₹33.7 lakh, excluding mounting structure, DC/AC cabling, balance of system (BOS), labour, civil works, design, and approvals.

Table 5. Approximate Cost of Selected PV Module and Inverter

Item	Model	Rating	Qty	Approx. Unit Price*
PV Modules	Longi LR7-66HTH-540M (mono PERC)	540 Wp	234	₹11,000 per module (≈ ₹20/Wp)
Inverter	Sungrow SG125CX-P2	125 kWac, 12 MPPT	1	₹7,50,000 – ₹9,00,000

2.6 Mathematical Validation

The analytical formulation relates the electrical output to incident irradiance, module efficiency and rooftop reflectivity. The overall electrical energy generated by the bifacial configuration can be expressed using the preceding expression as

$$E_{total} = E_{front} + E_{rear} \quad (1)$$

Where E_{front} is the total energy generated, E_{front} is the energy generated from the front surface E_{rear} represents rear side irradiance. [11]. The front side irradiance (GTI) incident on the modular surface controls the global tilted irradiance.

$$E_{front} = G_{POA} \,.\, A \,.\, \eta \quad (2)$$

where the plane-of-array irradiance is represented by GPOA (kWh/m²),

A is the module area (m²), η is the module efficiency[20]. The ground albedo reflected irradiance, which is a function of albedo (ρ), determines the rear side contributions in bifacial modules.

$$E_{rear} = \rho \,.\, GHI \,.\, A \,.\, \eta_{rear} \,.\, F_v \quad (3)$$

where GHI is the global horizontal irradiance and ρ is the ground albedo. η_{rear} is the rear-side efficiency factor, and F_v is the view factor representing the geometric relationship between the module and the reflecting surface [11]. Bifacial gain is used to calculate the relative performance improvement of bifacial modules in relation to monofacial modules [17]. This metric helps identify the albedo threshold at which bifacial modules begin to outperform monofacial systems, as observed in the simulation results.

$$Gain = \frac{E_{bifacial} - E_{mono}}{E_{mono}} \quad (4)$$

The performance ratio is used to assess the total system efficiency under actual operating conditions. where EAC is the system's AC energy output. System losses like temperature impacts, inverter losses, and mismatch losses are taken into consideration by the PR [10]

$$PR = \frac{E_{AC}}{G_{POA} \ . \ A \ . \ \eta} \quad (5)$$

The overall electrical energy generated by the bifacial configuration can be expressed as [5]

$$E_{total} = G_{POA} \ . \ A \ . \ \eta + \rho \ . GHI \ . A \ . \eta_{\ rear} \ . \ F_v \quad (6)$$

This expression highlights that:

- The rear side contribution is minimal, and monofacial modules perform better at low albedo values (ρ≈0.30).
- The rear side contributions increase significantly improving bifacial performances at higher albedo values (ρ>0.50).
- The simulation results indicate the existence of a transition threshold beyond which bifacial systems outperform monofacial systems.

3. Results and Discussion

The simulation outcomes indicate that the influence of rooftop albedo on bifacial PV performance is non-linear rather than proportional. Under low-reflectance conditions (albedo = 0.30), the reflected irradiance reaching the rear surface is insufficient to compensate for the lower front-side conversion efficiency of bifacial modules, resulting in slightly higher annual energy generation from the monofacial configuration. Increasing rooftop reflectivity progressively enhances rear-side irradiance, leading to a corresponding increase in the annual energy yield of bifacial photovoltaic systems. This behaviour indicates the existence of an operational transition region rather than a uniform increase in energy generation, demonstrating that rooftop albedo governs the practical operating range of bifacial photovoltaic systems.

