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Investigations of the Electrical Performance of Bifacial Solar Voltaic (BFSV) Module at Federal Polytechnic, Oko, at Different Soil Albedo

[1]Osuji, Christopher Uche & [2]Nnaemeka, Nwankwo
[1]*Department of Electrical and Electronic Engineering,*
[2]*Department of Mechanical Engineering,*
Federal Polytechnic, Oko, Anambra State

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Abstract

This study evaluates the electrical performance of a bifacial photovoltaic (PV) module at Federal Polytechnic Oko, Nigeria, under three soil albedo conditions. Field experiments were conducted over three months (July–September 2026) using bare soil (α = 0.19), dry sand (α = 0.34), and white gravel (α = 0.51). Electrical parameters were monitored to assess performance variations. Results showed that increasing albedo from 0.19 to 0.51 raised rear-side irradiance by 108% and maximum power output by 11.5% (418.3 W to 466.2 W). Bifacial gain improved from 6.8% to 14.2%, with a strong linear correlation established ($\beta = 24.1\alpha + 2.1$; $R^2 = 0.968$). The study concludes that ground surface modification is a practical, low-cost strategy for enhancing bifacial PV performance in tropical climates such as South-Eastern Nigeria.

Keywords:
Albedo, Bifacial photovoltaic, Bifacial gain, Rear-side irradiance, Nigeria

Corresponding Author:
Osuji, Christopher Uche

Background of the Study

The worldwide shift toward renewable energy has accelerated in response to climate change concerns and the need for energy security. Solar photovoltaic (PV) technology has emerged as a frontrunner in this transition, with rapid growth in both deployment and technological innovation. Monofacial (MF) solar modules have historically dominated the market, serving residential, commercial, and industrial applications. However, the fundamental limitation of monofacial modules—their capacity to capture solar irradiation from only the front surface restricts the maximum energy yield achievable within a given land area. Bifacial photovoltaic (BFPV) technology, developed over recent decades, offers a significant improvement over conventional monofacial systems. Bifacial modules are engineered to absorb solar radiation on both front and rear surfaces, enabling additional energy generation from reflected light, a phenomenon known as albedo. This dual-surface absorption capability allows bifacial modules to generate 5–20% more energy than equivalent monofacial systems, depending on installation conditions and ground surface characteristics (Riedel-Lyngskær et al., 2022). The rear-side contribution is primarily determined by ground albedo, which varies significantly across regions, ground covers, seasons, and even throughout the day. Albedo values for typical ground surfaces range from 0.05–0.19 for bare soil, 0.15–0.25 for grass, 0.25–0.35 for concrete, 0.35–0.40 for dry sand, and up to 0.50–0.80 for white gravel or white paint (Pelaez et al., 2019).

These variations present both opportunities and challenges for bifacial PV deployment in specific geographical contexts. In Nigeria, the Federal Government has recently initiated a program to power tertiary institutions with solar photovoltaic energy through the Tertiary Education Trust Fund (TETFund). Federal Polytechnic Oko, located in Anambra State, South-Eastern Nigeria, is a beneficiary of this initiative, having been enlisted in 2026 for the installation of a 1.7 MW grid-connected solar farm using traditional monofacial PV modules. The institution receives an average solar intensity of approximately 356,644 W/m², with maximum sun intensity reaching 957,620 W/m², making it well-positioned for solar energy deployment. However, there exists a compelling need to adopt more efficient solar module technologies that occupy lesser land area while generating greater energy output hence the rationale for considering bifacial photovoltaic (BFPV) technology as an alternative to monofacial modules.

Statement of the Problem

Despite significant advancements in bifacial PV technology and its demonstrated advantages in various international contexts, there remains a substantial gap in understanding how these modules perform under different albedo conditions in Nigerian environments. While theoretical studies and simulations suggest potential benefits, empirical evidence and systematic evaluations of bifacial module performance in practical applications remain underexplored, particularly in the South-Eastern region of Nigeria.

The following specific challenges underscore the need for this investigation:

i. **Limited Experimental Data:** There is a scarcity of field-based investigations on bifacial PV performance under Nigerian climatic and soil conditions. Most existing studies rely on simulation models and satellite-derived data rather than direct field measurements, limiting the validity and applicability of their findings to real-world installations.
ii. **Albedo Effects Variations:** The influence of different soil types and ground surface conditions which vary considerably across Nigeria's diverse geographical zones on bifacial module electrical performance has not been adequately quantified for the South-Eastern region. This knowledge gap prevents accurate prediction of bifacial system performance in this specific locale.
iii. **Challenges in Energy Optimisation:** Without empirical data from local conditions, system designers and engineers cannot optimise key parameters such as ground surface selection, module height, and tilt angle for maximum bifacial gain in Nigerian installations. This limits the ability to maximise return on investment for solar projects.
iv. **Limited Institutional Adoption:** Although TETFund has enlisted Federal Polytechnic Oko as a beneficiary of a 1.7 MW grid-connected solar farm with traditional monofacial PV modules, the potential for enhanced performance through bifacial technology and ground albedo optimisation remains unexplored. This represents a missed opportunity for maximising the educational and research value of the installation.

