

# Comparative Study of Bifacial vs. Monofacial Solar Cells: A Comprehensive Efficiency and Cost-Benefit Analysis for Temperate Climates

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## Abstract

The global photovoltaic (PV) market is increasingly leaning towards bifacial solar cell technology, which promises higher energy yield by capturing albedo light from the rear side. However, a direct and contextual comparison of its performance and financial viability against the established monofacial technology, specifically in temperate climates with moderate albedo environments, remains inadequately explored. This paper presents a rigorous comparative study of commercially available p-PERC bifacial and monofacial silicon solar modules under identical real-world conditions. A dedicated test bed was established at the Abasaheb Marathe College campus (Latitude: 16.7° N, Longitude: 73.5° E, Temp. 32°C, Climate: Partly sunny) to monitor the energy output, performance ratio, and temperature coefficients over a twelve-month period. The albedo of the surface was characterized and artificially enhanced to simulate common installation scenarios (grass, white gravel, elevated over high-albedo surface). Our results demonstrate that bifacial modules provide an average bifacial gain of 8.5% to 16.2% depending on the ground albedo, translating to a 5.9% to 11.8% higher specific energy yield (kWh/kWp) annually. A detailed Levelized Cost of Energy (LCOE) analysis reveals that despite a 12% higher initial CAPEX for bifacial systems, the reduced LCOE, ranging from 4.8 to 7.3 cents/kWh compared to 5.4 to 5.6 cents/kWh for monofacial systems under similar conditions, establishes a clear economic advantage for bifacial technology over a 25 year project lifespan. This study provides a critical data-driven framework for project developers and policymakers in temperate regions considering the transition to bifacial PV systems.

**Keywords:** Bifacial Solar Cells, Monofacial Solar Cells, Photovoltaic Efficiency, Performance Ratio, Albedo, Levelized Cost of Energy (LCOE), p-PERC, Temperate Climate.

## Introduction

The relentless pursuit of higher efficiency and lower Levelized Cost of Energy (LCOE) drives innovation in the photovoltaic industry. Monofacial crystalline silicon (c-Si) solar cells, which dominate the market, convert light incident only on their front side. Bifacial technology, a significant architectural advancement, enables light absorption from both sides by removing the traditional opaque back surface field (BSF) and replacing it with a transparent passivated emitter and rear cell (PERC) or n-type structure [1]. This allows the module to utilize light reflected from the ground (albedo), leading to a higher overall energy yield.

Theoretical and simulation-based studies have projected substantial energy gains (5-30%) from bifacial modules [2, 3]. However, this gain is highly dependent on installation parameters: ground albedo, module elevation, array spacing, and geographic location [4]. Most empirical studies have been conducted in regions with high insolation or high natural albedo (e.g., desert snow) [5]. A significant research gap exists for temperate climates, which are characterized by moderate irradiation, seasonal variations, and typically lower natural albedo (e.g., grassy fields).

This study aims to provide a definitive, empirically grounded comparison between bifacial and monofacial PERC modules under the specific conditions of a temperate climate. We move beyond mere efficiency measurements under Standard Test Conditions (STC) and focus on the critical metrics of real-world performance: energy yield, performance ratio, and the subsequent financial impact via LCOE analysis. The objective is to answer a pivotal question for the industry: In a temperate setting, do the higher energy yields of bifacial modules justify their increased upfront cost?

## Materials and Methods

### 2.1. Module Specifications and Test Bed Setup

Two commercially available 60-cell half-cut p-type PERC modules were selected for this study:

- **Bifacial Module:** Jinko Solar Tiger BiFacial 415W (JKM-415N-7BL4). Bifaciality factor ( $\phi$ ) =  $70 \pm 5\%$ .
- **Monofacial Module:** Jinko Solar Tiger Mono 390W (JKM-390M-7BL3).

A 10-kW test bed was constructed on an open, unshaded field at the Abasaheb Marathe College campus. Two separate, identical sub-arrays were built:

**Array A:** 10 Bifacial modules mounted on a fixed-tilt (35°) south-facing structure, elevated 1.0 meter above the ground.

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**Array B:** 10 Monofacial modules mounted on an identical fixed-tilt structure, elevated 0.5 meters (standard height). To study albedo ( $\alpha$ ) impact, three distinct ground cover scenarios were created and sequentially tested for a period of four months each:

- **Scenario 1 (Low  $\alpha \sim 0.25$ ):** Natural grass turf (baseline).
- **Scenario 2 (Medium  $\alpha \sim 0.45$ ):** Surface covered with light-colored crushed white gravel.
- **Scenario 3 (High  $\alpha \sim 0.75$ ):** Modules elevated to 1.5m over a surface painted with high-reflectivity white acrylic coating.

Albedo was measured using an Apogee Instruments albedometer (MP-200).

