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Energy, Economic, and Environmental Benefits of Cooling Photovoltaic Module with L-Shaped Fins and Reflector in Zakho, Iraq

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ABSTRACT

Solar energy is a renewable resource; however, high operating temperatures reduce photovoltaic (PV) performance. This study examines passive cooling and reflective enhancements on PV systems in Zakho, Iraq, during winter. Experiments were conducted on February 24 and 27 using two modified PV designs. While in Scenario I, L-shaped aluminum fins were attached to a PV module and compared with a reference panel. Scenario II combined fins with an aluminum reflector to increase the amount of incident solar radiation. Results showed notable performance gains. In Scenario I, power output rose by 14.2%, with peak efficiency improving from 10% (reference) to 12%. Scenario II achieved a 17.5% increase in power, with efficiency reaching 16.5% compared to 14% for the benchmark. Temperature decreases of 15.3°C (Scenario I) and 13°C (Scenario II) confirmed the effectiveness of passive cooling. An examination of life cycle costs (LCC) indicated reduced energy expenditures: $0.053/kWh for the reference scenario, down to $0.048/kWh with fins, and further lowered to $0.044/kWh with fins combined with a reflector. The payback periods have been decreased to 6.5, 5.9, and 5.5 years for reference, fins, and combined fins with reflector systems, respectively. The environmental analysis revealed yearly CO_2 emission reductions of 4.62, 5.25, and 5.93 tCO_2/year for reference, fins, and combined fins with reflector systems, respectively. Overall, integrating cooling fins and reflectors significantly improved PV performance, reduced energy costs, and enhanced environmental sustainability. This approach offers a practical and low-cost strategy to boost solar energy utilization in regions with similar climatic conditions.

Keywords:
Solar energy; Passive cooling technique; Reflector; Economic analysis; Environment performance

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1. INTRODUCTION

Solar energy is a highly beneficial renewable energy source [1]. It is a renewable energy source that is both long-lasting and environmentally benign. The increasing depletion of fossil fuels to fulfill expanding energy demands leads to environmental contamination, while their scarcity motivates the quest for alternative energy sources to ensure long-term growth [2]. PV technology is one of the most promising renewable energy technologies, with applications in a variety of fields [3]. PV cells convert 10-20% of solar energy into electricity, depending on chemical and physical parameters [4]. However, these modules' efficiency decreases with temperature, which can shorten their lifespan and reduce energy generation. Crystalline silicon modules heat up due to the absorption of sub-bandgap radiation and the thermalization of photon energy that exceeds the silicon bandgap. The generated heat is primarily dispersed into the environment by convection and radiation. Improving the efficiency of these heat dissipation systems lowers the module's operating temperature [5]. Because the PV system's power production drastically decreases as the temperature of the cells rises, using a cooling mechanism is essential to maintaining the temperature as low as possible [1]. This discovery led researchers to explore various cooling methods as part of their investigation into a simple passive cooling system. They tested the use of multiple aluminum fins attached to the backside of a photovoltaic (PV) panel and found that natural cooling was more effective at reducing PV temperatures before midday compared to the late afternoon. [6][7]. Additionally, solar concentration techniques were employed to decrease the required area of PV cells while maintaining power output, helping to reduce overall system costs, as PV modules can be relatively expensive. [8] Increasing the power output of a PV module by improving the solar radiation falling on it, booster reflectors have demonstrated potential in raising the irradiance on the panel surface [9]. Several studies have researched the usage of passive cooling systems and the effect of booster reflectors on solar system performance. Hamdan et al [6] used L-shaped aluminum inline fins on the rear of PV panels to provide natural cooling. Four monocrystalline PV panels were placed side by side, with one used as a reference. Fins placed 2 cm apart provided optimal performance, resulting in a 9.2°C drop in backside temperature, an 8.9% efficiency increase, and a 7.9 W power output gain. Krstic et al [10] explored the use of aluminum heat sinks with various geometries for the passive cooling of PV panels experimentally and numerically. The implementation of these heat sinks resulted in an average temperature reduction of 7.5 °C, which corresponded to an increase in open-circuit voltage by 0.27 V compared to a reference panel. Zhao et al [11] investigated the dual capture of solar energy through heat extraction in solar collectors and electricity generation in photovoltaic (PV) panels. The experiment tested three configurations of fins (0, 5, and 10 fins) under varying solar irradiance (200 to 600 W/m^2) and a fixed air mass flow rate of 0.011 kg/s. The results showed that the electrical efficiency for all fin configurations was around 16%, with minimal variation. Kumar et al [12] conducted an experiment to investigate a passive cooling solution during the peak summer season, and aluminum sheets were mounted on the rear side of the photovoltaic (PV) module for cooling purposes. The cooled panel achieved an average temperature of 41.09°C, while the reference panel recorded 51.08°C, indicating a temperature reduction of 10°C. This cooling effect resulted in a 4% increase in the PV module's efficiency. The cooled module produced an average power output of 12.19 W, compared to 11.14 W for the reference module, representing a 9.43% improvement. Malik et al. [13] studied the performance of a PV mirror reflector system deployed at optimum tilt angles and evaluated it over two years. The system has an average power boost of 10-19.84% in the summer and 10-13.23% in the winter. The ideal tilt angles for reflectors at the Hamirpur location in Himachal Pradesh, India, have been established to be 40° in the summer and 15° in the winter. Elbreki et al [14] used a Design of Experiment (DOE) approach to determine the best design parameters, such as fin height, pitch, thickness, number of fins, and tilt angle. The experimental work was conducted under real environmental conditions, with an average solar irradiance of 1000 W/m^2 and an ambient temperature of 33 °C. Lapping fins demonstrated the best performance, resulting in a mean PV module temperature that was 24.6 °C lower than the reference PV module. And the power output and electrical efficiency reached are as high as 37.1 W and 10.68%, respectively. The research conducted by Kabeel et al [15] aimed to enhance the efficiency of photovoltaic modules using reflectors under Egyptian conditions. Three cooling systems were evaluated on separate days: forced-air cooling with reflectors, water cooling with reflectors, and a combination of forced-air and water cooling with reflectors. The most efficient technique was water cooling combined with reflectors. The results showed net power outputs of 912 Wh/day, with improvements from reflectors and cooling of 80 Wh/day, and a projected conventional cost of $0.062 per kWh.

