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Bifacial Photovoltaic Systems: Performance Modelling, Energy Yield Optimization and Reliability: A Critical Review

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ABSTRACT

Bifacial photovoltaic (PV) modules convert solar radiation received by both their front and rear surfaces and can therefore deliver higher energy yields than comparable monofacial modules. This critical narrative review synthesizes the operating principles, module architectures, irradiance and electrical modelling methods, reported field performance, and reliability of bifacial PV systems. Evidence from analytical studies, numerical simulations, and outdoor investigations shows that bifacial energy gain is governed by the combined effects of ground albedo, module tilt and azimuth, clearance height, inter-row spacing, shading, and local weather conditions. Across the reviewed studies, additional energy yields commonly fall within approximately 5%–30%; however, these values are site- and configuration-dependent and should not be treated as universal performance guarantees. Analytical irradiance models offer computational simplicity, whereas electrical equivalent-circuit, ray-tracing, and multiphysics approaches provide progressively more detailed representations of electrical response, optical non-uniformity, and thermal behaviour. Nevertheless, prediction accuracy remains sensitive to input data, geometric assumptions, rear-side obstruction, and validation conditions. The review identifies the need for standardized characterization, simultaneous front- and rear-side measurements, and long-term validation in hot, dusty, and seasonally variable environments.

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INTRODUCTION

In response to the global transition towards low-carbon energy systems, interest has increased in renewable electricity technologies that can reduce dependence on fossil fuels and associated greenhouse-gas emissions (Amer et al., 2024; Kiss et al., 2020). Solar photovoltaic (PV) technology has become an important component of this transition. IRENA, 2026 documented substantial growth in global PV deployment between 2015 and 2026, reflecting improvements in technology, manufacturing, and project economics. The contribution of solar PV to installed renewable-energy capacity also increased markedly over the same period (IRENA, 2026; Figure 2). This expansion has stimulated interest in module technologies that can increase energy generation from a given land area and improve the economics of PV installations.

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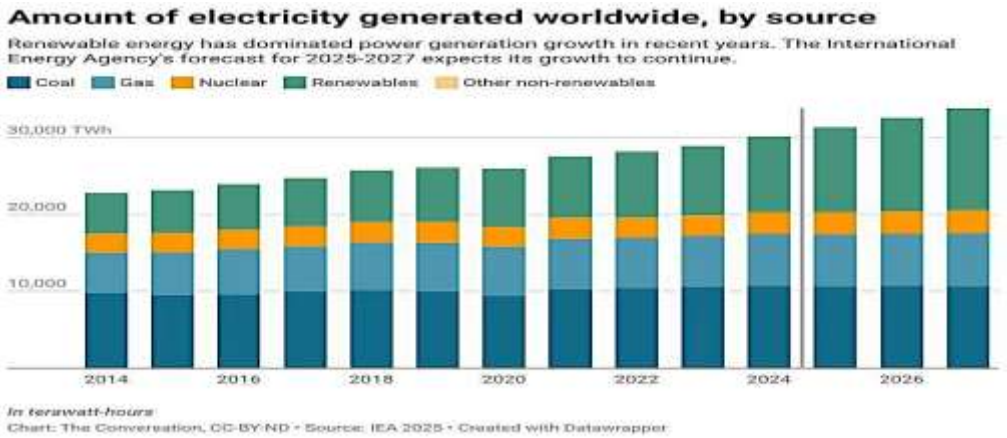
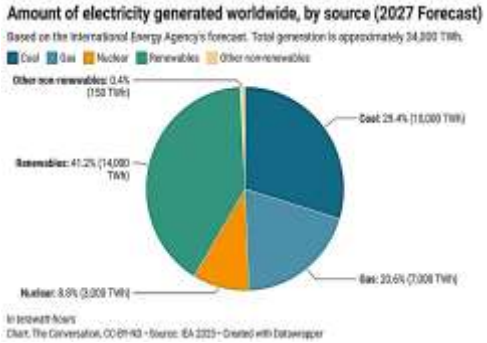


Figure 1. Global electricity generation from renewable energy sources, 2015–2025.



Source: Adapted from International Energy Agency (2026).

Figure 2 Global electricity generation from renewable energy sources, 2015–2025" and attributed to IEA (2026)

Against this background, bifacial PV technology has emerged as one promising development. Unlike monofacial modules, which primarily collect radiation through the front surface, bifacial modules are designed to convert radiation incident on both the front and rear surfaces. The rear surface can receive ground-reflected and diffuse radiation, increasing energy yield where the module design and installation geometry allow sufficient rear-side illumination (Guerrero-Lemus et al., 2016; Mouhib et al., 2022; Yakubu et al., 2024).

