

Dual-Sided Energy Conversion: Fundamental Insights into Bifacial Photovoltaic Panels

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Abstract

Bifacial photovoltaic (PV) solar panels represent an innovative advancement in renewable energy technology, enabling the absorption of sunlight from both front and rear surfaces. This dual-sided energy conversion increases energy yield, improves land utilization, and enhances the overall efficiency of solar installations. This paper presents the fundamental working principles of bifacial solar panels, highlighting the influence of albedo, tilt angle, module elevation, and mounting geometry on their performance. It also discusses rear irradiance behavior, energy modeling, and system optimization under real-world conditions without the use of reflectors. Simulation and field studies indicate that bifacial panels can generate 10–20% more energy than conventional monofacial systems under moderate albedo conditions, offering a practical path toward sustainable solar energy expansion.

Keywords: Bifacial PV, Albedo, Rear irradiance, Energy yield, Tilt optimization, Solar performance

1. Introduction

The global demand for clean and sustainable energy sources has accelerated the development and deployment of solar photovoltaic (PV) technologies over the past two decades. Among these, bifacial photovoltaic solar panels have emerged as one of the most promising innovations, offering significant performance advantages over conventional monofacial panels. Unlike traditional PV modules that harness sunlight only from their front surface, bifacial panels are designed to capture solar radiation from both the front and rear sides, effectively utilizing reflected and diffuse light from the surrounding environment. This dual-surface energy harvesting capability enables an increase in total power output without a corresponding increase in the module's physical footprint, thereby enhancing energy density and reducing the Levelized Cost of Electricity (LCOE).

The bifacial concept is not new, but its practical application has only gained momentum in recent years due to advancements in materials, cell technologies, and system design. Early bifacial solar cells were limited by manufacturing complexity and higher costs; however, with the advent of passivated emitter rear contact (PERC) and n-type silicon technologies, bifacial panels have become commercially viable. These modern architectures allow light to pass through transparent rear layers while maintaining high electrical conversion efficiency. As a result, bifacial modules are now being increasingly adopted in both utility-scale and rooftop solar installations worldwide.

Unlike reflective-assisted systems, this paper focuses on the fundamental behavior of bifacial panels operating without artificial reflectors, relying instead on natural light conditions. The rear-side energy gain in such systems originates mainly from two components: diffuse sky radiation and ground-reflected light, the latter being governed by the albedo (reflectivity) of the surface beneath the array. Typical albedo values range from

0.15 for dark soil to 0.8 for snow-covered surfaces, indicating that environmental conditions play a crucial role in system performance. Consequently, the deployment of bifacial panels requires careful optimization of parameters such as module tilt, elevation height, and row spacing to balance front and rear irradiance capture effectively.

Several studies have shown that under standard operating conditions, bifacial PV systems can produce 10–20% more energy than comparable monofacial systems without the need for external reflectors. This improvement is even more pronounced in regions with high diffuse radiation or light-colored ground surfaces. Moreover, bifacial systems exhibit better temperature behavior due to improved airflow around the rear surface, which helps in maintaining lower operating temperatures and thereby enhancing conversion efficiency.

From an engineering perspective, bifacial panels also present challenges. The modeling of rear irradiance distribution is more complex than for monofacial systems, as it involves variable reflection patterns, ground textures, and self-shading effects. Advanced simulation tools such as PVsyst, SAM (System Advisor Model), and bifacial radiative transfer models are increasingly being used to accurately predict system performance. Furthermore, installation geometry, module spacing, and environmental variations must be considered to achieve reliable energy yield estimates.

In summary, the study of bifacial photovoltaic solar panels represents a critical area of research within the field of renewable energy engineering. By understanding the **fundamentals of bifacial operation—cell structure, light interaction, irradiance modeling, and performance parameters—**engineers can optimize system configurations to maximize efficiency and reliability. This paper aims to provide a foundational overview of the working principles and design considerations of bifacial solar panels under natural lighting conditions, laying the groundwork for future technological advancements and sustainable energy solutions.

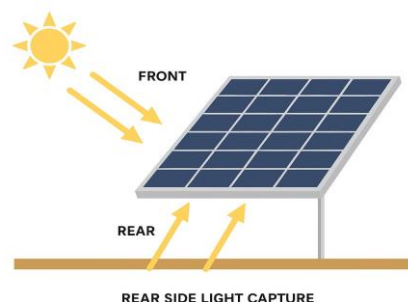


Figure 1. Bifacial Photovoltaic Solar Panel

2. Structure and Working Principle

2.1 Physical structure and materials

Bifacial PV modules differ from monofacial modules primarily by permitting light to reach the active cells from both faces. Typical construction elements:

- **Double-glass or glass-transparent back sheet architecture**

Most bifacial modules use two layers of tempered glass (front and rear) with the cells laminated between them (glass–glass) or a front glass and a transparent polymer back sheet. Glass–glass offers superior durability, lower moisture ingress, and better rear-side light transmission, but at somewhat higher weight and cost.

