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Comprehensive Review on Bifacial Photovoltaic (PV) Technology: Performance, Design, Mechanical Challenges, and Future Trends

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Abstract

Bifacial photovoltaic (PV) systems have emerged as one of the most efficient and sustainable solar energy technologies, capable of harvesting light from both front and rear sides to increase overall energy yield. With rapid adoption and declining costs, bifacial modules surpassed 90% of new solar installations globally by 2025. This review presents a comprehensive overview of recent advancements in bifacial PV technology, including performance optimization, optical and mechanical modeling, reflector design, and system integration. It highlights the interplay between electrical, thermal, and mechanical aspects, discusses modeling approaches such as ray-tracing and view-factor methods, and emphasizes mechanical challenges including wind loading, structural reliability, and rear-side soiling. Finally, the paper outlines future research directions focusing on adaptive reflectors, advanced materials, hybrid thermal management, and integration with smart grid systems.

Keywords

Bifacial photovoltaic (PV), solar energy, albedo, optical modeling, mechanical design, reflectors, wind loading, thermal management, renewable energy.

1. Introduction

The accelerating global transition toward renewable energy sources has placed solar photovoltaics (PV) at the forefront of sustainable power generation. With rising concerns about climate change, fossil fuel depletion, and the need for decarbonization, solar PV technologies have experienced exponential growth in both installed capacity and technological advancement. Among emerging PV innovations, bifacial photovoltaic systems have gained particular attention due to their ability to capture solar irradiance from both the front and rear sides of the module, leading to a substantial increase in overall energy yield compared to conventional monofacial modules. This dual-sided light absorption mechanism allows bifacial systems to utilize both direct sunlight and reflected (albedo) irradiance from the surrounding environment, thereby improving efficiency without a proportional increase in land or material use.

The global PV industry has rapidly embraced bifacial technology, with reports indicating that by 2025, over 90% of newly installed utility-scale PV systems incorporate bifacial modules (Keiner et al., 2025). The higher energy yield—ranging from 10% to 30% depending on surface reflectivity and environmental conditions—has made bifacial PV one of the most promising solutions for achieving lower Levelized Cost of Energy (LCOE) and maximizing return on investment. The technology's advantages are not limited to performance; it also offers enhanced reliability and longer operational lifespan through the use of glass–glass encapsulation, which provides improved resistance against moisture ingress, mechanical stress, and potential-induced degradation (PID).

However, despite these clear advantages, the design and deployment of bifacial PV systems introduce new optical, mechanical, and environmental challenges that differ significantly from those of traditional monofacial systems. Key influencing factors include ground albedo, module tilt, elevation height, row spacing, and surface conditions, which collectively determine rear-side irradiance and overall system gain. Moreover, bifacial modules experience complex mechanical loads due to double-glass construction, exposure to wind pressure from both sides, and variable thermal expansion under uneven irradiance. These issues necessitate interdisciplinary optimization involving mechanical design, thermal management, optical modelling, and materials engineering.

In recent years, extensive research has focused on developing accurate irradiance and performance models for bifacial PV systems. Traditional view-factor and isotropic models have evolved into more advanced ray-tracing and Monte Carlo simulations, enabling improved prediction of rear irradiance under varying albedo and terrain conditions (Ghafiri et al., 2024; Tonita et al., 2023). Concurrently, mechanical engineers have explored innovative mounting structures, CFD-based wind flow simulations, and FEA-based stress analyses to enhance structural stability and long-term reliability of bifacial arrays. Additionally, novel approaches such as adjustable reflectors and phase-change-material-based cooling systems have been introduced to enhance optical capture and manage thermal efficiency.

Beyond technical performance, bifacial PV systems play a critical role in achieving sustainable and cost-efficient energy transitions. Their higher energy density per unit area reduces land use, while compatibility with agrivoltaics, building-integrated (BIPV), and floating solar (FPV) applications enhances versatility across diverse environments. As nations aim to meet net-zero targets by mid-century, bifacial PV technology emerges as a pivotal contributor to scalable, clean, and affordable energy production.

Thus, this review paper aims to provide a comprehensive analysis of recent advancements in bifacial PV research, focusing on performance optimization, optical modelling, mechanical challenges, and system integration. It synthesizes findings from 2017 to 2025 to highlight evolving methodologies, engineering innovations, and future directions necessary for improving the efficiency, reliability, and sustainability of bifacial photovoltaic systems.

