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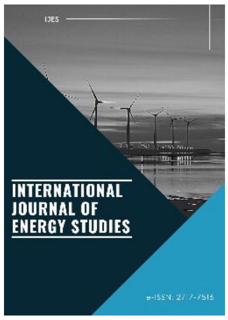

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Determining the effect of soil albedo on energy production of bifacial photovoltaic panels

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Highlights

- The energy performance of bifacial PV panels was evaluated under two different ground conditions: natural soil (albedo 0.20) and white gravel (albedo 0.50).
- Annual PVsyst simulations revealed that increasing albedo from 0.20 to 0.50 improves energy yield by 3.89% and PR by 3.25 percentage points.
- Eight-month experimental measurements (March–October 2024) confirmed a 4.29% increase in grid-injected energy for the white gravel case.
- Three-dimensional shading analyses showed that a 25° tilt angle provides the optimal balance between shading losses and rear-side irradiance.
- The study demonstrates that low-cost ground reflectivity enhancement is a highly effective method for maximizing bifacial PV performance in semi-arid climates.At least 3, max 5 highlights should be listed here

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ABSTRACT

The performance of bifacial photovoltaic (PV) systems is strongly affected by site-specific environmental conditions, making field-based analyses essential for reliable performance evaluation. This study investigates the effect of ground albedo on the energy performance of a 686 kWp utility-scale bifacial PV power plant located in Konya, Türkiye, with primary emphasis on real operational data obtained under actual climatic conditions. The analysis is based on eight months of measured production data (March–October 2024) collected from two identical bifacial PV arrays installed over different ground surfaces: natural soil (albedo ≈ 0.20) and white gravel (albedo ≈ 0.50). Field measurements indicate that the system installed over white gravel produced 496.49 MWh, compared to 476.87 MWh generated by the soil-based system. This corresponds to an additional energy yield of 19.63 MWh and a relative increase of 4.26%. Monthly evaluations show that albedo-induced gains are more pronounced during periods of moderate solar altitude, while remaining positive throughout the entire measurement period. Numerical modelling and shading analyses were employed as supporting tools to interpret observed trends and assess long-term behavior. Shading simulations identified a fixed tilt angle of 25° as the most suitable configuration, providing an optimal balance between rear-side irradiance collection and shading losses. PVsyst simulations predicted an annual energy gain of 3.89% and a 3.25 percentage-point improvement in the performance ratio when ground albedo was increased from 0.20 to 0.50, consistent with the tendencies observed in the field data. Overall, the results confirm that ground albedo enhancement offers a consistent and measurable performance benefit for bifacial PV systems. High-reflectance surfaces such as white gravel represent a low-cost, passive, and practical strategy for improving energy yield and system efficiency. These findings provide valuable guidance for the design and optimization of fixed-tilt, utility-scale bifacial PV installations, particularly in high-irradiance, semi-arid regions.

Keywords: Albedo, bifacial photovoltaic panels, shading analysis, solar energy

1. INTRODUCTION

Historically, the global energy system has been a primary driver of economic growth; however, the prevailing fossil-fuel-based model now presents significant obstacles by exacerbating environmental and energy security concerns [1, 2]. Excessive dependence on these fuels speeds up the accumulation of greenhouse gases, establishing climate change as a major worldwide threat. Consequently, the transition to low-carbon energy is both an environmental and a strategic economic necessity.

Global energy policy is now focused on expanding renewable energy capacity and reducing carbon emissions, consistent with international pacts such as the Paris Agreement [3]. Within this framework, solar energy has become a strategic technology due to its unlimited potential, rapidly declining costs, and high scalability. This growth is evident in global installed PV capacity, with shipments reaching 703 GW by 2024 [4].

The PV sector is currently dominated by bifacial cell technologies (accounting for almost 90% of global module output by 2024 [4]), as they boost energy production by capturing irradiance from both the front and back surfaces. The performance of these modules hinges critically on ground reflectivity (albedo), establishing it as a vital parameter for maximizing energy production and optimizing the Levelized Cost of Energy (LCOE) [5,6].