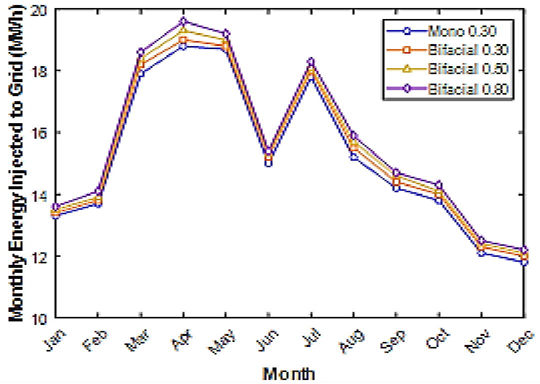

Figure 3. Monthly energy injected into the grid (E_grid) for monofacial (albedo 0.30) and bifacial PV modules (albedo 0.30, 0.50, 0.80)

Figure 3 demonstrates that the monthly energy generation profile remains similar for both technologies throughout the year, whereas the magnitude of energy production depends strongly on rooftop reflectivity. The improvement in bifacial performance is most evident during high-irradiance months (March–August), when increased incident solar radiation enhances the contribution of reflected irradiance from the rooftop surface. During periods of lower solar availability, the influence of albedo becomes less pronounced because reduced incident radiation limits rear-side energy collection.

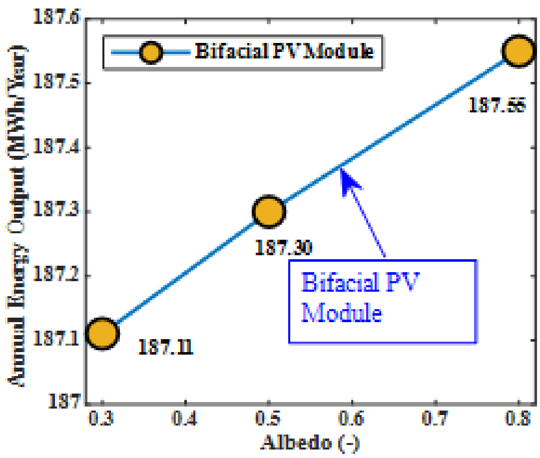

Figure 4. Annual energy injected into the grid as a function of rooftop albedo

The trend presented in Figure 4 indicates a progressive increase in annual energy generation with increasing rooftop albedo; however, the improvement is not uniform across the investigated range. The additional energy harvested from the rear surface remains relatively small at lower albedo values but becomes increasingly significant as rooftop reflectivity increases. This behaviour confirms that the energy advantage of bifacial modules depends on the availability of sufficiently reflective rooftop surfaces rather than on module technology alone. Although annual energy generation increases with rooftop albedo, the performance ratio exhibits a slight decline. This behaviour is primarily attributed to the increase in module operating temperature caused by enhanced rear-side irradiance, which introduces additional thermal losses. Nevertheless, the reduction in performance ratio is comparatively small relative to the increase in annual energy yield, indicating that the thermal penalty does not offset the overall energy benefit obtained under highly reflective rooftop conditions.

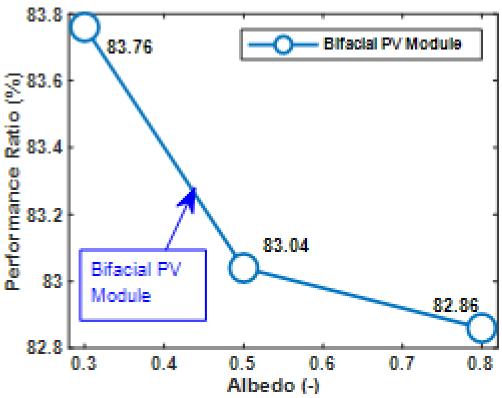

Figure 5. Performance ratio variation with rooftop albedo

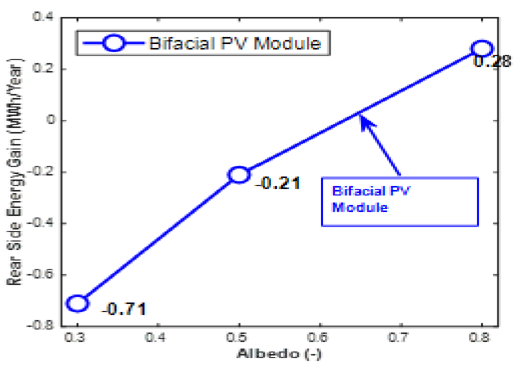

Figure 6. Rear-side energy gain as a function of rooftop albedo

Figure 6 demonstrates that rear-side energy gain increases systematically with rooftop albedo. At low-reflectance surfaces, the reflected component contributes only marginally to the total system output. As the rooftop surface becomes increasingly reflective, the rear-side contribution rises steadily, confirming that rooftop albedo is the dominant factor governing additional energy recovery in bifacial photovoltaic systems.

