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Comparative Evaluation of Bifacial and Monocrystalline PV Systems Using Solis 255 Kw Inverters

1. Abstract

India's rapid growth in solar PV (105.65 GW installation target by early 2025) has spurred interest in advanced technologies like bifacial modules to boost energy yield. This paper presents a comprehensive performance comparison between two utility-scale (≈255 kW) Solis string inverters – one coupled to Trina Solar monocrystalline **monofacial** modules (total DC ~313.5 kW) and the other to Trina **bifacial** dual-glass modules (DC ~307.2 kW). Over 12 months of operation in Gujarat (India), monthly energy readings from each inverter were analyzed for trends, anomalies, and correlation with simulated performance. **Simulation modeling** (using a PVsyst-based approach) was employed to predict expected output and bifacial gain under local irradiance and environmental conditions, providing context for the experimental data. Results show that the bifacial system consistently outperformed the monofacial system, delivering ~10% higher annual specific yield (≈1770 vs 1600 kWh/kW) under actual site conditions. The bifacial gain varied seasonally – in high-insolation summer months the gain was modest (~5–8%), whereas during diffuse-rich monsoon months it reached ~12–15%. A significant anomaly was observed in one month (monofacial output ~25% below expectation due to a suspected inverter downtime), temporarily inflating the bifacial gain. Excluding this outlier, the bifacial advantage remained aligned with model predictions and literature (e.g. ~13–16% under cloudy conditions vs ~13% on clear days). Performance ratio (PR) values for both systems were in the 0.75–0.80 range, with the bifacial array achieving a slightly higher PR due to additional rear-side harvest. Simulation results closely matched measured yields (within ~5–8% monthly), validating the modeling approach and assumptions (e.g. ground albedo ~0.25, bifaciality ~0.70). The integrated analysis highlights key factors influencing energy yield: solar irradiance profiles (direct vs diffuse), module bifacial gain, inverter clipping at high DC load, ambient temperature, and soiling/maintenance practices. **Design insights** are drawn to maximize bifacial benefits – including optimal tilt and spacing to enhance rear irradiance capture, maintaining reflective ground conditions, and ensuring regular cleaning to mitigate soiling losses. This work contributes novel field data from an Indian context, demonstrating that bifacial PV technology can reliably provide ~10% greater energy yield than monofacial systems under real-world conditions, and emphasizing considerations for system designers to harness this advantage in similar climates. The findings are expected to aid solar engineers and researchers in improving PV plant performance and guiding the transition to bifacial modules in large-scale deployments.

Keywords: Bifacial PV, Monocrystalline PV, Solis Inverter, Energy Yield, Simulation, Performance Ratio

2. Introduction

India has emerged as a global leader in solar energy deployment, driven by ambitious renewable energy targets and the need for sustainable power generation . By 2025 the country's installed solar capacity will be exceeded 100 GW , with a goal of reaching 500 GW of renewables by 2030. Achieving these targets will require continued improvements in photovoltaic (PV) system efficiency and energy yield, especially under India's diverse climatic conditions. In this context, **bifacial PV modules** – which convert light incident on both front and rear surfaces – offer a promising route to increase energy harvest without expanding plant footprint. Modern bifacial modules can generate significantly more electricity than traditional monofacial panels by capturing ground-reflected irradiance (albedo) and diffuse sky radiation on their rear side . Under ideal conditions (e.g. highly reflective ground and tilted open-rack mounting), fixed-tilt bifacial arrays can produce up to ~30% greater annual energy than equivalent monofacial arrays . More typically, field studies and simulations report bifacial energy gains on the order of 5–20%, depending on location and conditions . For instance, Johnson *et al.* (2023) mapped bifacial potential across India and found annual bifacial gains ranging from ~2.5% in low-albedo regions to over 20% in high-albedo desert areas . Abdallah *et al.* (2023) reported ~15% higher yield for bifacial vs monofacial modules at 22° tilt in a desert climate (albedo ~0.43) . These enhancements are especially pronounced under diffuse light conditions – bifacial panels have shown ~16.5% energy gain on cloudy days versus ~13% on sunny days in one study – since the rear side can utilize isotropic diffuse irradiance that monofacial panels miss. As bifacial technology matures (commercial modules now achieve front-side efficiencies >21% and bifaciality up to ~80%) and cost premiums narrow, it is gaining widespread adoption. Industry reports indicate that by late 2024, over 90% of utility-scale PV installations (by capacity in simulation studies) were using bifacial modules , underscoring a major shift toward bifacial systems globally.

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Despite this trend, **real-world performance data** directly comparing bifacial and monofacial systems in identical operating environments remain limited – particularly in the Indian context. Many published analyses of bifacial gains rely on simulations or controlled testbed measurements, which may not capture all practical factors (like soiling, inverter behavior, or maintenance downtime). There is a need for field studies evaluating how bifacial systems perform relative to monofacial ones in actual large-scale deployments, and how closely these outcomes align with predictions. Such studies can illuminate whether the theoretical advantages of bifacial modules translate into meaningful energy yield improvements in practice, and what site-specific factors influence the performance gap. They can also guide engineers in optimizing system design (e.g. module configuration, inverter sizing, cleaning schedules) to maximize bifacial benefits under real operating conditions.

3. Objective

This research aims to provide a rigorous, side-by-side performance comparison of two 255 kW scale PV systems – one with monocrystalline monofacial modules and one with bifacial modules – operating under the same environmental conditions in India. By analyzing a full year of operational data (monthly energy outputs) and leveraging simulation-based modeling, we seek to quantify the energy yield difference, identify any inconsistencies or anomalies in the data, and understand the underlying causes (weather, technical, or maintenance-related). The study's novelty lies in combining empirical field results with detailed modeling to not only measure the bifacial gain achieved, but also to interpret it in the context of expected performance. The focus is on **Indian climatic and installation conditions**, characterized by high solar insolation, a strong monsoon season, and issues like dust soiling – factors that could significantly affect both monofacial and bifacial PV yields . By reflecting actual installation outcomes, the findings will inform whether bifacial technology provides a justified performance boost in such settings and what design or operational strategies can further enhance system efficiency.

In the following sections, we present the methodology of the study, including details of the experimental setup and simulation approach. We then report and discuss the results, comparing measured performance of the two systems, evaluating model predictions against real data, and analyzing factors influencing any performance gaps. Finally, conclusions and recommendations are offered, highlighting key insights for PV system design and operation in the context of bifacial vs monofacial modules.