This research is the first examination of photovoltaic module cooling employing L-shaped fins and a reflector under winter conditions in Zakho, Iraq. The study evaluates the enhancement of solar module performance throughout winter, a season often overlooked for sustained energy supply. The study examines the integration of passive cooling and irradiance enhancement in relation to energy, economic, and environmental factors. This work provides fresh insights into the influence of seasonal weather on photovoltaic cooling strategies and highlights a cost-effective, regionally adaptive method to improve photovoltaic module performance, hence promoting renewable energy adoption in Northern Iraq. This study aims to empirically evaluate the performance enhancement of photovoltaic (PV) modules using a hybrid passive cooling approach that combines L-shaped aluminum fins with a reflective surface under cold-weather conditions in Zakho City. Unlike previous studies, which have largely focused on either cooling techniques or reflective enhancements in isolation, this work integrates both strategies and investigates their combined effect on PV performance. The analysis considers three key dimensions: energy performance, measured as the increase in electrical output; economic feasibility, assessed through cost-benefit analysis of the additional components; and environmental impact, quantified in terms of CO_2 emission reductions and overall sustainability. The novelty of this study lies in the simultaneous application of passive cooling and reflective improvements in a winter climate, providing a comprehensive evaluation of technical, economic, and environmental benefits for PV systems.

