

Bifacial Solar Photovoltaics Systems Design and Modelling

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Abstract

The rapid evolution of photovoltaic (PV) technologies has led to the emergence of bifacial solar modules as a superior alternative to conventional monofacial panels. Bifacial modules are designed to harness solar irradiance from both the front and rear surfaces, enabling increased energy yield through ground-reflected radiation, known as albedo. This paper presents the design and simulation-based modelling of bifacial solar PV systems, tailored to Indian climatic and geographic conditions. Using MATLAB/Simulink, both bifacial and monofacial systems were modeled and analyzed under varying environmental parameters including surface albedo, tilt angle, and panel elevation. The simulations reveal that bifacial modules can offer an energy gain of 10% to 30% over monofacial systems, depending on the reflectivity of the surface and array configuration. The work demonstrates that strategic optimization of design parameters, such as row spacing, tilt, and ground treatment, can significantly enhance the energy output and system efficiency. The results establish bifacial PV systems as a robust and cost-effective solution for next-generation solar energy deployment, especially in regions with high solar insolation and reflective terrains.

Keywords: Bifacial PV, albedo, photovoltaic systems, energy yield, solar irradiance, renewable energy

INTRODUCTION

The global shift toward sustainable and decentralized energy generation has led to widespread adoption of solar photovoltaic (PV) technology [1–3]. Traditional monofacial PV systems, which convert solar irradiance solely from the front surface into electricity, have been the standard for decades. However, advancements in materials and module design have led to the emergence of bifacial PV modules capable of capturing sunlight from both their front and rear surfaces [4, 5]. This dual-sided generation capability significantly enhances energy output, especially when deployed in high-albedo environments where ground-reflected light (albedo) can be utilized effectively. As a result, bifacial technology has become a promising solution for improving solar efficiency and reducing the levelized cost of electricity (LCOE) [6–9].

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Recent studies have demonstrated that bifacial PV systems can yield 10–30% more energy compared to their monofacial counterparts, depending on factors such as surface reflectivity, panel tilt angle, elevation height, and inter-row spacing [1, 3, 5]. Technologies, like PERC, HJT, and TOPCon, have further improved bifacial module efficiency, durability, and temperature resilience. Despite their growing adoption, the performance of bifacial modules under varying real-world conditions remains a complex function

of multiple variables. This has led to the need for detailed modeling and simulation to better understand and optimize system performance [10–15].

The motivation behind this research stems from India's ambitious goal of achieving 500 GW of non-fossil energy capacity by 2030. With vast solar potential, especially in high-insolation regions, bifacial PV systems offer a viable path for boosting energy yield from limited land area [16–20]. However, a data-driven understanding of how different installation parameters affect bifacial gain in Indian settings is still evolving. Thus, this work contributes to filling that gap by using simulation techniques to model and analyze system behavior.

The primary objectives of this work are to, (i) model and simulate bifacial and monofacial PV systems using MATLAB/Simulink; (ii) compare energy output, efficiency, and bifacial gain under varying tilt angles, albedo values, and mounting heights; and (iii) provide practical insights for optimizing system design tailored to Indian environmental conditions.

The importance of this research lies in its ability to offer a technically validated, simulation-based framework for evaluating bifacial PV performance. The outcomes can inform policy, guide infrastructure design, and support economic decisions in both utility-scale and distributed solar projects. It enables stakeholders to accurately estimate energy yields based on site-specific parameters, ensuring optimal system deployment. Moreover, it helps reduce uncertainty in performance prediction, leading to better financial planning and investment confidence.

The subsequent sections of this paper are organized as follows: Section II introduces the fundamentals of bifacial PV technology, including solar radiation and module architecture. Section III details the system modelling and simulation process. Section IV presents the simulation results and discussion. Finally, Section V concludes the study with key findings and future directions.

PHOTOVOLTAIC AND BIFACIAL TECHNOLOGY

Photovoltaic (PV) technology harnesses the photovoltaic effect on semiconductor materials to convert solar irradiance into electrical energy. While conventional monofacial PV panels absorb sunlight only from the front surface, bifacial modules are designed to capture irradiance from both the front and rear sides. This dual-sided functionality enables higher energy yields through the utilization of ground-reflected light, also known as albedo, in addition to direct solar radiation.