4. Methodology

The comparative study was conducted on two grid-connected PV sub-systems, each rated at ~255 kW_AC, located in Mehsana district, Gujarat, India (approximately 23.9°N latitude, 72.6°E longitude). The region features a **tropical semi-arid climate** with intense sunlight for most of the year, a hot dry summer (daily highs often 40–45 °C in May), and a mid-year monsoon (July–August) bringing frequent clouds and rainfall. Annual global horizontal irradiance (GHI) in this area is on the order of 1900 kWh/m², and typical ground albedo for the site (uncultivated dry soil between module rows) is estimated around 0.20–0.25. The two PV systems are installed in close proximity on flat terrain, ensuring they experience nearly identical solar irradiance and ambient weather conditions. Both systems use identical inverter models (Solis **250 kW-EHV-5G** three-phase string inverters) and mounting structures, differing only in the PV module type (monofacial vs bifacial) and string configurations.

Inverters: Each system is equipped with a Solis 250 kW (5th-generation) inverter, which features 14 independent Maximum Power Point Trackers (MPPTs) and a maximum efficiency of 99.0% . These inverters are 1500 V DC rated and designed to accommodate high-power modules (including >500 W bifacial modules) with a DC/AC oversizing tolerance up to 200% . In this installation, the AC output of each inverter is 250 kW_AC at 30 °C (derating to ~235 kW at 40 °C ambient per specifications). Both inverters feed into a 800 V AC bus and are monitored via integrated dataloggers. The use of identical inverter models (with the same firmware and settings) ensures that any performance differences are attributable to the PV arrays rather than the power electronics.

PV Arrays: The monofacial array consists of **Trina Solar Vertex** monocrystalline modules (rated ~550 Wp STC each, with white backsheet) , while the bifacial array uses **Trina Vertex Dual-Glass Bifacial** modules (rated ~640 Wp STC front-side) . Both module types use high-efficiency PERC cells; the bifacial modules have transparent dual-glass construction and a bifaciality factor ~0.70–0.75 (meaning the rear side can produce ~70–75% of front-side STC power under identical irradiance). Key specifications of the modules are summarized in Table 1. Each inverter's DC input is wired to multiple strings of modules configured to stay within the 1500 V and 26 A per MPPT limits . The monofacial array has 570 modules (15 strings of 38 modules each, with one MPPT accommodating two parallel strings) for a total DC capacity of ~313.5 kW_DC. The bifacial array has 480 modules (14 strings of 32 modules, with one MPPT having two strings) totaling ~307.2 kW_DC. These configurations yield DC/AC ratios of ~1.25 and ~1.23 respectively – a deliberate slight oversizing to ensure inverters can reach full power in all but the most extreme conditions. Both arrays are installed on fixed-tilt galvanized steel structures facing due south. The tilt angle is ~20° from horizontal, which is a typical compromise for year-round energy capture at this latitude (slightly less than latitude angle to reduce winter shading and wind loading). The bottom edge of the modules is elevated ~1 m above ground. Row spacing (pitch) is designed for a ground coverage ratio (GCR) of approximately 0.5, meaning minimal inter-row shadowing on the front side around solar noon, though some back-side shading occurs at lower sun angles. No significant external shading from trees or buildings is present.

Table 1. Key parameters of the PV modules used.

Module type	**Trina Vertex 550 (Monofacial)**	**Trina Vertex 640 (Bifacial Dual-Glass)**
Cell technology	Mono-PERC, 110 cells	Mono-PERC, 132 cells (dual-glass)
STC power (PMAX)	545–555 W (nominal 550 W)	640–665 W (nominal 640 W)
Module efficiency	~21.2% (at 555 W)	~21.4% (at 665 W)
Temperature coefficient	–0.34%/°C (power)	–0.34%/°C (power)
Backsheet/Rear design	Opaque white backsheet	Dual glass, bifacial (transparent)
Bifaciality factor	N/A (monofacial)	~0.70 (70% rear contribution)
Warranty degradation	0.55%/year (years 2–25)	0.45%/year (years 2–30)

Both arrays were commissioned in early 2024 under the same government solar promotion scheme. They are located within a few hundred meters of each other, effectively experiencing the same weather. The ground surface is natural soil; during dry months it is a light brown dust/dirt (albedo ~0.2–0.25) and during the monsoon some grass/weeds grow (temporarily lowering reflectance). The operations and maintenance (O&M) practices for both systems are identical. Module cleaning is performed manually approximately once every 2–3 months, supplemented by natural rain washing during monsoon season. The inverters were kept under similar load profiles and no power curtailment (grid export limit) was imposed, so each inverter could feed up to its full 250 kW_AC rating whenever available from the array.

5. Data Collection and Monitoring

Energy production of each system was recorded via the inverter's built-in monitoring system, which logs cumulative energy (kWh) exported to the grid. For this study, **monthly energy readings** were obtained for each inverter over a 12-month period (January through December 2024). These readings effectively measure the total AC energy delivered to the grid by each 255 kW system each month. Additional operating data (e.g. DC voltage, current, AC power, internal temperature) were monitored in real-time by the inverters, but only the monthly aggregated energy was used for primary analysis to smooth out short-term fluctuations. The choice of monthly interval aligns with typical energy billing periods and performance reporting, and it is sufficient to observe seasonal trends while averaging out daily variability.

Basic weather data for the site (ambient temperature and rainfall) were obtained from a nearby weather station and cross-checked with satellite-derived climate normals. However, on-site solar irradiance (e.g. from a pyranometer) was not available, which is a limitation addressed by using simulation modeling (described below) to estimate incident radiation and expected ideal yields. **Quality control:** The monthly energy logs were checked for consistency, and any anomalies (e.g. abnormally low values) were flagged for investigation. In the event of inverter resets or outages, the operations logs were reviewed to identify downtime duration. One notable event was an inverter fault in August 2024 on the monofacial system, which led to several days of lost production – this is reflected in the data and discussed later as an anomaly. No other major equipment failures or grid outages were recorded during the year.

Additionally, periodic performance ratio (PR) calculations were done by estimating monthly plane-of-array irradiance from satellite data (NASA POWER) to get an approximate PR = (Energy output) / (Irradiance incident on array plane * Array area * module efficiency). While these PR values help contextualize the performance, the uncertainty in irradiance estimates (especially including bifacial rear contribution) means PR is used qualitatively. Instead, we focus on **specific yield** (kWh per kW_DC) and **bifacial gain** (%) as more direct metrics of performance comparison.

6. Simulation-Based Performance Modeling

To interpret the experimental results, we developed a simulation model for each PV system using PVsyst (a widely-used PV performance simulation software) and supplemented by in-house calculations for bifacial contributions. The simulation aimed to predict the monthly energy output for both systems under typical meteorological year (TMY) conditions, and to quantify the expected performance difference attributable purely to module bifaciality (with other factors held constant).

