

IMPACT OF ILLUMINATION CONDITIONS ON ELECTRICAL PARAMETERS OF BIFACIAL PHOTOVOLTAIC MODULES

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ABSTRACT

This study presents an experimental evaluation of the photoelectric performance of bifacial photovoltaic modules based on monocrystalline silicon Passivated Emitter and Rear Cell (PERC) technology under different illumination conditions. The investigation focuses on variations in key electrical parameters when the modules are exposed to front-side, rear-side, and simultaneous bifacial illumination. A dedicated experimental setup was developed to obtain accurate current-voltage (I-V) and power-voltage (P-V) characteristics under controlled lighting conditions that closely represent real operating environments. The experimental results reveal a significant enhancement in module performance under bifacial illumination. In particular, the output power increased by approximately 22% compared to front-side illumination alone and by 41% relative to rear-side illumination. Additionally, the influence of reflective (high-albedo) surfaces on power generation was examined, demonstrating that bifacial modules installed in such environments can deliver more than 22% higher power output than conventional monofacial modules. These findings confirm the effectiveness of bifacial illumination in improving energy conversion efficiency and overall power yield. The results provide practical insights for optimizing the deployment of bifacial PERC-based photovoltaic modules in energy-efficient solar power systems, especially in applications where reflective surroundings can be utilized to maximize energy generation.



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I. INTRODUCTION

The continuous depletion of non-renewable energy resources and their associated environmental impacts intensify global efforts to transition toward sustainable and low-carbon energy systems. Increasing greenhouse gas emissions, climate change, and rising energy demand make the integration of renewable energy sources into national and industrial infrastructures a strategic priority worldwide. Among renewable sources, solar energy is one of the most abundant, scalable, and environmentally friendly options, establishing photovoltaic (PV) technologies as a cornerstone of modern energy systems. Photovoltaic systems convert solar radiation directly into electrical energy and have undergone rapid technological development and large-scale deployment over recent decades. A typical PV system includes solar modules composed of interconnected solar cells, along with power conditioning and energy management components. Silicon-based solar cells dominate the commercial market due to their proven reliability, long operational life, abundant availability, and mature manufacturing processes. Crystalline silicon solar cells, in particular, achieve a maximum experimental efficiency of 26.8%, approaching the theoretical efficiency limit of approximately 29% predicted for single-junction devices.

According to the Shockley–Queisser detailed balance limit, this efficiency represents a fundamental constraint arising from radiative recombination and spectral mismatch. Consequently, silicon-based technologies account for more than 96% of global PV production **Erro! Fonte de referência não encontrada.** As conventional monofacial PV modules approach these theoretical efficiency limits, further performance improvements through traditional material and junction optimization become increasingly challenging. Therefore, recent research emphasizes advanced device architectures and system-level solutions to enhance overall energy yield rather than cell efficiency alone. Bifacial photovoltaic modules emerge as a promising technology, capable of overcoming limitations inherent in monofacial designs. These modules collect solar radiation from both the front and rear surfaces, utilizing not only direct sunlight but also reflected and diffuse light from surrounding environments **Erro! Fonte de referência não encontrada.** The additional energy obtained from the rear surface of bifacial modules depends strongly on environmental and installation factors. Studies report that bifacial modules can generate 10–30% more electricity than monofacial modules under favorable conditions This bifacial gain is influenced by ground reflectivity (albedo), module elevation, tilt angle, row spacing, and local climatic conditions. High-albedo surfaces, including concrete, sand, snow, and engineered reflective coatings, significantly enhance rear-side irradiance and total power output. Extensive numerical, simulation-based, and experimental studies have investigated bifacial module performance **Erro! Fonte de referência não encontrada.** By demonstrated the impact of surface reflectivity on energy yield using numerical modeling. By **Erro! Fonte de referência não encontrada.** examined optimal mounting configurations and rear-side illumination to maximize bifacial gain. Thermal effects were analyzed by **Erro! Fonte de referência não encontrada.**, highlighting the influence of module temperature on efficiency.