For Türkiye, renewable energy investments are a strategic response to growing energy demand and structural dependence on imported fossil fuels, which puts persistent pressure on the national GDP [7]. Regulatory frameworks such as the YEK and YEKA models have successfully accelerated solar investment, resulting in 12GW of installed PV capacity by mid-2024. Given its high solar irradiation potential (1,527 kWh/m² annually), solar energy holds substantial value for the country.

Konya is often cited as "Türkiye's solar capital" thanks to its expansive flat terrain and high annual GHI (~ 1650 kWh/m²)[8]. However, it is constrained by the inherently low natural albedo (0.15–0.25) of its dark, organic-rich soils [9,10]. This restricted bifacial gain necessitates the artificial enhancement of ground albedo (e.g., via white gravel) as a highly effective strategy for boosting performance in this region [11].

Albedo is a dynamic and uncertain parameter varying significantly over time due to changes in surface moisture, color, texture, and seasonal conditions [10, 12,13]. While theoretical gains for high-albedo surfaces are 20–30%, field studies often report lower gains (~ 8–15%) due to limited maintenance [14]. This difference emphasizes the importance of robust real-world validation.

This study investigates the isolated effect of ground albedo on bifacial PV performance through a comparative analysis. Two panel groups within the same Konya PV plant—one on natural soil and one on a white gravel surface—are analyzed under identical conditions. This experimental setup provides a direct, quantitative assessment of surface reflectivity's contribution to real-world energy production, supporting more accurate modeling and cost-effective system design for low-albedo regions.

The remainder of the paper first outlines the materials and methods adopted in this study, detailing the system components, array configuration, ground surface characteristics, and the simulation framework. It then presents and discusses the results derived from both numerical analyses and field measurements, evaluating the influence of ground albedo on bifacial PV system performance and drawing overall conclusions.

2. MATERIALS AND METHODS

2.1. Inverter Technology

In this study, DC/AC conversion is carried out using two SUN2000-330KTL-H1 inverters, each rated at 285 kWe, providing a total installed AC capacity of 570 kW. The inverters convert the DC power generated by the PV modules into grid-compatible AC by employing high-frequency MOSFET/IGBT switching based on pulse-width modulation (PWM), followed by LC filtering to obtain a nearly sinusoidal output waveform suitable for grid integration.

The inverters offer MPPT, voltage and frequency regulation, and a comprehensive set of protection functions, including overcurrent, reverse polarity, residual current, insulation resistance monitoring, and anti-islanding. With a maximum DC input voltage of 1500 V, a peak efficiency of 99.03%, a nominal AC output of 800 V, a smart air-cooling system, and an IP66 protection rating, the devices are well-suited for harsh environmental conditions. [15].

Plant operation and monitoring are conducted via the FusionSolar platform, which provides real-time tracking of inverter-level power output, energy yield, performance ratio (PR), and fault diagnostics.

2.2. Module Technology

In this study, the field utilizes SPE-550 Half-cut Bifacial Mono PERC PV modules. Each module measures 2278 × 1134 × 35 mm, weighs approximately 28 ± 1 kg, and provides a nominal power of 550 Wp at STC with an efficiency of 21.3%. The module is composed of 144 half-cut monocrystalline M10 (182 mm) cells, encapsulated between 3.2-mm high-transmittance tempered front glass and a dual-glass rear structure, enabling bifacial operation. It features an anodized aluminum frame and an IP68-rated junction box equipped with three bypass diodes.

The module supports a maximum system voltage of 1500 V DC, a maximum series fuse rating of 30 A, and a static load capacity of up to 5400 Pa. Electrically, under STC conditions it delivers a Vmpp of 42.15 V, Impp of 13.07 A, a Voc of 49.74 V, and an Isc of 13.86 A. Under NOCT conditions, it provides 413 Wp maximum power, Vmpp of 39.0 V, and Impp of 10.60 A. Its temperature coefficients are –0.341%/°C for Pmpp, –0.269%/°C for Voc, and +0.045%/°C for Isc. With a bifaciality ratio of approximately 70 ±10%, rear-side contribution increases the output to 567–688 Wp. The module operates between –40°C and +85°C, includes MC4-compatible connectors, and is backed by a 12-year product warranty and a 25-year linear performance guarantee [16].