Meteorological Input: We derived hourly irradiance and weather data for the site from the NASA POWER database (which provides solar irradiance components and temperature for a 0.5° grid) for a typical year in the region. Global horizontal irradiance was translated to plane-of-array irradiance for the 20° south-facing tilt using the Hay-Davies transposition model (accounting for measured diffuse fraction and assuming typical aerosol conditions for rural India). The ambient temperature profile was used with module temperature coefficients to model thermal losses. The site's albedo was set to 0.25 for most of the year, with a slightly reduced value (0.20) during the monsoon months to reflect darker moist soil/vegetation. This simplification assumes a constant average albedo each month; actual daily variations (e.g. due to puddles or crop cycles) are not captured, but monthly average effects are represented.

System Configuration in Model: The exact system configurations (module type, count, inverter rating, tilt, orientation, and DC/AC ratio) were input into PVsyst for both cases. For the monofacial system, the standard transposition and thermal loss models in PVsyst suffice. For the bifacial system, PVsyst's 2D unlimited shed bifacial model was used – this requires specification of tilt, height, row pitch (spacing), and albedo to estimate rear-side irradiance via view-factor geometry. We modeled the bifacial array as modules 1 m above ground, row spacing 4 m (GCR ~0.5), albedo 0.25/0.20 (dry/wet), and bifaciality factor 0.70 (typical for bifacial PERC cells). This yields an annual rear irradiance contribution of roughly 10–12% of front irradiance, in line with expectations for this setup. The module power bifacial gain (i.e. additional DC power from rear side) is capped by the bifaciality factor and available rear irradiance; at noon on clear days it is small (since the ground directly under modules is shadowed), but in morning/evening and under diffuse conditions it is higher. Inverter efficiency and thermal derating curves were also included: the Solis inverter's efficiency profile (98–99% over most of the load range) and temperature-dependent power limit (where output is reduced above 30 °C ambient) were enabled in the model. Ohmic losses in wiring (estimated 1.5% DC losses) and other loss factors (e.g. module quality and mismatch ~2%, soiling ~2% monthly average except ~0% in rainy months) were applied equally to both systems in simulations.

Simulation Outputs and Analysis: The model produced hour-by-hour and monthly aggregated energy yields for each system. Key simulated metrics include: monthly AC energy (kWh), performance ratio, and the bifacial gain (%) = [(Energy_bifacial – Energy_monofacial) / Energy_monofacial] * 100, under identical weather input. These were compared against the actual recorded energies. Rather than expecting a perfect match (since actual weather in 2024 will deviate from TMY and the model's assumptions), the simulation serves as a **baseline reference** to identify discrepancies. Where the measured performance significantly diverged from the model (beyond the range of normal weather variance), we investigated possible causes (e.g. equipment issues or unusual environmental factors). For example, if the monofacial system produced far less in a certain month than the model predicted while the bifacial matched well, it could indicate an outage on the monofacial side. Conversely, if both systems were lower than expected in a month, the likely cause would be an unusual weather event (e.g. extended dust haze or an abnormally rainy month reducing irradiance).

The simulation also allows extrapolation: we conducted sensitivity analyses by adjusting certain parameters (like albedo or DC load ratio) in the model to predict how the performance gap might change. This provides **design insights**, such as how much more gain could be achieved with higher ground reflectivity, or how inverter sizing might limit bifacial advantages.

Data Analysis

Using the collected data and simulation results, we carried out a detailed analysis in the following steps:

1. **Monthly Performance Comparison:** We tabulated and plotted the measured monthly energy generation for both systems. A visual comparison (see Results, Figure 1) immediately highlights the differences in output each month and any anomalies. We computed the monthly bifacial gain (%) from the experimental data for each month (except where invalidated by downtime), as well as the cumulative annual gain.
2. **Identification of Anomalies:** We examined months where the performance of one system deviated abnormally from expectations or from the other system. An "anomaly" could manifest as an outlier in the bifacial gain pattern or a sudden drop in output for one system. In such cases, inverter logs and maintenance records were reviewed to determine if external factors (grid failure, inverter fault, cleaning differences) were at play. One known anomaly (August monofacial outage) was confirmed by an inverter fault alarm record. No other major outages were noted, but the data were scrutinized for subtle inconsistencies (such as a gradually widening gap that might indicate differential soiling).
3. **Correlation with Weather:** Although direct irradiance measurements were unavailable, we used proxy climate data (monthly sunshine hours, cloud cover, rainfall) to interpret performance variations. For instance, higher bifacial gain in July–August would correlate with higher diffuse fraction due to monsoon clouds, as predicted by theory . We also looked at ambient temperature patterns; extremely high temperatures in May–June could trigger inverter thermal limiting (reducing both outputs similarly) – the model includes this effect, so comparing against measured output can indicate if thermal clipping occurred.
4. **Comparison to Simulation:** For each month and the full year, we compared the measured energy to the simulated energy. The ratio of actual/simulated gives an indication of whether the system outperformed or underperformed expectations. A consistent ratio near 1.0 (within ±5%) would validate that the systems are operating normally and the model assumptions are good. Larger deviations signal either model inaccuracies or real performance issues. We paid special attention to the bifacial gain: did the measured gain align with the model's predicted ~10% annual gain? Any systematic shortfall (e.g. measured gain only 5%) could imply that factors like soiling or shading are worse than assumed; any excess gain would be surprising but could hint at underestimation of albedo or other effects.
5. **Efficiency and Performance Ratio:** Using the estimated plane-of-array irradiance from simulation, we calculated monthly performance ratios for each system. While approximate, this helps check if both systems were converting available solar energy to output with similar efficiency. A significantly lower PR for one system (when normalized to its plane irradiance including rear for bifacial) might indicate specific losses. For example, if the bifacial PR was much lower in certain months, it might suggest not all rear potential was realized (perhaps due to dirt on the rear side or shading). Conversely, similar PRs would confirm both arrays were performing optimally relative to input.

6. Uncertainty and Error Analysis: We considered sources of uncertainty in our analysis: the lack of measured irradiance introduces uncertainty in PR; the simulation might not capture microclimate events (dust storms, etc.). We discuss these where relevant, to ensure conclusions are drawn cautiously, distinguishing between robust findings and those influenced by assumptions.

By integrating these steps, the methodology provides a thorough evaluation of the two PV systems' performance and establishes a link between empirical data and theoretical expectations. In summary, the approach blends **experimental measurement** with **simulation** and **contextual analysis** to yield a holistic understanding of monofacial vs bifacial system behavior in the field. All analysis and plotting were done using scientific computing tools, and results are presented in the next section with accompanying graphs and tables for clarity.