2. EXPERIMENTAL SETUP

The experimental setup was positioned in the University of Zakho Presidency building in Zakho, at coordinates 37.15°N latitude and 42.67°E longitude. The test rig comprises two identical polycrystalline photovoltaic modules, characterized in Table 1, with dimensions of 67 × 60 × 2.5 cm. The photovoltaic modules are mounted on a steel frame, chosen due to their superior strength, durability, and ability to withstand harsh environmental conditions. They are oriented towards true south (zero orientation) at an angle of inclination of 37°. According to [16][17], the optimal tilt angle of a photovoltaic module can be calculated based on the site's latitude. Therefore, for Zakho city (latitude ≈ 37°), the inclination angle of the PV module was set to 37° to maximize annual energy yield. The first photovoltaic module serves as a reference. The second photovoltaic module employed L-shaped fins on its underside, both with and without a reflector. A polished aluminum booster reflector, matching the dimensions of the PV panels, was utilized to enhance reflection. the reflector tilt angle was fixed at 20° to the horizontal. This selection is based on the findings of [18], which showed that reflector performance depends significantly on inclination. An aluminum-sheet reflector set at 20° yielded the highest overall energy gain during the winter months (November–February), achieving an expected increase of 15.2% in collected energy. Furthermore, it indicated that angles between 15° and 20° consistently produced performance gains exceeding 10% throughout the year, confirming the effectiveness of this inclination, and at higher inclination angles, such as 25° or 30°, the reflectors could cast shadows on the PV modules. The reflector positioned at the forefront of the PV module to augment the solar irradiation of the PV module, as illustrated in Fig 1, An L-shaped aluminum fin (heatsink) including 141 fins, each with a base area of 9 cm^2, a length of 3 cm, a thickness of 1 mm, and a spacing of 2 cm between fins, was utilized in this study. The optimal fin spacing was established to be between 2 cm and 5 cm [19]. Based on this guideline, a panel consisting of 141 fins was selected, as illustrated in Fig. 2(a). The use of shorter fins enhances heat dissipation while minimizing thermal resistance [20]. Fig. 2(b) illustrates the positioning of L-shaped fins on the rear of the plate. The fins function to efficiently disperse heat from the photovoltaic (PV) panel by serving as heat sinks. The fins facilitate a reduction in the operating temperature of the PV module, mitigate internal component damage by promoting enhanced heat dissipation, and subsequently increase the panel's performance. Aluminum is utilized for fins because of its lightweight properties, exceptional thermal conductivity (237 $W\cdot m^{-1}\cdot K^{-1}$), and specific heat capacity of 903 $J/kg\cdot K$. Thermal paste was utilized to affix the fins to the rear of the photovoltaic panel.

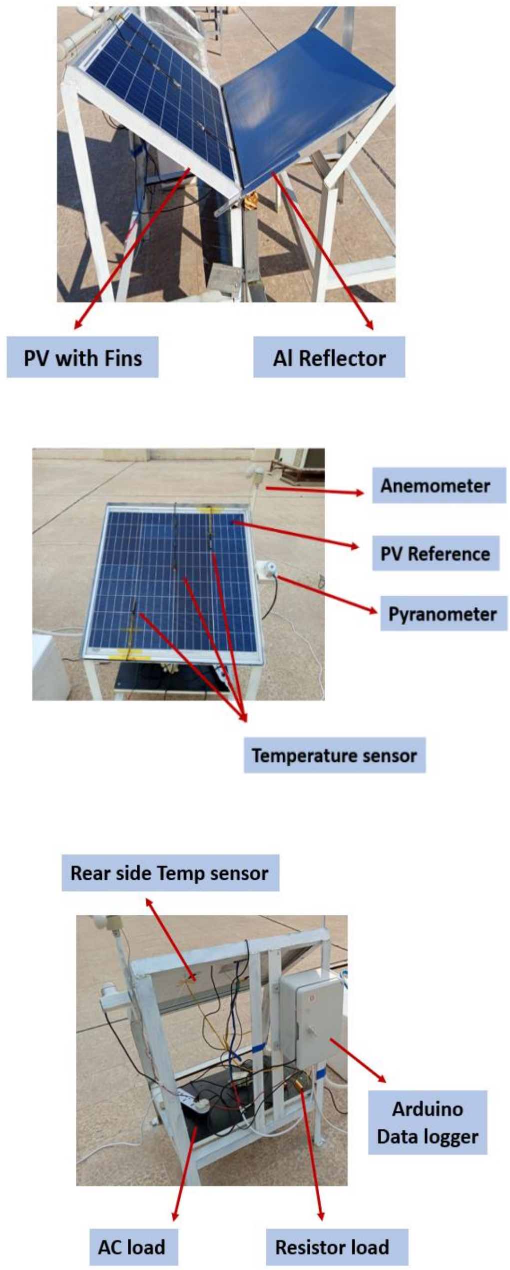
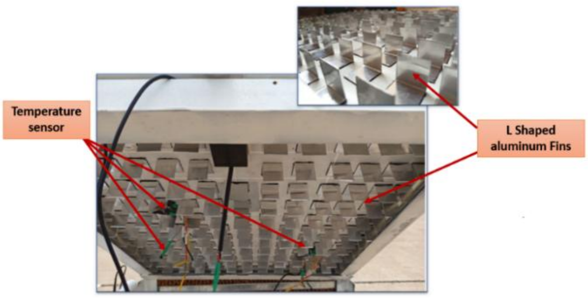