Importantly, however, the additional energy yield is not an intrinsic constant of a module. It depends on ground reflectivity (albedo), module elevation and tilt, row-to-row spacing, orientation, surrounding obstructions, and local solar and weather conditions (Deline et al., 2020; Kim et al., 2024; Peter et al., 2025). Consequently, reliable performance assessment requires models that represent both the optical environment and the electrical response of the module.

Despite the substantial body of research on bifacial energy yield and simulation, comparisons are complicated by differences in test conditions, modelling assumptions, performance metrics, and reporting practices. This review therefore synthesizes the fundamental operating principles, irradiance and electrical modelling approaches, experimental findings, and operational challenges reported in the literature. It also identifies methodological limitations and research needs relevant to the evaluation of bifacial PV systems in diverse climates, including hot and dusty environments.

REVIEW METHODOLOGY.

To address these issues, this article adopts a critical narrative-review approach to examine the fundamentals, modelling techniques, reported experimental performance, and reliability of bifacial photovoltaic (PV) systems. The review draws on the studies and technical publications cited in the manuscript. The literature is organized thematically to provide an integrated account of bifacial operating principles, irradiance and electrical modelling, experimental energy-yield

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findings, installation and environmental influences, and operational reliability.

Accordingly, the reviewed modelling approaches are grouped into analytical irradiance models, electrical equivalent-circuit models, ray-tracing techniques, and multiphysics simulations. They are compared in terms of required inputs, modelling capabilities, advantages, and limitations (Table 1). Reported performance findings are considered in relation to ground albedo, mounting height, tilt angle, row spacing, shading, and weather conditions. Reliability issues, including electrical mismatch and degradation mechanisms, are also synthesized to identify research gaps and implications for bifacial PV design and performance assessment.

FUNDAMENTALS AND MODELLING OF BIFACIAL PHOTOVOLTAIC TECHNOLOGY

Photovoltaic electricity generation

Crystalline-silicon PV cells convert incident radiation into electrical energy through the photovoltaic effect. Photons with sufficient energy generate electron–hole pairs in the semiconductor. The built-in electric field of the p–n junction separates these charge carriers, producing a photocurrent that can deliver power to an external load. The electrical output is commonly described by current–voltage (I–V) characteristics, with maximum power given by the product of current and voltage at the maximum-power point.

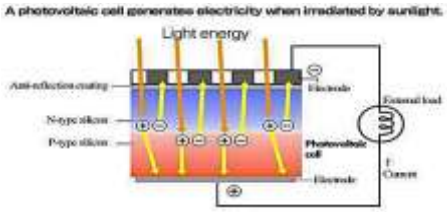


Figure 3. Schematic illustration of electricity generation in a photovoltaic cell (adapted from Krisciunas, 2023).

In addition to irradiance, module temperature also affects PV performance. For crystalline-silicon modules, increasing cell temperature generally reduces open-circuit voltage and maximum power, although the magnitude depends on cell technology and module construction. The temperature coefficient should therefore be taken from the relevant module datasheet or measured under the conditions of interest rather than assumed to be universal (Krisciunas, 2023).

Operating principle of bifacial modules

Bifacial modules are designed to collect radiation from both sides of the PV cells. The front surface receives direct-beam and diffuse sky radiation, while the rear surface can receive radiation reflected by the ground and nearby objects, together with diffuse sky radiation. The additional rear-side contribution is commonly described as bifacial gain. Transparent or semi-transparent rear structures, such as glass–glass construction or transparent back sheets, permit radiation to reach the rear surface (Jang et al., 2021; Mouhib et al., 2022).

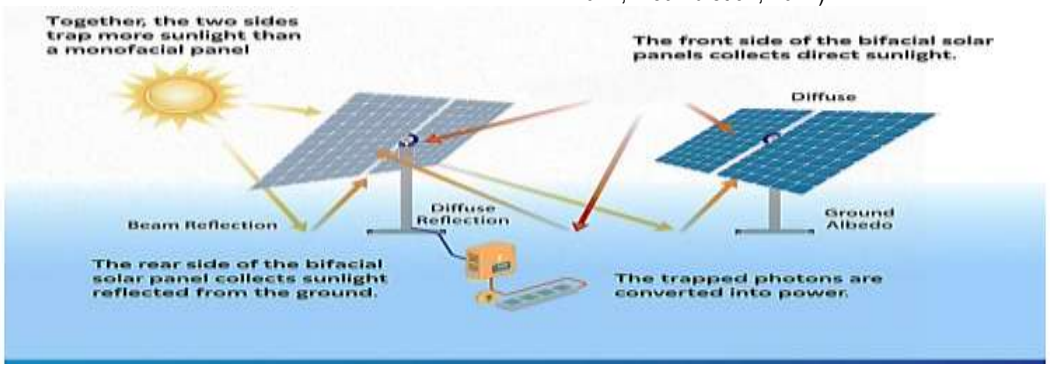


Figure 4. Operating principle of a bifacial photovoltaic module (adapted from Mouhib et al., 2022).