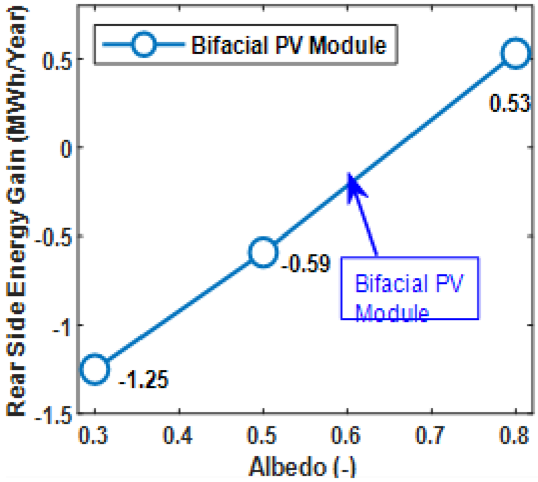

Figure 7. Rear-side energy gain of bifacial PV modules as a function of ground albedo

Figure 7 confirms the existence of an albedo-dependent transition region. Negative rear-side gain is observed under conventional rooftop conditions because the reflected irradiance is insufficient to compensate for the lower conversion efficiency of the bifacial module. Beyond the transition region, increasing rooftop reflectivity progressively enhances rear-side irradiance, enabling bifacial modules to outperform monofacial systems.

At lower albedo values, the rear-side contribution is insufficient to compensate for the efficiency difference, resulting in lower energy yield for bifacial panels. However, at higher albedo values (e.g., 0.80), corresponding to reflective rooftop surfaces, the bifacial system produces approximately +0.53 MWh more energy than the monofacial system. The Levelized Cost of Energy (LCOE) decreases with increasing albedo due to higher energy generation.

However, the bifacial LCOE remains higher than that of the monofacial system across all tested albedo values. Figure 8 shows the LCOE analysis for monofacial and bifacial solar panels at different albedo values.

The graph indicates that as the albedo increases from 0.40 to 0.80, the LCOE values decrease due to higher energy generation. Figure 8 illustrates the variation in payback period with respect to albedo values.

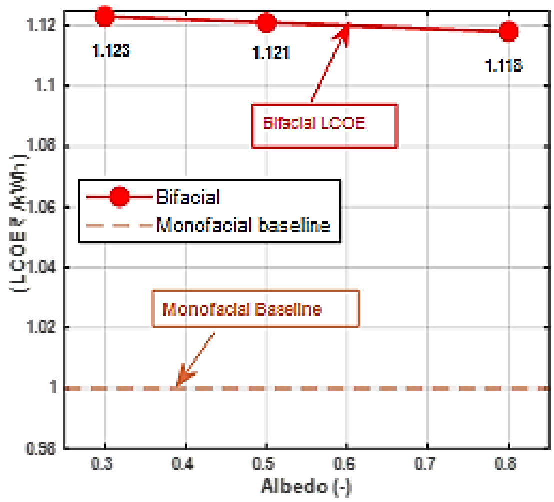

Figure 8. Variation of LCOE with rooftop albedo for monofacial and bifacial photovoltaic systems

The results show that the payback period decreases as the albedo increases. In the PVsyst simulation, the payback period ranges from approximately 2.15 to 2.40 years, with 2.40 years being the maximum observed value.