2.3. Array Layout and Installed Capacity

The PV system is installed in Islık Neighborhood, Karapınar District, Konya Province, on parcel 0/2256, and was commissioned in March. The overall plant capacity is 6.7 MW; however, the analyses in this study focus on the subsection connected to two inverters. This subsection comprises 1248 bifacial PERC modules rated at 550 Wp, corresponding to a nominal DC capacity of 686.4 kWp (1248 × 0.550 kW).

Modules are configured in 48 strings with 26 modules per string. The AC installed capacity of 570 kWe results in a DC/AC ratio of approximately 1.20, a typical design choice that increases annual energy yield without causing significant inverter clipping, and is well suited for utility-scale fixed-tilt PV plants.

2.4. Ground Albedo and Climate Data

Two ground-surface conditions were defined: natural soil with an albedo of 0.20 and white gravel with an albedo of 0.50. The dark, calcareous, clay-rich agricultural soils of Konya typically exhibit albedo values in the range 0.15–0.25, which justifies adopting 0.20 as a representative value for natural soil. To enhance rear-side irradiance for bifacial modules, a white gravel layer was applied in selected sections of the plant; for this surface, an albedo of 0.50 was chosen, in line with the 0.40–0.60 range reported in the literature for similar materials (Figure 1.) [17].

Figure 1. Application of high-reflectivity white gravel (albedo ≈ 0.50) beneath bifacial PV modules

In the simulations, albedo was treated as a constant parameter; seasonal variability, moisture effects, soiling and surface degradation were intentionally excluded to isolate the direct impact of ground reflectance on bifacial energy yield.

Climatic inputs were obtained from the Meteonorm 8.0 database embedded in PVsyst. Meteonorm provides long-term typical meteorological year (TMY) data derived from satellite observations, ground-based stations and climate models. For the Konya site, the dataset includes monthly and hourly GHI, DNI and DHI values, as well as ambient temperature, relative humidity, wind speed and direction. These parameters are used by PVsyst to estimate module temperature, cooling conditions and system losses under realistic climatic conditions.

2.5. Annual Simulation Studies

Following the definition of system parameters, annual performance simulations were carried out in PVsyst for two albedo scenarios:

Scenario 1: natural soil, albedo = 0.20

Scenario 2: white gravel, albedo = 0.50

In both cases, the array configuration, inverter model, tilt angle (25°), azimuth (0°), pitch (4.0 m) and climate data were kept identical; only the ground albedo value was varied.

Table 1. PVsyst simulation results

Albedo Value	Produced Energy (MWh)	Specific Production (kWh/kWp/year)	PR (%)
0.50	627.04	1827	86.81
0.20	603.55	1759	83.56

The annual results are summarized in Table 1. For the natural soil case (albedo 0.20), the annual energy yield is 603.55 MWh, with a specific production of 1,759 kWh/kWp and a performance ratio of 83.56%. When albedo is increased to 0.50 using white gravel, the annual energy rises to 627.04 MWh, specific production to 1,827 kWh/kWp,

and PR to 86.81%. This corresponds to an absolute gain of 23.49 MWh and a relative increase of approximately 3.89% in annual energy, along with a 3.25 percentage-point improvement in PR. These results indicate that ground-albedo enhancement constitutes an effective low-cost design lever for improving the performance of bifacial PV systems without altering the electrical configuration or plant capacity.

2.6. Monthly Simulation Studies

To examine the seasonal behavior of albedo-related gains, monthly E_Grid values from PVsyst were analyzed (Table 2.). For every month of the year, the white gravel scenario (albedo 0.50) yields higher energy than the natural soil case (albedo 0.20).

