Comparative Performance Analysis of Bifacial and Monofacial Photovoltaic Panels: A Computational Analyses

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Abstract. This paper presents a detailed techno-economic comparison between bifacial and monofacial crystalline-silicon photovoltaic (PV) modules for a planned 398 $MW_(DC)$ utility-scale plant near Oujda, Morocco. Hour-by-hour simulations using NREL's System Advisor Model (SAM) evaluate four key performance metrics—annual energy yield, long-term degradation, performance ratio, and total installed cost—while systematically varying module clearance (0–5 m) and tilt angle (10–50°). The simulation outcomes reveal that under the optimal configuration (30° tilt, 1 m clearance, albedo = 0.25), the bifacial Sunpreme MAXIMA GxB-330 module generates 728 GWh yr^{-1}, approximately 7.9 % more than the monofacial SunPower SPR-P17-330-COM. This increases the plant's capacity factor to 20.9 % and reduces the levelized cost of energy (LCOE) to USD 1.67 kWh^{-1}. Sensitivity analysis reveals that each additional meter of ground clearance enhances annual output by roughly 1.4 %. Although the capital-expenditure difference between the two module types is less than 0.001 %, bifacial technology offers superior lifetime value in high-albedo environments, while monofacial systems remain economically viable in low-reflectance sites with tighter balance-of-system constraints.

1 Introduction

In the face of growing energy demands and escalating environmental concerns, renewable energy technologies such as solar photovoltaics (PV) are pivotal for achieving sustainability and mitigating greenhouse gas emissions. Solar PV systems convert solar radiation directly into electricity without moving parts, heat generation, or emissions, making them one of the most environmentally friendly and efficient renewable technologies [1, 2, 4]. The advancement of PV technology is therefore essential to addressing global energy challenges and supporting a sustainable energy transition.

Solar PV technology lies at the intersection of material science and environmental engineering. Understanding the physical and electrical properties of photovoltaic materials enables the development of advanced systems that improve conversion efficiency and durability [3]. Globally, PV cell production in 2011 was dominated by China (57.3%), followed by Taiwan (11%), Japan (6.9%), and Germany (6.7%), with the United States contributing 3% [1].

Building on this foundation, the present study provides a detailed comparison of monofacial and bifacial PV systems under semi-arid Moroccan conditions. It analyzes annual energy yield, capacity factor, and performance ratio to highlight the superior efficiency and long-term potential of bifacial technology. These findings underscore the pivotal role of bifacial PV systems in future renewable-energy strategies, particularly for high-insolation regions such as North Africa.

2 Literature Review

The literature on photovoltaic (PV) technologies provides the theoretical and empirical foundations for assessing energy performance under diverse environmental conditions. This review synthesises prior work around three major themes: (i) the physical mechanisms governing the photovoltaic effect, (ii) the design evolution from monofacial to bifacial systems, and (iii) regional studies contextualising Morocco's solar potential and the computational tools used in techno-economic modelling. Together, these strands clarify the scientific and practical motivation for the present study.

2.1 Energy and the Photovoltaic Effect

Solar PV generation is grounded in the principle of converting sunlight directly into electricity, making it one of the most mature and scalable renewable-energy technologies [5]. The process is driven by the photovoltaic effect, where solar radiation ionises a semiconductor junction to generate an electric potential. Among various materials, crystalline silicon dominates global production because of its abundance, non-toxicity, and long-term stability [6].

Energy conversion in PV systems unfolds through three sequential stages: absorption, conversion, and collection [7]. Incident photons are either reflected or absorbed by the semiconductor layer; those with energies greater than the bandgap excite electrons, creating electron–hole pairs that are separated and collected at the electrodes, generating direct current (DC). This current is later inverted to alternating current (AC) for grid connection. Understanding this mechanism is fundamental to improving energy yield and module efficiency, particularly under non-uniform irradiance and reflective-ground conditions—key challenges addressed by bifacial technologies.