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Furthermore, the amount of rear-side radiation depends on the reflectance of the ground and the geometric view of the ground from the module. Surfaces such as light-colored concrete, sand, and snow can provide higher reflectance than dark surfaces, although actual albedo varies with material, moisture, cleanliness, solar angle, and time (Deline et al., 2020; Urraca et al., 2022).

Structural differences between monofacial and bifacial cells

In structural terms, a conventional monofacial module generally has an opaque rear structure or continuous rear electrode that prevents useful rear-side illumination. Bifacial cells instead use rear contacts that allow light to enter the cell from the back. Bifacial modules are commonly assembled using transparent rear materials or glass–glass encapsulation. The precise cell architecture, contact design, encapsulant, and module construction influence optical transmission, electrical collection, mechanical strength, and long-term reliability (Cuevas et al., 2019; Yakubu et al., 2024).

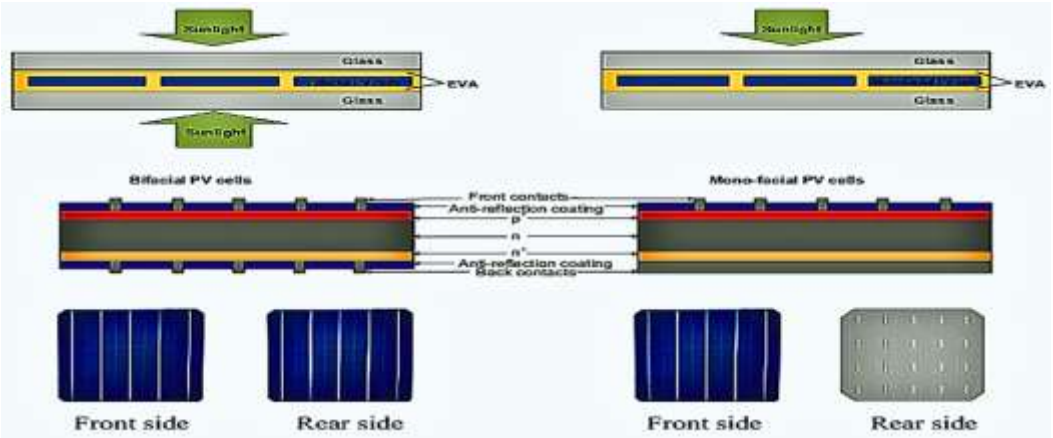


Figure 5. Schematic comparison of monofacial and bifacial PV cell architectures (adapted from Yakubu et al., 2024).

SOLAR GEOMETRY AND IRRADIANCE MODELLING FRAMEWORK

Solar geometry and irradiance components

The irradiance incident on a tilted PV surface depends on the relative positions of the Sun and the module. The angle of incidence (θ) is the angle between the incoming direct solar beam and the normal to the module surface. The solar zenith angle (θz) is measured between the Sun and the local vertical. The module tilt angle (β) is measured from the horizontal plane, while the surface azimuth angle (γ) specifies the module orientation relative to the selected reference direction. These angles vary with location, date, time, and module orientation and are fundamental inputs to plane-of-array irradiance calculations (Duffie & Beckman, 2013; Masters, 2013).

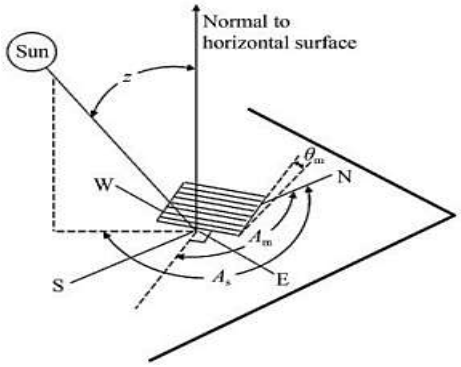


Figure 6. Solar and module angles used in irradiance calculations (source attribution in the supplied manuscript: “Authur et al., 2022”; full reference requires verification).

