



Original Research Article

Mounting-Height Effects on Rooftop Bifacial photovoltaic Performance in a Humid Subtropical Climate

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ABSTRACT

In the context of the energy transition and the goal of reducing greenhouse gas emissions, rooftop solar power systems for households are rapidly developing in Vietnam. Recently, bifacial solar panels have been increasingly applied because of their ability to capture radiation from both the front and rear sides, thereby increasing the electricity output compared to traditional monofacial panels. However, the rear-side efficiency of bifacial solar panels depends heavily on installation conditions, particularly the height of the mounting frame in relation to the rooftop surface. In actual residential construction in Vietnam, this height is often determined based on experience, without scientific basis or energy optimization. This paper focuses on comparing simulation scenarios of solar power systems using bifacial solar panels under humid subtropical conditions, with varying mounting frame heights. In addition, this study evaluates the factors affecting investment efficiency, including equipment costs, operational costs, and the potential for emissions reduction.

KEYWORDS

Rooftop solar power; Bifacial solar panels; Installation height.

INTRODUCTION

Solar power is gradually playing an important role in reducing dependence on traditional electricity grids [1]. Harnessing clean, locally available energy sources helps ease the burden on transmission systems and contributes to sustainable development goals [2]. The average levelized cost of electricity (LCOE) from solar power has dropped significantly over the past decade and is now lower than that of traditional sources such as coal or natural gas [3]. The success of solar power is attributed to key factors, including flexible modularity, which allows deployment at any scale from households to large plants, and high economic efficiency owing to low production costs, simple operation, and long system lifespan [4].

Bifacial photovoltaic (PV) modules are solar modules that capture sunlight from both the front and rear sides of the cells owing to their symmetrical structure and dual-glass protection

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[5]. Compared to conventional monofacial panels, bifacial modules enable additional capture of reflected and diffuse radiation from the surrounding environment, thereby increasing the electricity output of the solar power system [6]. Numerous studies have shown that the output increase (bifacial gain) of bifacial PV modules can reach up to 30% and is strongly dependent on the installation conditions and characteristics of the reflecting surface [7], [8]. Additionally, the glass–glass structure [9] provides the module with high mechanical durability, low power degradation, and a longer lifespan compared to traditional glass–backsheet modules [10].

However, the mounting height of bifacial solar panels relative to the reflective surface directly affects the level of reflected radiation shading, angle of incidence, and intensity of radiation on the rear side, as well as the module's ventilation and heat dissipation conditions [11]. Simulations have shown that increasing the installation height linearly improves the amount of solar energy harvested [12]. An IEA report evaluated that raising bifacial modules above ground level helps reduce self-shading and increases rear-side electricity output [13]. Ujah Peter et al. [14] investigated bifacial modules at mounting heights of 1.0, 1.5, 2.0, and 2.5 m under tropical conditions and reported the highest energy yield at 2.0 m on the concrete surface.

Vietnam is accelerating its transition towards green energy, with solar power identified as a key energy source in its sustainable development strategy [15]. Owing to its geography, which spans many latitudes and climatic zones, Vietnam's solar radiation potential is highly diverse. Notably, the northern region has a humid tropical monsoon climate, with the lowest average radiation intensity in the country [16]. The Vietnamese government has also set a goal to strongly develop rooftop solar power under a self-production and self-consumption model, particularly in residential areas, offices, and public buildings [17].

Recently, rooftop solar PV systems for households in Vietnam have attracted increasing interest from both the research community and practical application sectors. Several domestic studies have focused on technical, economic, and impact analyses of rooftop solar systems. Vu and Huu [18] analyzed the impact of rooftop solar PV systems on power quality and urban distribution grid indicators through network simulations and comparisons with Vietnamese, IEEE, and IEC standards, demonstrating that rooftop systems still comply with standard technical requirements in many cases of high energy penetration into the distribution grid. Additionally, Le et al. [19] employed the multi-criteria Analytic Hierarchy Process (AHP) analysis to assess factors influencing the decision to install rooftop solar PV in Northwestern Vietnam, identifying energy policies and installation incentives as major factors affecting household investment decisions. Furthermore, other studies such as those analyzing the operational performance of hybrid solar and storage systems at public facilities have demonstrated the technical and economic feasibility of rooftop systems under real operating conditions in Vietnam [20], [21] [22]. Simultaneously, another study evaluated the impact of rooftop solar power on voltage levels and losses in the low-voltage distribution grid in a coastal province, contributing additional data on the technical challenges of integrating distributed PV into the distribution system within the Vietnamese context [23]. These studies mainly focused on traditional single-sided (monofacial) rooftop solar systems and examined the overall effects of grid connection, operation, and household investment decisions.