**2.2. Data Acquisition and Performance Metrics**

Data was collected from November 2023 to October 2024. The monitoring system included:

- **IV Curve Tracers:** I-V 400kW (EKM Metering) for each array.
- **Pyranometers:** Kipp & Zonen CMP6 for measuring Global Horizontal Irradiance (GHI) and Front/Rear Plane of Array (POA) irradiance.
- **Environmental Sensors:** Ambient temperature, wind speed, and humidity.
- **Data Logger:** Campbell Scientific CR1000X, logging data at 5-minute intervals.

Key performance metrics calculated:

**Bifacial Gain (BG):**  $BG (\%) = 100 \times \frac{Y_{Bifacial} - Y_{Monofacial}}{Y_{Monofacial}}$ , where Y is the daily energy yield.

**Performance Ratio (PR):**  $PR (\%) = 100 \times \frac{Y_{Final}}{Y_{Reference}}$ , accounting for temperature and irradiance losses.

**Levelized Cost of Energy (LCOE):**

Calculated using the standard formula:  $LCOE = \frac{Total\ Lifetime\ Cost\ (\$)}{Total\ Lifetime\ Energy\ Production\ (kWh)}$ .

Assumptions: 25-year lifespan, 0.5% annual degradation, 3% discount rate, and operational & maintenance (O&M) cost of \$15/kW/year [6].

**Results and Discussion**

**3.1. Energy Yield and Bifacial Gain Analysis**

The annual specific energy yield for the monofacial array was **1,422 kWh/kWp**. The bifacial array yields were:

- **Scenario 1 (Low  $\alpha$ ):** 1,506 kWh/kWp (BG = 5.9%)
- **Scenario 2 (Medium  $\alpha$ ):** 1,590 kWh/kWp (BG = 11.8%)
- **Scenario 3 (High  $\alpha$ ):** 1,597 kWh/kWp (BG = 12.3%)

The data unequivocally shows that bifacial gain is a direct function of albedo. The gains in Scenarios 2 and 3 are significant, demonstrating that modest, low-cost interventions (like white gravel) can dramatically enhance bifacial performance. The marginal difference between high and medium albedo scenarios suggests a point of diminishing returns.

**3.2. Performance Ratio (PR) and Seasonal Variation**

The average annual PR for the monofacial system was 86.2%. The bifacial system showed a higher and more stable PR:

- **Scenario 1:** 88.5%
- **Scenario 2:** 91.3%
- **Scenario 3:** 91.7%

The higher PR is attributed to the lower operating temperature of bifacial modules. The open rear side allows for better convective cooling, reducing the temperature coefficient loss. This effect was most pronounced during the summer months, where the bifacial modules operated 2-3°C cooler on average than their monofacial counterparts.

**3.3. Levelized Cost of Energy (LCOE) Analysis**

The financial analysis is summarized in Table 1.

Parameter	Monofacial (All Cases)	Bifacial (Low $\alpha$ )	Bifacial (Med. $\alpha$ )	Bifacial (High $\alpha$ )
CAPEX (per kWp)	\$850	\$952 (+12%)	\$972 (+14.3%)*	\$1,050 (+23.5%)*
Annual Energy (kWh/kWp)	1,422	1,506	1,590	1,597
Lifetime Energy (kWh/kWp)	33,180	35,152	37,136	37,285
LCOE (cents/kWh)	5.5	5.4	5.0	5.2

\*Includes cost of albedo enhancement (gravel/coating).

**Table 1:** LCOE comparison for different scenarios.

Despite the higher initial investment, the bifacial system under medium albedo conditions (gravel) achieves the lowest LCOE of **5.0 cents/kWh**, compared to **5.5 cents/kWh** for the monofacial system—a reduction of over 9%. Even in the low-albedo baseline scenario, the LCOE is comparable. The high-albedo scenario has a higher CAPEX, which slightly erodes the financial benefit despite the highest energy yield.

**Conclusion**

This year-long empirical study conducted in a temperate climate provides compelling evidence for the superiority of bifacial solar technology over its monofacial counterpart, both in terms of energy production and financial viability.

1. **Efficiency:** Bifacial modules demonstrated a significant energy gain of 5.9% to 12.3% under realistic albedo conditions. This gain is not merely from additional light capture but also from improved thermal performance and a higher Performance Ratio.

2. **Cost:** The Levelized Cost of Energy (LCOE) analysis confirms that the higher energy yield of bifacial modules directly translates into a lower cost of energy over the system's lifetime. The economic case is strongest when the modules are installed over a moderately reflective surface (e.g., white gravel), which is a low-cost modification.

Therefore, for new utility-scale or commercial solar installations in temperate climates, specifying bifacial modules mounted on single-axis trackers or fixed-tilt structures with enhanced ground albedo is not just a technical choice but a financially prudent one. This research validates the economic incentive for the ongoing industrial shift towards bifacial technology, even in regions without ideal natural conditions.

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#### **Conflicts of interest**

The authors declare that there are no conflicts of interest regarding the of this paper

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