2.2 Overview of Monofacial and Bifacial PV Technologies

Conventional monofacial PV modules capture sunlight only on their front surface. They typically comprise an aluminium frame for mechanical strength, tempered glass for impact resistance, ethylene-vinyl-acetate (EVA) encapsulation for protection, a polyvinyl-fluoride (PVF) backsheet for insulation, and a junction box for electrical safety. These systems are well-established in both rooftop and utility-scale installations, offering reliability and cost-effectiveness [8].

However, bifacial modules mark a significant innovation in solar engineering. Their dual-active-surface design enables light absorption from both the front (direct irradiance) and the rear (reflected irradiance) sides, allowing the capture of albedo light from surrounding surfaces. This configuration enhances total energy generation and improves performance in high-reflectance environments such as deserts or semi-arid regions. Comparative studies confirm that bifacial systems consistently outperform monofacial ones under favourable

conditions, producing higher energy yields and reducing the levelised cost of energy (LCOE) [9].

Despite their advantages, the efficiency of bifacial systems is site-dependent, influenced by parameters such as tilt, elevation, and ground reflectivity. These variables determine the share of diffuse and reflected radiation reaching the rear surface, highlighting the importance of location-specific assessment—one of the central objectives of this study.

2.3 Solar Energy in Morocco and Simulation Tools

Morocco's commitment to renewable energy provides an ideal context for evaluating advanced PV technologies. Through progressive national policies and infrastructure investments, the country has become a regional leader in solar deployment. The Noor Solar Power Complex in Ouarzazate—comprising successive phases of 160 MW, 300 MW, 200 MW, and 150 MW—exemplifies this trajectory and supports Morocco's 2 GW Solar Capacity Installation Plan [10].

The Oujda region (34.69° N, –1.94° E) was chosen for this study as a representative semi-arid site characterised by high solar irradiance and moderate ground reflectivity. With a planned capacity of 398 MW (DC), Oujda offers both the climatic conditions and scale necessary for comparing the techno-economic feasibility of bifacial and monofacial PV configurations [11].

To simulate system performance, the research employed the System Advisor Model (SAM)—a robust, open-source software developed by the National Renewable Energy Laboratory (NREL) in collaboration with international partners. SAM integrates detailed physical models of system components with flexible financial algorithms, enabling accurate projections of energy yield, cost, and long-term economic performance. Because of its precision and versatility, SAM has become a benchmark tool in techno-economic solar research [12].

By combining Morocco's favourable solar conditions with SAM's analytical capability, this study bridges a gap in the literature: the lack of empirical and model-based comparisons of bifacial and monofacial PV systems under North African climatic conditions. The next section details the simulation design and parameters used to quantify these performance differences.

3 Simulation and analysis

In this section, the performance of solar photovoltaic panels is simulated using the System Advisor Model (SAM) to compare the two emerging solar photovoltaic technologies previously described. The simulation employs representative solar photovoltaic modules for each technology, ensuring comparability under identical conditions. Panels within the same category are utilized to match the power output of the original modules used in the analysis. Key parameters observed during the simulation include the number of modules required for each technology, energy yield, efficiency, and installation cost.
To standardize the comparison, both technologies utilize the same inverter, as the modules have identical power ratings. The selected inverter is the ABB PVS-60-TL-R-US, which features a maximum DC voltage of 800 V, ensuring consistency and cost parity in the system design.

3.1 Case 1: Monofacial solar panels

The baseline scenario reproduces the performance of the original monofacial array specified for the Oujda site, thereby providing a reference against which improvements can be gauged.

The selected site was analyzed and simulated using the Sun Power P17 multi-crystalline monopole performance series (SPR-P17-330-COM) photovoltaic modules, originally deployed during the initial construction phase. Each module, rated at 330 W, is optimized for large-scale solar power plants and contributes to a total DC capacity of 398 MW. The system design incorporates approximately 1,205,430 PV modules, spanning an area of 2,027 acres. To ensure compatibility with the modules' open-circuit voltage specifications, an appropriate inverter was selected. The performance indicators derived from the simulation, along with the monthly electricity production over one year, are presented in Table 1 and Figure 1, respectively.