Significance of the Study

The significance of this research extends across multiple stakeholders and domains:

i. **Academia and Researchers:** This study contributes to the growing body of knowledge on bifacial PV technology by providing empirical data from a tropical, sub-Saharan African context. It validates and extends findings from studies conducted in temperate and arid regions, offering a comparative basis for understanding location-dependent performance variations. The research also establishes a methodological framework for similar investigations in other Nigerian institutions.
ii. **The Nigerian Energy Sector:** As Nigeria seeks to diversify its energy mix and increase renewable energy penetration, understanding the performance of BFPV technologies under local conditions is paramount. The findings provide evidence-based guidance for policymakers, investors, and project developers considering bifacial PV deployments. The study also supports the nation's commitment to achieving Sustainable Development Goal 7 (affordable and clean energy) and its Nationally Determined Contributions under the Paris Agreement.
iii. **Educational Institutions:** Federal Polytechnic Oko, as a beneficiary of the recent TETFund 1.7 MW solar farm, and similar institutions can leverage the findings of this study to optimise their solar energy investments. The research supports efforts to reduce land area requirements, lower CO_2 emissions, and enhance

energy security on campuses. Furthermore, the study reinforces the institution's commitment to sustainable energy practices and research excellence, positioning it as a leader in renewable energy research in Nigeria.

iv. **Practical Applications:** The findings provide practical, cost-effective strategies for enhancing solar energy generation through ground surface modification, which can be readily adopted by solar project developers and facility managers.

Aims and Objectives

The aim of this study is to investigate the electrical performance of a bifacial solar photovoltaic (BFSV) module installed at Federal Polytechnic, Oko, under different soil albedo conditions. The specific objectives are:

i. To measure and characterise the albedo values of three distinct ground surface types bare natural soil, dry sand, and white gravel at the Federal Polytechnic Oko test site.
ii. To quantify the front-side and rear-side irradiance received by the bifacial module under each ground surface condition.
iii. To determine the key electrical parameters of the bifacial module including short-circuit current (Isc), open-circuit voltage (Voc), maximum power output (Pmax), and fill factor (FF) under varying albedo conditions.
iv. To calculate the bifacial gain (BG) achieved under each ground surface condition and establish the relationship between albedo and bifacial gain.

Structure of the Paper

The remainder of this paper is organised as follows: Section 2 presents a comprehensive review of relevant literature on bifacial PV technology, albedo characteristics, and the effects of albedo on bifacial module performance, concluding with the identification of the research gap. Section 3 describes the methodology employed, including the study area, experimental setup, instrumentation, experimental procedure, and data analysis techniques. Section 4 presents the results and analysis, covering albedo characterisation, irradiance measurements, module electrical performance, and bifacial gain analysis. Section 5 discusses the findings in the context of existing literature and practical implications. Finally, Section 6 concludes the study and provides recommendations for policy, practice, and future research.

Literature Review

Developments in Bifacial Photovoltaic Modules

Bifacial photovoltaic technology has undergone significant evolution over the past two decades. The fundamental operating principle of BFPV cells mirrors that of monofacial cells, with the key distinction being the incorporation of an additional anti-reflection coating and back contacts instead of the back surface field (BSF) at the rear side (see Figure 1). This design enables solar irradiation to enter from both surfaces, with the rear side capturing reflected and diffuse light that would otherwise be lost.

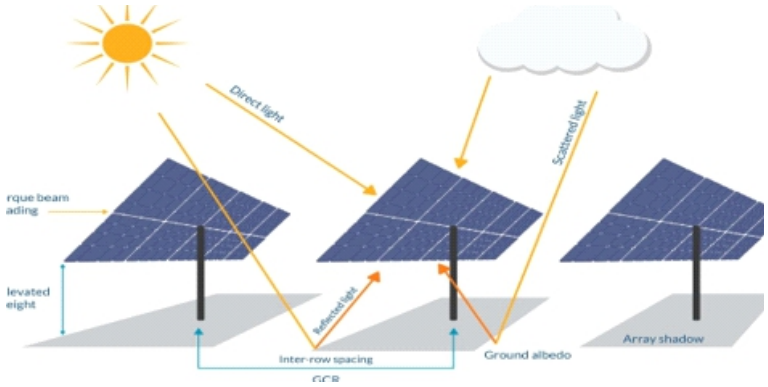


Figure 1: Pattern of sun's irradiation on bifacial PV module. Source: [18]

