

INVESTIGATION INTO THE EFFECT OF TILT ANGLE ON THE PERFORMANCE OF SOLAR PHOTOVOLTAIC SYSTEMS IN NGHE AN

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ABSTRACT

This study provides a quantitative assessment and performance comparison between monofacial and bifacial PV systems in Nghe An through in-depth PVSyst simulations. The research presented a multivariate analysis of factors directly impacting energy yield, including a tilt angle range from 7° to 17°, mutual shading effects, thermal loss coefficients (U_c), and degradation characteristics. Simulation results identify an 11° tilt angle as the optimal operating point for both technologies locally, achieving a perfect balance between plane-of-array (POA) irradiance capture and shading loss mitigation. For bifacial modules, performance added rear-side albedo, achieving a yield up to 2.22 times higher than monofacial modules under conditions. However, bifacial gain is more sensitive to tilt angle variations; exceeding the 11° threshold causes rear-side benefits to be significantly offset by shading losses due to increased effective height. The study also indicates that enhancing heat dissipation (U_d) is a critical factor for performance optimization, particularly for bifacial modules which exhibit higher sensitivity and yield growth potential when properly cooled.

Keywords: Bifacial PV modules, monofacial PV modules, PVSyst, tilt angle, losses.

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1. INTRODUCTION

Monofacial PV technology has long held a dominant role, with performance entirely dependent on front-side irradiance and material properties [1]. However, driven by the need to optimize land use and economic efficiency

for large-scale projects, bifacial PV technology has emerged as a breakthrough solution. By harvesting both direct front-side sunlight and rear-side reflected radiation (albedo) as shown in Figure 1, bifacial modules can increase energy yield from 5% to over 30% compared to traditional technology [2]. This not only provides a technical advantage but also improves long-term financial viability, establishing this technology as a new standard in the near future [3].

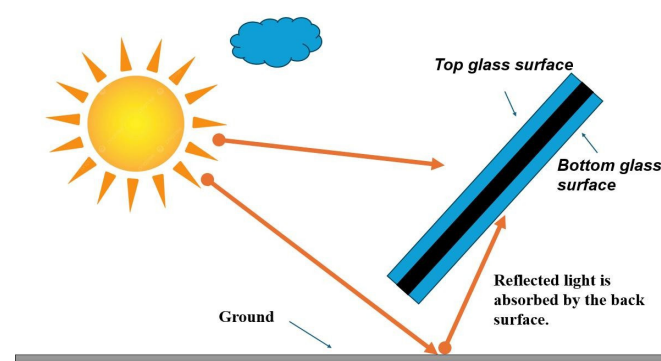


Figure 1. Operating principle of bifacial PV modules

Theoretically, total energy harvesting depends on Plane-of-Array (POA) irradiance, which comprises direct, diffuse, and reflected components. The tilt angle of the modules is the decisive parameter for the reception capacity of these components [4]. For monofacial modules, the optimal tilt angle is typically selected to approximate the local latitude to maximize front-side POA. However, the tilt angle optimization for bifacial modules is more complex due to its multivariate nature: increasing the tilt angle allows the rear side to capture more reflected radiation [5]. Simultaneously, it increases the module height, leading to mutual shading between rows during periods of low solar elevation [6]. This trade-

off between rear-side irradiance gains and shading losses is strictly dependent on geographic location, surface cleanliness, and operating temperature [7].

To address this problem, PVSyst software is utilized as the primary tool for detailed POA irradiance simulation and quantification of the energy conversion chain [8]. System loss mechanisms including shading, temperature, optical, and inverter efficiency are modeled systematically to reflect real-world operating conditions, [9]. Specifically, this study leverages PVSyst’s capability to quantitatively evaluate the trade-off between the bifacial gain and shading losses across a range of tilt angles [10], providing a basis for establishing the optimal configuration at the survey site.