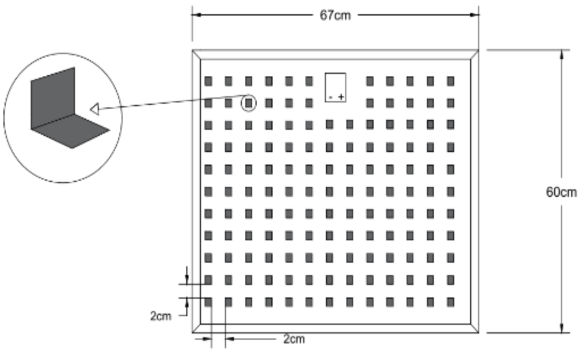
Fig.1 The Exprimental Setup.

Table 1. Electrical data at standard test conditionat (1000 W/m^2, 25 °C, 1.5 AM).

Characteristics	Values
Nominal Power (P_{max})	60 W
Maximum power current (I_{mp})	3.33 A
Short circuit current (I_{SC})	3.68 A
Maximum power voltage (V_{mp})	18V
Open circuit voltage (V_{oc})	22.1 V
Pmax Temperature coefficient	-0.45%/ºC
Temperature coefficient β	-0,45%/ºC
Module Efficiency (η)	14.91%



(a)



(b)

Fig. 2 (a) PV module with L shaped Fins. (b) dimensions of the PV module with L shaped fins.

Temperature readings were taken using 18 calibrated digital thermometers with an accuracy of ±0.5°C. For calibration, a mercury thermometer was employed, as seen in Fig. 3. Each PV panel included two thermometers on the back and three on the front (Fig. 1). Two thermometers detected the ambient temperature close to the fins, and six thermometers tracked the temperatures of the fins (three per fin, Fig. 2). The overall ambient temperature was recorded using a different thermometer. A DIY voltage sensor and an ACS712 current sensor were used to measure the electrical current and voltage, respectively. A WH-SP-WS01 anemometer was used to measure the wind speed. The panel tilt was used to align a YGC-JYZ pyranometer, which monitored solar radiation (0–1500 W/m², ±3 W/m²). An Arduino UNO was used to log data in real-time, with each minute being stored into an 8 GB memory drive. To guarantee precise voltage and current readings as well as system security, two 100 W, 6-ohm power resistors were utilized. The experiments were conducted over many days from 8:00 to 16:00 for validation. Instrument characteristics and uncertainties are described in Table 2.

Table 2. Types, ranges, units and uncertainties of each measurement instrument.

Item	Type/model	Range	Accuracy	Units
Digital Thermometer	DS18B20	-55 to 125	±0.5	°C
Voltage sensor	Module 25 V	Up to 25	0.02445	V
Current Sensor	ACS712	Up to 20	0.04	A
Pyranometer	YGC - JYZ	0-1500	±3	W/m²

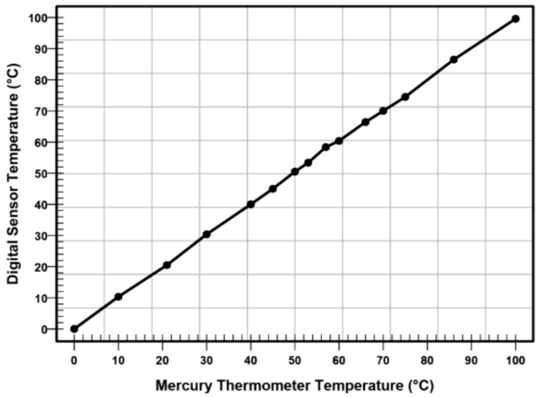


Fig. 3 The Calibration of Thermometer.