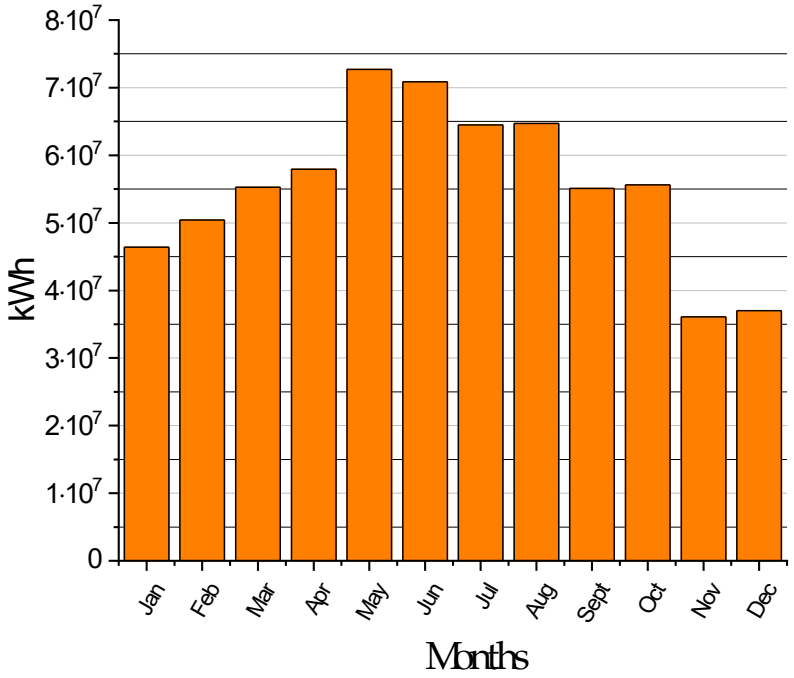

Fig.1. Monthly yield for one year using the SPR-P17-330-COM photovoltaic module

Table 1. Performance measurements using the spr-p17-330-com multicrystalline pv module for on-site installations.

Metric	Value
Annual energy	674,913,600 kWh
Capacity factor	19.4 %
Energy yield	1,696 kWh/kW
Performance ratio	0.79

Figure 1 presents the monthly energy yield of the SPR-P17-330-COM photovoltaic module over one year, with the highest production occurring from May to August—aligning with the peak solar radiation period in summer. As outlined in Table 1, the system delivered an annual energy output of 674,913,600 kWh, a capacity factor of 19.4%, an energy yield of 1,696 kWh/kW, and a performance ratio of 0.79. These findings underscore the system's effectiveness in producing substantial energy under site-specific conditions.

3.2 Case 2 : bifacial solar panel

The second scenario swaps the monofacial modules for commercially available bifacial counterparts while holding all other design parameters constant, isolating the incremental benefit attributable solely to bifacial operation.
The selected site was analyzed using the Supreme Inc. bifacial module (SNPM-GXB-330), a commercially available module with a power rating of 330 W. The system configuration utilized approximately 1,204,608 modules, spanning an estimated area of 1,884.2 acres. The same inverter model used in the monofacial case (Case 1) was employed, as it met all design requirements without any sizing constraints. The results of the performance analysis and the monthly energy yield are detailed in Table 2 and Figure 2, respectively.