2. RESEARCH METHODOLOGY AND INSTALLATION SITE

The following formulas are established to accurately describe the Plane-of-Array (POA) irradiance relative to the tilt angle, while integrating specific loss factors into the output power calculation process. This serves as the critical technical foundation for comparing and optimizing the performance between traditional monofacial and modern bifacial systems [11].

$$P_{out} = P_{STC} \times (G/1000) \times \eta \times [1 + \gamma(T - 25)] \times \beta \tag{1}$$

Where: P_{out} is the bifacial module output power; P_{STC} is the power at Standard Test Conditions (STC); G is the total effective irradiance; η is the relative efficiency; γ is the temperature coefficient; T is the actual cell temperature; and β is the Incidence Angle Modifier (IAM).

$$P = P_{clean} \times (1 - L_s) \tag{2}$$

where, P is the module output power; P_{clean} is the module output power under clean conditions; and L_s is the soiling loss index.

From the above calculations, it is evident that the solar PV system's output power is strictly dependent on incident irradiance, tilt angle, efficiency, temperature, losses, and module characteristics. However, in practice, these factors fluctuate continuously according to time and climatic conditions; thus, relying solely on theoretical formulas is insufficient for a comprehensive assessment. Therefore, the use of specialized simulation software such as PVSyst is essential for the accurate analysis and prediction of system performance.

This study addresses the gaps in existing literature by utilizing PVSyst for a quantitative comparison between monofacial and bifacial modules under the influence of soiling and temperature in Nghe An. The most significant contribution is the identification of an 11° tilt angle as the

optimal operating point, achieving a perfect balance between energy yield and mutual shading losses. These findings serve as a foundation for proposing practical solutions, such as optimizing mounting structures and periodic cleaning schedules, to enhance the operational efficiency of next-generation solar power projects.

Table 1. Equipment List and PV System Installation Conditions

Equipment	Technical Specifications
Installation Conditions	
System Capacity	10kWp
PV	- Risen Solar RSM132-8-700BHDG (Bifacial, 700Wp) - Risen SoLar RSM72-6-325-PM (Monofacia, 700Wp)
Inveter	Sungrow SG9.0Rs (10kW, MPPT voltage range from 40V to 560V)
Installation Layout	Consists of 15 modules, divided into 3 parallel strings
Pitch	6.6m
Shed total width	3.04m

The research system is established in Nghe An, which features an average solar irradiance of 4.6 - 5.2 kWh/m²/day. The site is characterized by a harsh tropical monsoon climate, involving hot, dry Lao winds (Foehn winds) and overcast winters that cause significant energy drops. The prevalence of arid environmental conditions leads to dust accumulation (soiling), forcing modern PV technologies to address the trade-off between leveraging tropical irradiance and enduring negative local fluctuations to maintain power output.

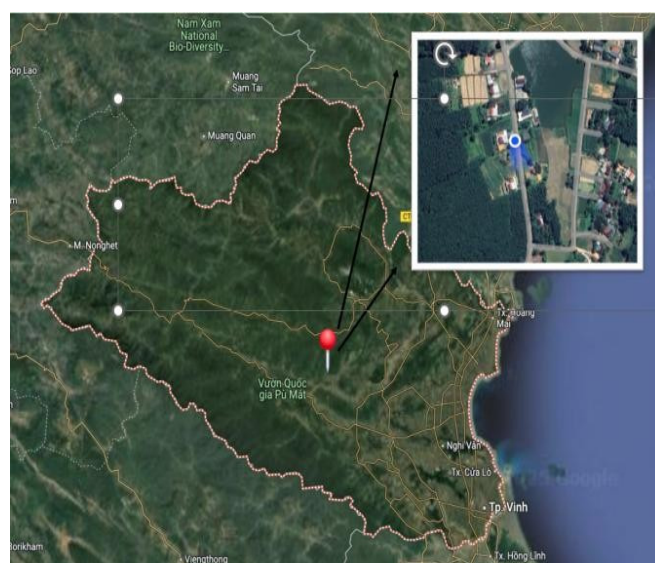


Figure 2. Simulation site location

Using PVSyst, two scenarios of Monofacial and Bifacial are simulated in parallel with a fixed inter-row spacing

(Pitch = 6.6m) and realistic albedo parameters. The multivariate investigation focuses on a tilt angle range of 7° - 17° and a thermal loss coefficient (U_c) from 10 - 35. By integrating site-specific climatic factors and degradation characteristics over a 25-year lifecycle, the study provides reliable data to identify the optimal operating point and evaluate the project's long-term economic feasibility. PVSyst delivers robust output data regarding useful energy yield and cumulative cash flow diagrams, serving as the foundation for establishing the optimal configuration and assessing the project's long-term financial performance.