Table 2. Comparison of Monthly E_Grid values

Month	E_Grid (MWh) – (Albedo 0.20)	E_Grid (MWh) – (Albedo 0.50)	Difference (MWh)	Increase (%)
January	34.52	35.31	0.79	2.29%
February	37.99	39.14	1.15	3.03%
March	48.38	50.06	1.68	3.47%
April	54.95	57.16	2.21	4.02%
May	63.62	66.75	3.13	4.92%

June	65.04	68.59	3.55	5.46%
July	64.35	67.72	3.37	5.24%
August	63.13	65.75	2.62	4.15%
September	56.59	58.48	1.89	3.34%
October	47.64	49.1	1.46	3.06%
November	35.89	36.88	0.99	2.70%
December	31.45	32.1	0.65	2.07%
Total	603.55	627.04	23.47	3.89%

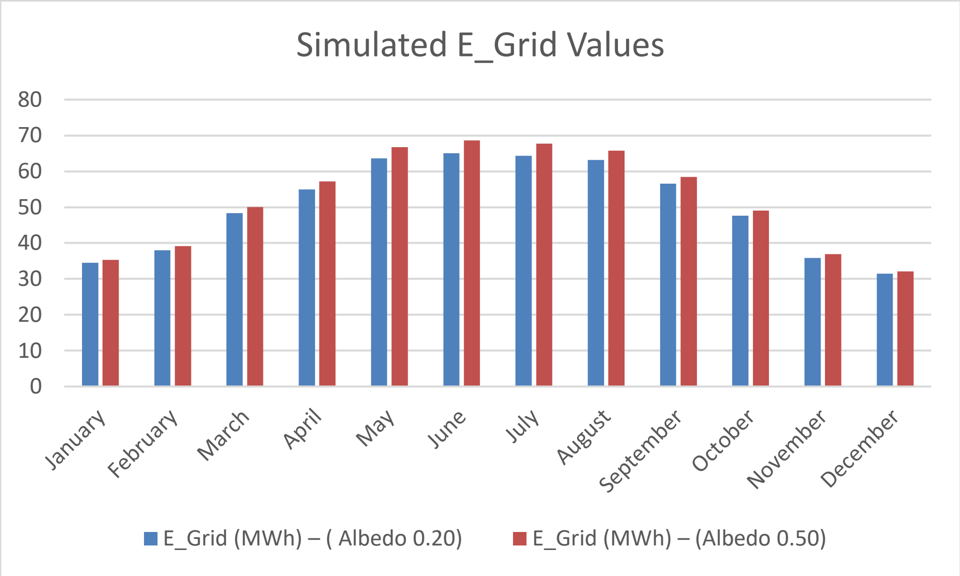

Figure 2. Monthly variation of simulated grid energy under albedo values of 0.20 and 0.50

As shown in Figure 2, the monthly variation of simulated grid energy reveals a clear dependence on ground albedo, with consistently higher E_Grid values obtained for an albedo of 0.50 compared to 0.20. The smallest monthly increase occurs in December (2.07%), whereas the highest is achieved in June (5.46%). Gains exceed 4% during the May–August period, reflecting the stronger contribution of albedo when solar elevation is high and rear-side irradiance is maximized. In winter, lower sun angles, shorter day lengths and higher atmospheric optical path reduce the fraction of reflected irradiance reaching the module rear side; however, even under these conditions, white gravel yields a 2–3% advantage over soil.

Table 3. Comparison of monthly E_Grid values (March–October 2024)

Month	E_Grid (MWh) – (Albedo 0.20)	E_Grid (MWh) – (Albedo 0.50)	Difference (MWh)	Increase (%)
March	48.38	50.06	1.68	3.47%
April	54.95	57.16	2.21	4.02%
May	63.62	66.75	3.13	4.92%
June	65.04	68.59	3.55	5.46%
July	64.35	67.72	3.37	5.24%
August	63.13	65.75	2.62	4.15%
September	56.59	58.48	1.89	3.34%
October	47.64	49.1	1.46	3.06%
Total	463.7	483.61	19.91	4.29%

Table 3. presents the March–October subset, corresponding to the eight-month period for which experimental data are available. In this interval, PVsyst predicts that the white gravel surface produces 4.29% more energy than natural soil, corresponding to a gain of 19.91 MWh. This provides a reference baseline for comparison with field measurements.