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INSTALLATION PARAMETERS GOVERNING BIFACIAL PERFORMANCE

The performance of bifacial photovoltaic (bPV) modules is governed by the interaction between module characteristics, the surrounding meteorological and geographical conditions, and the geometric configuration of the installation. In particular, ground-surface albedo determines the availability of reflected irradiance, while module tilt, azimuth, ground clearance and inter-row spacing influence how effectively the front and rear surfaces receive solar radiation. Accordingly, this review examines these interrelated factors because their combined effects determine rear-side irradiance, bifacial gain and the overall energy yield of bPV systems (Baloch et al., 2020).

Ground albedo

Among the installation variables, ground albedo, also referred to as surface reflectivity, is the ratio of reflected solar irradiance to incident irradiance and is commonly expressed on a scale from 0 to 1. It is particularly important in bifacial systems because radiation reflected from the ground contributes directly to the irradiance received by the rear surface. Therefore, an increase in surface reflectivity generally raises rear-side irradiance and, in turn, improves the electrical output and energy yield of a bPV installation (IEA PVPS, 2021; Wang et al., 2015).

Moreover, the relationship between ground albedo and bifacial energy gain is generally positive when front-side irradiance and other installation conditions remain relatively constant. Consequently, surfaces with higher reflectivity can provide a greater contribution to rear-side irradiance than surfaces with lower reflectivity. The estimated values presented in Table 1 illustrate this relationship: water and bare sand are associated with relatively modest expected yield gains, whereas reflective roof coatings and fresh snow are associated with substantially higher gains. These values should, however, be interpreted as representative estimates because actual performance also depends on module geometry, mounting height, solar conditions and the extent of rear-side shading (Performance analysis, 2023).

Table 1. Representative ground-albedo values and estimated bifacial energy-yield gains.

No.	Ground surface	Albedo (%)	Expected yield gain (%)
1	Water	5.0–8.0	4.0–6.0
2	Bare sand	10.0–20.0	6.0–8.0
3	Green grassland	15.0–25.0	7.0–9.0
4	Concrete	25.0–35.0	8.0–10.0
5	Dry sand	35.0–45.0	10.0–15.0
6	Reflective roof coating	80.0–90.0	23.0–25.0
7	Fresh snow	80.0–95.0	25.0–30.0

Note. Adapted from Bifacial photovoltaic systems energy yield modelling by Wang et al. (2015), and Performance analysis and comparison between bifacial and monofacial solar photovoltaic at various ground albedo conditions by Alam et al. (2023).

The estimated bifacial energy-yield gains are representative values and may vary with installation geometry, mounting height, irradiance conditions, and rear-side shading. Experimental and numerical evidence further supports the influence of albedo on bifacial performance. For example, Chiodetti et al. (2016), using outdoor measurements and numerical simulations at the EDF R&D testing facility in France, showed that the contribution of ground-reflected irradiance to total rear-side irradiance increased as surface reflectivity increased. Correspondingly, the measured bifacial gain rose across the ground materials examined. This agreement between the irradiance contribution and measured bifacial gain demonstrates why ground-surface selection is an important consideration in bPV system design.

Nevertheless, the benefit of increasing albedo is also affected by module mounting height. For a single-module configuration, energy yield and bifacial gain have been reported to increase approximately linearly with albedo. However, the rate of improvement is lower when

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modules are installed close to the ground because module self-shading restricts the amount of reflected irradiance reaching the rear surface. By contrast, greater clearance can reduce this limitation and allow a larger proportion of reflected radiation to reach the module (Asgharzadeh et al., 2018).

Module tilt angle

Alongside albedo, the tilt angle (β) is the inclination of a PV module relative to the horizontal plane. Its optimum value depends on geographical location, ground albedo and module clearance height. Unlike monofacial modules, for which tilt is commonly selected to maximize front-side irradiance, bifacial modules require a configuration that balances direct and diffuse radiation received by the front surface with ground-reflected irradiance reaching the rear surface. As a result, under some geographical and installation conditions, a bPV module may achieve a higher annual energy yield at a tilt angle different from that selected for a comparable monofacial module (Patel et al., 2019).

In addition, changes in tilt angle may affect front-side energy yield more strongly than rear-side energy yield. This is because diffuse atmospheric radiation and ground-reflected radiation can remain available to the rear surface over a range of module inclinations. Thus, the optimum tilt for a bifacial system is determined not only by the maximum front-side output but also by the combined contribution of both module surfaces.

The influence of system configuration was examined by Asgharzadeh et al. (2018), who used a radiance-based ray-tracing model to evaluate three south-facing arrangements: an isolated module, a single row containing five modules, and a multi-row array consisting of five rows with five modules in each row. Their simulations considered a ground albedo of 21% and a module clearance height of 1.0 m. The resulting energy-yield trends show that the relationship between tilt angle and bifacial performance depends on array configuration; therefore, a tilt angle optimized for an isolated module should not automatically be assumed to be optimal for a larger array.