3. RESEARCH RESULTS

3.1. System energy yield

Simulation results show that the energy yield of the photovoltaic system in nge an exhibits distinct fluctuations and deep seasonal variations, directly reflecting the climatic characteristics of the north central coast region [12]. The summer period from april to august records the highest harvesting efficiency, with production peaking in june at 579.8kWh/kWp/day due to the influence of the hot, dry southwest winds, which create clear skies and maximum radiation intensity. Although high ambient temperatures cause certain thermal losses, the abundant solar radiation during this period remains the dominant factor, maintaining an optimized output power. In contrast, energy output decreases sharply during the late and early months of the year, particularly in november and january, with values dropping to approximately 265.1 - 291.1kWh/kWp/day. This decline is a consequence of adverse weather patterns such as cold air masses, drizzle, and dense cloud cover, which weaken the effective solar irradiance (g) and shorten available sunshine hours. Transition months such as march, september, and october maintain a stable average production level ranging from 370.8 to 417.8kWh/kWp/day. This detailed quantification through simulation charts not only demonstrates the harshness of the local weather but also provides a vital database for evaluating the actual operational capacity of the system throughout its cycle.

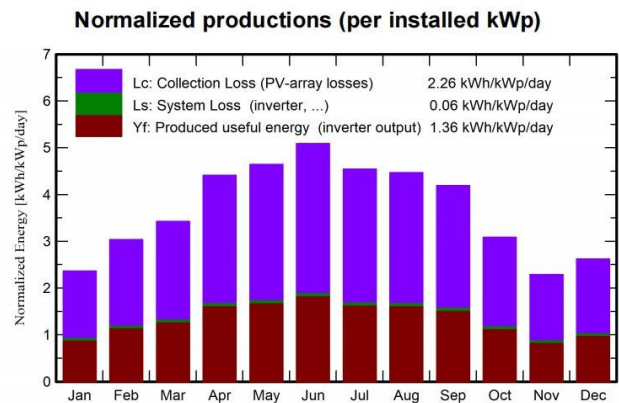


Figure 3. Annual average energy yield chart

Balances and main results

	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	PR ratio
January	70.5	52.91	16.48	73.2	67.8	309.7	291.1	0.379
February	82.5	60.92	18.16	85.0	79.0	357.2	339.9	0.381
March	104.6	77.13	21.23	106.1	98.7	438.3	417.8	0.375
April	132.0	79.63	25.25	132.4	124.0	535.1	512.9	0.369
May	145.8	93.05	29.29	143.9	134.5	573.0	550.8	0.364
June	156.0	86.44	30.97	152.6	143.0	601.6	579.8	0.362
July	143.4	90.06	30.51	140.9	131.4	557.0	535.1	0.362
August	139.1	89.13	29.18	138.5	129.4	552.0	529.6	0.364
September	124.0	72.47	26.88	125.7	117.7	503.1	481.6	0.365
October	93.5	72.73	24.81	95.6	88.7	390.6	370.8	0.369
November	66.2	49.50	21.68	68.6	63.5	282.9	265.1	0.368
December	77.2	54.52	18.14	81.4	75.4	342.9	324.9	0.380
Year	1334.7	878.49	24.41	1343.9	1253.2	5443.4	5199.3	0.368