Architecture and Principle

Bifacial PV modules are typically built using transparent backsheet or dual-glass constructions, allowing sunlight to pass through and reach the rear surface of the solar cells. The cells used in bifacial modules are often based on advanced technologies, such as Passivated Emitter and Rear Cell (PERC), Tunnel Oxide Passivated Contact (TOPCon), or Heterojunction Technology (HJT), can convert rear-side irradiance into usable power. The performance of bifacial modules depends not only on front irradiance but also on the design parameters such as module height, tilt angle, and inter-row spacing. These parameters influence how much reflected and diffused light reaches the rear surface [17, 18].

Solar Radiation and Albedo

Solar radiation is the primary energy input for PV systems and is composed of direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and global horizontal irradiance (GHI). Bifacial systems additionally benefit from albedo radiation, which is the portion of solar energy reflected from the ground or surrounding surfaces to the rear side of the module [18, 19].

The albedo coefficient, defined as the ratio of reflected to incident radiation, varies based on surface characteristics. Snow (albedo ~0.8–0.9), white concrete (0.5–0.6), and sand (0.3–0.4) provide high reflectivity, enhancing bifacial gain. Conversely, surfaces, like asphalt (~0.1) and vegetation

(~0.2), result in lower rear-side contribution. In bifacial design, optimizing the ground surface either naturally or with reflective materials is critical to boosting rear-side irradiance and overall system efficiency [19–21].

Solar Angles and Their Influence

Solar angles play a pivotal role in determining the magnitude and orientation of solar radiation incident on photovoltaic (PV) modules, directly impacting the energy output of both monofacial and bifacial systems. These angles govern the sun's position relative to the Earth and the orientation of PV panels, making them essential parameters in the design and performance analysis of solar installations.

The latitude angle (Φ) defines the geographic location of the PV installation and influences the sun's trajectory throughout the year. Sites located closer to the equator receive more consistent solar exposure year-round, while those farther away experience more seasonal variability. The declination angle (δ) represents the tilt of the Earth's axis relative to its orbital plane and varies seasonally between -23.45° (winter solstice) and $+23.45^\circ$ (summer solstice). This angle determines the vertical position of the sun at solar noon and thus influences the optimal tilt angle for maximizing solar capture across different months [3, 5].

The hour angle (Ω) measures the sun's angular displacement from the local meridian, changing by 15° every hour. It reflects the sun's east-to-west movement throughout the day and is critical for calculating the incident radiation on fixed or tracking PV systems. Complementing this, the solar altitude angle (α) refers to the height of the sun above the horizon. A higher solar altitude means that the sun is more directly overhead, resulting in greater irradiance on the PV surface, especially during midday hours [7, 9].

Lastly, the solar azimuth angle (γ) describes the sun's horizontal position relative to true north. It is vital for determining the directional orientation of PV modules, ensuring they face the optimal direction for maximum energy absorption. In the northern hemisphere, south-facing arrays typically yield the highest energy output [11].

These solar angles collectively influence the angle of incidence (AOI) – the angle at which sunlight strikes the panel surface. For bifacial PV systems, this is particularly important not only for the front surface but also for estimating the direction and intensity of ground-reflected radiation that reaches the rear surface. As the sun moves throughout the day and seasons, the changing AOI alters both direct and albedo irradiance, thereby affecting the bifacial gain. Proper understanding and modeling of these angles enable more accurate prediction of energy yields and inform decisions on optimal panel tilt, orientation, and spacing in bifacial PV system design [17–21].

Bifacial Gain and System Implications

The increased power output from bifacial modules termed bifacial gain can range from 5% to 30% depending on albedo, module geometry, and installation environment. Higher mounting structures, optimized tilt angles, and wider inter-row spacing enhance rear-side exposure. However, these modifications must be balanced against land-use efficiency and economic considerations [18, 19].

Bifacial PV systems are particularly suited to regions with high solar insolation and reflective surfaces. Their deployment in India, with its diverse climatic zones and growing solar capacity, presents an opportunity to maximize land productivity and reduce LCOE through higher energy yields [18–20].

MODELLING AND METHODOLOGY

This section presents the modeling approach and simulation methodology applied to the bifacial solar photovoltaic (PV) system, emphasizing its unique characteristics and performance factors compared to traditional monofacial panels.

modeling. The integration of these tools ensures a robust and flexible environment for performance evaluation and design optimization.