However, regarding the advancement of bifacial photovoltaic modules, a type of module capable of capturing radiation from both the front and back sides to optimize electricity generation, there have not yet been any published Vietnamese studies on this topic under household rooftop solar system conditions. Internationally, some studies have analyzed and simulated the potential for bifacial gain in rooftop-mounted PV systems, showing energy benefits when employing this technology with suitable surface reflectance and tilt angles. Although these international studies provide a technical basis related to the supplementary yield of bifacial modules, research conditions, surface reflectance materials, and rooftop installation configurations can differ significantly from actual conditions in Vietnam,

especially in the northern region where the humid subtropical monsoon climate prevails and the average solar irradiance is the lowest in the country.

In summary, previous studies on the deployment of residential rooftop photovoltaic (PV) systems in Vietnam have primarily focused on grid integration, investment feasibility, policy mechanisms, and overall assessments of technical and economic potential. However, the application of double-sided photovoltaic technology to residential rooftops remains largely unexplored. To date, no system studies have been reported on the performance of double-sided PV modules under Vietnam's tropical climate, nor have any design guidelines been established for critical installation parameters, such as installation height, on roofs constructed from commonly available local materials.

This lack of local scientific evidence represents a significant gap in the research. Specifically, the combined impact of panel installation height, roof surface reflectivity, thermal operating conditions, and seasonal radiation characteristics on energy yield from double-sided systems has yet to be quantified for Vietnamese households. This shortcoming is significant because the energy output of double-sided systems is highly sensitive to back-side radiation, convective cooling conditions, and roof reflectivity, all of which are strongly dependent on installation location and cannot be reliably extrapolated from studies conducted in temperate or arid regions.

This study addresses a pressing and previously overlooked research need by developing a location-specific evaluation framework for double-sided rooftop photovoltaic systems in Vietnam. The novelty of this study lies in integrating climatic characteristics, residential roof architecture, and material-dependent reflectivity into a unified performance evaluation model to determine the optimal installation configuration. By clearly quantifying the interaction between geometric design parameters and tropical environmental conditions, this study enhances the current understanding of the behavior of bifacial photovoltaic systems on rooftops in emerging markets in Vietnam. The contributions of this study are as follows:

- Determining the role of mounting frame height in the efficiency of rooftop solar systems using bifacial panels under a humid subtropical monsoon climate in the Red River Delta area of Vietnam.
- Expands the theoretical knowledge base of bifacial photovoltaics through experimental and simulation evidence for humid tropical climates, where published data are scarce.
- Providing practical design recommendations for Vietnamese households and industry stakeholders to maximize annual energy output and improve economic viability through optimized rooftop system configurations.

METHODS

This study analyzed and compared various simulation scenarios of rooftop solar systems using bifacial solar panels, conducted using Pvsyst software [24] [25]. The simulation results are presented through data tables, charts, and detailed technical reports, enabling engineers and investors to comprehensively evaluate the energy and economic performance of the project. The objective is to thoroughly assess the impact of installation frame heights (1.5 m, 2.0 m, and 2.5 m) on the efficiency, electricity output, operational losses, and economic effectiveness of residential rooftop solar systems employing bifacial panels under climate conditions of Red River Delta area.

This research stems from the reality that the efficiency of a solar power system is determined not only by solar radiation or equipment quality but is also significantly influenced by mechanical design factors (such as installation height and cooling capability) and the unique characteristics of bifacial photovoltaic modules. These factors directly affect the modules' operating temperature and their ability to absorb reflected radiation from the terrace flooring (albedo), thereby determining energy conversion efficiency.

The chosen simulation site is a household in Red River Delta area, a city with a tropical monsoon climate that exhibits distinct seasonal differences. Summer brings intense solar radiation and high temperatures, whereas winter has weaker radiation and many cloudy, foggy days. These conditions are typical of Northern Vietnam, enabling an assessment of the system's operational stability under various climate scenarios. Meteorological data for the Red River Delta area indicate that the average global solar irradiation reaches 1160 kWh/m² and the average temperature is 23.9°C.

The investigated system was installed on a flat reinforced-concrete rooftop finished with terrace tiles, a roof configuration commonly used for elevated residential PV systems in Vietnam. An albedo value of 0.20 was assigned to the roof surface in the PVsyst model and maintained constant across all scenarios. This controlled setting allowed the influence of mounting height to be evaluated independently. Corrugated metal and pitched tiled roofs were not considered because PV modules on these roofs are generally mounted close to and parallel to the roof surface, leaving insufficient clearance for effective rear-side irradiance collection and rendering the investigated height range of 1.5–2.5 m technically unrepresentative.

The research process is conducted in three main steps, as shown in Figure 1. The research methodology for simulating photovoltaic (PV) systems was implemented in three sequential stages to ensure technical accuracy and enable objective comparison of alternative system configurations. First, research scenarios were established, and basic input parameters were collected. The research objective was to evaluate the technical and economic performance of different PV design options under similar geographical and climatic conditions. Several simulation scenarios were developed by varying key parameters such as the height of the solar panel mounting frame. In addition, the technical parameters of the PV modules and inverters, along with economic assumptions such as investment and operating and maintenance costs, electricity prices, discount rates, and system lifespan, were compiled to serve as the basis for the simulations.