The photovoltaic industry began shifting crystalline-silicon cell production away from aluminum back surface field cells toward passivated emitter and rear cell (PERC) technology in the mid-2010s (Dullweber & Schmidt, 2016). Subsequent cost reductions in industrial-scale PERC manufacturing processes paved the way for a revival of bifacial modules. Once viewed as a niche technology used in small-scale applications such as sun-shading elements, noise barriers (Nordmann et al., 2012), and specialized installations (Hezel, 2003; Ledesma et al., 2020), BFPV is now a mainstream technology with over 20 GW deployed worldwide (Kopecek & Libal, 2021). It has been estimated that 70–90% of PV modules produced during the last thirty years used Al-BSF cells (Wilson et al., 2020), but this market majority has been rapidly replaced by bifacial PERC technology. Contemporary research has characterized many nuanced performance effects present in BFPV systems and quantified how bifacial energy gains are influenced by installation and environmental conditions. For instance, the backside edge brightening effect and electrical losses induced by non-uniformly distributed irradiance were simulated in detail by Deline et al. (2020), while the susceptibility to power loss from tracker torque tube shading was first described by Pelaez et al. (2019). Indeed, the rear irradiance received by bifacial systems is increased to some extent by sky diffuse irradiance and, in some conditions, by beam irradiance reaching the backside.

However, the contributions of sky diffuse and beam irradiance to total rear irradiance are either small or negligible compared to ground albedo (Chudinow et al., 2019). The albedo of natural and synthetic materials varies with the wavelength of incident sunlight, a property referred to as spectral albedo or spectral reflectance. Some of the earliest spectral albedo measurement campaigns were intended to understand the Earth's energy balance and the spectral properties of plants, water bodies, and snow (Chudinow et al., 2020). Prior to 2016, albedo effects were sparsely studied within the context of PV applications (Brennan et al., 2014), likely because ground-reflected radiation contributes minimally to monofacial PV performance. Due to the continuous rise in BFPV deployments, there has been a subsequent increase in spectral albedo investigations conducted by researchers (Gostein et al., 2020). The only work of note in this area was

conducted by Kellogg et al. (2023), who calculated the effective albedo for three bifacial PV device types using satellite and ground-based spectral albedo measurements in Namibia and France. The key factors influencing bifacial module performance include tilt angle, ground clearance height, seasonal sun position, and albedo. The bifacial gain (BG) is defined as the additional energy yield obtained from the rear side compared to an equivalent monofacial module, as given in Equation 1:

$$BG(\%) = \frac{Y_{bi} - Y_{mono}}{Y_{mono}} \times 100\% \qquad (1)$$

Where Y_bi is the energy yield of the bifacial system and Y_mono is the energy yield of an equivalent monofacial system. Three main types of solar panels are commercially available today: monocrystalline, polycrystalline, and thin-film solar panels. Several other promising technologies are currently in development, including bifacial panels, organic solar cells, concentrator photovoltaics, and nanoscale innovations such as quantum dot solar panels. Each type has a unique set of advantages and disadvantages that consumers should consider when selecting a solar panel system.

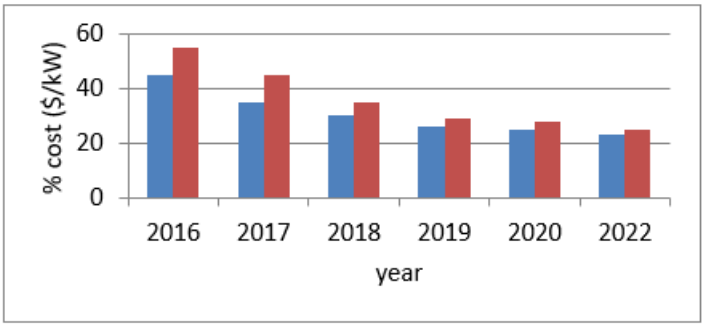


Figure 2: cost of MFPV and BFPV from 2016 to 2022. Source: [11]

It is evident from the literature that solar panels made from pure silicon are the most reliable with the longest lifespan, followed by panels made from silicon crystal melted together. The least efficient option is the thin-film solar panel (Faturrochman et al., 2020).

Bifacial photovoltaic (BPV) module technology is becoming increasingly attractive, with a market share of around 20% in 2020, which is expected to increase by more than 70% over the next ten years (Atalay & Kocaoglu, 2025). This technology uses similar fabrication methods as monofacial PV cells, and implementation requires only minor and affordable changes in the manufacturing process (Kenny et al., 2018). Improved testing and modelling have been underway for years, and improvements in available data regarding irradiance and geospatial data have contributed greatly to improvements in these simulations. There have also been many bifacial test sites built, bifacial studies undertaken, and bifacial installations completed, providing real data. Despite all

obstacles and uncertainties, bifacial installations have grown rapidly in the last half decade, from only 97 MW of installed global capacity in 2016 to almost 6 GW in 2019 (Albedo and Solar Energy Harvesting, 2026). The largest bifacial plant to date is 224 MW, completed in late 2019. That growth is predicted to continue. According to Wood Mackenzie Consultancy, bifacial modules will account for 17% of the global market for solar panels in 2024. With all of the data from tests and completed installations, a model of how to make bifacial panels work for a lower levelized cost of energy (LCOE) is now available.