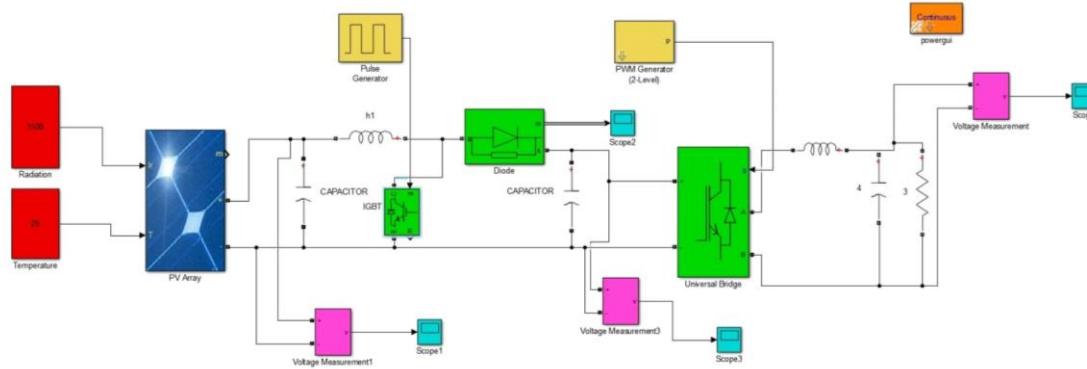


Figure 2. Simulink diagram of monofacial solar panel.

Electrical and Irradiance Modelling

The efficiency of a photovoltaic cell, which indicates the percentage of sunlight energy converted into electrical power, is calculated under standard test conditions (STC: 1000 W/m² irradiance, 25°C temperature). This efficiency (η) is given by the ratio of the electrical power output to the incident solar power on the panel area, expressed as equation (1) where, Power Output in Watts, and Area of the solar panel in m² [18–21].

$$\eta(\%) = \left(\frac{\text{Power Output}}{1000} \times \text{Area of the solar panel} \right) \times 100 \quad (1)$$

In bifacial panels, the total irradiance incident on the module is the sum of front-side and rear-side irradiance components. The rear-side irradiance is primarily due to sunlight reflected off the ground and surrounding surfaces, which depends on the ground albedo and the rear-side view factor that accounts for the module's geometry and environment. The total irradiance G_{total} is modeled as expressed in equation (2) [18–21].

$$G_{total} = G_{front} + \rho \times G_{ground} \times F_{rear} \quad (2)$$

where G_{front} is the direct solar irradiance on the front surface, ρ represents the ground albedo, G_{ground} is the ground-reflected irradiance, and F_{rear} is the rear-side view factor. The electrical behavior of the PV modules is modeled using the single-diode equivalent circuit, incorporating the effects of temperature and irradiance on the photocurrent, saturation current, and series and shunt resistances. Simulated current-voltage (I-V) characteristics and maximum power point tracking allow evaluation of module performance under varying environmental conditions.

Important parameters analyzed include front-side irradiance, which functions similarly to that in monofacial panels; rear-side irradiance, which is unique to bifacial panels and arises from reflected and diffused light; and bifacial gain, which quantifies the additional energy produced due to rear-side illumination. Module efficiency considers the combined electrical output from both surfaces. Additionally, the temperature coefficient is considered, representing the rate of efficiency decrease with rising temperature, which is critical for predicting performance in different climatic conditions.

Simulation Scenarios and Parameters

Simulations are conducted for various tilt angles, including 15°, 25°, and 35°, different mounting heights, and a range of ground albedo values, typically between 0.2 (grass) and 0.5 (concrete). The effects of ground cover ratio, rear-side shading, and row spacing are also examined to identify optimal system configurations. The model's accuracy is validated by comparing simulation results with experimental data reported in literature for bifacial PV systems installed under similar climatic conditions [18–21].

SIMULATION RESULT AND DISCUSSION

The MATLAB/Simulink-based simulation of bifacial solar photovoltaic (PV) systems revealed a clear enhancement in energy output when compared to conventional monofacial panels. This increase is attributed primarily to rear-side irradiance captured due to ground reflection and environmental scattering. Key influencing factors, such as ground albedo, tilt angle, and panel elevation, significantly affect bifacial gain, and their impact has been quantified through various simulation results.