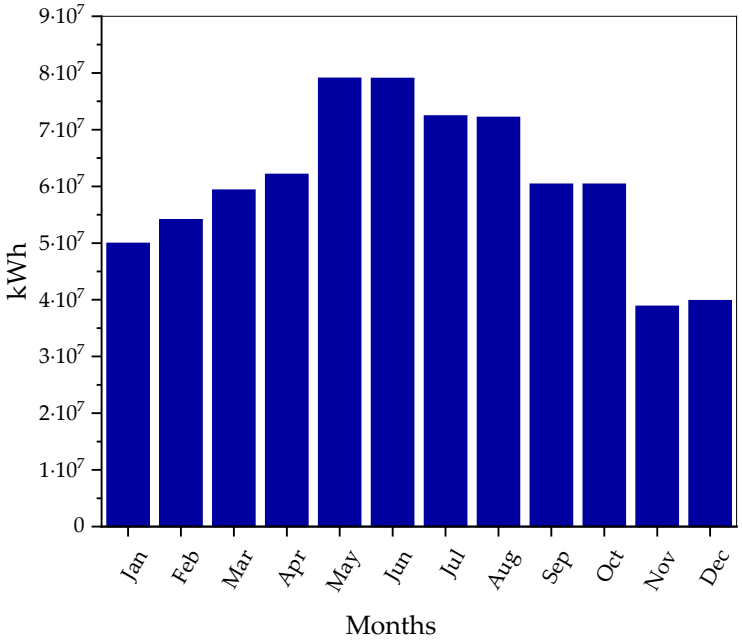

Fig. 2. Monthly yield for one year using the Supreme Inc bifacial PV PERC module SNPM-GXB-330.

The results in Table 2, show a higher energy yield of 1.829 kWh/kW and a higher performance rate of 86%. As expected, the illumination level during the summer months is higher, which in turn leads to an increase in the generated power. The site simulation with the bifacial modules also increased the capacity factor by about 20.9%.

Table 2. Performance measurements using the pv supreme inc bifacial module snpm-gxb-330 for field installations

Metric	***Value***

Annual energy	727,839,232 kWh
Capacity factor	20.9%
Energy yield	1,829 kWh/kW
Performance ratio	0.86

4 Discussion

Synthesising the numerical outputs, this section contrasts the two technologies across electrical, degradation and financial dimensions, and it interprets the practical significance of the observed differentials.

Two photovoltaic technologies, including the originally installed multicrystalline PV module, were analyzed to evaluate key performance parameters. The simulation results emphasize the advantages of emerging technologies, namely monofacial and bifacial PV modules, over conventional crystalline photovoltaic modules. This analysis aims to provide a comprehensive understanding of the most suitable technology for deployment under varying environmental, climatic, and economic conditions.

This section presents a detailed comparison of the two technologies in terms of energy production, panel degradation rates, performance efficiency, and cost metrics, offering insights into their potential applications in diverse scenarios.

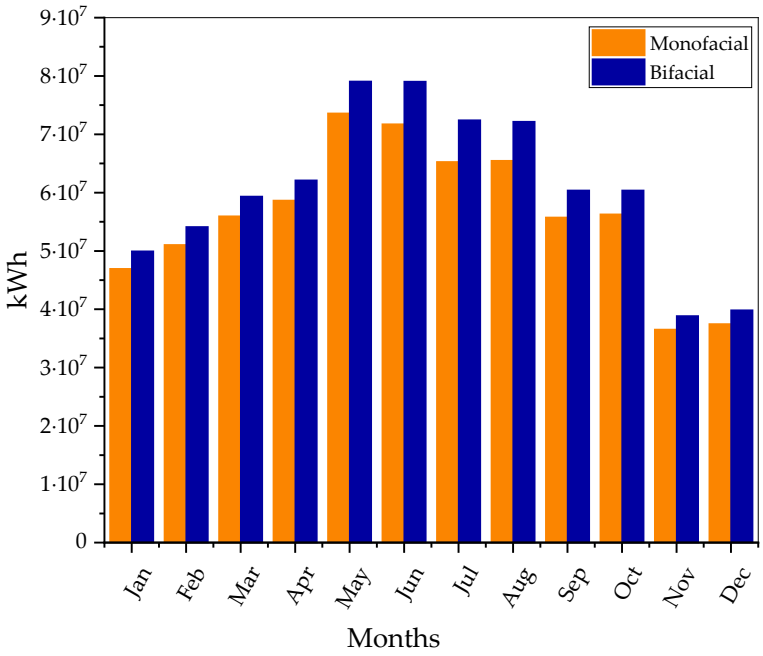

Fig.3. Comparison between two different photovoltaic technologies in terms of annual energy production

