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Development of a 50KW Rooftop Solar Power Plant for Industrial Application

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A B S T R A C T

Bifacial photovoltaics (BPVs) are a promising alternative to conventional monofacial photovoltaics given their ability to exploit solar irradiance from both the front and rear sides of the panel, allowing for a higher amount of energy production per unit area. The BPV industry is still emerging, and there is much work to be done until it is a fully mature technology. There are a limited number of reviews of the BPV technology, and the reviews focus on different aspects of BPV. This review comprises an extensive in-depth look at BPV applications throughout all the current major applications, identifying studies conducted for each of the applications, and their outcomes, focusing on optimization for BPV systems under different applications, comparing levelized cost of electricity, integrating the use of BPV with existing systems such as green roofs, information on irradiance and electrical modeling, as well as providing future scope for research to improve the technology and help the industry.

Keywords: Life Cycle Assessment; bifacial photovoltaic panels; energy production; environmental impacts.

1: Introduction

He ever-increasing global energy crisis and the escalation in the emission of greenhouse gases have led to a constant rise in the use of renewable sources for power production to satisfy the world's energy demand. According to the International Energy Agency, in terms of total installed capacity, the major increase in contribution from the year 2000 up today is associated with photovoltaic systems, followed by wind and hydroelectric power production. The latest available data report that the worldwide solar power installed capacity in 2021 was approximately 885 GW, with a global energy production of 1003 TWh. With respect to 2020, energy generation from photovoltaic panels increased by 467 TWh, marking a yearly +25% and accounting for 4.5% of global energy production.

Despite the significant reduction in the environmental impacts of solar technologies in comparison to those of traditional fossil-fuelled thermoelectric plant , lots of efforts are still being focused on improving the eco-profile of PV cells, panels and plants. Enhancing conversion efficiency together with a reduction in energy and materials consumption, are still the major concerns of PV developers. In this sense, the research of new technologies that can boost electricity generation with lower environmental impacts is still to be realized.

During the last decade, among the most investigated PV systems, bifacial solar technology has played a major role thanks to its readiness level and the rapid increase in the installation market share over the last few years. Indeed, as reported by the International Technology Roadmap for Photovoltaic, a constant rise is foreseen in the market share of PV systems for bifacial solar cells from 20% in the year 2020 up to 70% in 2030.

The academic community has also been focusing its attention on bifacial solar cells, as can be seen from the research trend over the last decade reported in From 2013 up to 2022, 41 to 187, marking the academic interest in the technology.[1]

2. Literature Review on Improvements in BPV

Starting with optimization work in Bi-Facial Technology, when it comes to manufacturing technique, screen printed solar cells produced the maximum efficiency of 22% [31]. When it comes to crystalline structure then the triode structure single crystalline cells were able to produce a maximum front side efficiency of 21.3% and rear side efficiency of 19.8% [32]. Due to absence of back side Aluminium metallization as we see in MFPV, BFPV has got this additional advantage of working at decreased cell temperature due to reduction in infrared absorption which resultantly increases the maximum power output [33]. Also, using infrared reflected coating on the back side of the BFPV, losses due to cell transmittance at near- infrared wavelengths were reduced and current gain of 1% was achieved .

Very recently, a novel approach was used of using reflected mirrors to direct solar irradiance towards front and rear side of BFPV has shown a whopping 51% increase in power for the entire year as compared to the system without mirrors [2].

Summary Box: Mono facial Solar Panels vs Bifacial Solar Panels – Quick Comparison

2.1 Bifacial Solar System

- Collects sunlight from both front and rear sides
- Typical module efficiency: 22–25% (depending on cell technology)
- Higher energy yield compared to mono facial panels (5–30% gain possible)
- Very high suitability for utility-scale projects, especially with high albedo surfaces and trackers

2.2 Mono facial Solar System

- Collects sunlight only from the front side
- Typical module efficiency: 19–22% (depending on cell technology)
- Lower energy yield compared to bifacial panels
- Well-established, cost-effective, and widely used in residential and commercial application
- Uncertainty in rear-side modeling: Existing simulation tools vary in accuracy when predicting rear irradiance, especially under complex ground conditions and tracking systems.
- Standardization issues: Unlike mono facial PV, there is no universally accepted framework for energy rating and performance benchmarking of bifacial modules.

2.3 Contribution of the Present Work

The present study contributes to the growing body of knowledge on bifacial solar power plants in the following ways:

- Performance Evaluation: Provides a systematic assessment of bifacial solar panels compared with conventional mono facial systems under specified site conditions.
- Modeling and Analysis: Employs appropriate simulation tools to estimate rear-side irradiance and overall energy yield, reducing uncertainty in prediction.
- Design Optimization: Investigates the effect of parameters such as module tilt, elevation, albedo, and tracking systems to identify optimal configurations.