Module clearance height

Another important geometric variable is module clearance height, defined as the vertical distance between the lowest edge of a PV module and the ground surface. It is a significant design parameter in bPV systems because it affects the amount of ground-reflected irradiance that can reach the rear surface. In general, increasing module elevation reduces obstruction and self-shading, expands the rear surface's view of the ground and can consequently improve rear-side irradiance, bifacial gain and energy yield (Yusufoglu et al., 2015).

However, the improvement does not continue indefinitely. As demonstrated by the production-versus-elevation relationship presented in Figure 7, energy production increases rapidly over the lower range of mounting heights and then approaches a plateau. This saturation effect means that additional elevation beyond a certain point produces progressively smaller gains in energy yield and bifacial gain. Accordingly, the selection of clearance height should balance the expected electrical benefit against structural requirements, installation cost and available land. A range of 0.5–1.5 m may be considered for practical installations, although the appropriate value depends on albedo, array configuration and local environmental conditions (Asgharzadeh et al., 2018).

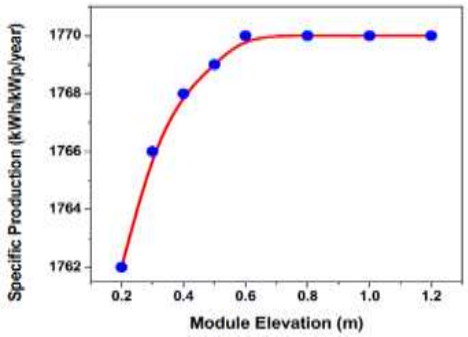


Figure 7. Relationship between module elevation and energy production (adapted from Asgharzadeh et al., 2018).

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Ground coverage ratio and inter-row spacing

For multi-row installations, the ground coverage ratio (GCR) describes the proportion of the ground covered by the array and is closely related to the pitch, or spacing, between adjacent rows. A larger row pitch generally corresponds to a lower GCR. This geometric relationship is important for bifacial systems because the amount of unshaded ground visible to the rear surface affects the availability of reflected irradiance.

As inter-row spacing increases, a larger area of ground is exposed to sunlight and the rear surface can receive reflected radiation over a wider field of view. Wider spacing can also reduce mutual shading between adjacent rows. Consequently, bifacial gain and energy yield generally increase with row spacing until the improvement approaches a saturation point, beyond which additional spacing produces only marginal benefits. Shoukry et al. (2016) similarly demonstrated that increasing the distance between adjacent rows can enhance bifacial gain by reducing mutual shading and improving access to ground-reflected radiation.

Nevertheless, excessively wide row spacing may reduce the number of modules that can be installed within a fixed area, particularly on rooftops and other space-constrained sites. It may also increase cabling, mounting-structure and other balance-of-system costs. Therefore, GCR should be selected by considering the geographical location, available installation area, module tilt, expected shading conditions and the desired balance between energy yield and system cost.

Module azimuth angle

Finally, the azimuth angle (γ) defines the compass orientation of a PV module or array relative to a reference direction, commonly true south in the Northern Hemisphere. It determines the orientation of the module with respect to the sun's apparent movement during the day and therefore influences the distribution of irradiance received by both the front and rear surfaces of a bifacial module (Yakubu et al., 2022). Azimuth effects can be assessed in fixed-tilt as well as solar-tracking systems.

Although single-axis and dual-axis tracking can increase total energy production by improving the capture of direct solar irradiance, the relative bifacial gain may be lower than that of a comparable fixed-tilt system. This can occur because tracking arrangements are commonly configured to improve front-side irradiance capture, whereas the rear-side contribution may not increase at the same rate. Thus, total energy yield and relative bifacial gain should be treated as related but distinct performance measures.

An east–west orientation provides a further alternative to conventional equator-facing configurations. Abotaleb and Abdallah (2018) reported that east–west-oriented bifacial modules may produce a lower annual energy yield than optimally tilted, equator-facing systems under comparable conditions. However, vertically mounted east–west bifacial modules can distribute generation more evenly across the day: the east-facing surface receives greater irradiance in the morning, while the west-facing surface receives greater irradiance in the afternoon. This produces a characteristic bimodal power profile, in contrast to the predominantly single midday peak typically associated with equator-facing monofacial modules. Consequently, east–west orientation may be useful where a broader temporal distribution of electricity generation is desirable or where conventional equator-facing installation is impractical.