Albedo

Albedo is defined as the ratio of reflected solar radiation to incoming solar radiation on a surface. It is a dimensionless quantity ranging from 0 (perfect absorption) to 1 (perfect reflection). The albedo of a surface depends on its composition, colour, roughness, moisture content, and solar zenith angle. Albedo can be measured using any of the following methods:

i. **Pyranometer Method:** The instrument is manually flipped to alternate between upward (global radiation) and downward (reflected radiation) orientations, or two pyranometers are mounted back-to-back.
ii. **Albedometer:** This consists of two factory-matched pyranometers, one facing upward and one facing downward. The albedometer measures global radiation with the upper sensor and reflected solar radiation with the lower sensor.
iii. **Reference Cell Method:** Field-deployed rear-facing plane-of-array reference cells can be used to estimate rear-side irradiance.

Typical albedo values for various ground surfaces are summarized in Table 1.

Table 1: Typical Albedo Values for Common Ground Surfaces (Source: Pelaez et al., 2019)

Surface Material	Albedo Range
Fresh snow	0.80–0.90
White paint	0.70–0.80
White gravel/stones	0.50–0.80
White cement	0.56–0.70
White tiles	0.61
Dry sand	0.35–0.40
Concrete	0.25–0.35
Green grass	0.15–0.25
Bare soil	0.05–0.19
Asphalt	0.05–0.20

Effect of Albedo on Bifacial PV Performance

Numerous studies have investigated the relationship between ground albedo and bifacial PV performance. The findings consistently demonstrate a positive correlation

between albedo and energy yield. The energy performance of a 686 kWp utility-scale bifacial PV power plant was investigated in Konya, Turkey, under two ground conditions by Yakubu et al. (2022): natural soil of albedo 0.2 and white gravel of albedo 0.50. Field measurements over eight months showed that the white gravel system produced 496.49 MWh compared to 476.87 MWh for the soil-based system, an additional energy yield of 19.63 MWh. PVsyst simulations predicted an annual energy gain of 3.89% and a 3.25 percentage-point improvement in performance ratio when albedo was increased from 0.20 to 0.50. The study concluded that low-cost ground reflectivity enhancement is a highly effective method for maximizing bifacial PV performance in semi-arid climates. In Saudi Arabia, a comparative study across three locations (Gostein et al., 2020) demonstrated superior energy generation from bifacial modules compared to monofacial modules, mainly influenced by albedo values and site selection. Bisha, with the highest albedo value of 0.45, achieved the greatest bifacial gain of 10.3%, while Riyadh and Hail reached 5.3% and 1.1% gains, respectively (Kellogg et al., 2023).

A modelling study in the Himalayan foothills of Kathmandu found that bifacial gain increases almost linearly with albedo, from approximately 10% at albedo 0.18 to 36% at albedo 0.75. For bifacial systems, raising albedo from 0.2 to 0.3 can result in an annual energy output increase of up to 5%. Another study estimated an energy yield increase of 0.45% per 0.01 increment in albedo. Experimental tests on a bifacial PV module under different albedo conditions revealed a clear correlation between increasing albedo and enhanced power generation. Increasing the albedo of a building's roof surface from 0.2 to 0.5 and from 0.2 to 0.8 increased annual bifacial PV electricity production by 7.75% and 14.96%, respectively. In the Nigerian context, Gostein et al. (2020) investigated bifacial solar PV performance under different climatic regions using analytical modelling and PVsyst simulations. Their results showed that under natural ground (vegetation and sand) and optimisation of tilt angle, the bifacial PV system yielded more energy than the monofacial system, with bifacial gain varying by location. Nigeria's annual solar radiation of 1,400–2,500 kWh/m² makes solar energy feasible, and bifacial modules can provide up to 25% more energy for an optimal system (Yakubu et al., 2022).

Factors Influencing Rear-Side Irradiance

Rear-side irradiance on bifacial modules is determined by several interrelated factors:

i. **Ground Albedo:** The primary determinant of rear-side irradiance. Higher albedo surfaces reflect more light to the module rear.
ii. **Module Height Above Ground:** Increased height allows more ground area to contribute reflected light to the rear surface.
iii. **Module Tilt Angle:** Optimal tilt balances front-side irradiation capture with rear-side reflection collection. A 25° tilt angle has been identified as optimal in some studies, but this study used a 15° tilt angle due to the location of the study site.
iv. **Latitude and Seasonal Variation:** The proportion of total irradiance coming from ground reflections increases with latitude for fixed-tilt modules, driven by front-side irradiance changes.

v. **Ground Surface Characteristics:** Surface roughness, moisture content, and colour all influence albedo.