The simulation focused on electrical performance outputs, namely current-voltage (I-V) and power-voltage (P-V) characteristics and showed how these parameters evolved during different hours of the day. The bifacial system's capacity to capture reflected irradiance from the backside contributed to a smoother and higher DC output profile, particularly evident during peak irradiance hours.

The voltage-time profile for the monofacial panel demonstrated a bell-shaped curve across different times of the day. As shown in Figures 3–5, voltage began to rise after sunrise, peaked around noon, and declined post-15:00 hours, approaching zero at sunset. This pattern reflects the typical diurnal solar insolation cycle and is affected by factors such as cloud cover, panel orientation, and shading.

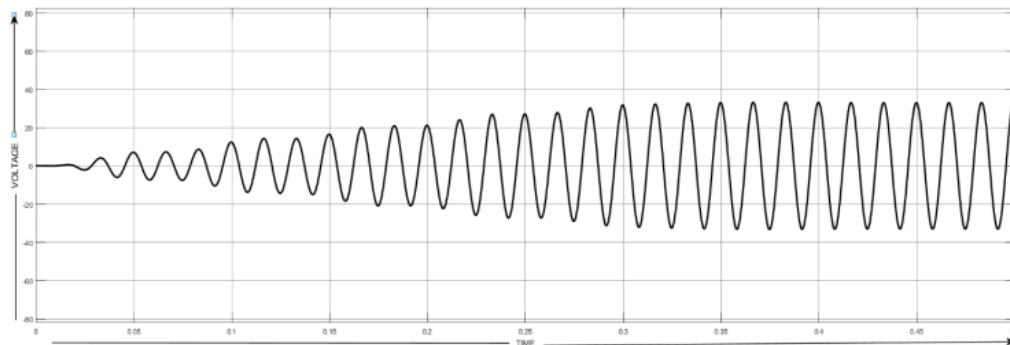


Figure 3. Output waveform of monofacial solar cell at 07.00 o'clock.

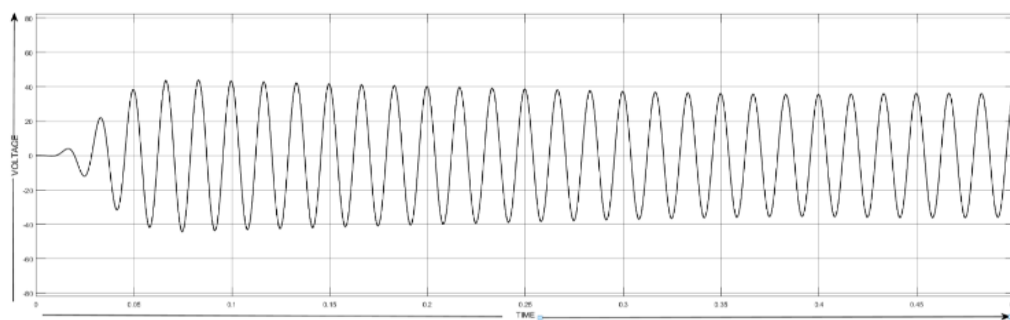


Figure 4. Output waveform of monofacial solar cell at 12.00 o'clock.

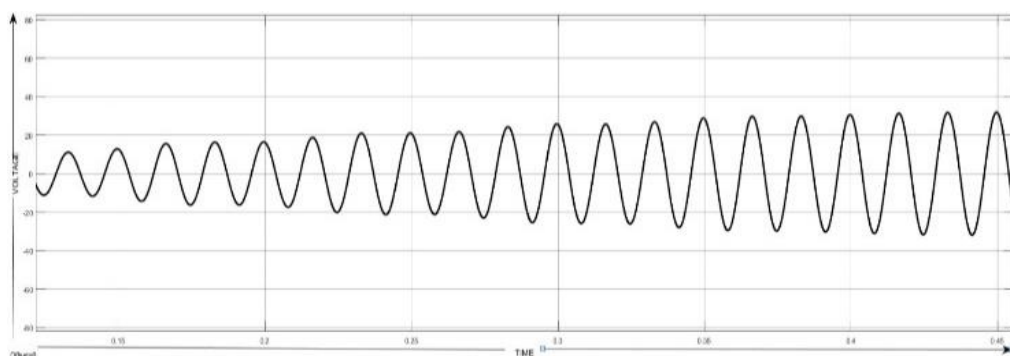


Figure 5. Output waveform of monofacial solar cell at 18.00 o'clock.