Figure 3 presents a comparison of annual energy production between the monofacial and bifacial photovoltaic (PV) technologies. Despite using modules with the same power rating, bifacial PV technology demonstrated superior energy output due to its higher efficiency. This advantage stems from its ability to utilize light reflected onto the back side of the panel,

allowing bifacial modules to extract more energy under identical solar irradiation conditions. Consequently, bifacial modules are particularly advantageous in environments with high albedo, where reflective surfaces significantly enhance energy generation.

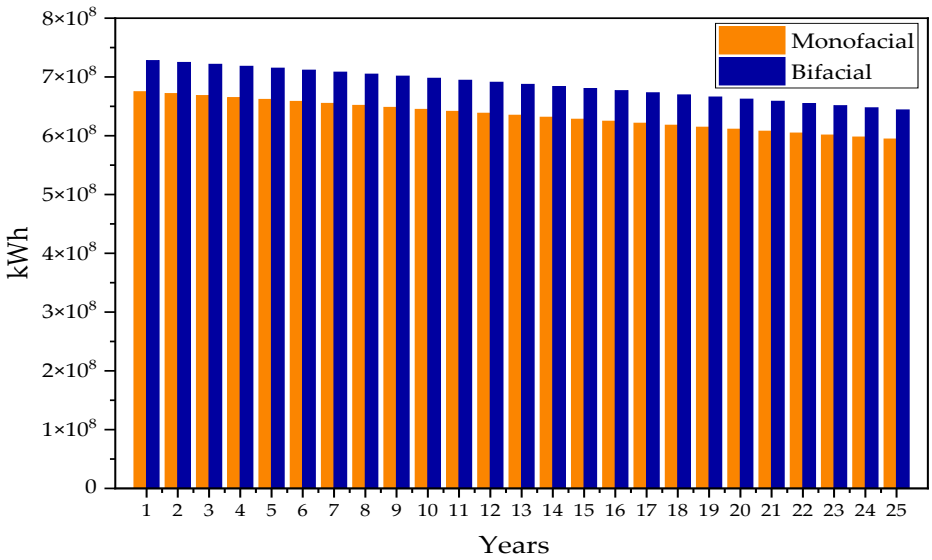

Fig.4. Comparison between two different photovoltaic technologies in terms of degradation rate of solar panels over a period of 25 years.

Figure 4 illustrates the degradation rates of the solar panels over a 25-year operational period. The monofacial PV module experienced a degradation rate of 12%, reducing its energy production to 594,286,000 kWh. In comparison, the bifacial module exhibited a slightly lower degradation rate of 11.6%, maintaining a higher energy production of 643,916,000 kWh over the same period. These results highlight the durability and superior long-term performance of bifacial technology, which allows for more energy extraction over time, even with minimal differences in degradation rates.

Table 3. Comparison of the electrical parameters of the two different photovoltaic technologies.

Parameters	**Monofaciale**	**Bifaciale**
Annual energy	674,913,600	727,839,232
Capacity factor	19.4	20.9
Energy yield	1,696	1,829
Performance ratio	0.79	0.86

Table 3 provides a comparison of key electrical performance metrics for both technologies. The bifacial PV panels outperform the monofacial panels in all major parameters, including annual energy production (727,839,232 kWh vs. 674,913,600 kWh), capacity factor (20.9% vs. 19.4%), energy yield (1,829 kWh/kW vs. 1,696 kWh/kW), and performance ratio (0.86 vs. 0.79). These findings underscore the potential of bifacial technology as a robust and efficient option for solar energy projects.
The cost comparison, summarized in Table 4, reveals that the bifacial PV system has a slightly higher total setup cost of $447,036,386 compared to $447,032,737 for the monofacial

system. This marginal cost difference is attributed to minor variations in module, inverter, and installation costs. However, the cost per kWh is notably lower for bifacial technology ($1.67) compared to monofacial technology ($1.80), making it more economically viable in the long term.