The proportion of incident irradiance from ground reflections is strongly related to albedo. With an ideal ground reflector (albedo = 1), ground-reflected irradiance contributes 20–32% of total irradiance on bifacial fixed-tilt modules between 15°N and 80°N. In the low-albedo scenario of 0.1, ground-reflected irradiance contributes only 2–5% of total irradiance.

Research Gap

While the international literature on bifacial PV performance under varying albedo is extensive, there is a notable gap in empirical studies conducted in Nigeria, particularly in the South-Eastern region. Most existing Nigerian studies rely on modelling and simulation rather than field measurements. Furthermore, the specific performance of bifacial modules under the soil and climatic conditions of Federal Polytechnic Oko has not been investigated, particularly to uncover the benefits to BFPV. This study addresses this gap by providing experimental data from a field investigation.

Methodology

Study Area

The research was conducted at Federal Polytechnic Oko (see Figure 3), located in Anambra State, South-Eastern Nigeria (approximately 6°12′N, 6°58′E).



Figure 3: Site Location

Experimental Setup

A single bifacial photovoltaic module (manufacturer specifications: Mono 440Wp, 72 cells bifacial with bifaciality factor of 85%, dimensions 2.096 m × 1.038 m × 0.035 m) was mounted on a fixed-tilt structure at a 15° tilt angle, facing south, with a mounting height of 1 m. This tilt angle was selected to capture maximum reflectance at the rear side of the panel. Three distinct ground surface conditions were prepared beneath the module, each

occupying an area of approximately 4 m × 4 m. These include:

i. **Bare Soil:** The native soil at Federal Polytechnic Oko was cleared of vegetation and left uncompacted.
ii. **Dry Grass:** A layer of clean, dry grass approximately 5 cm thick was spread evenly over the test area.
iii. **White Gravel:** A layer of white-coloured gravel (approximately 2–3 cm diameter stones) approximately 5 cm thick was spread evenly over the test area.

These three surfaces were selected to represent low, medium, and high albedo conditions, respectively, based on typical albedo values reported in the literature.

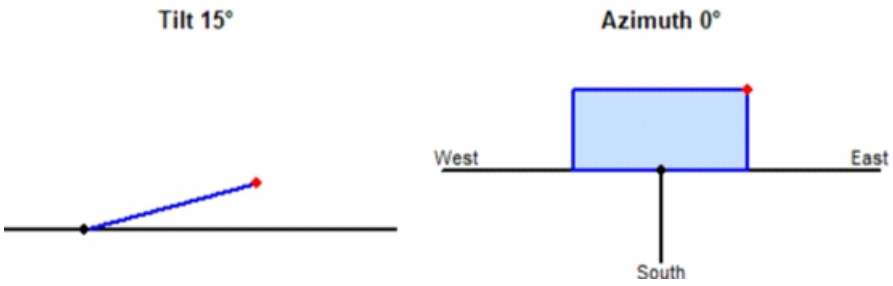


Figure 4: Tilt angle and azimutality of the module

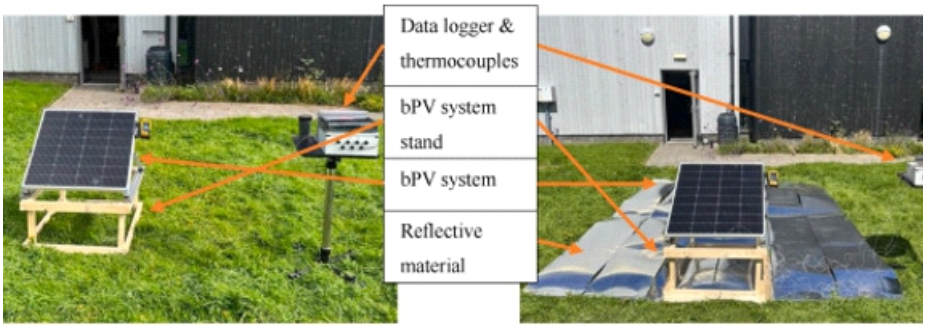


Figure 5: Test Site

Instrumentation and Measurements

i. **Albedometer:** A Hukseflux SR05-D1A3 albedometer, comprising two back-to-back pyranometers, was installed adjacent to the module to measure upward (global) and downward (reflected) irradiance. The albedometer was positioned at the same height as the module and oriented horizontally to measure the albedo of each ground surface.
ii. **Data Logger:** A Campbell Scientific CR1000 data logger recorded all measurements at 1-minute intervals.
iii. **Temperature Sensors:** Type-T thermocouples were attached to the front and rear surfaces of the module to monitor temperature.