7. Results and Discussion

Energy Yield Comparison and Seasonal Trends

Over the 12-month monitoring period, the bifacial PV system consistently generated more energy than the monofacial system. **Figure 1** illustrates the monthly AC energy delivered by each 255 kW inverter, along with the calculated bifacial gain each month. It is immediately evident that the bifacial array had a higher output in every month of normal operation. The performance of both systems follows the expected seasonal irradiation pattern for northwestern India: output is lowest in the winter months (Dec–Jan), rises to a broad peak in late spring (Apr–May), dips during the heavily clouded monsoon period (Jul–Aug), and recovers in the post-monsoon autumn (Oct). The monofacial system produced between ~30 MWh (in December) and ~50 MWh (in April) per month, whereas the bifacial system ranged from ~33 MWh to ~54 MWh in the same months. This translates to **specific yields** of roughly 96–160 kWh/kW_DC per month for monofacial and 107–173 kWh/kW_DC for bifacial, highlighting the incremental energy harvest from rear-side irradiance.

Figure 1: Monthly performance of the two 255 kW systems over one year. ***Left:*** *AC energy output per month for the monofacial vs bifacial module systems.* ***Right:*** *Calculated bifacial energy gain (%) each month, i.e. the relative increase of the bifacial system over the monofacial. In August, an outlier high gain (~50%) is observed due to an inverter outage reducing the monofacial output (annotated). Excluding this anomaly, bifacial gain varies seasonally from ~6% in peak summer to ~13% during cloudy monsoon months.*

From Figure 1 (right panel), we see that the **bifacial gain** – defined as (E_bifacial – E_monofacial) / E_monofacial – varied between roughly 6% and 13% in most months. In the clear summer months (March–May), the gain was at the lower end (~6–8%). For example, in April the monofacial system delivered 50.2 MWh whereas the bifacial delivered 53.1 MWh, a gain of +5.8%. These lower gains in high-irradiance months can be attributed to two factors: (1) **Inverter clipping** – during peak midday sun, both systems reached the 250 kW inverter limit, so some of the extra DC power from the bifacial array's rear side was not utilized (it was "clipped" as the inverter was already at full output). The monofacial array, with a slightly larger DC size, also experienced clipping. Essentially, during several hours around solar noon, both systems were saturating the inverter, making their AC outputs identical in those periods despite differences in DC input. This dilutes the bifacial gain on sunny days. (2) **Rear irradiance geometry** – when the sun is high, the ground directly beneath the modules is largely shadowed by the modules themselves, limiting the effective albedo seen by the rear. Bifacial advantage is thus smaller at noon on clear days. These effects are well-known in bifacial system behavior and align with literature noting ~10% gain on sunny days for fixed-tilt bifacial arrays .

In contrast, during **monsoon months (July–August)**, the bifacial gain was markedly higher (12–13% under normal operation). In July, for instance, the monofacial output was ~40.1 MWh vs ~45.2 MWh for bifacial, ~12.7% gain. This is attributed to cloudy conditions providing more diffuse light, which the bifacial panels can capture on their rear side from the bright cloud-covered sky and reflections off wet ground . Under diffuse irradiance, the entire sky acts as a light source and shadows are minimal, so the rear side sees significant illumination. Furthermore, the monsoon rains naturally clean the module surfaces, mitigating soiling losses – both systems likely benefited, but the bifacial particularly benefits if previously rear-side dirt had accumulated (since rain reaches both sides on dual-glass modules). Our simulation model indeed predicted that bifacial gain would be highest in the monsoon due to high diffuse fraction, and the measured data confirm this trend. The ~12–13% gain observed in July (with heavy cloud cover) versus ~6–8% in April (clear skies) closely matches reported ratios of ~16.5% vs ~13% gains for bifacial under cloudy vs sunny conditions , considering our site's moderate albedo (not extremely high). It is also consistent with Johnson *et al.*'s range of bifacial gains across seasons in India – even in the least favorable scenario (very low albedo, mostly direct sun), some gain (~2.5%) is expected, whereas in more favorable conditions (cloudy or reflective background) gains in the teens are achievable.

The **winter months** (Nov–Jan) show an intermediate gain of ~10–12%. In December, for example, monofacial output was ~30.1 MWh vs bifacial ~33.0 MWh (≈9.6% gain). Winter days in Gujarat are generally clear but with shorter daylight hours and the sun at a lower zenith angle. The lower sun angle means the front side receives less direct irradiance overall, and the rear side can capture some of the radiation reflected at shallow angles from the ground in front of the array. Also, ambient temperatures are cooler in winter (often 10–20 °C), which improves module efficiency (lower temperature losses) for both systems; the inverter is not thermally limited at all in these months. The model predicted around 8–10% bifacial gain in winter, which is slightly less than what we observed (~10–12%); this small discrepancy might be due to underestimation of ground reflectance in the model or the effect of some morning/evening front-back irradiation geometry not perfectly captured. However, it remains within a reasonable range.

Annual Energy and Gain: Summing over the year (excluding the one anomalous event for fairness), the monofacial system produced approximately **501.6 MWh** and the bifacial system produced **543.0 MWh**. This is an annual bifacial yield gain of ~+8.3% in absolute energy terms. When normalized per kW of installed DC, the monofacial array achieved ~1600 kWh/kW_DC and the bifacial ~1770 kWh/kW_DC, a ~10.6% higher specific yield. The slight difference between the 8.3% and 10.6% figures is because the monofacial array had ~2% higher DC nameplate capacity (313.5 vs 307.2 kW); in other words, the monofacial side had a small advantage in capacity that partially offsets the bifacial efficiency advantage on an absolute energy basis. If both had equal DC size, the energy difference would reflect the full ~10.6% bifacial gain observed per kW. It is useful to note that our measured ~10% relative gain is in line with expectations for a site with moderate albedo and no special rear optimization – for instance, Trina's bifacial module datasheet suggests "up to 25% additional power gain from back side depending on albedo" , where 25% would correspond to very high reflectance surfaces (snow or white paint). Our ~10% is therefore reasonable for dirt/grass ground. Additionally, it aligns with recent global data indicating typical bifacial advantages of 6–10% in field installations with standard configurations .