2.7. Experimental Setup

To experimentally validate the simulation results, two equivalent inverter systems located within the same PV plant were selected. The strings of one inverter were installed over natural soil (albedo ≈ 0.20), while those of the other inverter were installed over a white gravel surface (albedo ≈ 0.50). All other parameters—module type, tilt angle (25°), azimuth, pitch, cabling, inverter model and operational practices—were kept identical.

Table 4. Comparison of monthly E_Grid values (March–October 2024)

Month	E_Grid (MWh) – (Albedo 0.20)	E_Grid (MWh) – (Albedo 0.50)	Difference (MWh)	Increase (%)
March	21.93	23.00	1.07	4.90%
April	56.49	60.17	3.68	6.50%
May	65.22	68.05	2.83	4.30%
June	70.31	72.83	2.53	3.60%
July	73.48	76.02	2.54	3.46%
August	71.81	74.35	2.54	3.54%
September	63.32	64.89	1.58	2.49%

October	54.31	57.17	2.86	5.27%
Total	476.87	496.49	19.63	4.26%

Energy production data for the March–October 2024 period are presented in Table 4. In this eight-month interval, the system installed over white gravel outperforms the soil-based system in every month. The monthly relative gains range from 2.49% (September) to 6.50% (April), with a total additional production of 19.63 MWh and an overall increase of 4.26%. The lower energy in March is attributed to the plant's mid-month commissioning.