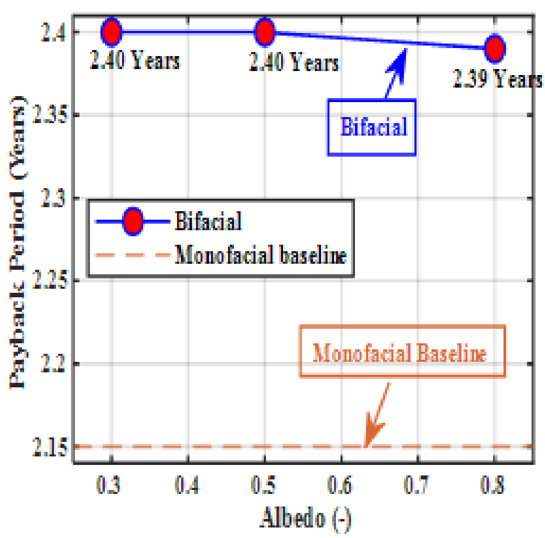

Figure 9. Albedo vs. Payback Period

Figure 9 illustrates the concept of the payback period as a function of albedo, comparing bifacial and monofacial panels. The results indicate that the bifacial panel achieves a shorter payback period at higher albedo values.

A comparative loss study of monofacial and bifacial modules under various albedo conditions is shown in Table 6. The analysis includes various loss parameters such as global incident loss, irradiance loss, ohmic loss, and inverter efficiency losses, evaluated across different albedo values.

Table 6. Comparison of loss parameters for monofacial and bifacial photovoltaic modules under different rooftop albedo conditions

Loss type	Mono 0.30	Bifacial 0.30	Bifacial 0.50	Bifacial 0.80
Global Incident Loss	–7.7	–7.7	–7.2	–6.4
IAM Loss	–3.2	–2.5	–2.6	–2.7
Irradiance Level Loss	–0.6	–0.6	–0.6	–0.6
Temperature Loss	–8.0	–9.4	–9.5	–9.5
Module Quality	+0.8	+0.8	+0.8	+0.8
Mismatch Loss	–2.0	–2.0	–2.0	–2.0
Ohmic Loss	–1.0	–1.0	–1.0	–1.0
Inverter Efficiency Loss	–2.0	–2.0	–2.0	–2.0
Inverter Over Nominal Loss	–1.4	–1.3	–1.3	–1.3

3.1 Economic Analysis

The economic assessment indicates that improved electrical performance does not necessarily translate into improved economic viability. Although bifacial modules generate higher annual energy under reflective rooftop conditions, the higher initial investment associated with bifacial modules results in a modest increase in both the levelized cost of electricity and the investment recovery period. Consequently, the economic viability of bifacial technology depends not only on energy generation but also on the availability of sufficiently reflective rooftop surfaces capable of maximising rear-side irradiance. With a reduced LCOE of around ₹1.98/kWh and a shorter payback period of 4.22 years, the economic comparison indicates that the monofacial configuration remains the lower-cost option under the adopted capital cost assumptions. In contrast, the bifacial system involves higher CAPEX and provides only a marginal energy gain under normal rooftop conditions, resulting in a higher LCOE (approximately ₹2.19–2.21/kWh) and a longer payback period (approximately 4.66–4.70 years). Table 7 shows that the bifacial configuration requires higher initial investment than the monofacial configuration despite only modest gains in annual energy production.

Table 7. Comparative cost analysis of monofacial and bifacial photovoltaic systems

Component	Qty	Monofacial Cost (in Lakhs)	Bifacial Cost (in Lakhs)
PV Modules	234	₹25.7	₹29.2
Inverter: Sungrow SG125CX-P2	1	₹8.0	₹8.0
Mounting Structure	–	₹6.0	₹7.2
Balance of System (BOS)	–	₹4.5	₹4.7
Installation & Commissioning	–	₹3.5	₹3.7

The simulation results indicate that even at a high albedo value of 0.80, although the energy yield is higher for bifacial panels, the LCOE remains greater than that of monofacial systems under the given CAPEX conditions. Monofacial modules are therefore the most cost-effective choice for rooftop installations in tropical regions with natural albedo values around 0.30. In contrast, bifacial panels involve higher costs and require additional rooftop modifications to achieve improved energy yield. To enhance bifacial performance, the rooftop surface should be made more reflective, such as by using white tiles or aluminium sheets, maintaining albedo values greater than 0.50 for optimal energy generation. Table 8 indicates that although increasing rooftop albedo improves annual energy production, the economic indicators continue to favour monofacial modules under conventional rooftop conditions.