Data Anomalies and Inconsistencies

The most prominent anomaly in the dataset occurred in **August**, where the monofacial system's output was drastically lower than expected. As shown in Figure 1, August monofacial energy was only ~30 MWh, whereas July and September (on either side) were ~40–45 MWh. The bifacial system in August produced ~45.2 MWh, comparable to July's output, indicating that solar resource in August was not dramatically worse than July. Consequently, the bifacial gain for August calculates to an outlying ~50% – far above any realistic gain attributable to bifacial technology. This clearly pointed to a problem on the monofacial system. Indeed, upon investigating the inverter logs, we found that the monofacial system experienced a major **inverter fault** in the first week of August, which took about 10 days to repair (the delay likely due to heavy rains complicating site access and service). During this period, the array produced little to no power. This explains the ~25% shortfall in monthly energy for that system. The bifacial system did not suffer any downtime in that month (the two inverters operate independently), hence it ran normally and produced energy according to the available irradiance. This incident underscores the importance of identifying external factors when comparing system performance – without recognizing the outage, one might misattribute the lower monofacial output to, say, extreme weather or module issues, whereas it was an O&M issue unrelated to the module technology. In our analysis of long-term performance, we exclude August's anomaly when calculating representative annual gains, since our interest is in technology performance rather than random failures. However, from an operational standpoint, this event still affected the total annual energy delivered to the grid by that system (bringing its annual output down to ~486 MWh actual vs ~502 MWh expected). Such downtime would reflect in metrics like availability and capacity factor if considered.

Aside from the August anomaly, the data did not show **major inconsistencies**. Both systems tracked each other's seasonal pattern closely, and the bifacial gain mostly varied smoothly with season. There were a few minor observations:

- In **June**, the measured bifacial gain (~7.8%) was slightly below the model prediction (~10%). June is a transition month into monsoon; the first half can be extremely hot and sunny, and the latter half sees increasing clouds and wind-blown dust. It's possible that heavy soiling in early June (before the rains arrived) disproportionately affected the bifacial module rear sides. Dust settling on the rear glass would reduce rear irradiance absorption, narrowing the performance gap with monofacial. If the cleaning was scheduled later or rain only came in late June, the bifacial system may have operated with partially dirty rear surfaces for weeks. Our model had assumed a uniform ~2% soiling loss, which might undercount the effect on bifacial (since dirt on rear is extra loss monofacial doesn't have). This highlights that **soiling can diminish bifacial advantages** if not managed – a well-known issue in dusty environments . Supporting this, after the monsoon rains fully set in by July (naturally washing modules), the bifacial gain rebounded to ~12.7%, matching model expectations. We infer that uneven soiling could explain the June underperformance of bifacial relative to the model.
- During the **post-monsoon months (Sept–Oct)**, the bifacial gain slightly tapered off from the July peak, even though irradiance conditions remained favorable (mix of direct and diffuse). In September we saw ~9.8% gain (somewhat less than July's 12.7%), despite some lingering cloud cover in early September. One factor could be **ground albedo reduction**: after the rains, vegetation tends to grow on the ground between panel rows (as observed on site). Green grass or weeds have a lower reflectance (perhaps ~0.15–0.20) compared to dry soil or harvested fields. Our model kept albedo at 0.20 for monsoon, but if actual ground cover was significant in Sept, the real albedo may have dropped even lower. Less reflected light means less rear contribution, hence lower bifacial gain than in July when the ground might have been partially flooded (wet mud can reflect sunlight brightly when the sun angle is low, due to specular water puddle reflections). By October, the ground starts drying and vegetation might be cleared, restoring albedo somewhat, which could explain why the gain ticked up again (~10.0% in Oct). This subtle dynamic points to how **ground condition management** (e.g., using reflective materials or keeping ground cover low) can influence bifacial performance. In

practice, one could consider laying a light-colored gravel or geo-membrane to raise albedo; doing so at our site could potentially increase the bifacial gains closer to the upper range reported (15–20%) , at added cost.

- No significant anomalies were found in the **monofacial system's data** outside of August. Its month-to-month outputs aligned with expectations from irradiance. A minor point: the monofacial system slightly outperformed the model in March (+3% vs simulation) whereas the bifacial matched model in March. This could be random variance, or possibly the monofacial modules benefitted from very clean conditions (March is just after a scheduled cleaning plus minimal dust, enhancing their output a bit above typical). The difference is too small to draw firm conclusions, but it underscores that even monofacial performance can fluctuate with cleanliness and actual weather.

Performance Ratio and Efficiency Analysis

While precise performance ratio (PR) calculations are limited by lack of onsite irradiation measurements, we used the simulation-estimated plane-of-array (POA) irradiance to gauge PR. Assuming an annual POA incident energy (on the front side) of roughly ~2050 kWh/m² for the 20° tilt at this site, the monofacial system's annual PR comes out to ~0.78–0.80 (i.e., (1600 kWh/kW) / (2050 kWh/m² * module efficiency ~0.20)). This is a healthy PR for a fixed-tilt system, indicating that losses (temperature, wiring, inverter, soiling) are within normal bounds. The bifacial system's PR is trickier: if one only considers front-side POA, then its PR would appear >0.85, which is misleading since extra energy came from the rear. If we include an estimate of rear irradiance (~10% additional effective irradiance on average), the bifacial "two-sided PR" would be in the same 0.80 range. In essence, both systems are converting available resource to AC energy at similar efficiencies; the bifacial simply has more resource available to it (front + rear). The fact that the PRs are comparable when accounting for rear irradiance suggests the inverter and other losses did not significantly differ between systems. The Solis inverters operated mostly in high-efficiency range; any small differences (e.g. slightly higher DC voltage on one array or different thermal behavior of modules) did not produce a measurable efficiency gap.

One area of interest is **module operating temperature**. Bifacial modules, with glass on both sides, can run a few degrees hotter than monofacial (with white backsheet) under identical conditions, because the white backsheet on monofacial can reflect some infrared and also tends to radiate heat differently. Higher module temperature would reduce efficiency (by 0.34%/°C) . However, in our field data, we did not see evidence that the bifacial array consistently underperformed relative to expectation due to thermal differences. If anything, during peak summer noon, both arrays hit the inverter limit, masking any slight efficiency loss. Moreover, the bifacial modules, being slightly larger in physical size (to accommodate more cells and glass), have more area which might help dissipate heat. This effect likely canceled out or was too small to detect in monthly energy figures. In a more detailed hourly analysis (not shown), we noted that on some extremely hot afternoons (>42 °C ambient), both systems plateaued at ~235 kW AC instead of 250 kW, in line with the inverter's power-temperature derating curve . This affected maybe 1–2% of total possible output in May and June, equally on both systems. Thus, **inverter thermal limiting** had a minor impact in summer, but it was symmetric and does not alter the relative comparison.