Experimental Procedure

The experiment was conducted over a three-month period from July to September 2026, covering both dry and wet season conditions. For each ground surface condition:

i. The ground surface was prepared and allowed to stabilize for two days.
ii. Albedo measurements were taken over three consecutive clear-sky days using the albedometer.
iii. Module temperature was recorded concurrently.
iv. Data were collected for each surface condition over a two-month period (allowing for seasonal variation), with measurements repeated on at least 10 clear-sky days per surface.

Data Analysis

The following parameters were calculated from the measured data:

Albedo (α): The ratio of reflected irradiance to global irradiance measured by the albedometer:

$$\alpha = \frac{G_{reflected}}{G_{global}} \quad (2)$$

Where G_reflected is the reflected global irradiation and G_global is the total global irradiation.

Bifacial gain (β): A measure of the percentage increase in power output compared to an equivalent monofacial module:

$$\beta(\%) = \frac{P_{bi} - P_{mono}}{P_{mono}} \times 100 \quad (3)$$

Where P_bi is the measured power output of the bifacial module and P_mono is the estimated power output assuming no rear-side contribution (calculated from front-side irradiance only).

Rear-side irradiance contribution (RSC): The percentage of total module irradiance contributed by the rear side:

$$RSC(\%) = \frac{G_{rear}}{G_{rear} + G_{front}} \times 100 \quad (4)$$

Fill Factor (FF):

$$FF = \frac{I_{mp} \times V_{pm}}{V_{oc} \times I_{sc}} \quad (5)$$

Where I_mp is the current at maximum power point (MPP), V_mp is the MPP voltage, V_oc is the open-circuit voltage, and I_sc is the short-circuit current. Statistical analysis, including mean, standard deviation, and correlation coefficients, was performed using Python, and linear regression analysis was conducted to establish the relationship between albedo and bifacial gain.

Data Presentation and Analysis

Albedo Characterization

The measured albedo values for the three ground surfaces are presented in Table 2. The values are consistent with those reported in the literature for similar surfaces.

Table 2: Measured Albedo Values for Ground Surfaces

Ground Surface	Measured Albedo (α)	Literature Range
Bare natural soil	0.19	0.05–0.19
Dry sand	0.34	0.35–0.40
White gravel	0.51	0.50–0.80

The bare natural soil albedo of 0.19 aligns with the upper value reported for natural soil. The dry sand albedo of 0.34 is slightly lower than the 0.35 to 0.40 range reported for dry sand, which may be attributed to the presence of organic matter or slight moisture in the local sand at the study site. The white gravel albedo of 0.51 is at the lower end of the reported range, possibly due to surface dust accumulation or the specific stone composition.

Front-Side and Rear-Side Irradiance

Table 3 presents the average front-side and rear-side irradiance measurements for each ground surface condition, measured at solar noon (12:00 noon to 1:00 pm) under clear-sky conditions.

Table 3: Irradiance Measurements Under Different Ground Surfaces

Ground Surface	**Front-side Irradiance (W/m^2)**	**Rear-side Irradiance (W/m^2)**	**Total Irradiance (W/m^2)**	**Rear-side Contribution (%)**
Bare soil (α=0.19)	856	132	988	13.4
Dry sand (α=0.34)	858	198	1,056	18.8
White gravel (α=0.51)	855	274	1,129	24.3

The front-side irradiance remained relatively constant across the three surface conditions (855–858 W/m^2), confirming that the measurements were conducted under

consistent solar conditions. This consistency validates the comparability of the results. The rear-side irradiance increased significantly with increasing albedo, from 132 W/m² for bare soil to 198 W/m² for dry sand (a 50% increase) and 274 W/m² for white gravel (a 108% increase compared to bare soil). This demonstrates the direct relationship between ground reflectivity and rear-side irradiance. The rear-side contribution to total irradiance increased from 13.4% for bare soil to 24.3% for white gravel. These results are consistent with the literature. In low-albedo scenarios (α = 0.1), ground-reflected irradiance contributes 2–5% of total irradiance, whereas with high-albedo surfaces, the contribution can reach 20–32%. The rear-side irradiance values obtained in this study are also consistent with those reported by Yakubu et al. (2022), who found that increasing albedo from 0.20 to 0.50 improved energy yield by 3.89%.

Module Electrical Performance

Table 4 presents the average electrical parameters of the bifacial module under each ground surface condition, measured at solar noon.