Empirical findings also indicate that the optimum azimuth is site-specific. Dhimish & Silvestre (2019), reported that PV installations investigated in Huddersfield, United Kingdom, achieved their highest energy production within an azimuth range of −4° to +2° at one of the study sites. In a separate experimental investigation of a bifacial module in Jaipur, India (26.91° N, 75.78° E), the authors used a Taguchi-based full-factorial design to optimize installation parameters. They identified an optimum azimuth of 22.5°, a tilt angle of 40° and a clearance height of 0.8 m for maximum power generation. These results reinforce the need to optimize module orientation in relation to local solar conditions rather than adopting a universal azimuth setting (Raina et al., 2022).

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Integrated design implications

Overall, the reviewed studies show that bifacial photovoltaic performance is controlled by the combined effects of the ground environment and installation geometry. Higher ground albedo generally increases rear-side irradiance, while module clearance and inter-row spacing determine how much of the reflected radiation is accessible to the rear surface. At the same time, tilt and azimuth influence the distribution of incident radiation over the day and throughout the year. These parameters are therefore interdependent: for example, the benefit of a highly reflective ground surface may be constrained by low module clearance, while the effect of row spacing depends on the array's tilt and overall layout.

Taken together, the evidence suggests that bPV system design should not optimize each parameter in isolation. Instead, albedo, tilt angle, azimuth, clearance height and GCR should be considered jointly in relation to the site's geographical and meteorological conditions, land availability and economic constraints. This integrated approach is necessary to improve rear-side irradiance utilization and energy yield while avoiding unnecessary structural and installation costs (Guerrero-Lemus et al., 2016; Almarshoud et al., 2024; d'Alessandro et al., 2024; Yakubu et al., 2022).

Previous researches on bifacial photovoltaic (PV) systems have focused on enhancing energy yield by capturing sunlight on both the front and rear surfaces, leading to higher efficiency compared to traditional monofacial modules. Studies have investigated the effects of albedo, mounting configurations, and environmental conditions on performance optimization. Additionally, research has explored modeling approaches to assess feasibility and integration in diverse applications.

CRITICAL SYNTHESIS OF REPORTED PERFORMANCE AND MODELLING EVIDENCE

This section critically synthesizes findings reported in the cited literature. It is not a presentation of new experimental measurements generated by the authors. The discussion is organized around reported energy gains, modelling performance, installation and environmental influences, and reliability challenges.

Experimental performance and reported bifacial gains

When the evidence is considered collectively, bifacial modules generally produced higher energy yields than comparable monofacial modules when the rear surface received appreciable reflected or diffuse radiation. The magnitude of the gain varied with site conditions and system configuration. Deline et al. (2020) describe the importance of ground conditions and mounting geometry, while Kim et al. (2024) report that high-albedo surfaces can improve rear-side illumination. The literature commonly reports gains in the approximate range of 5%–30%, but this range should be treated as indicative rather than universal.

Kim et al. (2024) report a positive relationship between albedo and annual energy output, with gains approaching 30% for a ground albedo of 0.5 in the conditions they examined. Alam et al. (2023) similarly report that the advantage of bifacial configurations increased as albedo rose, with reported gains of approximately 10% at an albedo of 0.2 and 30% at 0.5 for the configurations studied. These results support the conclusion that ground reflectance is a major determinant of bifacial performance; however, they do not establish that the same gains will occur at every site.

Installation height also affects rear-side irradiance. Deline et al. (2020), as summarized in the supplied manuscript, reported a rear-side energy contribution of 9.1% for a module elevated by 1 m, compared with a maximum of 4.6% for a ground-mounted configuration. This illustrates how greater clearance can improve the rear surface's view of the ground and reduce obstruction, although the optimum height must be balanced against structural cost, wind loading, and land-use requirements.

The influence of surface type is also evident in the results reported by Wei et al. (2016), who observed output improvements of

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approximately 7.6% over grass, 15% over sand, and 29.2% over snow for the module and conditions studied. These values should not be interpreted as direct comparisons across climates because irradiance, module orientation, albedo measurement, and test duration may differ. Vyas et al. (2024) report substantially different relative gains under sunny and cloudy conditions, reinforcing the need to distinguish absolute energy yield from percentage gain and to state the reference condition clearly.

Evidence from tropical and regional studies is particularly relevant to deployment outside temperate climates. Yakubu et al. (2022) evaluated bifacial modules under different climatic regions in Nigeria, while Peter et al. (2025) considered the influence of tilt and mounting height in tropical conditions. Such studies indicate the importance of local validation rather than transferring design parameters directly from high-latitude or snow-dominated environments.