While monofacial systems may be a feasible option for projects with stringent cost constraints, bifacial systems demonstrate higher energy efficiency, superior performance metrics, and lower lifetime energy costs. These advantages position bifacial PV technology as an optimal choice for large-scale solar installations, particularly in regions with high albedo and significant solar reflection.

Table 4. Cost comparison between the two photovoltaic technologies.

Parameter	***Monofaciale PV ($)***	***Bifaciale PV ($)***
Number modules	1,205,430	1,204,608
Module cost	163,179,685	163,181,018
Invertir cost	47,759,908	47,760,297
Installation cost	218,899,578	218,901,364
Subtotal	429,839,171	429,842,679
Replacement and cotingeney (4% of subtotal)	17,193,566	17,193,707
Total setup cost	447,032,737	447,036,386
Cost per kWh	1.80	1.67

5 Sensitivity Analysis: Tilt and elevation effects

Because bifacial gain is highly site-specific, controlled outdoor experiments were designed to validate the model and to identify the parameters with the greatest leverage on energy yield

The study demonstrated that bifacial photovoltaic (PV) panels are more effective and efficient than monofacial panels. To further validate the proposed model, a series of outdoor tests were conducted using a south-facing bifacial PV module. These tests were performed in Oujda, Morocco, located at approximately 34.41°N latitude, under clear sky conditions. Key parameters known to significantly influence the performance of bifacial PV modules were varied individually, including:

- ✔ Tilt angle
- ✔ Elevation of the module above ground

These controlled experiments provided additional insights into the optimal configurations for maximizing the energy output of bifacial PV systems under real-world conditions.

5.1 Tilt Angle Effect on Performance

Tilt angle determines the angular incidence of both direct and diffuse irradiance and therefore ranks among the primary design variables for bifacial arrays. In addition to its role in solar energy capture, tilt influences structural wind loading, shading losses, and self-cleaning efficacy. Thus, optimising this parameter is critical not only for electrical performance but also for mechanical reliability and long-term maintenance efficiency.

Table 5. Comparison, by varying the angle of inclination.

Angle tilt (°)	**Annual energy (kWh)**	**Capacity factor (%)**	**Energy yield (KWh/kW)**

10°	698,756,352	20.0	1,756
15°	715,901,632	20.5	1,799
20°	727,839,232	20.9	1,829
25°	734,407,424	21.1	1,845
30°	736,188,352	21.1	1,850
35°	732,732,736	21.0	1,841
40°	724,879,232	20.8	1,821
45°	712,974,784	20.4	1,791
50°	697,629,952	20.0	1,753

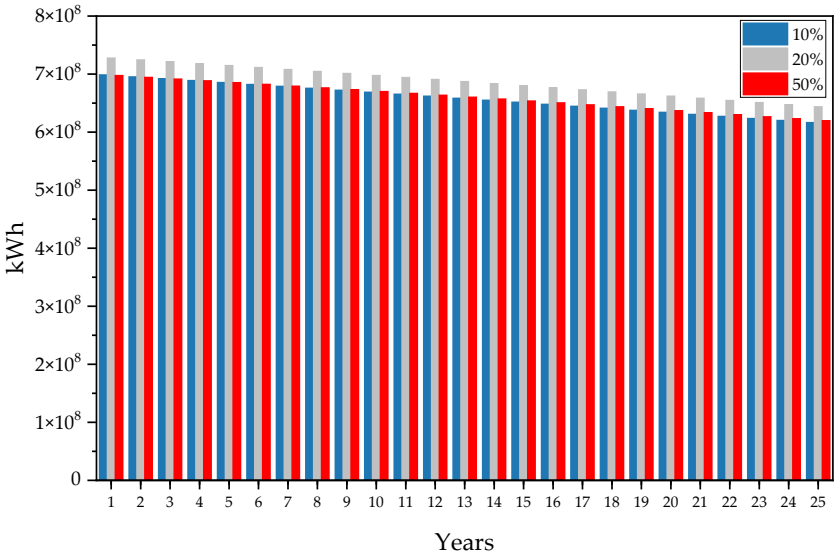

Fig.5. Comparison between the three tilt angle conditions for bifacial solar panels.