Table 8. Comparison of annual energy generation, LCOE and payback period for the investigated PV systems

Panel Case	Annual Energy (kWh/yr)	LCOE (₹/kWh)	Payback (years)
Monofacial (albedo 0.30) (base)	188,450	₹1.980	4.22
Bifacial (albedo 0.30) (base)	187,110	₹2.207	4.70
Bifacial (albedo 0.50)	187,860	₹2.199	4.68
Bifacial (albedo 0.80)	188,980	₹2.186	4.66

3.2 Practical Engineering Implications

The identified albedo transition threshold provides a practical framework for rooftop photovoltaic system design in tropical regions. The findings indicate that replacing conventional monofacial modules with bifacial technology alone does not necessarily improve system performance under standard concrete rooftop conditions because the rear-side irradiance remains insufficient to compensate for the lower front-side conversion efficiency and additional installation cost. Conversely, highly reflective rooftop treatments, including cool-roof coatings, reflective concrete surfaces and aluminium roofing, substantially enhance rear-side irradiance utilisation and improve annual energy generation. These findings suggest that rooftop surface optimisation should be considered simultaneously with module selection during the preliminary design stage rather than treating module technology as an independent design decision. Consequently, improving rooftop reflectivity may provide a more cost-effective strategy for enhancing bifacial PV performance than increasing module capacity alone.

4. Conclusion

The present investigation demonstrates that rooftop surface reflectivity is a decisive parameter governing the relative performance of monofacial and bifacial photovoltaic systems under tropical climatic conditions. The findings show that technology selection should not be based solely on module type, but also on the reflective characteristics of the rooftop surface. Monofacial modules remain the more favourable option under conventional low-albedo rooftops because their higher front-side conversion efficiency compensates for the limited rear-side irradiance available to bifacial modules. In contrast, bifacial modules become practically advantageous only when rooftop reflectivity exceeds the identified transition region, establishing an albedo-dependent engineering criterion for photovoltaic technology selection. From a practical perspective, the results indicate that integrating bifacial modules with cool-roof materials or other highly reflective surface treatments can improve rear-side irradiance utilisation and annual energy generation. Therefore, optimisation of rooftop surface characteristics should be considered alongside module selection during the early design stage of rooftop photovoltaic installations.

The present work is based on PVsyst simulations and does not include long-term experimental validation. Furthermore, the analysis assumes constant rooftop albedo, a fixed tilt angle, and site-specific climatic conditions, whereas actual operating environments exhibit seasonal and environmental variability. Future research should focus on experimental validation, dynamic albedo modelling, advanced thermal and rear-side irradiance analysis, and comprehensive life-cycle techno-economic assessment to further validate and extend the proposed engineering framework.

Nomenclature

A	Area of PV module or rooftop surface (m²)
α	Solar altitude angle (°)
β	Tilt angle of PV module (°)
DHI	Diffuse Horizontal Irradiance (kWh/m²/day or W/m²)
E_grid	Annual energy injected into the grid (MWh/year)
Erear	Rear-side irradiance / bifacial gain (MWh/year)
GHI	Global Horizontal Irradiance (kWh/m²/day or W/m²)
GTI	Global Tilted Irradiance (kWh/m²/day or W/m²)
H	Module mounting height (m)
IAM	Incidence Angle Modifier loss (%)
Imp	Maximum power-point current (A)
LCOE	Levelized Cost of Energy (₹/kWh)
PAC	AC output power (inverter output) (kW)
PDC	Total DC array power (kW)
Pnom	Nominal DC power of PV system (kWp)
PR	Performance Ratio (%)
T	Ambient temperature (°C)
Tcell	PV cell operating temperature (°C)
Voc	Open-circuit voltage (V)
Vmp	Maximum Power-Point voltage (V)
η	PV module conversion Efficiency (%)
ρ	Ground albedo / rooftop reflectivity (-)

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