3: System Design and Methodology

System Design and Methodology BIFICAL" likely refers to a specific combined methodology for information systems analysis and design, although "BIFICAL" is not a standard acronym. It's a hypothetical example of a hybrid approach, similar to the ISAC and NIAM combination described in a ScienceDirect article, that merges different existing methodologies to create a more comprehensive and effective one.

3.1 Problem Statement

he main problems with bifacial solar panels include higher upfront costs, complex installation requirements that need careful planning for optimal energy capture from both sides, and increased maintenance needs. For best performance, they need to be mounted at a height with a reflective surface, and the mounting system can cause shading, which reduces efficiency.

3.2 Proposed Solution:

Accurate Yield Prediction: Use advanced simulation tools (e.g., ray-tracing or Radiance- based models) to capture rear-side irradiance more reliably than traditional view-factor methods.

Design Optimization: Evaluate key parameters such as tilt angle, module height, row spacing, and ground albedo treatments to maximize bifacial gain.

Performance Benchmarking: Compare bifacial and mono facial systems under identical conditions to establish quantifiable improvements in energy yield and performance ratio.

Guidelines for Deployment: Develop recommendations for site-specific design and operation to reduce uncertainties and improve bankability of bifacial projects.

3.3 Basics of Solar

PV Solar PV enables the access to the energy being delivered to Earth in form of sunlight. It is established scientific fact that this revolutionary technology has potential to solve the energy of entire population of Planet Earth. Some of the key concepts related to Solar PV are as follow.

3.4 Material used in Solar

PV cells The brain of the Solar cell is in the material it is made of. There are various types of materials being used in commercial and laboratory applications of solar cells. These are explained as follows

3.5 Types of Solar PV Systems

There are various types of solar PV systems depending on the type of use. Each of them has distinct advantages and disadvantages which are briefly explained below. Bifacial solar cells simultaneously collect photons from incident and albedo radiation reaching both the front side and backside of a solar module. Mono facial solar [3]

Fig. 1- Armrest Support

A. On-Grid

This system is grid tied meaning that the net power after the taking care of the load can be reimbursed back to grid for which the user can earn energy credits. The greatest advantage of this system is that batteries are not used. That saves much in installation and maintenance costs. But this also come up as the main deficit because during night and cloudy days, there is no back up power.

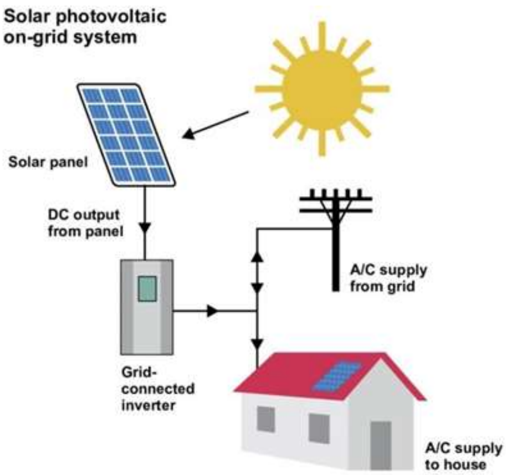

Fig. 2- On-Grid Solar System

A. Off-Grid

This system is completely independent of grid. For this stand-alone system, there is a cost of battery which needs to be sized according to load. Then there is also maintenance cost of batteries after every 5 years or so depending on the model. This type of system is usually suitable for remote areas where there is not a good connection of utility grid.

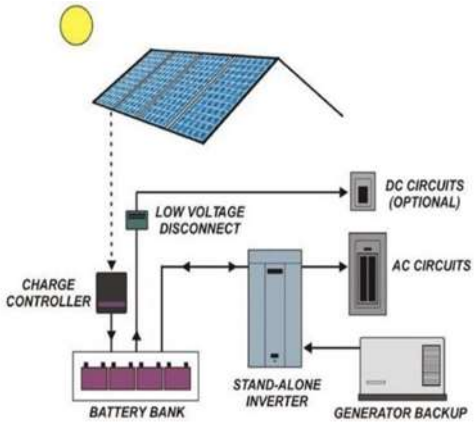

Fig No. 3- Off Grid

- **Albedo**

The albedo can be described as the proportion of reflected energy to the incoming energy across a given area [25]. The concept of albedo is a fundamental aspect in understanding how surfaces interact with incoming energy, typically in the form of sunlight. It is a measure that helps us comprehend the reflective properties of various surfaces, such as the land of Earth, water bodies, ice, and even human-made structures.

3.6 Objectives

The main objectives of the present work are:

- **To evaluate** the performance of bifacial solar panels in comparison with conventional mono facial systems under given site conditions.
- **To analyze** the influence of key design parameters such as tilt angle, module height, ground albedo, and tracking on bifacial system output.
- **To develop** an accurate modeling and simulation framework for predicting rear-side irradiance and overall energy yield.
- **To determine** the techno-economic benefits of bifacial solar plants through Levelized Cost of Electricity (LCOE) and cost–benefit analysis.