Experimental investigations provide additional insight into bifacial PV operation **Erro! Fonte de referência não encontrada.** In turn studied rear-side illumination and recombination mechanisms in bifacial modules employing Passivated Emitter and Rear Cell (PERC) technology. Cuevas and Piliouras **Erro! Fonte de referência não encontrada.** simulated performance variations under different illumination conditions, while **Erro! Fonte de referência não encontrada.** reported that high-reflectivity surfaces can increase energy yield by 20–30% relative to monofacial modules, even though low-albedo environments provide limited improvement. Despite these advancements, practical challenges remain, particularly in comparing front-side, rear-side, and simultaneous bifacial illumination under controlled conditions. Many studies rely on simulations or outdoor measurements, where environmental fluctuations complicate isolation of illumination effects **Erro! Fonte de referência não encontrada.** Therefore, controlled experimental evaluations are necessary to systematically quantify the electrical performance of bifacial PERC-based modules under well-defined lighting scenarios. In this study, a dedicated experimental setup is developed to evaluate the photoelectric performance of monocrystalline silicon PERC-based bifacial PV modules. Modules are tested under front-side, rear-side, and simultaneous bifacial illumination. Current–voltage (I–V) and power–voltage (P–V) characteristics are measured to assess the impact of illumination direction on output power, current, and energy conversion efficiency. The results provide insights for optimizing bifacial module performance and support effective deployment in energy-efficient photovoltaic systems, particularly in high-reflectivity environments.

II. MATERIALS AND METHODS

This experimental study aims to evaluate the performance of a small-sized bifacial photovoltaic module composed of monocrystalline silicon solar cells under different illumination conditions, and to investigate the effect of a V-shaped reflector on enhancing rear-side illumination.

II.1 STRUCTURE OF THE DEVICE AND REFLECTOR.

The main objective of the experiment is to analyze the operational performance of a small-sized photoelectric module, built from bifacial monocrystalline silicon solar cells, under different illumination conditions, and to investigate the effect of a V-shaped rear-side reflector on enhancing the backside illumination. For the experiment, a miniature photoelectric mod-ule was constructed by series-connecting two bifacial monocrystalline silicon solar cells, each with a size of $5.2 \times 5.2 \text{ mm}^2$ (Fig. 1). The module was illuminated using a xenon lamp with a power of 1000 W as an artificial light source. This lamp is capable of simulating the AM1.5G spectral distribution and provides a stable and continuous light flux. The intensity of the light radiation reaching the module surface from the artificial light source was measured using an RS-RA-V10-AL pyranometer. During the experiments, the lighting conditions on both the front and rear surfaces of the module were systematically varied and controlled. To enhance rear-side illumination, a V-shaped reflector with a silver-coated sur-face was positioned behind the module, which enabled effective activation of the bifacial light-receiving capability of the photoelectric module.

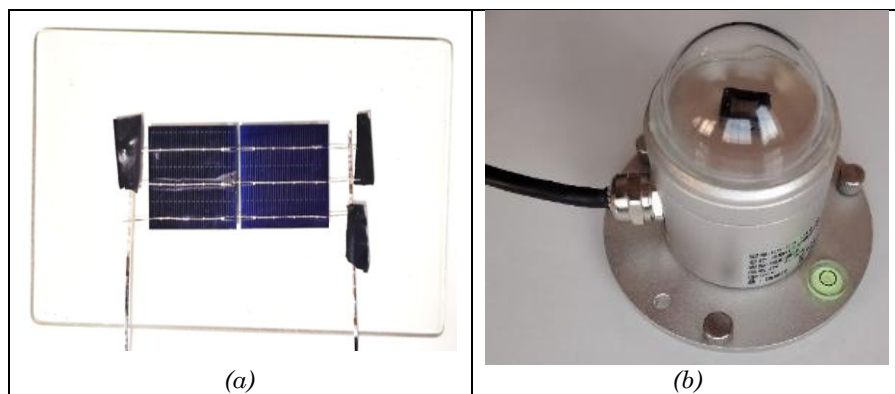
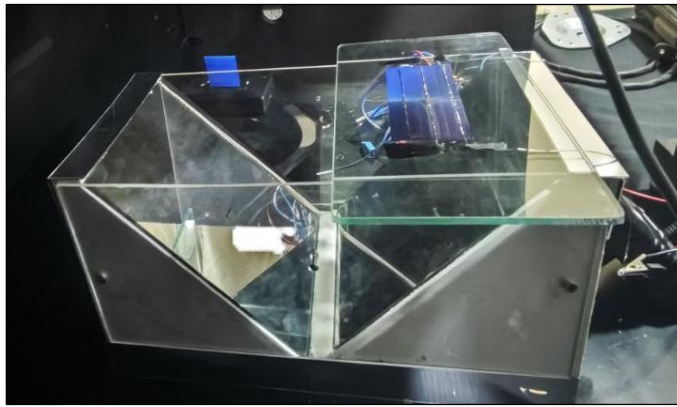