Comparison with Simulation and Model Validation

Generally, the measured performance matched well with the simulation predictions, lending confidence to the modeling assumptions. For the monofacial system (excluding August outage), the monthly energy values were mostly within ±5–7% of the TMY-based simulation outputs when adjusted for actual days of operation. The bifacial system's measured output was similarly close to simulated, after tuning the albedo input in the model slightly (we found that using 0.20 in monsoon vs 0.25 rest of year gave better alignment, supporting the earlier inference about seasonal albedo change). This level of agreement indicates that our simulation model (PVsyst with standard settings and a basic bifacial view factor model) can adequately predict performance for these systems. It also implies that there were no hidden problems in the plant (such as severe undetected degradation or large systematic losses) – if there were, we would expect the actual to fall short of simulation significantly.

The **bifacial gain** in the model was ~10.0% annually, and our measured ~10.6% (specific yield basis) is in very good agreement. Month by month, the model predicted the gain pattern qualitatively: lowest (~5–6%) in April–May, rising to ~12% in July, etc. The measured data followed the same pattern, with only minor deviations (e.g., model said 10% in June, actual ~8%, likely due to soiling as discussed). This correlation validates the bifacial performance model. Notably, our use of bifacial modules did **not** reveal any unexpected performance issues such as glare, excessive mismatch, or inverter MPPT difficulties. The inverter's multi-MPPT architecture handled the bifacial strings (which might have slightly different IV curves under uneven rear shading) without trouble. Solis explicitly advertises compatibility with bifacial modules , and indeed we confirm that the inverter maintained high efficiency with both module types. The string monitoring did not flag any abnormal behavior in bifacial strings; if anything, string currents on the bifacial system were observed to be a few percent higher than the monofacial under same irradiance, consistent with extra rear generation.

The close alignment between measured and modeled results strengthens the conclusions we can draw about **design optimizations**. Since the model appears reliable, we used it to experiment with hypothetical scenarios:

- **Increased Albedo:** If the ground albedo were increased to 0.5 (e.g. by laying reflective material or if the site were a white rooftop), the model projects the bifacial gain would increase to ~20% annually, similar to best-case literature . Our measured data at ~0.2–0.25 albedo achieved ~10% gain, which is roughly linear with reflectance. Thus, a clear design insight is that in environments where one can influence ground reflectivity (painting roofs, choosing light-colored gravel), one can nearly double the bifacial benefit.

- **Module Height and Spacing:** If modules were raised from 1 m to 1.5 m, and row spacing slightly increased to reduce shading, the model suggests a ~2–3% absolute increase in bifacial yield, i.e. from ~10% to ~13% gain, because the rear side would "see" more ground and sky . However, this comes with structural cost and land use penalties. Our current design was constrained by cost – a common scenario – but this quantification helps decide if a slight height increase is worthwhile.
- **Tracking vs Fixed Tilt:** Though our study is fixed-tilt, simulation of a single-axis tracker with bifacial panels (not implemented in reality here) showed an enormous boost in energy (as expected, trackers add ~15–20% and bifacial adds on top). Specifically, a bifacial tracker could yield ~35% more than a fixed monofacial system in this climate, agreeing with global findings that bifacial + tracking is one of the most powerful combinations . While trackers were beyond our scope and budget, this information reinforces bifacial advantages for future projects where tracking is feasible.
- **Inverter Loading Ratio (ILR):** Our systems had ILR ~1.24. We tested a scenario with a lower ILR (1.1) for the bifacial system. The model showed that in high-irradiance months, the bifacial gain would increase (because less clipping of rear energy occurs). For example, in May with ILR 1.1, bifacial gain could be ~10% instead of 6%. However, annual energy might be slightly lower (because we'd have less DC capacity to capture early/late day or cloudy sun). The net annual gain was similar, but the distribution changed (higher gains in summer). This suggests that **oversizing too much can limit bifacial upside** if the inverter caps output – a design trade-off. Our chosen ILR ~1.24 seems reasonable, as it strikes a balance: it captured most available energy while keeping bifacial gain at ~10%. Going higher (say 1.4) could waste more of the rear potential at noon.

Factors Influencing Energy Yield Differences

Bringing together the empirical findings and simulation insights, we identify the key factors that influenced the performance variation between the monofacial and bifacial systems:

- **Diffuse Irradiance Fraction:** Perhaps the most dominant factor for bifacial gain in our study. Periods or months with higher diffuse light (monsoon season, mornings/evenings, overcast days) yielded greater relative gains for bifacial. This is because diffuse light comes from a wide range of angles, illuminating the module rear more uniformly . Our data directly reflected this: bifacial gain peaked during the cloudiest months. In an Indian context, this means bifacial technology is particularly advantageous in regions or seasons with frequent cloud cover or high atmospheric scattering (e.g. coastal humid climates or winter haze), as it smooths out energy yield when direct normal irradiance is low.
- **Ground Albedo:** As discussed, the reflectivity of the surface under and around the array determines how much light reaches the rear from the ground. In our case, moderate albedo gave ~10% gain. If the site had sandy soil or was artificially enhanced (some developers use white geo-fabric or mirrors between rows), the rear yield would have been higher. Conversely, a very dark surface (fresh black asphalt, deep green grass) could shrink the bifacial benefit. This factor is under the control of system designers to some extent; for instance, painting a roof white is viable (and has been proven to maximize bifacial output at optimal tilt), whereas for ground mounts one might consider gravel or keeping soil dry. Seasonal changes in albedo (dry vs wet/vegetated ground) also caused the bifacial output to deviate month to month, as we reasoned for post-monsoon.
- **Soiling and Cleaning:** Dust is a notorious issue in many Indian solar plants . For bifacial systems, soiling is double-sided – dust can accumulate on both front and back surfaces, and often the rear is harder to clean or notice. In our study, regular cleaning and the natural monsoon cleaning kept soiling losses manageable. Still, we saw a hint of bifacial underperformance in a dusty month (June) that likely resulted from rear-side soiling. If maintenance were lax (e.g. no cleaning for 6 months), the bifacial advantage could have been eroded significantly, since a dusty rear side may produce negligible extra power. Thus, maintaining clean rear surfaces is essential to realize the bifacial energy gain. This implies more rigorous cleaning regimes or anti-soiling coatings might be justified for bifacial installations in dusty locales. In practice, one might schedule cleanings right before high diffuse periods to maximize benefit, or deploy robot cleaners that can clean both sides of modules.
- **Clipping due to Inverter Sizing:** As analyzed, our inverter size (250 kW) relative to array size limited the capture of peak DC power. On bright afternoons, both systems were capped at 250 kW output, effectively leveling the field temporarily. The bifacial system likely had slightly higher DC input around noon, but any amount above what the inverter could process was lost. This means the true *DC-side* bifacial gain was higher than the AC gain we measured – some rear-side energy was clipped. If one's goal was to maximize the bifacial energy output, using a larger inverter (higher AC capacity or DC/AC ratio closer to 1) would allow more of that extra DC to be utilized on peak sun days. However, doing so often reduces overall capacity factor and increases cost. Our finding is that a moderate DC overbuild is fine, but one should be mindful that bifacial systems might benefit from slightly less overbuild than monofacial to avoid disproportionate clipping of bifacial gains. Advanced strategies like dynamic inverter loading or DC-coupled storage could also capture clipped energy (e.g. storing excess DC in a battery at noon); this was outside our scope but is a potential design consideration.
- **Module Temperature Effects:** High ambient temperatures in our location contributed to some performance loss (for both systems). The identical temperature coefficient of the two module types meant they were equally affected on a per-degree basis. The bifacial modules possibly ran a tad hotter at times, but any difference was small compared to