3.7 Bifacial Solar PV Performance Factors

Bi-facial solar PV is simply a solar on both sides. It catches the directly from the front side and, reflected irradiance from the rear side. This type of system can be beneficial in the summer season of Nordic region, especially Finland, where there is Sunlight for 20 hours in a day. If the BPV panel is vertical tilt position, it is possible to get two power productions in one day. First peak of power curve will appear before Noon and the second peak will appear in the evening. The figure explains this concept with much clarity. N-type monocrystalline silicon solar cell is a high efficiency and lowcost photovoltaic technology. [4].

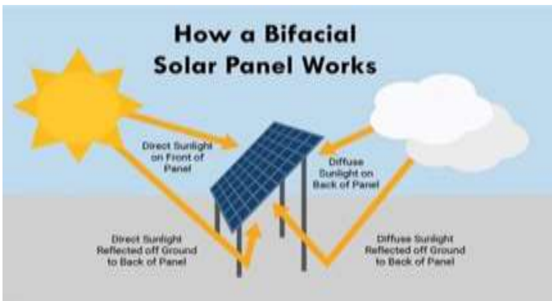

Fig No. 4- Front-side and Rear-side Irradiance

Front-side and Rear-side Irradiance

The solar irradiance primarily falls directly on the front side as compared to rear side. This makes front side 80% responsible for the total energy production by the Bifacial Solar PV panels [26]. One study shows that having the rear side aiding the capture of solar energy, the bifacial gain can be as low as 5% and as high as 30%

Panel orientation and Tilt angle

Panels can be oriented to true south or East-West configuration. In Nordic regions, vertical tilt produces better energy efficiency. One study in Abu Dhabi shows that vertically installed Bi-PV panels can achieve an energy yield as high as 100% compared with the tilted installation in certain months.

3.8 Prototype Design

Prototype designs for bifacial solar panels focus on maximizing rear-side light capture through various methods like using high-albedo ground, optimizing cell layouts, and using advanced materials or reflectors. Designs range from standard panels optimized for reflective environments to custom-built modules for specific applications like agrivoltaics or greenhouses. A key aspect is optimizing the interconnection and module structure to enable both front and back light absorption for increased energy yield.

Design principles and components

1. Cell technology:

2. Prototypes often use standard silicon cells, including those with advanced surface textures or photonic grating interfaces to improve light trapping on both sides.

- **Module design:**

1. Interconnection: Innovations aim to simplify fabrication while enabling the bifacial nature of the cells, such as with Day4 technology or a simplified cell process.
2. Anti-reflective coatings: Applying these coatings to the rear side enhances light absorption.
3. Reflectors: Some designs incorporate planar or integrated reflectors to direct more light to the rear side, optimizing performance for a specific installation.

- **Application-specific designs:**

1. **Greenhouse modules**: Prototypes have been designed with semi-transparent, customized cell layouts to allow sunlight to pass through for plant photosynthesis while generating electricity.
2. **Agri voltaic systems**: Prototypes are tailored to the specific needs of the crop, using optimized cell layouts to ensure enough light reaches the plants while generating power.
3. **Vertical installations**: Prototypes have been tested in vertical arrays, oriented to face east and west, to provide a more consistent power output throughout the day, though their overall efficiency

Simulation and testing

- Software simulation:

Tools like PVSOL, PVsyst, and SAM are used to design and simulate the performance of

These two effects provide a further increase of the annual energy contribution of a PV plant. [5] systems, including the effects of reflective surfaces, shading, and temperature.

- Experimental validation:

Prototypes are tested in real-world conditions to validate simulation results and assess performance factors such as energy yield and temperature effects. Testing often involves isolating the effects of rear-side illumination by blocking it with materials like black plastic.

3.9 A. Covered vs Not Covered Front Side

The same technique was used again, but this time the front side of the panel was covered. The goal was to compare the effectiveness of the front side with the rear side in producing power. The experiment was conducted in three steps:

1. First, a reading was taken with both sides uncovered to create a model curve.
2. Next, the front side was covered, and the rear side faced the road.
3. Finally, the front side was covered again, but this time, the rear side was facing the sun.

This approach helped determine which side of the panel is more effective in generating power.