Figure 6 provides a bar graph representation of monofacial output values across a 24-hour cycle. The blue bars denote temperature progression during the day, rising in the afternoon and falling by night. The orange bars show energy output, which begins around 07:00 hours, peaks between 11:00 and 14:00 hours, and diminishes post 17:00 hours, consistent with sunlight availability. This confirms that monofacial panels generate power only during the daytime and their performance closely aligns with solar irradiance trends.

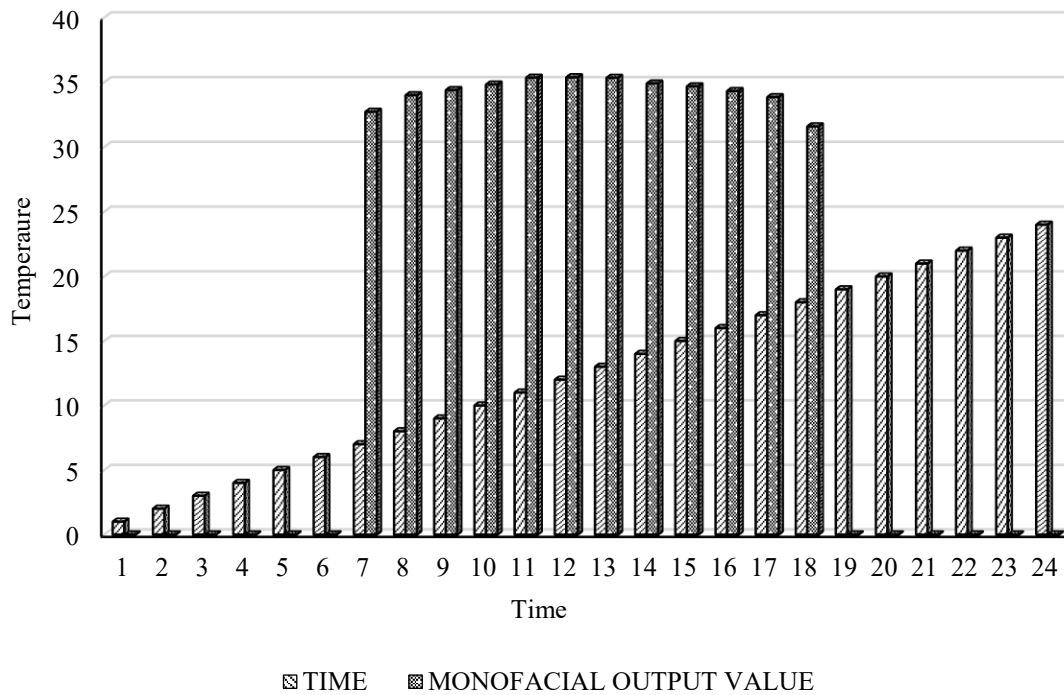


Figure 6. Monofacial output 24 hour cycle.

In contrast, bifacial panel simulation shown in Figures 7 & 8 depicts DC output waveforms that are smoother and higher in magnitude due to the combined contribution of both front and rear irradiance. These figures underscore how the additional capture of reflected and diffused light from the surroundings (albedo light) improves energy yield.

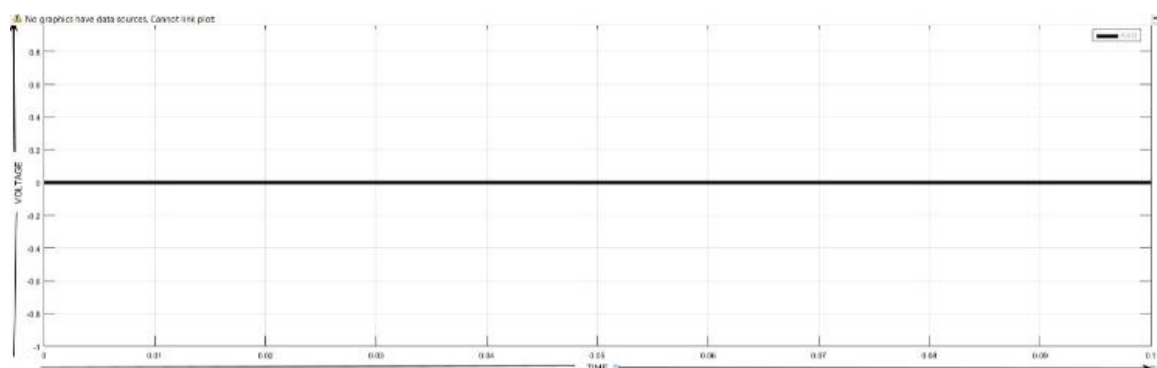


Figure 7. Output waveform of bifacial solar panel.