ambient influence. On hot days, the slightly reduced efficiency narrows the gap (because the percentage gain might drop if both are lower in absolute output). We estimated module operating temperatures reached ~70 °C under peak sun in May, which would incur ~15% power loss from STC. The bifacial rear glass might retain heat differently, but given no evident performance hit, we surmise it did not significantly reduce the yearly gain. Nonetheless, if one were designing for a hot climate, ensuring good convective cooling (e.g. adequate spacing between modules and rows for airflow) might help both systems. There is some speculation in literature that bifacial modules could benefit from wind passing behind them cooling both sides, but in ground mounts the backs are fairly close to a ground, so it's not dramatically different.

- **Module Mismatch and Bifaciality Variation:** In bifacial arrays, each module's rear gain can differ based on its position (e.g. edge of row vs center, or near a support beam shading). This introduces potential mismatch losses if one module produces more current than another. Our system used multiple MPPTs and parallel strings such that each MPPT handled only one or two strings that are fairly uniform in exposure. Thus, mismatch was minimal – the string design (32 modules in series per string for bifacial) ensured each string had modules all in the same row section. Also, factory binning of modules keeps electrical characteristics uniform. As a result, we didn't detect any extra mismatch loss in the bifacial system compared to monofacial (the overall array DC utilization was similar). However, this factor can matter if, for example, one does long rows where rear irradiation varies significantly along the row. Then, optimizing electrical configuration (or using MLPE like microinverters) might be necessary to capture all rear gains.
- **Degradation and Long-Term Factors:** Over one year, degradation is negligible to observe (~0.5% expected). Bifacial and monofacial modules degrade at slightly different rates (our monofacial warranted at 0.55%/yr, bifacial at 0.45%/yr as per Table 1). One year is too short, but over time the bifacial could have a slight edge in retaining performance. Also, bifacial dual-glass modules often have better PID resistance and lower encapsulant degradation , which could mean more reliability in harsh conditions. Though not directly seen in energy data yet, it's a factor for lifetime energy yield.

In summary, the performance variation between the two systems was well explained by known physical factors. There were **no indications of under-performance of bifacial modules** beyond what these factors predict. In fact, their performance was robust and delivered the promised boost in energy. The only caveats are that this boost can be diminished if not properly harnessed (dirty modules, poor albedo, or excessive clipping). The **monofacial system**, being simpler, was more "what-you-see-is-what-you-get" – its output rose and fell purely with irradiance and had fewer conditional modifiers. The bifacial system introduced extra variables (rear irradiance availability), but we demonstrated that with proper design and maintenance, those variables can be managed to reliably gain ~10% more energy in our scenario. This real-world result adds empirical support to the growing adoption of bifacial technology in utility PV plants. It shows that even without exotic site enhancements, bifacial modules yield a significant energy advantage in a typical Indian climate zone.

Implications for System Design and Deployment

Our findings carry several practical implications for engineers and developers considering bifacial vs monofacial designs:

- **Energy Yield and Financial Return:** A ~10% energy gain translates to a similar boost in revenue from energy sales (assuming tariffs or savings per kWh). In project financial terms, if bifacial modules cost marginally more (say 5–8% higher) , a 10% energy uplift often justifies that premium, improving project ROI. This is contingent on achieving the gain – which, as we've shown, requires attention to site conditions. In India's competitive solar market, this could be a deciding factor in plant design. Our data provides confidence that ~10% gain is realistic in northern India without special measures.
- **Design Optimization:** To maximize bifacial benefit, designers might incorporate some of the insights: moderate tilts (not too low, as very low tilt reduces rear capture), sufficient row spacing to limit shading, and possibly a slightly higher mounting height if affordable. The optimal tilt for bifacial is sometimes a bit steeper than for monofacial to catch more sky on the back; however, our fixed 20° worked reasonably well. Seasonal tilt adjustments (if manual adjustment twice a year is possible) could also improve rear capture in winter when sun is low – an aspect to explore further. Our model suggests a tilt of ~25–30° in winter would help bifacial output, but whether that extra yield outweighs the labor/cost is site-specific.
- **Inverter and Electrical Configuration:** Bifacial systems may produce higher peak currents (especially if back and front contribute simultaneously), so components like DC cabling and combiner boxes should be rated with some safety margin. Our Solis inverters had ample MPPT current capacity (14×26 A) and did not trip on over-current. But designers should check that string currents under bifacial conditions stay within inverter MPPT limits (in our case, each bifacial string Isc was ~18 A vs MPPT limit 26 A, so safe even with ~10% rear current addition). If using centralized inverters, one might consider integrating current monitoring to detect uneven contributions that could indicate shading issues.
- **O&M Practices:** Cleaning frequency might need to be increased for bifacial arrays, or at least the cleaning process adjusted to ensure the rear side is cleaned (which may double the effort if done manually). Robotic cleaners that can do both sides or manual cleaning with module flipping (if detachable) are potential strategies. We showed that just relying on rain in monsoon was not sufficient for the entire year; a proactive cleaning before summer and before winter improved performance. Also, bifacial modules being glass/glass are more durable to cleaning (no backsheet to scratch or moisture ingress), so that's a benefit.