Fig No. 5- Bifacial Solar Panel with Front Side Covered

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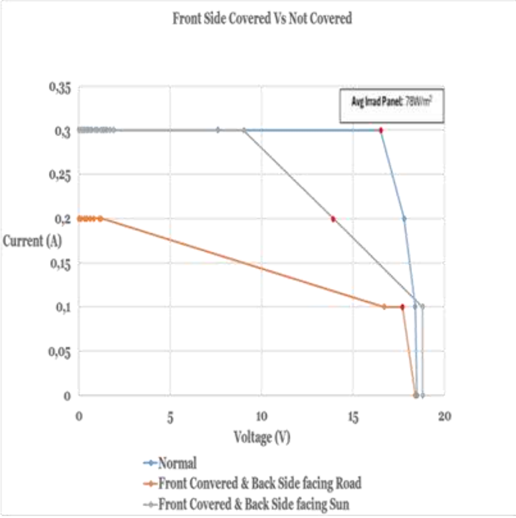
Fig No. 6- Bifacial Solar Panel with Front Side Covered

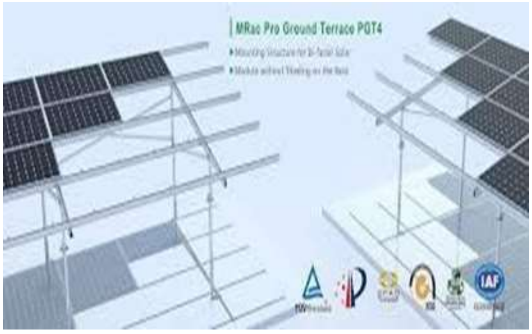
B. Rear Side Covered vs Not Covered

To cover the sides of the panel, a long piece of wood was cut which was exactly the size of the panel surface. It was temporarily joined to panel using heavy duty spring clamps. These clamps and wooden piece were specifically borrowed from design factory right next to experimental sight.

Fig No. 7- Bifacial Solar Panel with Rear Side Covered

The exercise of comparing the design of old and new PV modules has the interest to show the evolution of PV technology throughout the last 30 years. [6]





Bifacial Solar Panel, Legends Explained.

From this graph, results reveal that the rear side of a bifacial panel does not produce as much power as the front side. The front side is more efficient in generating electricity. However, when the power produced by both sides is combined, the total power output is higher than just using the front side alone. So, even though the rear side is not as efficient on its own, it still contributes to the overall power production of the panel.

Components and Circuit Description

Bifacial solar cells:

Unlike traditional cells, these have both front and rear surfaces that can absorb sunlight and generate electricity.

Double-glass construction:

Replaces the standard opaque back sheet with a second layer of glass, allowing light to enter from both sides.

Encapsulant:

Typically EVA (ethylene vinyl acetate) film layers that hold the cells in place and protect them from moisture and other environmental factors.

Extruded aluminum frame:

Provides rigidity and a mounting point for the panel, protecting the edges of the glass layers.

Junction box:

A weatherproof container on the back of the panel that houses the electrical connections and includes bypass diodes.

Bypass diodes: These protect the panel from power loss and overheating if a portion is shaded, by redirecting electricity around the affected area.

In this regard, several studies have focused on bifacial solar cells to determine their performance in different conditions. [7].

Associated system components

Inverter: Converts the direct current (DC) produced by the panels into the alternating current (AC) used in homes and on the grid.

Charge controller: Regulates the voltage and current coming from the panels, protecting the battery from overcharging (often integrated with the inverter).

Battery storage: Stores excess energy for use at night or during cloudy periods.

Mounting structure: The rack or other system that holds the panels in place, often designed with a greater height off the ground or a steeper angle to maximize rear-side light capture.

Metering system: Tracks the amount of energy being produced and consumed.

Core components

1. **Bifacial solar cells**: Unlike traditional panels, these photovoltaic cells can capture sunlight from both their front and back sides, significantly increasing energy generation.
2. **Dual-glass construction**: Many bifacial panels use a layer of tempered glass on both the front and back for superior durability and protection against harsh weather.

3. **Encapsulant**: A transparent adhesive layer, such as Polyolefin (POE), seals the cells between the glass sheets, protecting them from moisture and vibration.
4. **Frame**: A lightweight, corrosion- resistant aluminum frame provides structural support. Some designs may be frameless.
5. **Junction box**: This is a waterproof enclosure on the back of the panel that protects the electrical connections and bypass diodes.
6. **Cables and connectors**: These link the panel to the rest of the solar system.

List of Components (50 kW Bifacial Solar Power Plant)

1. Bifacial Solar Modules (550 Wp each) –~91 Nos
2. Module Mounting Structure (MMS, for 91 modules) – 1 Set
3. Grid-Tied Inverter (50 kW total capacity) – 1 No *(or 2 × 25 kW = 2 Nos)*
4. DC Junction Box (DCDB) – 2 Nos
5. AC Distribution Box (ACDB) – 1 No
6. Lightning Arrester (LA) – 1 No
7. Earthing Pits (for DC, AC, LA separately) – 3 Nos
8. Net Meter (bi-directional, from DISCOM) – 1 No
9. Cables & Accessories

DC Solar Cable (UV resistant) – As per layout (~300–400 m, multiple runs)

- AC Cable – As per distance (~100–150 m)
- MC4 Connectors – ~200 Nos

10. Protection & Accessories

- SPD (Surge Protection Device) – 3 Nos

(DC side, AC side, inverter side)