Modelling approaches and prediction accuracy

In explaining these performance differences, the reviewed literature includes analytical irradiance models, electrical models, ray-tracing tools, and multiphysics simulations. These approaches address different parts of the prediction problem. Analytical models estimate incident irradiance using solar geometry, sky conditions, albedo, and view factors. Electrical models translate irradiance and temperature into I–V and power–voltage (P–V) characteristics. Ray-tracing methods represent optical interactions and spatial non-uniformity in greater detail, while multiphysics tools can couple electrical output with module temperature and heat transfer.

Bouchakour et al. (2021) compared the use of monofacial electrical models for bifacial PV simulation under varying albedo conditions. The supplied manuscript reports average daily errors below 1% for normal albedo and approximately 3% for high albedo, with estimated gains of 4.18% and 9.56%, respectively. These results suggest that simplified models can be useful under defined conditions, but their performance may deteriorate when rear-side illumination becomes non-uniform or when shading and low-irradiance effects are inadequately represented.

Sahu et al. (2025) are reported to have proposed an electrical model that accounts for different front- and rear-side illumination and reduces I–V prediction deviation relative to conventional approaches. The manuscript reports an RMS deviation of about 7% for the proposed model, compared with 11.9%–12.3% for conventional models. This comparison highlights the importance of representing bifacial electrical behaviour rather than assuming that a monofacial model can be transferred without modification.

Nygren and Sundström (2021) developed a simulation and optimization framework that considered dynamic albedo. The supplied manuscript reports coefficients of determination of 93% for front-side irradiance and 91% for rear-side irradiance, together with energy gains that differed between tilted and vertical systems. These findings emphasize that time-varying ground reflectance and system geometry should be represented when predicting rear-side performance.

Longares et al. (2023) compared PVsyst and COMSOL Multiphysics for bifacial module analysis. As reported in the source manuscript, PVsyst was more computationally efficient, whereas COMSOL provided more detailed thermal modelling and lower errors in some of the evaluated conditions. Becerra et al. (2024) validated BifacialSimu against empirical data from multiple locations; the source reports an R^2 of 0.99 and an NRMSE of 7.8% for the ray-tracing approach. These metrics indicate good agreement for the evaluated datasets, but they should be interpreted in the context of the sites, sensors, and validation procedures used.

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Table 2. Comparative assessment of modelling approaches for bifacial photovoltaic systems

Modelling approach	Main inputs/parameters	Main capabilities	Advantages	Limitations
Analytical irradiance model	Solar geometry, DNI, DHI, GHI, albedo and view factors	Estimates front- and rear-side irradiance	Computationally efficient and relatively simple to implement	Sensitive to geometric assumptions, albedo estimation and shading simplifications
Electrical equivalent-circuit model	Front/rear irradiance, cell temperature and electrical parameters	Predicts I–V and P–V characteristics and electrical output	Provides detailed electrical performance evaluation	May underestimate mismatch losses under non-uniform illumination if not properly adapted
Ray-tracing model	Module geometry, optical properties, ground reflectance and surrounding structures	Determines spatial irradiance distribution and optical interactions	Captures complex shading and non-uniform rear-side illumination	Requires detailed geometric information and considerable computational resources
Multiphysics simulation	Optical, thermal and electrical parameters	Examines coupled optical, thermal and electrical behaviour	Provides comprehensive assessment of temperature effects and electrical performance	Requires extensive input data, computational resources and experimental validation

Note. Compiled based on Wang et al. (2015), Asgharzadeh et al. (2018), Bouchakour et al. (2021), Longares et al. (2023), and Sahu et al. (2025).

Installation and environmental influences

Beyond the modelling approach itself, ground albedo is consistently identified as a key driver of bifacial gain. A high-reflectance surface can increase rear-side irradiance, but the actual benefit depends on the spectral and angular properties of the surface, its condition, and the module's view of the ground. Moisture, dust deposition, vegetation growth, and seasonal changes can alter albedo and should be considered in long-term assessments (Urraca et al., 2022).

Module height, tilt, azimuth, and row spacing jointly determine the view factors and shading patterns experienced by the rear surface. Greater ground clearance and wider row spacing can improve rear-side exposure, but excessive spacing may reduce installed capacity per unit land area. Tilt and orientation also affect the balance between front-side direct irradiance and rear-side reflected irradiance. Consequently, an optimum design should be based on annual energy yield and project constraints rather than a single geometric parameter.

Weather conditions influence both absolute energy production and the relative bifacial gain. Under diffuse-dominated skies, the rear side may receive a larger share of the available irradiance than under conditions dominated by direct beam radiation. However, the precise response depends on module orientation, surroundings, and sky distribution. Reported percentages from different studies should therefore be compared only after considering their weather conditions and reference systems.