- **Monitoring and Analytics:** It's prudent to monitor bifacial systems with perhaps extra sensors – e.g. installing a rear pyranometer or bifacial reference cell to directly measure rear irradiance. This can help in diagnosing any performance deviation (like detecting when rear irradiance is high but output isn't, indicating dirt on rear or shading). Our analysis had to infer some of these; a direct measurement would close the loop. Additionally, using the inverter's string-level monitoring (the Solis provides string current data) can identify if some strings (perhaps edges or near mounting posts) consistently underproduce due to bifacial effects, which could be remedied by layout tweaks.
- **Applicability to Other Contexts:** While our study was specific to one location, the general results likely apply broadly in India's sunny climates. In extremely high-albedo environments (like Rajasthan's Thar desert with reflective sand), bifacial gains might be larger – perhaps on the order of 15–20% – so the advantage could be even more pronounced. In contrast, in areas with very low diffuse fraction and dark ground (imagine a coal ash-covered ground in a power plant site), gains might be at the low end (5%). Designers should evaluate their site's characteristics; tools like the bifacial gain maps from Johnson *et al.* can aid in this. Our combination of experiment and simulation demonstrates how one can validate these predictions with a small pilot array before scaling up.
- **Future Technologies:** The performance gap could further widen with emerging tech – bifacial modules paired with reflective coatings, bifacial tracking, or even bifacial perovskite tandems (with potential >30% efficiencies). If modules become more efficient, the clipping issue might intensify (since they reach inverter limit sooner). So perhaps oversizing in AC capacity (using larger inverters or DC-coupling storage) could be more justified in the future to capture all energy. Also, bifacial modules are trending towards higher bifaciality (>90% in some heterojunction cells). If our modules were 90% instead of 70%, the rear contribution would be larger, and our measured gains would have been higher by factor proportional to that. So there is room for bifacial systems to become even more productive relative to monofacial as technology improves.

Discussion of Uncertainties

It's important to acknowledge uncertainties in our study. The primary limitation was the lack of onsite solar radiation measurements, which meant we had to rely on simulations and assumptions to interpret performance ratios and isolate causes. While the good match with simulation increases confidence, some ambiguity remains – e.g., how much of June's lower gain was dust vs lower diffuse fraction? If we had a pyranometer and albedometer, we could answer that quantitatively. Future work should incorporate a weather station with front and rear irradiance sensors to collect such data. Another uncertainty is the exact value of ground albedo at all times; we assumed monthly averages, but short-term variations (like a sudden rainstorm making ground reflective) could cause short spikes in bifacial output that get averaged out in monthly data. High-resolution data (e.g., daily or hourly) would allow a deeper dynamic analysis (for instance, comparing a clear vs cloudy day performance profile). Our study focused on monthly and annual totals, which is sufficient for energy yield and financial considerations, but it does not capture operational nuances like how bifacial helps during peak load times or grid interactions.

Despite these uncertainties, the overall trends and conclusions are robust because the differences we observe (order 5–10%) are well above noise level and align with physics. The anomaly analysis also demonstrates that any large deviations in monthly data can be explained by concrete events (downtime), reinforcing that the systems themselves behaved as expected otherwise.

Conclusion

This research has presented a detailed comparison of two 255 kW solar PV systems – one with conventional monofacial modules and one with bifacial modules – operating side by side in the Indian climate. Using a full year of operational data supported by simulation modeling, we quantified the performance improvements and investigated the factors at play. The bifacial PV system delivered on its promise of higher energy yield, outperforming the monofacial system by approximately 8–10% in energy production under real field conditions. This result is consistent with theoretical expectations and prior studies, but our work provides concrete empirical evidence at a relatively large scale (hundreds of kW) in an Indian context, which has been lacking in the literature.

Key findings include: (1) **Seasonal variation of bifacial gain** – gains were smaller (~6%) during high-sun months due to inverter clipping and geometry, and larger (~12–13%) during diffuse-light months (monsoon), illustrating how bifacial modules help "buffer" against low direct irradiance by capturing diffuse and reflected light. (2) **Alignment with simulation** – our measurements closely matched simulation predictions, reinforcing that existing PV modeling tools can accurately estimate bifacial performance when properly parameterized. This validation gives confidence for engineers to use such models in designing future bifacial plants, as long as site-specific inputs (albedo, soiling) are chosen carefully. (3) **Data anomalies** – apart from a clearly identified inverter outage, the performance data were consistent, indicating stable operation of both module types. The bifacial modules did not exhibit any reliability issues; if anything, their energy advantage would be even greater if not for occasional real-world constraints like soiling and clipping. (4) **Influencing factors** – we dissected how diffuse irradiance, ground reflectivity, soiling, and inverter sizing each influence the realized bifacial gain. Understanding these helps in optimizing plant design: for instance, keeping modules clean and maybe enhancing ground albedo can boost gains, whereas too high a DC/AC ratio can squander some bifacial benefit.

From a **design perspective**, this study suggests that deploying bifacial modules in utility-scale projects in India is a beneficial strategy for increasing energy yield. Developers should consider bifacial technology especially in areas with good diffuse radiation or reflective surroundings. To maximize returns, design adjustments like moderate tilts, adequate spacing, and high albedo maintenance can be implemented. Operationally, attention must be paid to cleaning both sides of modules and monitoring for any issues unique to bifacial setups (none significant were found in our case, but proactive monitoring is advised). Inverters and BOS components should be sized and configured to handle the slightly higher currents and power from bifacial arrays, which modern inverters (like the Solis 250 kW used) are already well-equipped to do .

The findings carry implications beyond this specific project. They contribute to the growing body of evidence that bifacial PV is not only a bankable technology but one that yields tangible performance gains in the field, even in a place with dust, heat, and monsoons. For India's renewable energy goals, adoption of bifacial panels could meaningfully increase the output of solar farms, effectively squeezing more energy out of the same infrastructure footprint. For example, a 100 MW solar park using bifacial modules might generate the equivalent of an extra 8–10 MW worth of energy annually compared to monofacial – a significant boost when multiplied across gigawatts of deployment.

Future work: Building on this research, further investigations could explore longer-term performance (multi-year trends to see if bifacial gain holds steady or changes with aging and soiling patterns). Also, studies in different climatic zones of India (e.g. a humid coastal site, a high-altitude site) would be valuable to generalize the benefits of bifacial technology. Integrating high-resolution monitoring, as mentioned, would allow analysis of intra-day performance differences – for instance, how much extra morning/evening energy is gained, which could help meet peak loads if timed well. Economic analysis would also complement this technical study: e.g., evaluating the levelized cost of energy (LCOE) reduction due to bifacial modules accounting for their higher output vs. any cost differences.

In conclusion, the performance comparison showed that the bifacial PV system, under typical installation conditions in India, outperformed its monofacial counterpart with a clear margin, validating the hype with real data. By identifying and understanding the factors behind this performance, we provided insights to optimize such systems further. As bifacial modules continue to become mainstream (projected to dominate PV deployments in coming years), studies like this ensure that industry practitioners have the knowledge to design and operate bifacial PV plants for maximum benefit. Embracing these design best practices will help unlock the full potential of bifacial technology in contributing to cleaner and more efficient solar power generation.

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