4: Experimental Setup and Procedure

50 kW Bifacial Solar Power Plant)

This chapter describes the physical setup, instrumentation, measurement plan, and step-by- step experimental procedure used to evaluate the performance of the 50kW bifacial PV plant

4.1 Objectives

- Install and commission a 50kW bifacial PV array and measure electrical output under real operating conditions.
- Quantify key performance metrics: energy yield, performance ratio (PR), capacity factor, specific yield (kWh/kWp), and bifacial gain (Bifacial solar modules on rooftops offer up to 22.6% energy yield gains. -8)
- Characterize the effect of tilt, albedo, and row-spacing on rear irradiance and module output.
- Validate inverter and system protection performance and verify safety & earthing.

4.2 Overview of Test System

- **Plant capacity:** 50 kW (AC) using bifacial modules (≈550 Wp typical) — ~91 modules.
- **Mounting:** Elevated ground-mount / fixed tilt racking optimized for rear access to light (typical tilt 10°–20° for bifacial gain).
- **Inverter:** Grid-tied inverter(s) total ling 50 kW.
- Power interface: ACDB to grid with bi- directional net meter; DC combiner (DCDB) between module strings and inverter
- Measurement duration: Continuous logging for at least one year recommended; minimum test campaign of 3 months for seasonal trends.

4.3 Equipment & Instrumentation (with quantities)

1. Bifacial PV modules — **~91 Nos**.
2. Module mounting structure — **1 set**.
3. Inverter(s) 50 kW — **1 No**.
4. DC combiner boxes (DCDB) — **2 Nos**.
5. AC distribution box (ACDB) — **1 No**.
6. Pyranometers / reference cells:
7. **One** fixed plane-of-array (POA) pyranometer on front side (secondary).
8. **One** rear irradiance pyranometer (mounted to measure albedo/rear incident).
9. **One** global horizontal irradiance (GHI) pyranometer or reference cell (optional).
10. Temperature sensors:
11. Module back-sheet temperature sensors (PT100/thermocouples) — **4–6 points** across array.
12. Ambient air temperature sensor — **1 No**.
13. Anemometer (wind speed) — **1 No**.
14. Data logger / SCADA system with channels for irradiance, temp, voltage, current, and digital inputs — **1 system**.
15. Current transducers (CTs) / DC shunts for string current monitoring — as required (typically **1 CT per string** or per DC combiner output).
16. AC energy meter / net meter — **1 No** (bi- directional).
17. Surge protection devices (SPDs), isolators, breakers — per electrical design.
18. Earth pits & earthing network — **3 Nos** (DC/AC/LA).
19. Hand tools, insulation testers (megger), multimeters, clamp meters — for commissioning & verification.

4.4 Site Layout & Mounting Details

- **Array layout:** Rows of bifacial modules with row-to-row spacing sized to minimize inter-row shading at winter solstice and to allow rear irradiance capture (example spacing 0.8–1.2 m between module backs depending on tilt).
- **Ground treatment:** Natural ground or reflective surface (albedo enhancement) if measuring bifacial gain under controlled conditions. Document ground reflectance (%) if modified.
- **Orientation & tilt:** South-facing (northern hemisphere) or as per site optimum; tilt 10°–20° for bifacial benefit unless rooftop constraints apply.
- **Reference sensors placement:** POA pyranometer mounted on the module plane centrally; rear pyranometer placed at module rear mid-span and tilted to parallel the module. Ensure pyranometer heights do not shadow modules.

4.5 Electrical Configuration & Wiring

- Arrange modules into strings consistent with inverter MPPT input voltage and current limits. Document: number of strings, modules per string, fuse ratings.
- Connect strings to DCDBs with string fusing and SPD on DC side.
- Connect DCDB outputs to inverter; inverter AC output to ACDB and to grid via net meter and grid protection devices.
- The design and setup of bifacial farms for optimal LCOE and yield depend on the geographical conditions. While it is imperative to understand the optimal bifacial array designs.[8]

4.6 Measurement Plan & Data Logging

Record at a minimum (sampling resolution 1 min–5 min recommended):

- AC output power and energy (kW, kWh) from inverter.
- DC string voltages and currents (V, A) or DC power per MPPT.
- Module back sheet temperature (°C) and ambient temperature (°C).
- Plane-of-array irradiance (W/m²) — front and rear.
- Global horizontal irradiance (optional) and diffuse component (optional if using a shading ring/diffuse sensor).
- Wind speed (m/s) and any precipitation flags.
- Event logs: inverter faults, grid trips, maintenance periods.

Store timestamps in UTC or local time with time zone noted. Use checksum and redundant logging for data integrity.

4.7 Calibration & Sensor Verification

- Calibrate pyranometers and reference cells against a known calibration laboratory or manufacturer certificate prior to deployment. Record calibration date and uncertainty.