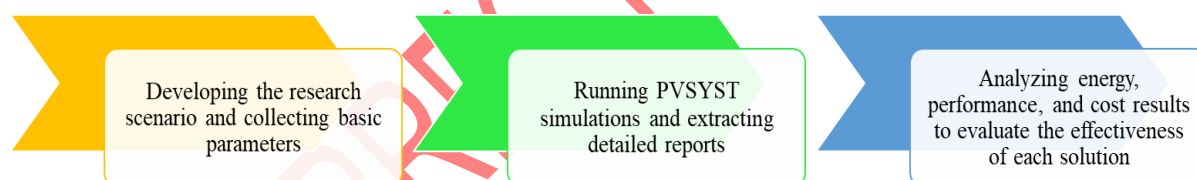


Figure 1. Flowcharts of research process

Second, all scenarios were modeled and simulated using PVsyst software. Technical parameters were incorporated to reflect actual installation conditions. Furthermore, system losses, including heat, conductor, mismatch, dirt, and inverter conversion losses, were incorporated into the model. Annual simulations were performed for each scenario under identical climatic conditions. Detailed output reports were extracted from PVsyst, including annual energy output, specific output, efficiency ratio, normalized loss graph, and monthly energy output profile.

Finally, the simulation results were analyzed to evaluate the effectiveness of each solution. The technical performance was assessed by comparing the annual energy output, system efficiency, and loss distribution. Environmental economic feasibility was evaluated using indicators such as payback period and CO₂ emission reductions. Comparative analysis allowed the identification of the most suitable configuration by balancing the energy output, investment costs, and long-term profitability. Based on these results, practical recommendations were proposed for selecting the optimal PV system design under the study conditions.

This approach ensures data consistency and clearly highlights the differences among system configurations. The criteria used for comparison are divided into three main groups: technical,

economic, and environmental. In the technical group, key parameters include annual energy output (E_{grid}), yield (kWh/kWp/year), and system performance ratio (PR). The economic group focuses on the investment payback period. Additionally, the environmental group considers the amount of CO₂ emissions reduced during system operation to assess the system's sustainability benefits. The selection of these criteria ensures a comprehensive evaluation of the effectiveness of solar power systems, not only in technical aspects but also in economic feasibility and environmental impact. These indicators are all extracted directly from the PVsyst simulation report, ensuring consistency and accuracy in the analysis.

The electricity yield [21] are calculated as follows:

$$Y_a = \frac{E_a}{P_0} \quad (1)$$

where: P_0 is rated power of the solar array [kWp]; E_a is output electricity of the solar array [kWh]. Y_a is daily yield of the solar array [kWh/kWp/day].

$$Y_f = \frac{EACout}{Pmax} \quad (2)$$

where: Y_f is final yield [kWh/kWp/day]; EACout is output solar electricity; Pmax is total installed capacity under standard conditions.

$$PR = \frac{E_{Grid}}{GlobInc \times PnomPV} \quad (3)$$

where: PR is Performance ratio (%); E_{Grid} is output solar power to the utility grid (MWh); GlobInc is global incident in collector plane (kWh/m²); PnomPV is the Standard Test Conditions (STC) installed power (kW).

The bifacial calculation was performed using the PVsyst simplified 2D model. Because all modules had uniform dimensions, tilt, azimuth, and mounting height, the array was represented by an equivalent regular cross-section defined by table width, pitch, number of rows, tilt angle, and height above the roof. The roof-reflected irradiance was calculated using an albedo, the Lambertian reflection assumption, and geometric view factors. The rear-side contribution was then weighted by the module bifaciality factor. Individual supporting components and nearby 3D objects were not explicitly included in the rear-side calculation; their effects were approximated through the structure-shading and rear-side mismatch factors.

Besides, the rooftop grid-connected solar power system was experimentally studied in an urban area of the Red River Delta at a longitude of 105°46'.23", latitude of 20°57'.44". The system uses 18 bifacial solar panels (Canadian Solar 580 Wp) connected to a 3-phase grid-tied inverter (Deye 10 kW), as shown in Figure 2. This system has been operating stably since May 2025.



Figure 2. The rooftop grid-connected solar power system using bifacial PV

SOLAR POWER INSTALLATION PLAN

In Figure 3, the solar panel system is installed on the rooftop of the building, which is unobstructed and very well-ventilated. The panels are firmly fixed on a 10-degree tilted frame, securely attached to the roof beam system, ensuring mechanical durability and operational safety. The installation site is open and free from obstructions by surrounding structures or objects, allowing the modules to receive direct sunlight for most of the day.