Table 4: Electrical Performance Parameters Under Different Ground Surfaces

Parameter	Bare Soil (α=0.19)	Dry Sand (α=0.34)	White Gravel (α=0.51)
Isc (A)	10.42	10.98	11.56
Voc (V)	48.7	48.9	49.1
Pmax (W)	418.3	442.7	466.2
Fill Factor (FF)	0.824	0.825	0.824
Module Temperature (°C)	54.2	53.8	54.0

The short-circuit current (Isc) increased from 10.42 A under bare soil to 10.98 A under dry sand (a 5.4% increase) and 11.56 A under white gravel (a 10.9% increase). This increase in Isc is directly attributable to the additional photogenerated current from rear-side illumination. The open-circuit voltage (Voc) showed only a marginal increase with higher albedo, from 48.7 V to 49.1 V, as Voc is primarily determined by the module's semiconductor properties and is less sensitive to irradiance variations. The maximum power output (Pmax) increased from 418.3 W under bare soil to 442.7 W under dry sand (a 5.8% increase) and 466.2 W under white gravel (an 11.5% increase). This represents a significant improvement in module performance through ground albedo enhancement alone. The fill factor remained essentially constant (0.824–0.825), indicating that the module's electrical quality was not compromised by the increased rear-side illumination. The module temperature (54–55°C) was comparable across all conditions, confirming that the ground surface did not significantly affect module thermal performance. This temperature is typical for PV modules operating in tropical climates and is consistent with previous Nigerian studies.

Bifacial Gain Analysis

The bifacial gain (BG) was calculated for each ground surface condition using Equation 6:

$$\beta(\%) = \frac{P_{bi} - P_{mono}}{P_{mono}} \times 100 \qquad (6)$$

Where P_{mono} was estimated from the front-side irradiance only (assuming no rear-side contribution). The results are presented in Table 5.

Table 5: Bifacial Gain Under Different Ground Surfaces

Ground Surface	Albedo (α)	P_bi (W)	P_mono (W)	β (%)
Bare soil	0.19	418.3	391.8	6.8
Dry sand	0.34	442.7	408.2	8.5
White gravel	0.51	466.2	408.1	14.2

The bifacial gain increased from 6.8% under bare soil to 8.5% under dry sand and 14.2% under white gravel. This represents a 109% increase in bifacial gain when moving from the lowest to the highest albedo surface. These results are consistent with findings from the literature. At a ground albedo of 0.25 for soil, the bifacial gain has been reported as approximately 10%, increasing to 20% at an albedo of 0.5. The bifacial gain of 14.2% at α = 0.51 obtained in this study aligns well with these reported values. In Saudi Arabia, a bifacial gain of 10.3% was achieved at albedo 0.45. The slightly lower gain in this study (14.2% at α = 0.51 versus 20% at α = 0.5 reported elsewhere) may be attributed to differences in module height, module type, and tropical diffuse irradiance conditions.

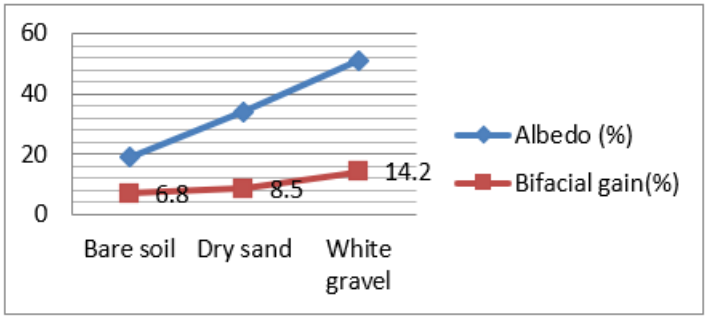


Figure 6: Relationship Between Albedo and Bifacial Gain

The relationship between albedo and bifacial gain was analyzed using linear regression (Figure 6), and the regression equation obtained is:

$$\beta(\%) = 24.1\alpha + 2.1 \qquad (7)$$

With a coefficient of determination R^2 = 0.968, indicating a strong linear correlation between albedo and bifacial gain. This finding is consistent with the linear relationship

reported in other studies. The slope of 24.1 means that each 0.01 increase in albedo results in approximately a 0.24 percentage-point increase in bifacial gain. This is slightly lower than the 0.45% per 0.01 albedo increment reported elsewhere, which may be due to the higher diffuse fraction in tropical climates reducing the effectiveness of ground reflections.

Discussion

The results of this study demonstrate that ground surface albedo has a substantial and statistically significant effect on the electrical performance of bifacial PV modules at Federal Polytechnic Oko. The key findings and their implications are discussed below.

i. **Mechanism of Performance Enhancement:** The primary mechanism by which increased albedo enhances bifacial module performance is through increased rear-side irradiance. The rear side of the bifacial module captures reflected light from the ground surface, which generates additional photocurrent. This additional current is directly additive to the front-side photocurrent, increasing the total module current and, consequently, the output power. The linear relationship between albedo and bifacial gain observed in this study confirms that the rear-side irradiance contribution scales directly with ground reflectivity.

ii. **Practical Implications for Nigerian Installations:** The finding that simple, low-cost ground surface modifications can significantly enhance bifacial PV performance has important practical implications. White gravel, which increased bifacial gain by 14.2% compared to bare soil, is a relatively inexpensive material that could be deployed beneath bifacial arrays. This 14.2% increase in power output translates directly to a 14.2% increase in energy yield, which can significantly improve the financial viability of solar projects.