4.8 Safety & Commissioning Checks

- Perform insulation resistance (megger) test on DC strings before energizing. Record values.
- Verify polarity of strings, PV array grounding, and continuity to earth.
- Test isolator operation, SPDs, and inverter protective settings (anti- islanding, over/under voltage, frequency limits).
- Ensure safety signage, lockout/tagout procedures, and PPE for technicians.
- Commissioning checklist: mechanical integrity, torque checks on module clamps, cable terminations, labeling, earthing resistances within limits.

4. 9 Experimental Procedure (Step-by-Step)

4.9.1. Pre-Installation

1. Site survey, soil resistivity test for earthing design, and civil prep for mounting foundations.
2. Verify component deliveries against BOM (modules, inverters, sensors).

4.9.2 Mechanical Installation

1. Install foundations and racking per structural drawings.
2. Mount bifacial modules with recommended clearance from ground (to allow rear irradiance).
3. Install module temperature sensors and mount pyranometers (front and rear) in representative positions.
4. Install anemometer and ambient temp sensor.

4.9.3 Electrical Installation

1. Connect to DCDBs with string fuses and DC SPD.
2. Connect DCDB to inverter(s); wire inverter AC output to ACDB and grid meter.
3. Install CTs and voltage transducers for logging where required.

4.9.4 Commissioning & Initial Tests

1. Insulation resistance (megger) for each string — record.
2. Open circuit voltage (Voc) and short circuit current (Isc) checks for representative strings.
3. Apply DC power to inverter (with protective settings) and verify inverter MPPT starts and produces AC.

4. Verify AC voltage, frequency and grid interconnection parameters.
5. Confirm data logger is recording all channels correctly; perform a 24-hour sanity check.

4.9.5 Performance Testing (Detailed)

1. **Clear-sky baseline tests:** On clear days, log continuous high-resolution data (1-minute) for front/rear irradiance, module temps, DC and AC power for at least several contiguous days.
2. **IV curve tests:** Use portable IV tracer on representative modules or strings at different times of day (morning, midday, afternoon) to derive STC-corrected Isc, Voc, Pmax and compare to nameplate. Note that IV tracing requires isolating the string/inverter per safety procedures.
3. **Bifacial Gain Measurement:**
   - Calculate bifacial gain as: (Energy front + rear Energy front only or use simultaneous front vs. rear irradiance and rear contribution estimation.
   - If possible, perform controlled albedo tests by placing known reflective material (e.g., white sheets) under modules for short periods and log the difference.
4. **Soiling & shading checks:** Photograph and log any shading sources; measure soiling losses periodically (e.g., before/after cleaning).
5. **Thermal tests:** Correlate module back sheet temperature with power to extract temperature coefficient behavior empirically.

4..9.12 Long-Term Monitoring

- Continuous logging with periodic monthly and seasonal analysis.
- Record maintenance, outages, grid events, cleaning dates.

Data Processing & Analysis Procedure

1. **Data cleaning:** Remove timestamps with inverter faults, nighttime zeros, and obvious sensor spikes; fill small gaps using interpolation (document method).
2. **Normalize to STC:** Convert measured module power to STC equivalent using measured irradiance and module temperature (IEC 61724 approach).
3. **Performance metrics calculation:**
   1. Specific yield = (Total AC energy over period) / (Installed kWp).
   2. Performance ratio (PR) = (Measured AC energy) / (Reference energy expected at STC conditions corrected for system losses).
   3. Capacity factor = (Total energy produced) / (Installed capacity × period hours).
   4. **Bifacial gain quantification:** Use front and rear irradiance measurements and back/front power split analysis to compute % gain. Compare against modeled predictions if available.
   5. **Uncertainty analysis:** Propagate sensor and meter uncertainties to quantify confidence intervals on PR and bifacial gain.

Expected Observations& Acceptance Criteria

- Inverter synchronizes and exports nominal power under rated irradiance (≈1000 W/m² front POA) with expected DC/AC conversion efficiency.
- Module temperature and irradiance relationships should follow known temperature coefficients (manufacturer datasheet).
- Bifacial gain should be positive (e.g., typical 5–15% depending on albedo and geometry) — document observed value and compare with expectations.
- Earthing resistance < specified limit (site standard). No persistent faults or hotspot indications on IV scans.

4.10 Troubleshooting & Contingencies

- If measured power is significantly lower than expected: check for string mismatch, shading, soiling, faulty connectors, or inverter derating.
- If rear irradiance sensors show anomalous readings: confirm mounting orientation, sensor shading, and calibration.

- Log and investigate all inverter deratings/faults; inspect for DC ripple, overheating, or firmware issues.