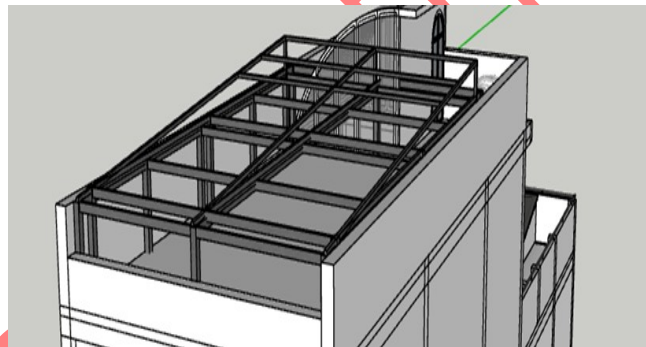


Figure 3. Installation plan for the solar panel support frame on the building's rooftop

The solar panels are connected in series to form a string of 18 bifacial panels with a capacity of 580Wp, totaling 10.44 kWp, as shown in Figure 4. The solar panel system is fixed to the roof using iron frames. The panels are secured to each other by rails, end clamps, and mid clamps. When the solar panels receive sunlight, it is converted into direct current (DC). This current is then converted by a 10 kW grid-tied inverter into alternating current (AC) with the same frequency, phase, and voltage as the national power grid and supplied to the household loads for use.

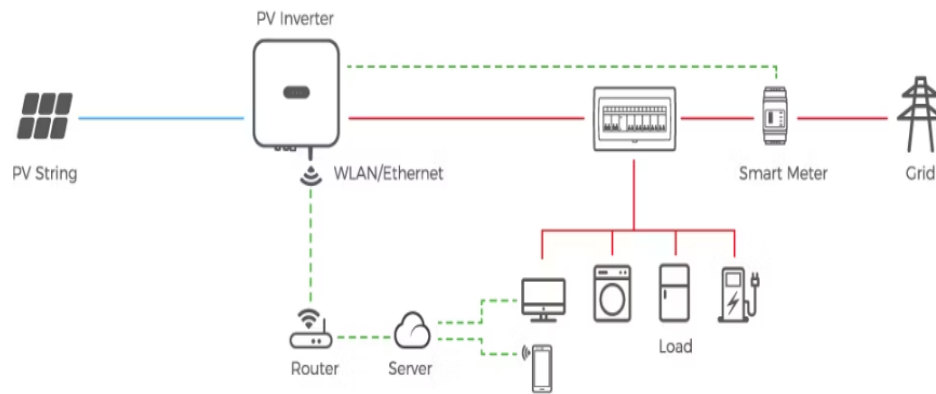


Figure 4. Rooftop solar power system connection diagram

The simulated technical parameters in Table 1 are kept constant for all options that change the height of the solar panel mounting frame (1.5 m, 2.0 m, and 2.5 m), and the terrace tile surface reflectance coefficient (albedo) is 0.2.

Table 1. PV modules and array configuration

Solar panel parameter	Value
Module type	Bifacial
Nominal maximum power	580 Wp
Voltage at maximum power	43.1 V
Current at maximum power	13.46 A
Open circuit voltage	52.2 V
Short circuit current	13.93 A
Module efficiency	22.5%
Power bifaciality	80%
Maximum system voltage	1500 V DC
Array configuration	Value
Number of modules	18
String configuration	1 string × 18 modules in series
Total installed DC capacity	10.44 kWp
String voltage at maximum power	775.8 V
String open circuit voltage	939.6 V
String current at maximum power	13.46 A
String short circuit current	13.93 A
Array tilt angle	10°

SIMULATION RESULTS

Technical Results

The simulation results in Table 2 show that both the efficiency and electricity output of the solar power system with bifacial glass modules tend to increase significantly as the installation height increases.

Table 2. Table comparing the technical aspects of the different options

Scenario	Electricity (MWh/ year)	Specific production (kWh/kWp /day)	PR (%)	PV loss due to temperature (%)
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S1 - frame height 1.5 m	9.97	2.62	83.27	-6.72
S2 - frame height 2.0 m	10.1	2.65	84.37	-5.52
S3 - frame height 2.5 m	10.17	2.67	84.96	-4.87

This improvement stems not only from the bifacial module's ability to capture additional radiation reflected from the ground but also from the thermodynamic and optical characteristics unique to this type of module. Specifically, when installed at a higher height, the panels' cooling capacity is enhanced, reducing the cells' average operating temperature and thereby improving energy conversion efficiency.