Further, Figure 9 compares the performance of monofacial and bifacial panels using a bar chart that plots output values across different hours of the day. It shows clearly that bifacial panels outperform their monofacial counterparts, especially between 08:00 and 17:00 hours, demonstrating a significant bifacial gain during peak sunlight hours.

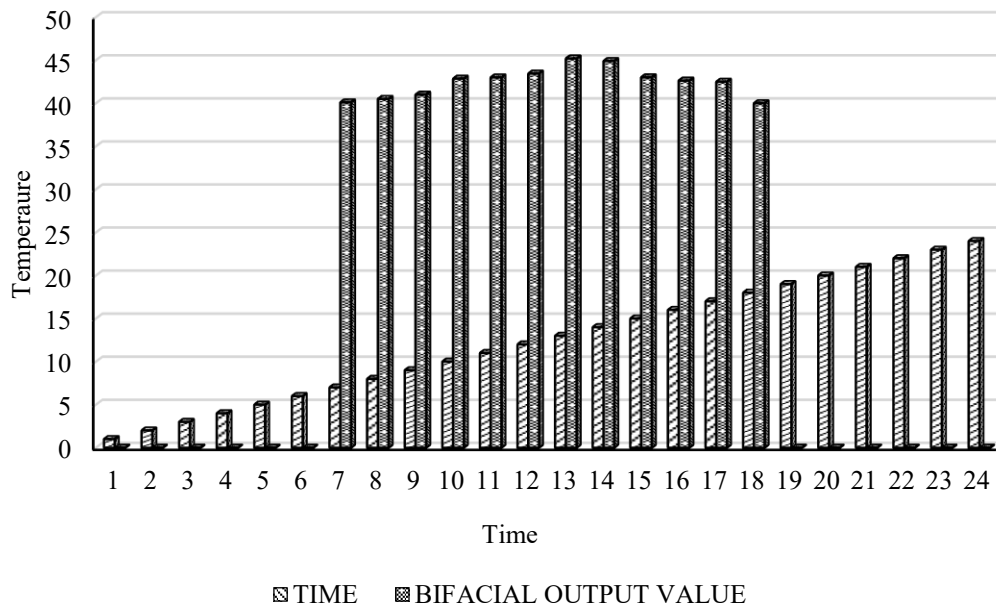


Figure 8. Bifacial output 24 hour cycle.