3. DATA REDUCTION

The maximum power output in Watts is calculated using the maximum power point voltage and maximum power point current, both collected by the data logger, as illustrated in the following equation [21][3]:

$$P_m = I_{mp} \times V_{mp} \quad (1)$$

Where:
I_{mp}: maximum power current, Amp.
V_{mp} : maximum power voltage, Volts.

The electrical efficiency is defined as the ratio of the maximum power output to the solar energy incident on the surface area of the photovoltaic panel, as expressed in the following formula [22] [23]:

$$\eta_{el} = \frac{P_m}{G \times A_p} \quad (2)$$

where:
G represents solar radiation intensity, W/m^2.
A_p is the Area of the photovoltaic module, m^2.

4. UNCERTAINTY ANALYSIS

To analyze the uncertainty of electrical efficiency and power, electrical power is to be articulated in terms of voltage V and current I. Consequently, the uncertainty of the output electrical power is determined as [24]:

$$\frac{W_P}{P} = \left[\left(\frac{W_V}{V}\right)^2 + \left(\frac{W_I}{I}\right)^2\right]^{1/2} \quad (3)$$

The electrical efficiency can be determined using [16]:

$$\frac{W_\eta}{\eta} = \left[\left(\frac{W_V}{V}\right)^2 + \left(\frac{W_I}{I}\right)^2 + \left(\frac{W_G}{G}\right)^2\right]^{1/2} \quad (4)$$

The uncertainties of V, I, P, G, and η are denoted by w_V, w_I, w_P, w_G , and w_η, respectively, in equations (3) and (4).

The uncertainty estimates for power output and electrical efficiency are 1.4% and 1.41% , respectively, due to measurement data.

5. ECONOMIC ANALYSIS

This section evaluates the cost-effectiveness of several solar systems in this study, including a typical PV module, passive cooling, and passive cooling with a reflector.

The critical economic evaluation criterion is the Cost of Energy (COE), which primarily depends on the Life Cycle Cost (LCC) defined by[25]:

$$LCC = C_{capital} + C_{operating} \quad (5)$$

where $C_{capital}$ denotes the capital expenditure for all equipment, including the system design and installation. $C_{operating}$ encompasses the total operating and maintenance expenses incurred throughout the year. The energy cost unit for the system's production can be approximated as follows [26],[27]:

$$COE = \frac{LCC}{\sum_1^N E_{PV}} \quad (6)$$

In Eq. (6), N represents the years for the life cycle cost. The other measure is Net Present Value (NPV), utilized to determine the net profit produced by the plant.

E_{PV} represents the annual energy production of the photovoltaic system, as indicated by the following relation, [28]:

$$E_{PV} = A_{PV} \sum_{n1=1}^{8760} P_{(n1)} \quad (7)$$

When n_1 denotes the hour number, P(n_1) represents the electrical output of the photovoltaic system at hour n_1, and A_{PV} signifies the active area of the photovoltaic array.

The economic benefit of the planned plant is realized when the NPV is positive, which may be computed as follows,[29][30]:

$$NPV = \sum_{t=0}^{N} \frac{Revenue}{(1+i)^t} - InitialCost \quad (8)$$

where N represents the plant's lifespan, t denotes the year, and i signifies the interest rate. The annual income estimation is derived as follows, [27][31]:

$$Revenue(year = i) = EnergyProduced \times EnergyPrice \quad (9)$$

The Payback Period (PBP) is the duration necessary for repaying the initial investment, [32]:

$$Payback\ Period\ (PBP) = \frac{Initial\ Investment}{Annual\ Cash\ Flow\ (Net\ Savings)} \quad (10)$$

6. ENVIRONMENT ANALYSIS

Photovoltaic (PV) panels are an effective method for reducing CO_2 emissions, promoting energy sustainability, and generating clean, renewable energy. These technologies significantly reduce the carbon footprint by replacing electricity from fossil fuels, thereby reducing the overall carbon footprint. The calculation of CO2 emission avoidance is straightforward [33].