At the same time, the rear side of the bifacial glass module can absorb a portion of the diffused and reflected radiation from surrounding surfaces, contributing to an increase in the system's AC power output. The detailed mechanisms of these two influencing factors will be analyzed in the following sections to clarify the relationship among installation configuration, optical-thermal characteristics, and the overall operational PR and energy yield of the solar power system. S3 with a frame height of 2.5m achieved the highest values for AC power output, Final Yield, and Performance Ratio (PR), at 10.17 (MWh/year), 2.67 (kWh/kWp/day), and 84.96 (%) respectively. The height of the support frame is a mechanical parameter that directly affects the thermodynamic characteristics and photovoltaic operation of the PV system. When modules are installed 1.5 m above the roof surface, the space behind the panel is limited, reducing the intensity of natural convection, leading to less effective cooling and causing the operating temperature of the photovoltaic cells (T_{cell}) to be about 2 – 4°C higher than in cases where they are installed at a height of 2.5 m. Due to the physical properties of silicon material, the efficiency of photovoltaic cells decreases by an average of about 0.42% for every degree Celsius increase above the standard condition of 25°C (STC); therefore, a temperature difference of 2–3°C is enough to reduce power generation efficiency by about 0.8–1.3%. Simulation results from PVsyst reflect this trend: the system performance ratio (PR) of bifacial solar panels increases from 83.27% to 84.96%. In addition to reducing thermal losses, increasing the height also helps improve the distribution of radiation across the entire surface of the panel, reduces the risk of local hot spots, and decreases mismatch losses among module strings. Simultaneously, stronger airflow at higher elevations helps limit dust accumulation, a common cause of performance degradation in flat-roof systems in Vietnam. Thus, raising the frame height brings clear technical benefits, increasing the average energy yield by 0.03 - 0.05 (kWh/kWp/day) (see Figure 5) and improving the PR by about 1.1 - 1.69%, while also ensuring stable and sustainable operating conditions for the entire system.

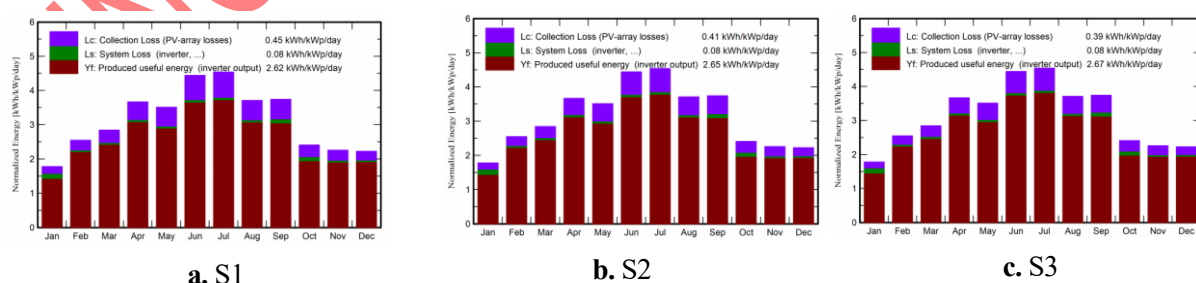


Figure 5. Produced useful solar power

When the height of the support frame increases from 1.5 m to 2.5 m, the airflow behind the photovoltaic modules improves significantly. Improved ventilation reduces the average operating temperature of photovoltaic cells, thereby decreasing thermal losses. In Figure 6, thermal losses decrease from -6.72% to -4.87%, demonstrating the cooling effect of a higher

frame clearance. This result directly impacts the total system loss, which drops from about 16.73% to nearly 15%, clearly illustrating the positive effect of increasing the frame height on energy conversion efficiency. Designing the frame with a reasonable gap not only helps cool the modules but also enhances the performance and electricity generation capacity of the entire system.

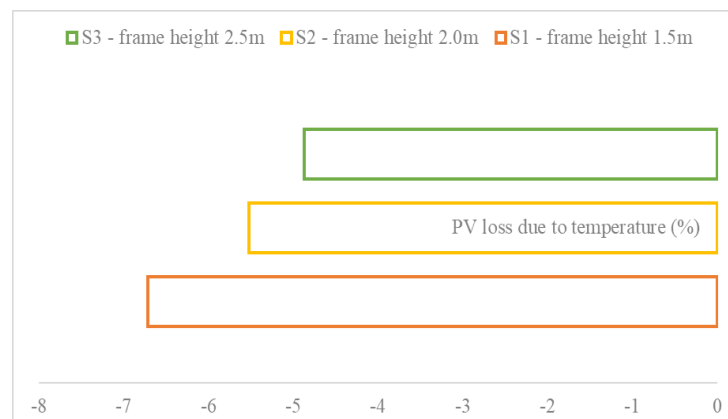


Figure 6. Chart comparing temperature losses among different options

From an overall comparison, it can be affirmed that two main mechanisms govern system performance: (1) convective efficiency reduces thermal losses as installation height increases, and (2) the ability of the bifacial module to absorb reflected radiation from the ground. Under the combined influence of these two mechanisms, the system performance ratio (PR) increases from 83.27% to 84.96%. The bifacial glass-glass module installed at a height of 2.5 meters demonstrates technically superior performance compared to other configurations. This improvement results from the synergistic effect of the two main physical mechanisms.