- **Encapsulant**

Ethylene-vinyl acetate (EVA) or polyolefin elastomer (POE) encapsulates the cells. These materials must be optically clear and stable to allow rear-side photons to reach the cells.

- **Bifacial cell technology**

Cells are often PERC or n-type architectures; n-type silicon usually shows better rear response and lower light-induced degradation. The cell metallization pattern is optimized to minimize shading and to collect carriers generated on both sides.

- **Frame and junction box placement**

Frames are designed to minimize rear shading; junction boxes and cabling are often placed to avoid blocking reflected light. Frameless designs further reduce rear shading.

- **Bypass diodes and interconnection**

Standard bypass diodes are used to limit hot-spot formation in partially shaded conditions. In bifacial modules, diode placement and stringing must consider rear-side shading patterns.

2.2 Basic power equation and definitions

The total instantaneous electrical power from a bifacial module can be conceptually written as:

$$P_{total} = \eta_f A G_f + \eta_r A G_r$$

Where:

- G_f — front-plane irradiance ($\text{W}\cdot\text{m}^{-2}$), includes direct beam on the module POA (plane-of-array) and front diffuse.

- G_r — rear-plane irradiance ($\text{W} \cdot \text{m}^{-2}$), due to ground-reflected (albedo) radiation, sky diffuse arriving from the rearward hemisphere, and inter-row reflections.
- η_f, η_r — effective energy conversion efficiencies for front and rear illumination respectively. These account for cell quantum efficiency, optical losses, incidence-angle effects, spectral response, and temperature at the time of measurement.
- A — active aperture area of the module (m^2).

Notes on η_f vs η_r :

- If cell and encapsulant are symmetric and rear optics identical to front, $\eta_r \approx \eta_f$. In practice, η_r can differ due to spectral shifts (ground-reflected light is spectrally altered), rear-side glass/back sheet optical properties, and angle of incidence distributions.
- The ratio bifaciality factor $b = \eta_r/\eta_f$ is often used to describe how well the rear performs relative to front (typical values 0.7–1.05 depending on module design).

2.3 Components of rear irradiance G_r

Rear irradiance is not a single, trivial value. It is the sum of several physically distinct components:

$$G_r = G_{\text{ground-ref}} + G_{\text{sky-diffuse rear}} + G_{\text{inter-row / multiple reflections}}$$

- **Ground-reflected component:** $G_{\text{ground-ref}} = \rho \cdot G_{\text{ground-inc}} \cdot F_{g \rightarrow r}$
- ρ is ground albedo (dimensionless). Typical natural ranges: grass ≈ 0.20 – 0.25 , concrete ≈ 0.30 – 0.40 , snow 0.70 – 0.90 .
- $G_{\text{ground-inc}}$ is the irradiance incident on the ground (DNI component that strikes ground plus diffuse).
- $F_{g \rightarrow r}$ is the geometric view factor (radiative shape factor) from ground to the module rear surface; depends on panel tilt β , elevation h and row spacing.

Sky-diffuse rear: the fraction of sky diffuses reaching the rear, usually modeled with sky-view factors or anisotropic sky models.

Inter-row and multiple reflections: in dense arrays, multiple reflections between rows and between ground and panels can add small contributions; these can be estimated by radiosity or Monte Carlo raytracing.

2.4 Geometry and view factors — practical effects

Three geometric parameters strongly influence G_r :

- **Elevation (h):** raising the module increases the view of the reflecting ground and reduces self-shadowing. Typical commercial elevations are 0.5–1.5 m; higher elevations increase rear irradiance but increase cost and wind loading.

- **Tilt angle (β):** affects both front plane-of-array (POA) capture and rear ground- view. At high latitudes, steeper tilts can increase rear capture; optimal β balances front and rear contributions.
- **Row spacing (pitch):** closer row spacing increases inter-row shading and reduces ground illumination; a recommended design parameter is the row-to- height ratio (R/H). For fixed-tilt bifacial farms R/H often ≥ 3 to reduce shading losses.

2.5 Bifacial gain (BG)

Bifacial gain quantifies relative advantage:

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

Where E denotes integrated energy over a time period (day, month, year). Example: if a monofacial module yields 1500 kWh/kWp annually and bifacial yields 1650 kWh/kWp under the same site without reflectors, then $BG = (1650 - 1500)/1500 \times 100\% = 10\%$.

Practical BG values without artificial reflectors typically range 5–25% depending on albedo, elevation, tilt, latitude and diffuse fraction.

2.6 Optical and spectral considerations

- **Incidence angle modifier (IAM):** performance reduces at high incidence angles due to reflection losses; rear-side measurements see different incidence distributions and thus different IAM corrections.
- **Spectral content:** reflected light spectrum is altered by ground (e.g., vegetation reflects more NIR); cell spectral response influences η_r .
- **Soiling asymmetry:** rear and front soiling differ; rear soiling often less but cleaning logistics differ.