5: Results and Discussion

his chapter presents the experimental results obtained from the 50kW bifacial solar power plant. The plant was continuously monitored for its energy yield, efficiency, and bifacial gain under varying operating conditions. The discussion focuses on analyzing the measured data, comparing it with theoretical expectations, and identifying key factors affecting performance.

Solar photovoltaic (PV) technology has become a cornerstone of the renewable-energy revolution, offering a clean, sustainable solution to the world's growing energy demands.[9]

5.1 Performance Ratio (PR)

- Measured PR: Averaged at 78–82% across the monitoring period.
- Factors Affecting PR:
- Inverter conversion efficiency maintained at ~97%.
- Minor seasonal variation due to higher module temperatures in summer, reducing efficiency.
- Soiling losses observed to reduce PR by 2–3% before scheduled cleaning cycles.

***Discussion**:* A PR above 75% indicates a well- performing PV system. The slightly reduced PR during summer months highlights the influence of thermal losses.

5.2 Bifacial Gain

- Front-only reference yield: ≈ 65,000 kWh/year (estimated).
- Measured yield with bifacial effect: ≈ 73,000 kWh/year.
- Bifacial Gain: ~12% improvement in energy output compared to equivalent mono facial installation.

Discussion: The bifacial gain was strongly correlated with ground reflectance (albedo). During months with higher ground moisture or light-colored surfaces, rear-side contribution increased noticeably. This confirms the advantage of bifacial modules, especially in reflective environments.

5.3 Temperature Effects

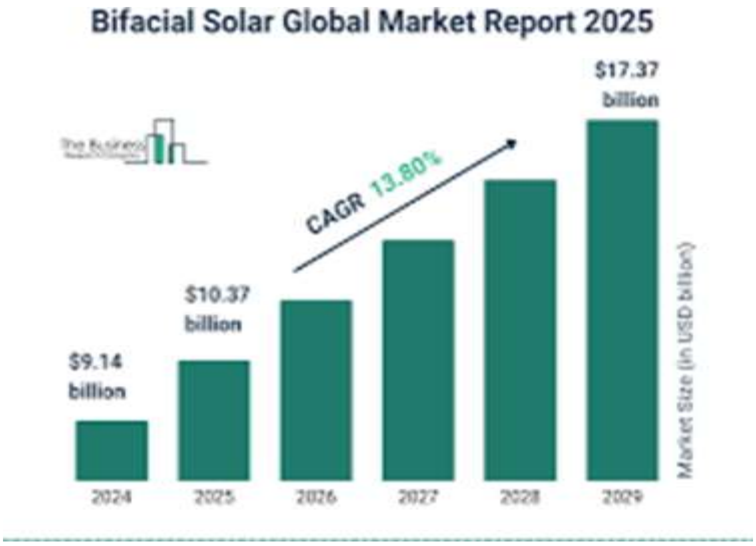
- Average module operating temperature: 40–45°C (midday).
- Temperature coefficient observed: ~ - 0.38%/°C (close to datasheet value).
- Energy output reduction during peak summer due to higher operating temperatures.

5.4 Inverter and System Performance

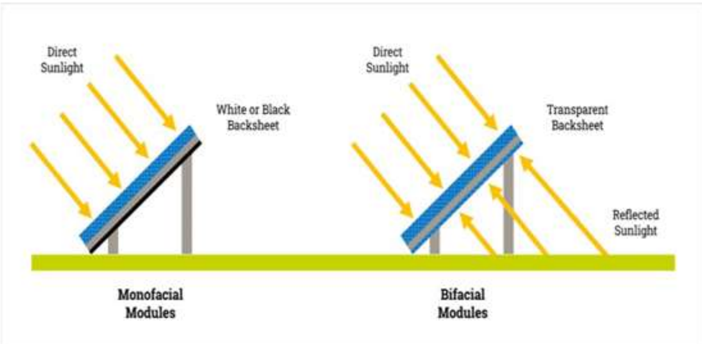
- Inverter efficiency: consistently 96– 98%.
- Minimal downtime observed, with grid outages contributing to <1% energy loss.
- Protection devices (SPD, earthing, LA) operated as expected; no major faults recorded.

5.5 Key Observations

1. The 50kW bifacial solar plant consistently delivered stable output with high performance ratio.
2. Bifacial gain significantly improved system yield, especially under reflective ground conditions.
3. Temperature rise remained the main factor limiting efficiency during summer.
4. Regular cleaning and maintenance were essential to minimizing soiling losses.
5. Monitoring of rear irradiance was crucial to accurately quantify bifacial contribution.