First, increasing the mounting frame height from 1.5 m to 2.5 m significantly enhanced natural convection at the rear side of the module, thereby reducing the average operating temperature of the photovoltaic cells and reducing thermal losses. Lower temperatures not only help maintain the module's instantaneous performance but also limit its long-term power degradation.

Second, the bifacial solar panel structure enables additional absorption of reflected and scattered radiation from the ground. As a result, the DC electrical output of the panel string is notably improved without increasing the installation area or nominal capacity.

The present study shares several methodological features with Ujah Peter et al. [14], including the use of bifacial modules, and mounting heights of 1.5, 2.0, and 2.5 m. Furthermore, the roof albedo of 0.20 is comparable to the surface albedo range of 0.19–0.23 investigated in their study. Both studies confirm that mounting height significantly affects rear-side irradiance and energy output. However, Peter et al. reported the highest yield at 2.0 m, whereas the present simulation showed a continued, but diminishing, increase up to 2.5 m. This difference indicates that the preferred mounting height is location and configuration specific and depends on climatic conditions, surface reflectance, tilt angle, array geometry, and system scale.

Economic and Environmental Aspects

The grid-tied solar power system is capable of stable operation, maximizing the use of generated energy, and increasing economic efficiency. Under normal conditions, solar electricity is prioritized to supply loads, reducing grid electricity consumption and thereby saving about 2,500 VND per kWh. When radiation is weak or at night, the system automatically draws power from the grid to ensure uninterrupted supply without the need for a separate backup source.

The comparison results in Table 3 show that the installation frame height directly affects the system's initial investment cost. When the frame height increases from 1.5 m (S1) to 2.0 m

(S2) and 2.5 m (S3), the investment cost rises from 121.32 million VND to 125.72 million VND and 130.12 million VND, respectively. The main reason is that the material and structural requirements for the supporting frame increase with installation height. Meanwhile, the operation and maintenance (O&M) costs remain unchanged at 6.17 million VND per year for all options, indicating that frame height does not significantly affect operation costs throughout the system's lifecycle. In terms of economic efficiency, the payback periods shown in Figure 7 for the S1 and S2 options are nearly identical at approximately 5.3 years, despite S2 having a higher initial investment. This demonstrates that increasing the frame height from 1.5 m to 2.0 m does not diminish the project's financial effectiveness. In contrast, the S3 option has a longer payback period (5.5 years), indicating that the increase in investment cost at a height of 2.5 m is not sufficiently offset by the corresponding economic benefits.

Table 3. Overall economic comparison of simulation options with varying frame heights

Scenario	Investment cost (VND)	O&M cost (VND/year)	Payback period (year)
S1 - frame height 1.5 m	121,321,200	6,170,347.44	5.29
S2 - frame height 2.0 m	125,721,200	6,170,347.44	5.3
S3 - frame height 2.5 m	130,121,200	6,170,347.44	5.5

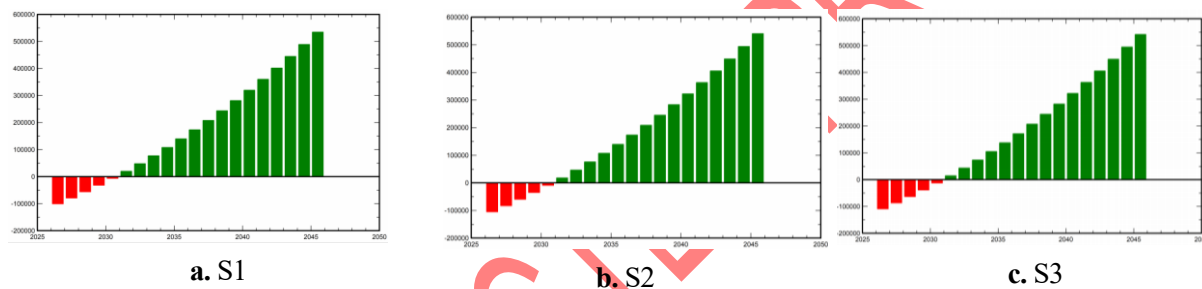


Figure 7. Payback Periods of the Simulated Scenarios

In the optimal scenario S2, the solar power system produces an average of 10.1 MWh/year. With the emission factor of Vietnam's electricity grid in 2025 projected at 0.6235 tCO₂/MWh [26], the solar power system can reduce CO₂ emissions by approximately 6.29 tons/year.

EXPERIMENTAL STUDY

Figure 8 shows the experimental and simulation results (optimal scenario S2) for 12 months of a solar power system using bifacial solar cells. Overall, both datasets showed a clear seasonal variation, with the output increasing in the middle months of the year and gradually decreasing towards the end of the year and the beginning of the following year. This is consistent with the changing patterns of solar radiation intensity, daylight hours, and actual weather conditions.