2. Overview of Bifacial PV Technology

Bifacial photovoltaic (PV) modules are designed to capture solar energy from both the front and rear sides of the panel, unlike conventional monofacial modules that absorb sunlight only from one surface. The front side of a bifacial module functions like a standard PV panel, converting direct solar radiation into

electricity through photovoltaic cells. The rear side, however, is engineered to harness reflected and scattered light (albedo) from surrounding surfaces such as the ground, water, concrete, or artificial reflectors.

Structurally, bifacial modules are typically encapsulated using glass–glass or glass–transparent back sheet configurations. This design ensures transparency and protection for both surfaces, allowing sunlight to pass through the cells and reflect onto the rear side. The bifaciality coefficient, which represents the rear-to-front power output ratio, generally ranges between 70% and 95%, depending on the cell technology (n-PERT, TOPCon, or HJT).When sunlight strikes the ground beneath the array, part of it is reflected upward and captured by the rear surface. The magnitude of this rear irradiance depends on several parameters — primarily ground albedo, module height, tilt angle, row spacing, and orientation. For instance, higher elevations and brighter ground surfaces increase the rear irradiance fraction. The combined energy from both sides enhances the total energy yield per unit area without requiring additional panels or land.

Modern bifacial systems also employ single- or dual-axis solar trackers to adjust the panel orientation throughout the day, maximizing incident irradiance on both sides. Simulation tools such as NREL's SAM, PVsyst, and bifacial radiance are widely used to model performance and optimize system parameters.

2.1 Advantages of Bifacial PV Systems

1. Higher Energy Output:
Bifacial panels generate 10–30% more energy than monofacial ones, depending on environmental conditions and ground reflectivity.

2. Lower Levelized Cost of Energy (LCOE):
The increased energy yield reduces the cost per kWh of electricity generated, enhancing economic viability.

3. Durability and Longevity:
Glass–glass encapsulation improves resistance to UV radiation, moisture, and mechanical stresses, resulting in longer module lifespan.

4. Better Diffuse Light Performance:
Bifacial modules capture scattered light during cloudy conditions and from surroundings, providing more stable output.

5. Land-Use Efficiency:
Higher power generation per square meter reduces land requirements — advantageous for utility-scale and agrivoltaics installations.

6. Reduced Soiling on Vertical Configurations:
Vertically mounted bifacial panels experience less dust accumulation and require minimal cleaning compared to tilted monofacial arrays.

7. Compatibility with Multiple Applications:
Suitable for rooftop, ground-mounted, floating (FPV), and building-integrated (BIPV) systems, as well as agrivoltaics setups.

3. Literature Review

3.1 Market Evolution and Performance Trends

The global photovoltaic market has shifted dramatically toward bifacial module adoption due to its superior efficiency and declining cost per watt. According to Keiner et al. (2025), bifacial PV systems surpassed 90% of the global solar market, typically delivering an energy gain under standard operating conditions and even higher in high-albedo environments.

The total energy output of a bifacial system can be expressed as:

$$E_{total} = \eta \times A \times (G_{front} + G_{rear})$$

where $E_{total}$is the total generated energy, $\eta$is module efficiency, $A$is panel area, $G_{front}$and $G_{rear}$are front and rear irradiance (W/m^2).

Similarly, Zubair et al. (2025) found that bifacial panels harvest light from both sides, providing 10–20% higher annual energy than monofacial systems. Their analysis using NREL's SAM model showed that vertical east–west arrays provide balanced generation during morning and evening hours.

The bifacial gain (BG), a critical metric of system performance, is mathematically defined as:

$$BG(\%) = \frac{E_{bifacial} - E_{monofacial}}{E_{monofacial}} \times 100$$

Yakubu et al. (2024) reported up to 30% yield improvements depending on module height, albedo, and climatic variations. They concluded that glass-glass modules outperform glass–back sheet due to symmetric light capture and enhanced reflectivity.

Braga et al. (2023) compared surface coatings and found that polymer-covered surfaces improved albedo to $\rho = 0.5$, raising output by over 5%, whereas bare soil ($\rho \approx 0.15$) gave minimal benefits. The relationship between albedo and rear irradiance was given by:

$$G_{rear} = \rho \times G_{global} \times f(\theta, h)$$

where $f(\theta, h)$is the view-factor function dependent on tilt (θ) and elevation (h). Overall, bifacial systems improve energy yield and reduce LCOE, confirming their dominance for both utility and rooftop applications.

3.2 Optical and Irradiance Modeling

Accurate modeling of rear irradiance remains one of the most challenging aspects of bifacial PV system design. Ghafiri et al. (2024) compared bifacial_radiance (ray-tracing) with pvfactors (2D view-factor) and found that while ray-tracing captures non-uniform reflections more precisely, it is computationally heavier.