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Material choice can also influence the performance and application of bifacial PV. Transparent back sheets and glass–glass structures affect optical transmission and reliability. Organic and semi-transparent PV technologies offer alternative design possibilities for façades and windows, although the efficiencies reported in the cited organic-cell studies are not directly comparable with those of commercial crystalline-silicon modules (Alam et al., 2024; Çokduygulular et al., 2024; Yang et al., 2021).

RELIABILITY AND OPERATIONAL CHALLENGES

Despite these performance opportunities, rear-side shading remains a distinctive challenge for bifacial modules. Junction boxes, cables, mounting rails, and structural members can obstruct rear-side illumination and create non-uniform current generation. Türkdoğru and Kutay (2022), report irradiance as low as 47 W m^{-2} near an obstruction compared with 83 W m^{-2} in other cell locations. Such spatial differences can produce mismatch losses and reduce the expected bifacial gain.

Degradation mechanisms also require attention. Light-induced and elevated-temperature-induced degradation can reduce module output, while potential-induced degradation can affect cells and module surfaces under particular electrical, environmental, and encapsulation conditions. Repins et al. (2023) discuss long-term effects of light- and elevated-temperature-induced degradation in PV arrays. Seok et al. (2021) report changes in short-circuit current density, open-circuit voltage, and fill factor associated with degradation in p-type PERC modules. Yamaguchi et al. (2022) investigate polarization-type potential-induced degradation and report differences between cell types and module sides.

The presence of transparent rear structures and glass–glass encapsulation does not remove reliability risks. Instead, it can change the pathways through which moisture, electric fields, thermal stress, and mechanical loads affect the module. Long-term field studies should therefore monitor front- and rear-side electrical performance separately and record environmental exposure, module temperature, insulation behaviour, and visible defects.

RESEARCH GAPS

Taken together, the reviewed studies demonstrate progress in bifacial irradiance estimation, electrical modelling, and field-performance assessment. However, comparisons remain difficult because studies use different test conditions, albedo measurements, system geometries, reference modules, and definitions of bifacial gain. Future work should therefore adopt more consistent characterization and reporting procedures, including clearly stated irradiance, temperature, spectral conditions, area conventions, and reference-system definitions.

A second priority is site-specific validation. Models developed or calibrated under temperate, snow-dominated, or controlled conditions should not be transferred directly to hot, dusty, or seasonally variable environments without local measurements. Simultaneous front- and rear-side irradiance monitoring, ground-albedo characterization, module-temperature measurement, and documentation of mounting geometry are needed to test model performance across seasons.

CONCLUSION

In conclusion, bifacial photovoltaic (PV) technology offers considerable potential for improving solar energy yield by harnessing solar radiation incident on both the front and rear surfaces of modules. However, the reviewed literature demonstrates that bifacial performance is highly dependent on site-specific and installation parameters, particularly ground albedo, mounting height, tilt angle, row spacing, orientation, shading, and prevailing climatic conditions. Consequently, reported bifacial gains cannot be generalized across different locations and operating environments. The review further establishes that accurate performance prediction requires appropriate modelling techniques. Analytical models provide computationally efficient and transparent estimates, while electrical, ray-tracing, and Multiphysics

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approaches offer more detailed assessments of optical, electrical, and thermal interactions. Nevertheless, reliable deployment requires these models to be supported by experimental validation and comprehensive site-specific measurements. In addition, rear-side shading, electrical mismatch, soiling, and degradation mechanisms must be considered to ensure sustained system performance.

Future research should focus on establishing standardized approaches to bifacial photovoltaic (bPV) performance characterization, incorporating simultaneous front- and rear-side irradiance measurements and year-round experimental validation under diverse climatic conditions. Particular emphasis should be placed on hot, dusty, and seasonally variable environments, where fluctuations in environmental conditions may substantially affect energy yield, operational performance, and module reliability. Furthermore, the integration of optical non-uniformity, electrical mismatch, thermal behaviour, and long-term degradation into a unified assessment framework is essential for improving the accuracy of performance prediction and reliability evaluation. Such investigations should also account for the effects of rear-side obstructions, including junction boxes, cables, and mounting structures, alongside environmental stressors such as surface soiling and moisture ingress.

Consequently, combining energy-yield prediction with long-term degradation assessment would provide a more comprehensive understanding of bifacial PV system performance and establish a stronger technical basis for their design, optimization, and sustainable deployment. These priorities represent research directions arising from the limitations and reliability concerns identified in the reviewed literature rather than experimental findings generated by the present review.

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