Figure 8. The experimental and simulation results (optimal scenario S2)

The simulation results generally reproduce the seasonal operating trend of the system; however, the simulated output exceeds the measured values in several months, particularly from May to October 2025. The leading cause of this discrepancy is likely the difference between the representative meteorological dataset used in PVsyst and the actual irradiance, cloud cover, ambient temperature, and wind conditions during the monitoring period. Simplified assumptions concerning soiling, shading, wiring losses, inverter performance, module temperature, and rear-side irradiance may also contribute to the observed differences. Conversely, the higher measured output observed in some months of early 2026 suggests that the actual solar resource during these periods was more favorable than that represented by the meteorological input dataset. Electricity production also depends heavily on the radiation absorption capacity of the back of the bifacial solar panel. If the model uses a higher ground reflectance coefficient (albedo) than reality or does not fully account for shading between the panel rows, the simulation results will be higher than the experimental measurements. However, in some months of early 2026, the experimental values were higher than the simulations, suggesting that the real-world system may have received more favorable radiation conditions than the meteorological input data.

The simulation model accurately reflected the operating trend of the bifacial solar panel system, but there was still a certain margin of error in absolute values. Therefore, it is necessary to adjust the loss parameters, weather data, and actual installation conditions to improve the accuracy of the simulation in future electricity production studies and forecasts.

Figure 9 shows that the simulated and experimental power profiles are generally consistent in terms of operating time, daily trend, and peak power. Both systems begin generating at approximately 06:00–06:30, reach a maximum of about 9.5–9.7 kW around midday, and stop after 18:00. Differences between simulation and experiment are expected because the simulation uses representative meteorological inputs and simplified loss assumptions, whereas actual output is affected by transient clouds, irradiance and temperature fluctuations, soiling, component behaviour, and other operating conditions.

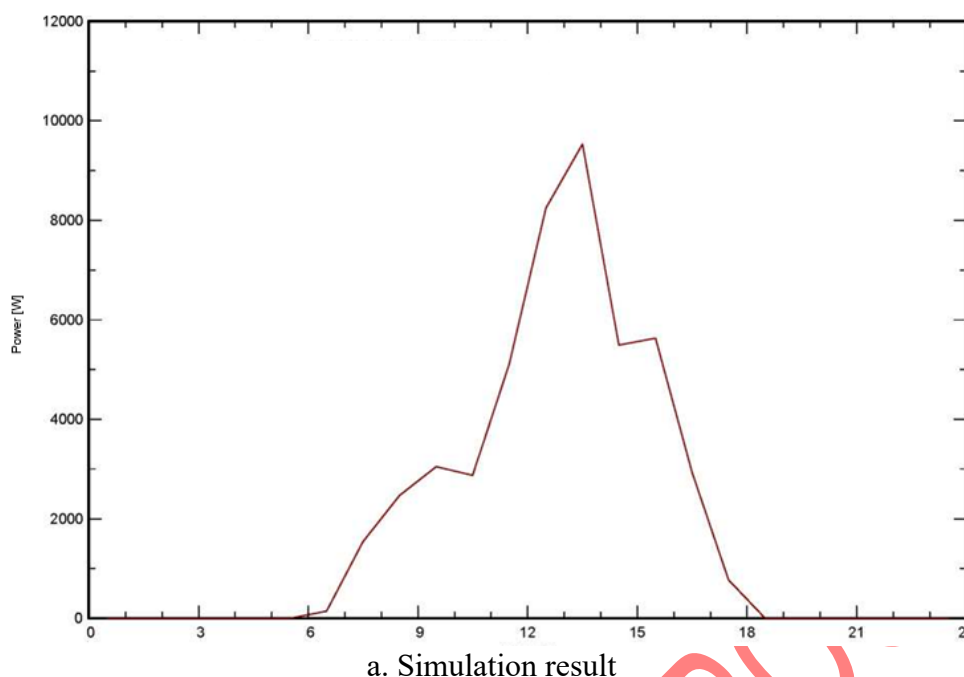
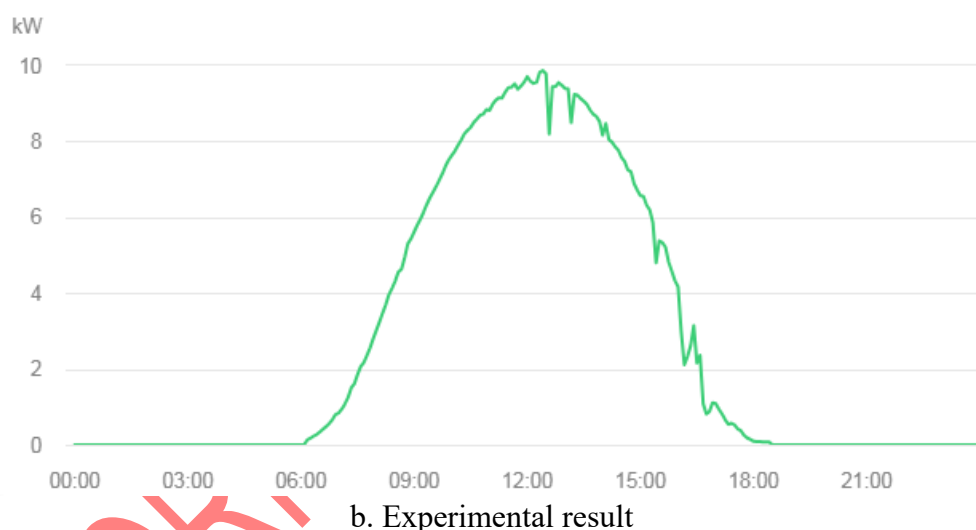