Figure 4. Monthly energy yield

3.2. Impact of tilt angle power output under shading conditions

Simulation results within the tilt angle range of 7° to 17° identify 11° as the optimal operating point for both technologies, reaching peak yields of 5211.2kWh (monofacial) and 11808kWh (bifacial), respectively; However, beyond this optimal threshold, the performance maintenance capabilities of the two systems diverge significantly: while monofacial modules maintain impressive stability, bifacial modules record a sharp decline in power output, particularly at 17° where the loss reaches up to 205kWh compared to the 11° angle. This severe reduction is a direct consequence of the mutual shading effect between panel rows as the effective height increases. When implementing a scenario that eliminates shading factors, the power charts for both systems not only increase in absolute value but also exhibit a more stable variation trajectory, confirming that for double-glass bifacial technology, the benefits gained from rear-side radiation (albedo) are completely offset by shading losses if the tilt angle exceeds the optimal

threshold, necessitating rigorous calculations of installation geometry to preserve the yield advantage.

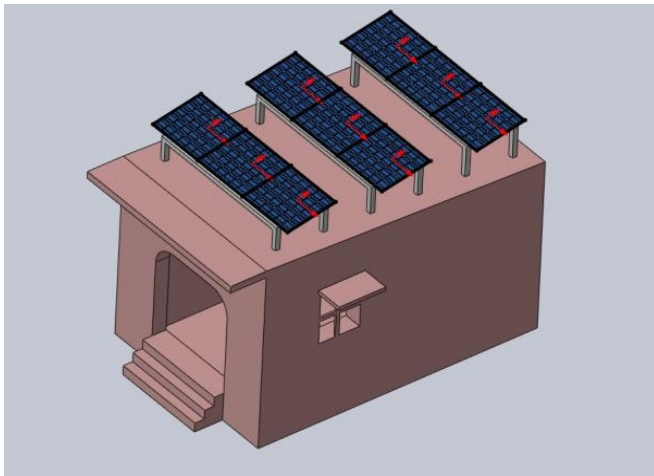


Figure 5. 3D perspective of the PV system

Table 2. power output of monofacial and bifacial systems with and without shading effects

Tilt angle (°C)	Shading Effect		No shading effect		Difference between shading effect and without shading	
	monofacial (kWh)	bifacial (kWh)	monofacial (kWh)	bifacial (kWh)	monofacial (%)	bifacial (%)
7	5199.3	11781	5984.2	13210	13.11	10.81
9	5207.5	11799	6032.1	13334	13.67	11.51
11	5211.2	11808	6246.5	13857	16.57	14.78
13	5210.3	11806	6035.1	13543	13.66	12.82
15	5204.4	11793	6002	13146	13.28	10.29
17	5194.0	11603	5897	12986	11.92	10.64

3.3. Impact of heat dissipation on system power output

Simulation results establish a strong positive correlation between the thermal loss parameter (U_c) and energy yield, proving that improving heat dissipation is a key factor in optimizing operational efficiency. When the U_c value increases from 10°C to 35°C, the output of monofacial modules rises from 4739.6kWh to 5685.3kWh (an increase of 945.7kWh). Meanwhile, bifacial modules exhibit a more powerful breakthrough as their output grows from 11620kWh to 13146kWh, reaching an absolute difference of up to 1526kWh. This disparity in growth magnitude confirms that bifacial modules have a higher sensitivity to environmental cooling conditions. This is explained by the specialized structure of bifacial cells, which allows for better airflow circulation, more

effectively mitigating the negative impacts of temperature on the photovoltaic cells compared to traditional modules. Therefore, optimizing the U_c parameter through ventilated mounting frame designs is not just a technical solution but a mandatory requirement to fully exploit the power potential of bifacial technology, especially in hot and humid tropical climates. These results provide an important foundation for designers in selecting installation structures to unleash the system's power generation capacity throughout the project lifecycle.