Durusoy et al. (2020) proposed a modified Liu–Jordan isotropic model, combining direct, diffuse, and ground-reflected components:

$$G_{rear} = G_b \cos\theta + G_d \frac{1+\cos\beta}{2} + \rho G_g \frac{1-\cos\beta}{2}$$

where $G_b$is beam irradiance, $G_d$diffuse irradiance, $G_g$global irradiance, βtilt angle, and ρground reflectance. Their model achieved <1.4% annual yield deviation from pyranometer measurements.

Tonita et al. (2023) introduced the Scaled Rear Irradiance (SRI) method for spectral correction of the rear side:

$$G_{SRI} = G_{rear} \times \frac{EQE_{rear}}{EQE_{front}}$$

where EQE represents the external quantum efficiency for spectral weighting, enhancing laboratory-to-field correlation.

Yan et al. (2025) optimized adjustable rear reflectors using the Taguchi method, treating reflector angle, height, and material reflectivity as control factors. Their model used signal-to-noise ratio (S/N) optimization:

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right)$$

where $y_i$represents energy yield for each trial configuration. These advancements reflect the shift toward hybrid models combining geometric optics, spectral correction, and experimental optimization.

3.3 Influence of Albedo and Reflectors

Ground reflectivity (ρ) plays a decisive role in enhancing bifacial performance. Haque et al. (2023) experimentally found that high-albedo surfaces (white paint, concrete, reflective polymer) enhance rear irradiance by 15–20% over natural soil.

The rear-side irradiance contribution can be modelled as:

$$G_{rear,eff} = \rho \cdot G_{front} \cdot \frac{H_{rear}}{H_{front}}$$

where $H_{rear}/H_{front}$is the ratio of ground-reflected to direct light incident geometry.

Westerhof et al. (2024) observed that grass behaves as a retroreflective surface, redirecting light toward the sun, reducing rear-side collection. Periodic trimming increased yield by ~6.6%. Hasan et al. (2020) reported floating bifacial PV systems achieved rear gain up to 55%, driven by high reflectivity of water ($\rho_{water} \approx 0.6$) and passive cooling.

Sun et al. (2017) globally modeled bifacial configurations and proposed a correlation between elevation (h), tilt (θ), and rear gain (BG):

$$BG = k \cdot \rho \cdot \left(\frac{h}{L}\right)^{0.4} \cdot \cos(\theta)$$

where Lis module length and ka proportionality constant.
This highlight how moderate elevation and optimized tilt can maximize rear contribution without excessive shading or cost.

These studies confirm that site-specific albedo management and reflector integration—especially adjustable reflective systems—provide a cost-effective means to boost bifacial system performance in low-albedo environments.

3.4 Structural and Mechanical Aspects

The mechanical robustness of bifacial systems directly affects their reliability and performance lifespan. Badran et al. (2024) showed that vertical bifacial arrays yield 10–30% higher energy while reducing soiling but face greater wind pressure. The aerodynamic force (F) on a tilted module can be expressed as:

$$F = \frac{1}{2} C_d \rho_{air} A v^2$$

where $C_d$is the drag coefficient, Ais panel area, ρ_{air}air density, and vwind velocity. CFD analysis was used to optimize structures against oscillations and fatigue.

Rasheed et al. (2022) evaluated ASHRAE solar load models and found that static coefficients overestimated front pressure and underestimated rear suction forces. Integrating CFD-validated correction factors reduced the mean error by 15%.

Ernst et al. (2024) integrated thermal-electrical coupling for rooftop bifacial systems. The module efficiency was modeled as:

$$\eta = \eta_{ref}[1 - \beta(T_c - 25)]$$

where $T_c$is cell temperature and βthe temperature coefficient. They demonstrated that non-uniform irradiance distribution can cause thermal gradients leading to local stresses and long-term degradation.

Patel et al. (2020) examined bifacial panels with single-axis tracking, reporting 45% yield gain near the equator. The tracker's power output (P) variation over time twas modeled as:

$$P(t) = \eta A G_{front}(t)[1 + \alpha G_{rear}(t)]$$

where αrepresents bifaciality factor (typically 0.7–0.9).

These studies conclude that bifacial PV systems require a co-optimized design integrating optical, thermal, and mechanical parameters for durability and consistent performance over decades.