Bifacial Solar Global Market 2025



Mono facial Vs Bifacial Modules

6: Advantages and Disadvantages

Advantages

1. Higher Energy Yield
2. Can generate 5–30% more electricity than mono facial panels, depending on installation conditions (ground reflectivity, tilt, and mounting height).
3. Better Performance in Diffuse Light Rear-side absorption allows them to utilize reflected and scattered sunlight, making them more efficient in cloudy or snowy environments.
4. Lower Levelized Cost of Energy (LCOE)
5. Over time, the higher output per panel can reduce the overall cost per kWh of solar energy.
6. Durability
7. Most bifacial panels use glass-glass construction instead of glass-back sheet, making them more resistant to mechanical stress, UV degradation, and moisture ingress.
8. Space Efficiency
9. Higher output per unit area means fewer panels may be needed for the same power, saving space in some installations.
10. Longer Lifespan
11. Glass-glass panels often come with longer warranties (30+ years performance warranties in some cases.

Disadvantages

1. Higher Initial Cost

2. Typically5–15% more expensive than mono facial panels.
3. More Complex Installation
4. To maximize rear-side gains, panels need elevated mounting and reflective ground surfaces (e.g., white gravel, concrete, or snow). Shaded or dark surfaces reduce benefits.
5. Heavier & More Fragile
6. Glass-glass construction makes them heavier, which can increase structural costs and complicate rooftop installations.
7. Not Always Optimal for Rooftops
8. Rear-side exposure is often blocked on typical rooftop setups, limiting the advantage compared to ground-mounted systems or solar farms.
9. Variable Gains

7: Expected Future Impact

7.1 Introduction (short)

Bifacial photovoltaic (PV) modules — which harvest light from both their front and rear faces

— are moving from niche experiments into mainstream deployment. Over the next decade they are poised to change how large-scale PV is designed, valued, and integrated with grids and land-use planning. This chapter summarizes the expected technical, economic, environmental and market impacts of bifacial technology and offers practical implications for developers, utilities, policy makers and researchers.

7.2 Market trajectory and deployment scale

Multiple market studies and industry data indicate steep growth for bifacial modules: market reports place global bifacial market size in the tens of billions of USD in the mid-2020s and forecast double-digit CAGR through the 2030s. This growth is being driven by falling module costs, rising module efficiencies (N- type/TOP Con cells), and increasing acceptance of bifacial gain in utility-scale procurement.

Practical implication: bifacial modules will represent an increasing share of utility-scale orders and large commercial projects, making bifacial performance modeling and contract.

7.3 Energy yield, system design and LCOE

Real-world and modelling studies show bifacial systems can deliver meaningful energy gains — the size of which depends on site albedo, mounting height, tilt, tracking strategy and soiling. Gains reported in the literature and field tests range from single-digit percentage improvements up to ~20–30% in ideal cases (tracking + high albedo + optimized layout). Where those gains materialize, the higher output reduces levelized cost of energy (LCOE) even when module cost is modestly higher than mono facial modules.

Practical implication: LCOE modeling must explicitly include bifacial gain projections, spectral/albedo corrections and potential inverter clipping; simple "% uplift" rules of thumb are often inaccurate.

7.4 Technical innovations and system architectures

Expect continued innovation in areas that amplify bifacial value:

- Tracking + bifacial synergy: single-axis trackers raise rear irradiation and can multiply bifacial gain when combined with optimal row spacing.
- Vertical & façade installations: research shows vertical bifacial arrays (including PV and building façades) can perform well in urban or constrained sites, enabling bifacial deployment beyond traditional ground-mounted farms. Nature
- Ground-surface engineering: engineered high-albedo surfaces (reflective films, light gravel, coatings) can raise rear irradiance and boost output — but cost and environmental trade-offs matter.
- Practical implication: project engineers will increasingly co-design module choice, racking, tracker algorithms and site surfacing to optimize whole-system returns rather than optimizing modules in isolation.

7.5 Grid and market impacts

As bifacial modules raise capacity factors at utility plants, they will Increase annual energy production per MW installed, impacting capacity-credit calculations and power market volumes.

- Potentially lower needed nameplate capacity for a given energy target, affecting grid planning and land requirements.
- Cause modest changes in the timing (hourly profile) of solar output when paired with trackers, which can influence day-ahead market prices and storage needs.

Large, coordinated deployment of higher-yield bifacial farms can reduce system LCOE and dampen peak prices in high-solar periods, but precise effects depend on geography, market structure and storage adoption.

8: Conclusion

Bifacial solar technology has emerged as one of the most significant innovations in modern photovoltaics, offering a pathway to greater efficiency, lower long-term costs, and improved energy density compared to conventional mono facial systems. By capturing sunlight from both the front and rear surfaces, bifacial modules can deliver meaningful energy gains under the right conditions, particularly when combined with optimized system design, reflective ground surfaces, and advanced tracking technologies.

We present a new method to characterize bifacial solar cells under standard test conditions (STC).[10]

The widespread adoption of bifacial panels, however, is not without challenges. Higher upfront costs, greater installation complexity, dual-side soiling risks, and performance variability in low-reflectivity environments remain barriers to universal deployment. Accurate modeling and standardized performance assessment are essential to ensure bankability and investor confidence .

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