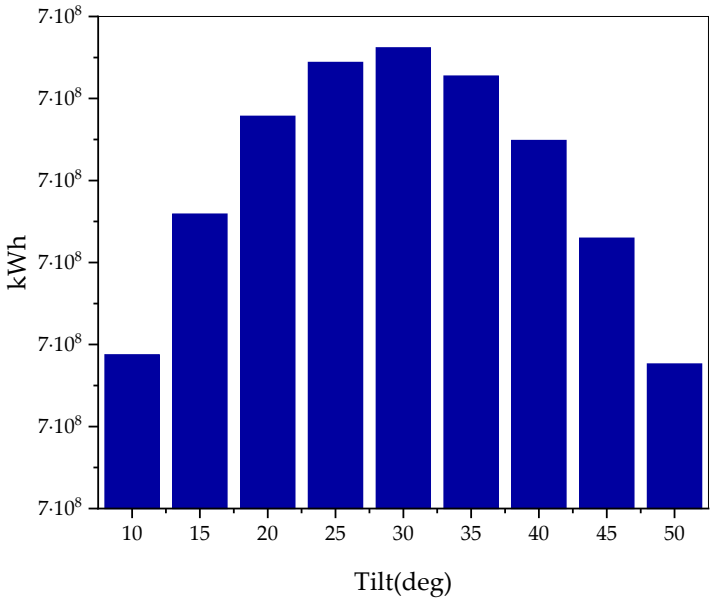

Fig.6. Variation of the annual energy as a function of the tilt angle.

Table 5 collates the simulated annual energy output, capacity factor, and energy yield for tilt angles ranging from 10 ° to 50 °. Figures 5 and 6 visualize these data: Figure 5 compares three representative configurations (10°, 30°, and 50°), while Figure 6 shows the continuous variation in energy yield across all tilt values. The experimental results show strong agreement with the simulated data provided by the model, confirming its accuracy in predicting performance under different tilt conditions. At noon, a tilt angle of 10° resulted in an annual energy production of 698,756,352 kWh with a performance ratio of 86%. For a tilt angle of 50°, the energy output decreased slightly to 682,756,352 kWh, with a performance ratio of 83%. Notably, the optimal tilt angle was found to be 30°, which achieved the highest energy production of 736,188,352 kWh and an energy yield of 1,850 kWh/kW. It is important to note that the tilt angle directly influences the energy yield. As the tilt angle increases, the energy yield improves, reaching its peak at 30°. Beyond this point, however, energy productivity declines for angles of 35° and above, as clearly illustrated by the downward curve in Figure 6.

5.2 Effect of Module Elevation

Alongside tilt angle, the elevation of PV modules plays a pivotal role in enhancing rear-side irradiance capture—a defining advantage of bifacial systems. By increasing the distance between the module and the ground, designers can boost the amount of albedo light reaching the panel's backside, which is especially beneficial in high-reflectance environments. The following test series quantifies this effect.

Table 6 presents the performance results as the elevation of bifacial modules is increased from 0.5 m to 2 m. The associated variation in energy output and efficiency is illustrated in Figure 7, which compares three elevation configurations to highlight their influence on rear-side irradiance collection. As elevation increases, a greater portion of ground-reflected light reaches the rear surface of the module, resulting in improved performance.

At 0.5 m elevation, the annual energy production is 718,435,584 kWh, corresponding to a capacity factor of 20.6%, an energy yield of 1,805 kWh/kW, and a performance ratio of 85%. Raising the module to 1.0 m increases output to 727,839,232 kWh, with a capacity factor of 20.9%, an energy yield of 1,829 kWh/kW, and a performance ratio of 86%. Further increasing the elevation to 2.0 m results in the highest observed performance, with an annual output of 740,142,336 kWh, a capacity factor of 21.2%, an energy yield of 1,860 kWh/kW, and a performance ratio of 87%.