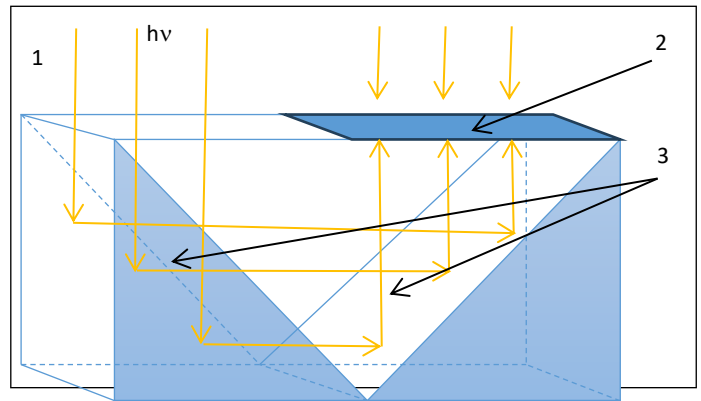
Figure 1: A small-sized photoelectric module (a) consisting of series-connected bifacial monocrystalline silicon solar cells, each with a dimension of $5.2 \times 5.2 \text{ mm}^2$, and (b) a view of the RS-RA-V10-AL Pyranometer.

Source: Authors, (2026).

In order to enhance the illumination on the rear sur-face of the photovoltaic module, two silver-coated reflec-tive mirrors were positioned in a V-shaped configura-tion at an angle of 45° (Fig. 2). This reflector setup ef-fectively directs the reflected light rays toward the rear side of the module, significantly increasing the overall illumination intensity.



(a)



(b)

Figure 2: Experimental sample (a) and schematic representation (b) of the V-shaped silver-coated mirror structure designed to illuminate the small bifacial photovoltaic module under various lighting conditions. 1 – Solar radiation, 2 – Bifacial monocrystalline silicon solar cells, 3 – Silver-coated mirror.

Source: Authors, (2026).

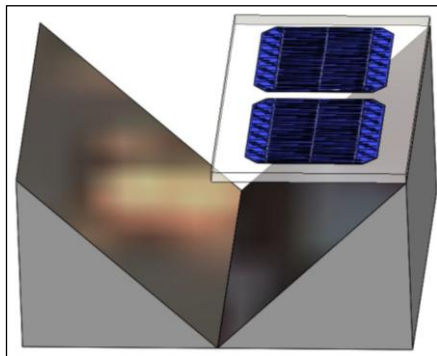
II.2 ILLUMINATION CONDITIONS.

The experimental investigation was conducted under three different lighting conditions, as illustrated in Fig. 3:

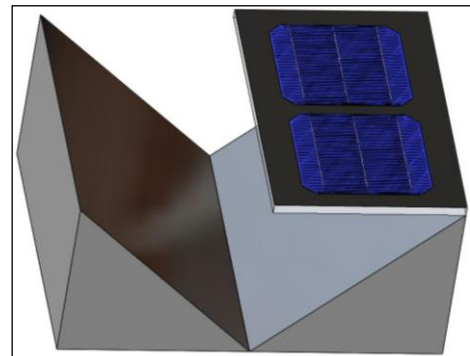
(a) Bifacial illumination: The photovoltaic module was illuminated vertically from above with direct light. Simultaneously, reflected light from the rear side was provided using V-shaped silver-coated mirrors. This configuration models the ideal bifacial working condition.