Figure 9. The simulation and experimental results on a typical day (3/10/2026)

This is a typical graph for a day with good radiation conditions and minimal prolonged cloud cover, indicating stable system operation and high energy conversion efficiency. However, there are some short power drops or stepped reductions around 12 PM and between 3:30 PM and 5 PM. This phenomenon is likely due to the local cloud cover.

The power output is close to 10 kW demonstrates that the system is well designed in terms of the power of the solar array and inverter, while the solar panels maintain good efficiency. For bifacial solar panel technology, in addition to direct radiation from the front, the back collects reflected light from the roof or the surrounding environment. This increases electricity production compared to conventional solar panels, especially when the roof is well ventilated, has good reflectivity, and is effectively air-conditioned. The graph shows that the system is relatively well-utilizing this advantage.

In Table 4, the experimental results of this study are compared with those of experimental studies published in other journals; these results are entirely consistent with the general trend of bifacial solar cell technology.

Table 4. Comparison analysis

Comparison criteria		Experimental system of this study	Similar research results	References	Scientific remarks
Peak Power	Output	~9.7/10 kW (97%)	~490/500 W (98%)	[27]	System performance is very good
			~254/305 W (84%)	[28]	
Generation Duration		~06:30 to ~17:30	~06:00 to ~17:00	[28]	Stable operation
Power Reduction		Caused by shading	Caused by shading	[29]	Shading mitigation recommended

The comparison table shows that the bifacial solar cell system in this study has good practical performance and is consistent with trends published in international studies. In terms of the percentage of nominal power, all three cases show good potential for exploiting bifacial cell technology, ranging from 84% to 98%.

The system in the study operated from approximately 06:30 to 17:30, which is nearly equivalent to study [28] (06:00–17:00). This demonstrates that bifacial solar cells can maintain power generation for extended periods by utilizing diffuse radiation and reflected light from the surrounding environment. In tropical or subtropical climates, extended power generation time is a major advantage, increasing total daily electricity output.

Besides, the table shows that both this study and work [29] noted that the main cause was shading. This is a very important result because it confirms that, although bifacial solar cells receive light from two sides, the system remains sensitive to shading of the solar cells. In practice, shading not only reduces instantaneous power but can also cause an imbalance in the solar cell array, reducing the overall system efficiency. From a scientific perspective, the comparative results indicate that bifacial solar cells achieve high operating efficiency, deliver long power-generation periods, and are suitable for rooftop systems. However, the ultimate efficiency depends not only on the solar panel itself but also on the installation design, tilt angle, ventilation distance, and shading control. By optimizing these factors, the research system can further increase power output and better exploit the benefits of bifacial technology.

CONCLUSIONS

This paper has comprehensively evaluated the impact of bifacial glass-glass solar panels under different installation heights (1.5 m, 2.0 m, and 2.5 m) on efficiency, output, energy losses, and the economic effectiveness of a grid-connected solar power system in the Red River Delta area. The simulation results provide a clear understanding of the relationship between mechanical design, PV structure, and energy harnessing capabilities in the distinctive tropical monsoon climate of Northern Vietnam.

Technical analysis shows that increasing the mounting frame height from 1.5 m to 2.5 m improves ventilation and reduces the average operating temperature of the bifacial solar panels, thereby increasing the system performance ratio (PR) by an average of 1.1–1.69% and boosting electricity output by approximately 0.03–0.05 (kWh/kWp/day). Economically, the results indicate that the payback periods for scenarios S1 and S2 are nearly equivalent, both reaching around 5.3 years, despite S2 requiring a higher investment cost. This demonstrates that increasing the frame height from 1.5 m to 2.0 m does not reduce the project's financial efficiency.

After further consideration of technical factors and real-world operating conditions, such as ventilation requirements, maintenance accessibility, and the need to utilize the space beneath the system, scenario S2 with a 2.0m-high frame offers the most viable techno-economic solution among the evaluated options.

Under the adopted meteorological data and modeling assumptions, increasing the mounting height improved the simulated energy yield and performance ratio. However, the magnitude of this benefit may be affected by meteorological uncertainty. The preferred mounting height is therefore site- and climate-specific and should be further validated using on-site weather data and simultaneous measurements at different heights.

A multi-objective analysis integrating energy yield, structural safety, cost, and architectural constraints is recommended for future research.

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