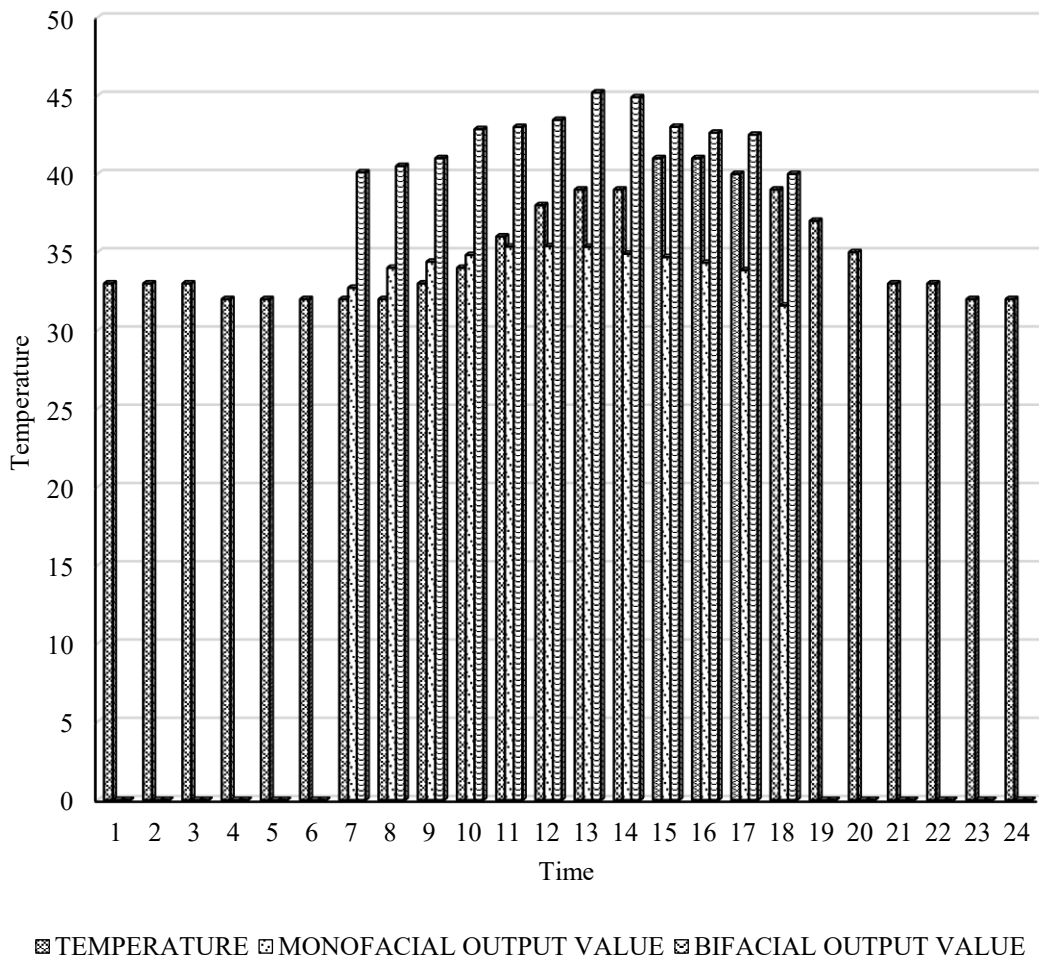


Figure 9. Monofacial and bifacial output 24 hour cycle.

The albedo effect also plays a critical role in bifacial systems. Surfaces with high reflectivity, like snow or white-painted concrete, maximize rear-side irradiance. This relationship is summarized in Table 1, where various ground surfaces and their corresponding albedo values are listed along with the resulting bifacial gain and energy output. For instance, snow with an albedo of 0.8–0.9 offers high bifacial gain, whereas asphalt with a low albedo of 0.1–0.2 results in minimal additional energy capture.

Table 1. Impact of albedo on bifacial solar panels.

Surface	Albedo Value	Bifacial Gain	Energy Output
Light-Colored Surfaces (e.g., white paint)	0.8–0.9	High	Increased.
Dark-Colored Surfaces (e.g., asphalt)	0.1–0.2	Low	Decreased.
Vegetation (e.g., grass)	0.2–0.3	Moderate	Moderate.
Snow	0.8–0.9	High	Increased.
Concrete	0.3–0.5	Moderate	Moderate.

CONCLUSIONS

This work presents a detailed analysis and performance comparison of bifacial and monofacial solar photovoltaic (PV) systems using MATLAB/Simulink modeling. The MATLAB simulation of a bifacial solar panel demonstrates its enhanced performance compared to monofacial panels, primarily due to its capability to capture solar irradiance from both the front and rear sides. The developed model incorporates varying irradiance levels, panel orientation, temperature effects, and albedo values to evaluate the power output with accuracy.

The results clearly highlight a noticeable increase in total energy generation, particularly in environments with high ground reflectivity. The bifacial gain, measured to be approximately 27% higher than monofacial systems, contributes significantly to the overall system efficiency and ensures a better energy yield throughout the day. The time-voltage and DC output waveforms further confirm that bifacial systems maintain a smoother and higher power profile, indicating consistent performance under variable environmental conditions.

This analysis confirms that temperature coefficients and rear-side irradiance play a critical role in determining real-world output, underlining the relevance of including such parameters in simulation models. The findings underscore the potential of bifacial PV technology as a viable and efficient solution for next-generation solar installations, especially when deployed with optimal elevation, tilt, and surface reflectivity considerations.

MATLAB-based modeling and simulation serve as powerful tools for conducting feasibility studies, performance optimization, and system design of bifacial photovoltaic systems. Future research can focus on experimental validation, integration with tracking systems, and real-time control strategies to further enhance deployment in diverse climatic and geographic settings.

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