(b) Front-side only illumination: The module was illuminated vertically from the top. To block any light from reaching the rear side, a black opaque paper sheet was placed underneath the module, ensuring complete elimination of rear illumination.

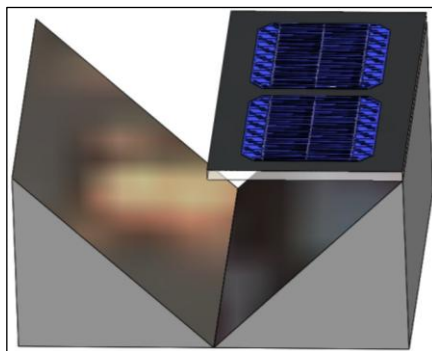
(c) Rear-side only illumination: The module was again illuminated from above with vertical light. A black opaque paper was placed beneath the module while the rear side of the module was oriented upward, allowing only light incident from below (via the rear) to reach the cell. This configuration ensured illumination exclusively from the rear side.



(a)



(b)



(c)

Figure 3: Illumination conditions of the bifacial-sensitive small photovoltaic module: (a) bifacial illumination, (b) front-side only illumination, and (c) rear-side only illumination.

Source: Authors, (2026).

II.3 MEASUREMENT METHODS AND PARAMETERS.

To determine the output electrical parameters of the photovoltaic modules under different lighting conditions, the current–voltage (I – V) characteristic measurement method was employed. This experimental approach allowed for the extraction and analysis of the photoelectric parameters of the solar cell in a steady-state (static) operating mode. The experiments were conducted using a specially designed laboratory stand. An adjustable load (a resistor bank) was used as the external load and was varied step-by-step. At each load level, the output current (I) and voltage (V) of the module were measured using high-precision digital ammeters and voltmeters (Fig. 4).



Figure 4: The circuit assembled for experimental measurement of the I – V characteristics.
Source: Authors, (2026).

Based on the measurement results, the I – V characteristics of the photovoltaic module under front-side, rear-side, and bifacial illumination conditions were plotted on a single graph for comparative analysis. From this graph, key photoelectric parameters — short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power point (P_{mpp}) — were determined. This experimental approach enabled the assessment of the module's performance under various illumination scenarios in laboratory conditions, providing insights into output power variations and overall efficiency comparison.

III. RESULTS AND DISCUSSIONS

In this study, the output photoelectric parameters of a bifacial-sensitive photovoltaic module (PM) were experimentally investigated using a specially designed V-shaped silver-mirrored test stand. Based on the experimental results, the current–voltage (I – V) and power–voltage (P – V) characteristics of the module were plotted on a single graph (Fig. 5), representing measurements under three different illumination conditions.

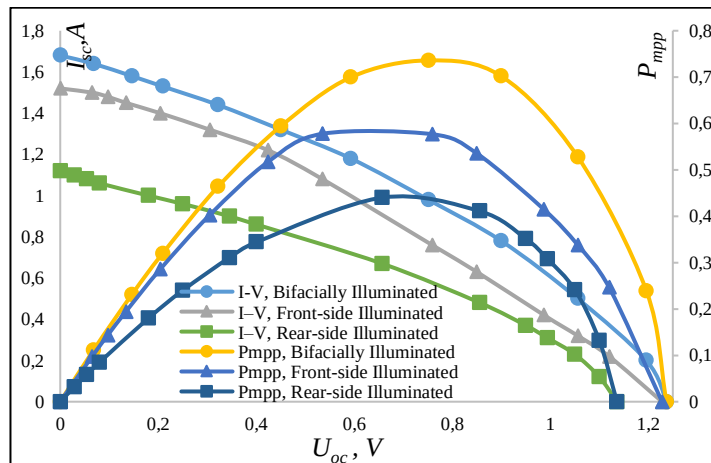


Figure 5: I – V characteristics of the bifacial-sensitive photovoltaic module under bifacial —, front-side —, and rear-side — illumination, and the voltage-dependent output power curves under bifacial —, front-side —, and rear-side — illumination conditions.