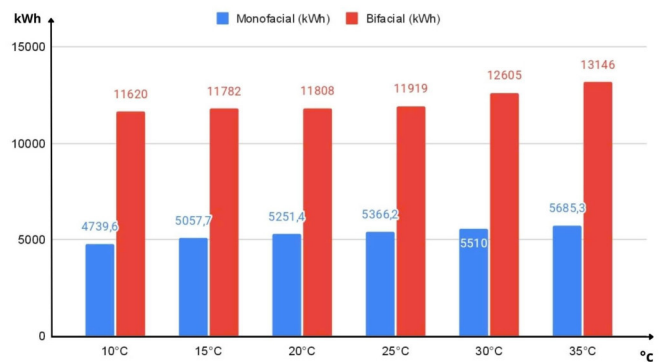


Figure 6. Power output chart as a function of heat dissipation coefficient

3.4. Impact of aging on the system

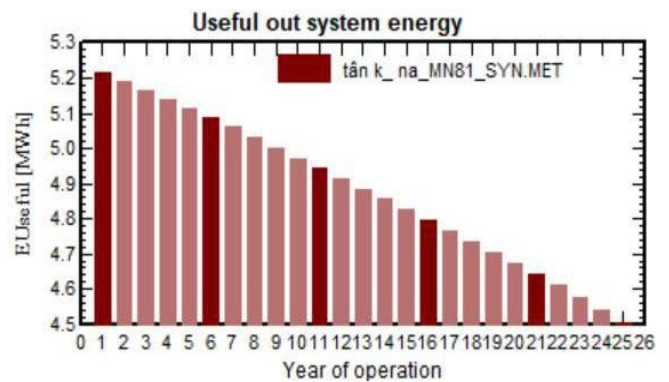


Figure 7. Degradation of the monofacial PV

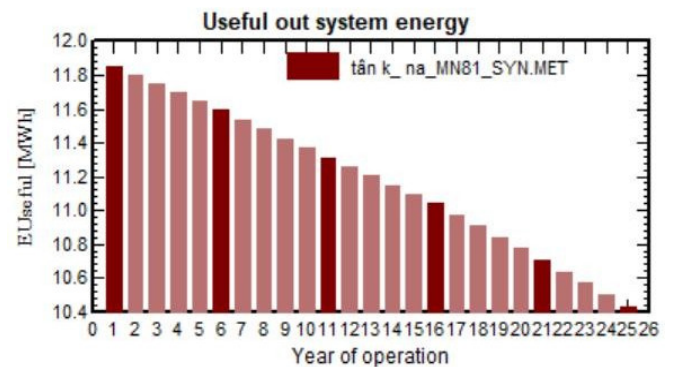


Figure 8. Degradation of the bifacial PV

In long-term projects, performance degradation is a decisive factor for the Levelized Cost of Energy (LCOE).

Simulation results from PVSyst over a 25-year lifecycle show that the monofacial module system experiences a yield loss of up to 13.6% (from 5.21MWh down to 4.50MWh), whereas bifacial modules not only maintain a significantly higher energy baseline thanks to the rear-side contribution but also exhibit a slower degradation rate, ending the cycle at 10.45MWh. This durability advantage stems from the double-glass structure; unlike the polymer backsheets in traditional modules, which are prone to embrittlement and moisture penetration under the influence of ultraviolet rays and high humidity in Nghe An, the dual tempered glass structure creates an absolutely airtight environment that prevents photovoltaic cell corrosion and minimizes Potential Induced Degradation (PID) risks. Consequently, bifacial technology not only increases instantaneous yield but also serves as an optimization strategy for system reliability and lifespan, ensuring sustainable financial efficiency throughout the project lifecycle.

4. CONCLUSION

Based on research results and simulation data, it can be concluded that the selection of technology and installation configuration plays a decisive role in solar energy efficiency in the Nghe An region. The study establishes a tilt angle of 11° as the optimal operating point, providing a perfect balance between capturing plane-of-array radiation and minimizing mutual shading losses between rows. Technologically, bifacial modules demonstrate a superior advantage by effectively utilizing back-side albedo radiation, achieving a yield 2.22 times higher than monofacial modules under ideal conditions. Although this module type is more sensitive to temperature factors in terms of absolute loss figures, the double-glass structure provides the system with a slower degradation rate and higher durability in harsh environments. In summary, the combination of bifacial technology and an 11° tilt angle not only optimizes instantaneous output but also ensures economic efficiency and operational reliability for solar power projects throughout their 25-year lifecycle in Nghe An.

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