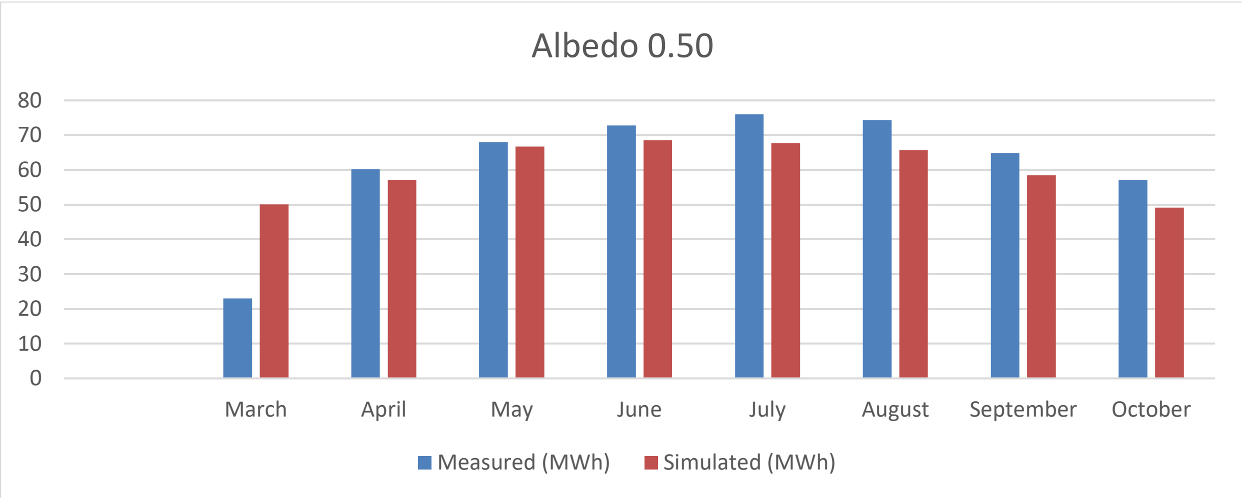

Figure 3. Monthly measured and simulated E_Grid values for Albedo = 0.50

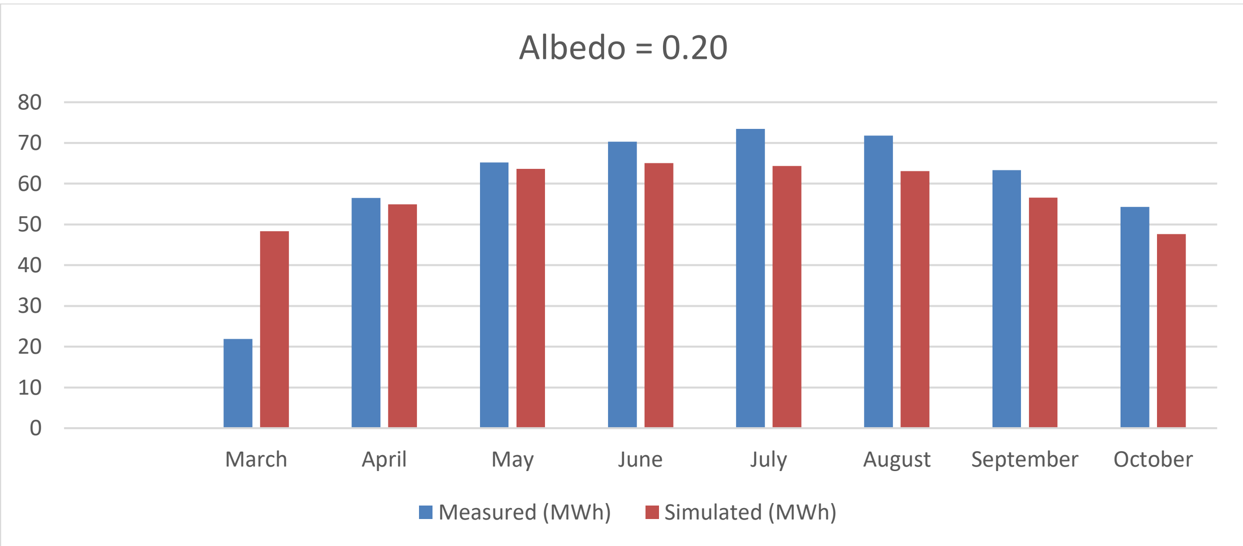

Figure 4. Monthly measured and simulated E_Grid values for Albedo = 0.20

Figures 3 and 4 present the monthly comparison between the measured field data and the PVsyst simulation results for albedo values of 0.50 and 0.20, respectively. Overall, a strong agreement is observed between the experimental measurements and the simulated energy production, particularly from April to October, indicating that the numerical model reliably represents the real operational behavior of the bifacial PV system under different ground conditions.

A noticeable deviation is observed in March for both albedo values, where the measured energy production is lower than the simulated results. This discrepancy can be attributed to the commissioning date of the PV plant. Since the system became operational during March, the measured data do not correspond to a full operational month, whereas the simulation assumes continuous operation throughout the entire month. Consequently, the lower measured values in March do not indicate a modeling error but rather reflect the incomplete operational period.

In addition, the comparison demonstrates that the higher albedo surface (0.50) consistently results in increased energy generation compared to the lower albedo condition (0.20) in both measured and simulated datasets. The close alignment between experimental and simulated results under both ground conditions further validates the effectiveness of using white gravel surfaces to enhance rear-side irradiance and improve the overall performance of bifacial photovoltaic systems. The experimentally observed 4.26% gain is in excellent agreement with the 4.29% increase predicted by PVsyst for the same period, with a difference of only 0.03 percentage points. This close match confirms that the simulation model realistically represents the contribution of ground albedo under field conditions.

From a physical standpoint, the high reflectance of the white gravel surface enhances the diffuse and reflected irradiance reaching the rear of the bifacial modules, thereby increasing bifacial gain, while the brighter surface can also help mitigate thermal losses by limiting ground-induced heating. Taken together, the simulation and experimental findings demonstrate that optimizing ground albedo is a robust, scalable and economically attractive strategy for improving the performance of bifacial PV systems in high-irradiance regions such as Konya.

3. DISCUSSION AND CONCLUSION

This study investigated the influence of ground albedo on the performance of a bifacial photovoltaic (PV) system operating under the climatic conditions of Konya by integrating shading analysis, numerical modelling, and experimental observations. The three-stage methodology enabled a comprehensive assessment of how geometric configuration, optical ground properties, and real environmental conditions collectively influence bifacial energy yield.

In this study, a 25° tilt angle, a 4.00 m row spacing, a mounting height of 0.60 m, and an azimuth angle of 0° (true south) were selected.