Source: Authors, (2026).

According to the graph shown in Fig. 5, it is evident that the output power under front-side illumination is 1.27 times higher than that under rear-side illumination. This phenomenon can be attributed to the fact that in bifacial solar cells, when illuminated from the rear side, photogenerated electrons in the p -region are likely to recombine before reaching the contact in the emitter region, thus reducing the photocurrent. Moreover, under simultaneous illumination from both the front and rear sides, the output power was found to be 1.22 times greater than that of front-side-only illumination and 1.41 times greater than that of rear-side-only illumination. This increase in performance indicates a significant enhancement in total photogeneration due to bifacial exposure. The observed differences in output power are explained by the variation in photoelectron generation depth and recombination rate within the solar cell.

In particular, rear-side illumination leads to a reduction in photocurrent as the electrons generated in the p -type base recombine before reaching the emitter layer. The efficiency differences resulting from front- and rear-side illumination are primarily due to the photogeneration process, minority carrier diffusion lengths, recombination mechanisms, and the internal structure of the solar cell. Specifically, under rear-side illumination, most photons are absorbed in the p -type base. The minority carriers (electrons) generated in this region must traverse a longer distance to reach the n -type emitter, and recombination losses are more likely, especially if the diffusion length is short or surface passivation is inadequate. Consequently, reduced photocurrent is observed under rear-side illumination (Fig. 3(c)). Under front-side illumination, photons are absorbed near the n -type emitter and the p - n junction, where an electric field facilitates rapid transport of minority carriers (holes) to the contacts, minimizing recombination losses. Therefore, the photocurrent under front-side illumination is significantly higher than under rear-side illumination (Fig. 3(b)). Furthermore, in the case of bifacial illumination, the incident photons on both surfaces contribute to increased overall photogeneration. Independently generated carriers on the front and rear sides reach the respective contacts simultaneously, leading to a noticeable increase in power output. Additionally, the reflective surfaces on the rear side enhance the illumination intensity, resulting in a higher albedo effect, which further increases the rear-side contribution (Fig. 3(a)). It follows that the maximum output power of the module is achieved under bifacial illumination, which fully utilizes the optical symmetry of the solar cells. Additionally, the observed reduction in power under rear-side illumination suggests a need for optimizing the device geometry from a technological perspective. For instance, rear-emitter designs or low-recombination p -type substrates can help mitigate these losses.

IV. CONCLUSIONS

This study presents experimental investigations on the performance efficiency of bifacial photovoltaic modules under different illumination conditions. Using a purpose-built experimental setup, the modules' photoelectric characteristics (I - V and P - V curves) were measured and analyzed under front-side, rear-side, and bifacial lighting. The results revealed that the modules' photoelectric behavior strongly depends on the direction of illumination. It was found that front-side illumination generates an output power 1.27 times higher than rear-side illumination, which is attributed to the photocarrier (electrons and holes) generation depth and the likelihood of carriers reaching the emitter n -region. Specifically, under rear-side illumination, the total photocurrent decreases due to recombination losses of electrons generated in the p -type region. Under bifacial illumination, the module produced 1.22 times higher output power than with front-side-only illumination and 1.41 times higher than with rear-side-only illumination. The study also showed that in highly reflective environments, such as those with silver-mirrored reflectors, bifacial modules can deliver up to 22% more electrical power compared to conventional monofacial modules. Another notable advantage is the potential for integration into high-efficiency photovoltaic systems, which can be enhanced using solar tracking systems, light concentrators, or cost-effective reflectors to improve rear-side illumination. Overall, the findings indicate that the use of bifacial photovoltaic modules in energy systems enhances the effective utilization of solar energy and offers a promising avenue for the development of advanced high-performance solar devices.

VII. AUTHOR'S CONTRIBUTION

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