4. Mechanical Engineering Relevance

Mechanical engineers play an indispensable role in enhancing the performance, reliability, and safety of bifacial photovoltaic (PV) systems. Since bifacial modules capture sunlight on both surfaces, their structural configuration and mechanical design become more complex compared to conventional systems. Mechanical engineers must ensure that the mounting structures, support frames, and tracking systems can withstand dynamic environmental loads, such as high wind pressure, snow accumulation, and thermal stresses caused by temperature fluctuations. Advanced Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) tools are increasingly being used to simulate these effects, optimizing material selection and frame geometry for stability and cost efficiency.

Thermal management is another critical aspect, where Phase Change Materials (PCMs) and heat spreaders are integrated into module designs to prevent overheating and maintain electrical efficiency. Engineers also focus on fatigue testing, vibration analysis, and life cycle assessment to ensure long-term durability under cyclic loading. Moreover, the development of adjustable reflectors and tracking mechanisms requires precision mechanical linkages to optimize solar incidence angles without compromising robustness. Therefore, mechanical engineering principles are central to ensuring the structural integrity, thermal reliability, and operational efficiency of bifacial PV systems in diverse environmental conditions.

5. Discussion

The reviewed literature consistently demonstrates that bifacial photovoltaic (PV) systems provide 10–30% higher energy yield than traditional monofacial panels, depending on site albedo, tilt, and environmental conditions. However, these energy gains are accompanied by complex interactions among optical, thermal, electrical, and mechanical parameters, which are often treated independently in existing research. Many analytical and simulation-based studies focus on irradiance modeling accuracy but overlook the mechanical stresses caused by wind pressure, module weight, and temperature gradients. Consequently, system-level optimization remains incomplete.

Emerging studies advocate for an integrated multi-physics modeling approach that couples optical, electrical, and structural simulations. Such approaches allow realistic predictions of performance under variable irradiance and mechanical stress. Additionally, the environmental effects—such as dust deposition, snow coverage, and humidity—should be incorporated into reliability analyses to represent real-world operating conditions. The discussion further emphasizes the importance of field validation and long-term performance data, as laboratory models alone cannot capture degradation dynamics or reflector-soiling interactions. Hence, future bifacial PV development depends on coordinated efforts between electrical and mechanical engineers to design systems that are both energy-efficient and mechanically resilient, ensuring high reliability and reduced maintenance throughout their operational life.

6. Future Scope

The future of bifacial PV technology lies in the integration of advanced modeling, smart materials, and intelligent control systems to enhance efficiency and mechanical reliability. Future research should focus on coupled CFD–FEA simulations to predict wind-induced stresses and thermal gradients simultaneously, providing accurate insights into real-world conditions. Incorporating AI-based control systems can enable adaptive optimization of reflector angles, tracker movements, and tilt mechanisms for maximum rear irradiance capture. Additionally, the use of Phase Change Materials (PCMs) and thermally conductive composites can effectively dissipate heat, maintaining optimal operating temperatures and extending module lifespan.

Further advancements are expected through the development of lightweight, corrosion-resistant support structures, such as aluminum–polymer hybrids or composite alloys, that reduce both mechanical fatigue and installation cost. Standardization is another key area—new IEC and ISO testing protocols should integrate bifacial performance calibration, spectral albedo characterization, and structural load analysis to ensure global reliability benchmarks. Long-term field studies on fatigue resistance, soiling effects, and degradation under varying climates will also be essential. In essence, the future scope of bifacial PV technology is rooted in mechanical innovation and interdisciplinary design, merging energy performance with structural sustainability.

7. Conclusion

Bifacial photovoltaic (PV) technology has emerged as a transformative evolution in the solar energy landscape, offering higher energy yields, improved durability, and reduced cost per watt compared to traditional monofacial modules. Its unique ability to utilize both direct and reflected solar irradiance enhances power generation without expanding land area, making it a vital solution for sustainable power infrastructure. The reviewed studies confirm consistent energy gains of 10–30% across diverse environments, reinforcing its technical and economic viability.

Nevertheless, achieving the full potential of bifacial PV systems requires a holistic engineering approach. Mechanical and structural challenges—such as wind load resistance, rear-surface soiling, and temperature-induced stress—must be addressed alongside optical and electrical optimization. Innovations in materials, cooling mechanisms, and adaptive reflectors can further enhance reliability and lifespan. The integration of AI-based monitoring, CFD–FEA simulations, and advanced manufacturing techniques will bridge the gap between theoretical performance and real-world operation.

In conclusion, bifacial PV systems represent the next frontier of solar energy engineering—merging mechanical resilience, optical precision, and sustainable design to deliver efficient, reliable, and cost-effective renewable power for future generations.

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