The PVsyst simulations were used to quantify expected performance trends associated with enhanced ground reflectance. Increasing albedo from 0.20 (natural soil) to 0.50 (white gravel) raised annual energy production from 603.55 MWh to 627.04 MWh, corresponding to a 3.89% improvement. Specific production increased from 1,759 to 1,827 kWh/kWp, and the performance ratio rose from 83.56% to 86.81%. These results indicate that albedo enhancement effectively increases rear-side irradiance and improves system performance not only optically but also thermally by limiting ground-induced heating.

Experimental results obtained from March–October 2024 further supported the model predictions. The system installed over white gravel produced 496.49 MWh compared to 476.87 MWh from the soil-based system, representing a total difference of 19.63 MWh and an overall increase of 4.26%. For the same period, PVsyst predicted an increase of 4.29%, indicating an almost perfect match between the model and real-world performance with a deviation of only 0.03 percentage points. This level of agreement confirms the reliability of PVsyst in estimating bifacial gains under controlled surface conditions.

Seasonal evaluations showed that the periods of maximum albedo benefit differed between simulations and field measurements. PVsyst predicted the highest relative gains in June and July (5.46% and 5.24%), which correspond to the highest solar elevations of the year. However, the experimental system recorded its highest gains in April (6.50%) and October (5.27%), reflecting the influence of diffuse irradiance distribution, moderate solar altitude, thermal conditions, and soiling behavior under real field environments. Despite these seasonal deviations, both simulation and experimental datasets consistently demonstrated positive albedo-driven gains in every month, confirming that ground reflectance acts as a persistent and year-round performance-enhancing parameter.

The experimentally measured average increase of approximately 4% is consistent with values reported in previous studies where only the albedo variable was altered within comparable technology types. Thus, this research contributes to the growing body of real-system investigations by presenting one of the few studies that simultaneously integrates bifacial modelling and field validation under the regional conditions of Konya.

The findings demonstrate that high-reflectance surface treatments (e.g., white gravel, light-colored minerals or reflective coatings) can serve as low-cost, passive and scalable methods to increase the energy yield of bifacial systems. Even modest increases in reflectance can translate to substantial annual gains and significantly shorten investment payback periods. The results highlight the importance of including ground optimization as a key design parameter, particularly in high-irradiance regions such as Central Anatolia where the albedo effect becomes more pronounced.

Despite its comprehensive approach, the study has certain limitations. Albedo values were assumed constant throughout the simulation and analysis period (0.20 for natural soil and 0.50 for white gravel), whereas in reality albedo fluctuates due to seasonal moisture, soiling, surface degradation, and irrigation activities. Furthermore, the investigation was limited to fixed-tilt systems, and the albedo effects observed here cannot be directly generalized to single-axis or dual-axis tracking systems, where rear-side irradiance geometry differs significantly.

Future work will focus on long-term albedo durability, maintenance requirements and the environmental implications of alternative high-reflectance surfaces such as light-colored concrete, reflective membranes, and engineered coatings. Additionally, integrating real-time albedo monitoring into bifacial performance modelling may further improve simulation accuracy and support more robust bifacial PV optimization strategies.

NOMENCLATURE

DHI	Diffuse Horizontal İrradiance
DNI	Direct Normal Irradiance
GDP	Gross Domestic Product
GHI	Global Horizontal İrradiance
Isc	Short Circuit Current
kWp	Kilowattpick
MPPT	Maximum Power Point Tracking
NOCT	Nominal Operating Cell Temperature
Pmpp	Maximum Power Point Power
PR	Performance Ratio
STC	Standard Test Conditions
TMY	Typical Meteorological Year

Voc	Open Circuit Voltage
YEK	Renewable Energy Law of the Republic of Türkiye
YEKA	Renewable Energy Resource Areas

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

İnci Nur Atalay: Performed the experiments and analyse the results, performed the numerical simulations and wrote the manuscript.

Sıtkı KOCAOĞLU: Conceived of the presented idea, verified the analytical methods and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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