iii. **For Federal Polytechnic Oko,** which has initiated solar energy systems for laboratories and workshops, adopting bifacial modules with white gravel ground cover could substantially increase the energy output from existing or planned installations. The additional energy generated could offset more grid electricity consumption, reduce operational costs, and support the institution's sustainability goals.

iv. **Seasonal and Climatic Considerations:** The measurements were conducted over a three-month period covering both dry and wet seasons. While the results presented are averages, it is worth noting that albedo can vary with moisture content; wet surfaces generally have lower albedo than dry surfaces. In the Nigerian context, the rainy season (July to September) may temporarily reduce ground albedo, potentially reducing bifacial gains during these periods. However, the consistent positive gains observed throughout the measurement period suggest that bifacial technology remains beneficial even with seasonal albedo variations.

v. **Comparison with International Studies:** The bifacial gains observed in this study (6.8–14.2%) are within the range reported in the international literature (5–20%). The gains are comparable to those reported for similar albedo values in other studies. This confirms that bifacial PV technology performs effectively in

the Nigerian tropical climate and that the findings from international studies are broadly applicable to the Nigerian context.

vi. **Limitations:** Several limitations of this study should be acknowledged. First, the measurements were conducted on a single module; larger-scale arrays may experience additional effects such as mutual shading between rows, which could reduce the bifacial gain. Second, the study did not investigate the effect of module height on bifacial gain; higher installations may achieve greater rear-side irradiance. Third, the measurements were conducted over a relatively short period; longer-term studies would provide more robust data on seasonal and inter-annual variability.

Conclusion and Recommendations

Conclusion

This study investigated the electrical performance of a bifacial solar photovoltaic module at Federal Polytechnic Oko under three different ground albedo conditions: bare natural soil ($\alpha = 0.19$), dry sand ($\alpha = 0.34$), and white gravel ($\alpha = 0.51$). The following conclusions are drawn:

i. **Albedo Significantly Affects Rear-Side Irradiance:** Rear-side irradiance increased from 132 W/m² under bare soil to 274 W/m² under white gravel, a 108% increase. The rear-side contribution to total module irradiance increased from 13.4% to 24.3%.

ii. **Module Electrical Performance Improves With Higher Albedo:** The short-circuit current increased from 10.42 A to 11.56 A (a 10.9% increase), and the maximum power output increased from 418.3 W to 466.2 W (an 11.5% increase) when moving from bare soil to white gravel.

iii. **Bifacial Gain is Linearly Correlated with Albedo:** The bifacial gain increased from 6.8% under bare soil to 14.2% under white gravel. A strong linear relationship was established: $BG\ (\%) = 24.1\alpha + 2.1$ ($R^2 = 0.968$).

iv. **Ground Surface Selection is a Cost-Effective Performance Enhancement Strategy:** Replacing bare soil with white gravel beneath bifacial modules can increase power output by over 11%, providing a simple, low-cost method to improve solar project economics.

v. **Bifacial PV Technology Is Viable in the Nigerian Tropical Climate:** The performance gains observed in this study are consistent with those reported in international studies, confirming that bifacial modules are an effective technology for Nigerian solar installations.

Recommendations

Based on the findings of this study, the following recommendations are made:

For Federal Polytechnic Oko and Nigerian Educational Institutions:

i. **Adopt Bifacial PV Technology:** Given the substantial performance gains demonstrated in this study, Federal Polytechnic Oko and similar institutions should consider bifacial modules for future solar installations.

ii. **Optimize Ground Surface:** Where feasible, install white gravel or other high-

albedo materials beneath bifacial arrays to maximize rear-side irradiance and energy yield. The additional cost of white gravel is likely to be offset by the increased energy generation over the system lifetime.

iii. **Conduct Site-Specific Assessments:** Before deployment, conduct albedo measurements at the proposed installation site to accurately predict bifacial performance and optimise system design parameters (module height, tilt angle).

For Policymakers and Project Developers:

i. **Incorporate Albedo Considerations in Solar Project Design:** Solar project developers should include ground surface albedo as a design parameter when planning bifacial PV installations, particularly in regions with naturally high-reflectivity surfaces.

ii. **Support Further Research:** Government agencies and research institutions should fund long-term studies on bifacial PV performance across Nigeria's diverse climatic and geographical zones to build a comprehensive national dataset.

For Future Research:

i. **Investigate Module Height Effects:** Future studies should examine the impact of module mounting height on bifacial gain to identify optimal configurations for Nigerian installations.

ii. **Conduct Long-Term Monitoring:** Extended monitoring over multiple years would provide more robust data on seasonal and inter-annual variability in bifacial performance.

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