Table 6. Comparison, by varying the elevation of the module.

Elevation (m)	**0.5**	**1**	**2**
Annual energy (kWh)	718,435,584	727,839,232	740,142,336
Capacity factor (%)	20.6	20.9	21.2
Energy yield (kWh/kW)	1,805	1,829	1,860
Performance ratio	0.85	0.86	0.87

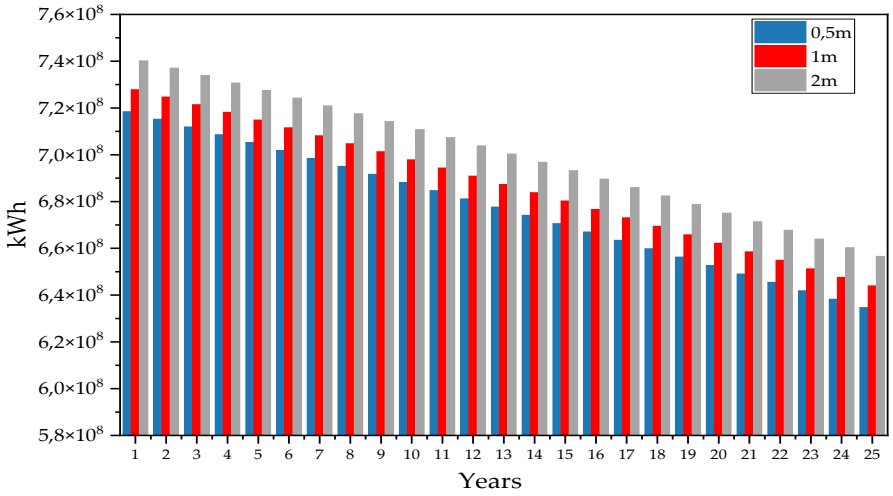

Fig.7. Comparison between the three conditions of the module elevation with respect to the ground.

These findings confirm that higher module elevation enhances the collection of reflected light and boosts system performance. Nevertheless, the associated structural implications—such as increased wind loading, material costs, and installation complexity—must be carefully considered when optimizing for elevation. As illustrated in Figure 7, the performance curve shows diminishing returns at higher elevations, suggesting that gains beyond 2.0 m may be marginal relative to their cost.

6 Conclusion

Drawing together simulation and field-validation findings, the conclusion distils actionable guidance for developers selecting between monofacial and bifacial modules in high-insolation, high-albedo regions such as eastern Morocco.

This study delivers a comprehensive techno-economic evaluation of bifacial and monofacial photovoltaic (PV) technologies using the System Advisor Model (SAM), a well-established simulation tool widely adopted by engineers and energy analysts. SAM enables detailed modelling of both energy performance and project financials, supporting technology selection tailored to site-specific conditions.

The simulation results consistently show that bifacial PV modules deliver superior performance in terms of annual energy output, energy yield per installed kilowatt, and long-term durability. Over a 25-year horizon, bifacial systems exhibit slightly lower degradation rates and higher cumulative electricity generation. These technical advantages translate into lower levelised energy costs (LCOE) when site conditions—such as high albedo and ample rear-side irradiance—are favourable.

However, the financial analysis also reveals that monofacial modules maintain a competitive edge under certain constraints. Specifically, they incur marginally lower capital costs and exhibit slightly better returns on investment where land reflectivity is limited or when structural simplicity and cost containment are paramount. Overall, while bifacial technology emerges as the preferred option for maximising yield and long-term economic return in optimised settings, monofacial modules remain a practical and cost-effective alternative in scenarios prioritising budget efficiency. These findings underscore the need for nuanced, site-aware design strategies in utility-scale PV deployment.

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