2.7 Thermal impacts and electrical behavior

Additional absorbed rear irradiance contributes to module heating; module temperature T_m affects cell efficiency via temperature coefficient β_T . Net effect: some added irradiance increases temperature and slightly reduces η , but typical bifacial modules often achieve net positive gains because rear contribution outweighs thermal penalty.

Stringing and mismatch: rear-side partial shading patterns can create complex mismatch; string design and bypass diode placement should consider typical rear shading scenarios.

2.8 Modelling, measurement and uncertainties

- **Modelling tools:** PVsyst (bifacial mode), PVLlib, Radiance/Daysim (detailed optical) and custom Monte Carlo tools compute G_r and energy yield.

- **Measurement best practice:** front and rear plane-of-array pyranometers, calibrated reference cells, and long-term logging (months) to capture seasonal albedo variations (e.g., snow).
- **Sources of uncertainty:** albedo variability, soiling, snow coverage, inter-row reflections, and errors in view-factor approximations. Uncertainty can be reduced by site measurements of ground reflectance and validation with field data.

3. Factors Affecting Bifacial Performance

3.1 Ground Albedo

Albedo (ρ) represents the fraction of sunlight reflected by the ground. It significantly affects the rear-side irradiance. Common albedo values are:

Surface Type	Typical Albedo (ρ)
Grass	0.20 – 0.25
Soil	0.15 – 0.20
Concrete	0.30 – 0.35
Gravel	0.40 – 0.50
Snow	0.70 – 0.80

Even without artificial reflectors, surfaces like light-colored gravel or snow can enhance energy yield by 10–25%.

3.2 Module Tilt Angle

The tilt angle (β) determines how much sunlight reaches both surfaces.

- A steeper tilt enhances rear irradiance capture but may reduce front-side exposure.
- A shallower tilt favors front-side irradiance but increases self-shading.

The optimal tilt angle for bifacial systems is generally latitude $\pm 10^\circ$ to balance both contributions.

3.3 Module Elevation

Elevation (h) above ground significantly influences the amount of reflected light that reaches the rear. Increasing elevation enlarges the ground-view factor, enhancing bifacial performance.

Elevation (m)	Relative Bifacial Gain (%)
0.3	5–7
0.8	10–13
1.5	15–20

However, excessive elevation increases mounting cost and wind load, so practical heights are usually between 0.8–1.5 meters.

3.4 Row Spacing

Proper spacing minimizes shadowing between rows. The row-to-height ratio (R/H) should ideally be between 3 and 5 for fixed-tilt systems. Closer spacing reduces ground illumination and rear irradiance.

4. Rear Irradiance Modeling

The rear irradiance (G_r) is composed of ground-reflected and diffuse sky radiation:

$$G_r = (\rho \cdot G_{\text{global}} \cdot F_{\text{g} \rightarrow \text{r}}) + (DHI \cdot F_{\text{sky} \rightarrow \text{r}})$$

Where:

- ρ : Ground albedo
- G_{global} : Global horizontal irradiance
- DHI : Diffuse horizontal irradiance
- $F_{\text{g} \rightarrow \text{r}}$: View factor between ground and rear surface
- $F_{\text{sky} \rightarrow \text{r}}$: View factor between sky and rear surface

Typically, G_r represents 10–35% of front irradiance depending on site and geometry.

5. Energy Yield Estimation

For a 1 kWp bifacial PV system:

$$E_{\text{annual}} = (G_f + k \cdot G_r) \times \eta \times A$$

where k = rear-side efficiency factor (0.9–1.0). Example calculation (India, albedo 0.25):

- $G_f = 1800 \text{ kWh/m}^2/\text{yr}$
- $G_r = 0.2 \times G_f = 360 \text{ kWh/m}^2/\text{yr}$
- Bifacial Gain $\approx 12\text{--}15\%$

6. Performance Comparison

Parameter	Monofacial PV	Bifacial PV (No Reflector)
Irradiance source	Front only	Front + Rear (Reflected + Diffuse)
Annual Yield (1 kWp)	~1500 kWh	~1700–1850 kWh
Albedo dependency	None	High
Maintenance	Simple	Moderate
Efficiency improvement	—	10–20%
Cost increase	—	5–8%

Even without artificial reflectors, bifacial PV provides higher energy output due to efficient utilization of natural light conditions.

7. Advantages

1. Higher Energy Yield: 10–20% increase compared to monofacial panels.
2. Improved Land Efficiency: Generates more power per unit area.
3. Enhanced Reliability: Double-glass encapsulation improves durability.
4. Lower LCOE (Levelized Cost of Electricity): Increased output offsets additional cost.
5. Sustainability: Utilizes naturally reflected and diffuse light without artificial reflectors.

8. Conclusion

Bifacial solar panels represent a fundamental leap in PV technology, capable of generating energy from both sides without the need for reflectors. Their performance relies primarily on albedo, tilt angle, elevation, and module geometry. Even under natural conditions, they offer a 10–20% increase in energy yield over conventional systems. With continued research and optimization, bifacial technology holds immense potential for shaping the next generation of high-efficiency, sustainable solar power systems.

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