$$CO_2\text{emission avoidance } = E_{PV} \times GI \quad (11)$$

Where GI is the greenhouse gas intensity in $kgCO_2/kWh$

Energy Payback Time (EPBT) is a crucial metric for assessing the sustainability of renewable energy systems like photovoltaics. It measures the time it takes for a system to consume the same amount of energy throughout its life cycle, varying across different PV technologies[34]:

$$EPBT = \frac{Total\ Embedded\ Energy}{Annual\ Energy\ Output} \quad (12)$$

7. RESULTS AND DISCUSSIONS

This section presents and analyzes the experimental findings. The measurements were recorded from 08:00 to 16:00 on two clear days, February 24th and 27th, 2025, at the rooftop of the Presidency Building at the University of Zakho, Iraq (latitude 37.1° N). The experimental tests were conducted on multiple days, and the best-performing days were selected for detailed analysis. The purpose was to determine the most effective strategy for photovoltaic (PV) modules, evaluating two methods: cooling alone and cooling combined with a reflector, compared to a reference PV module. The two test scenarios are described as follows:

Scenario I:
This study investigated the effects of passive cooling technologies on the efficacy of solar panels. It utilized L-shaped aluminum fins to do this.

Scenario II:
The performance of the photovoltaic module was examined in relation to a reflector and the fin cooling technique. An aluminum reflector was utilized in front of the photovoltaic module to achieve this.

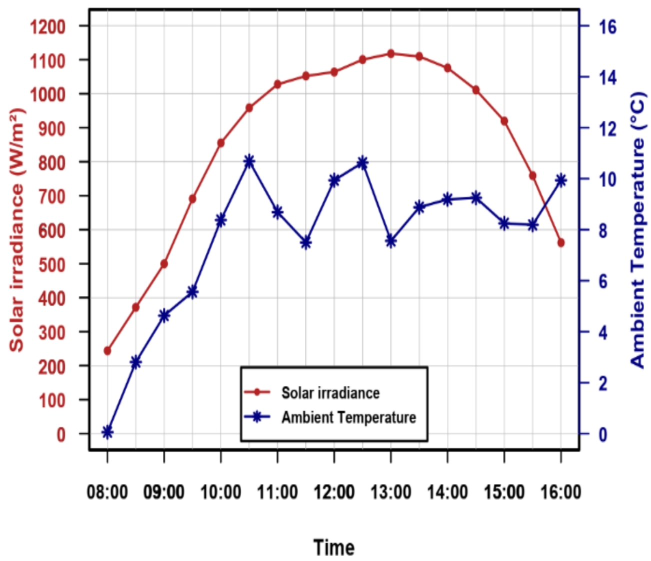
Table 3 presents a comparison of the efficiency improvements between the findings of the current study and those reported in previous investigations, emphasizing the efficacy of the present methodologies. The comparisons demonstrated a reasonable agreement with prior studies. The distinction between the current study and others arises from the variability of geographical and environmental factors.

Table 3. Valditation of the present work.

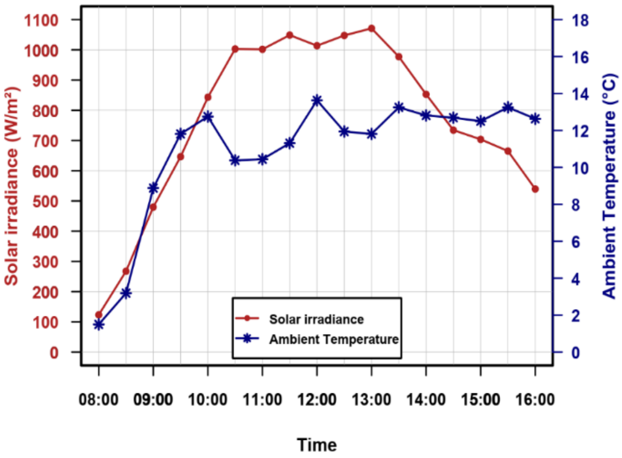
Authors	Method of cooling	% Increase in efficiency
Present work	L-shaped aluminum fins	12%
Soliman et al [35]	Aluminum plate fins	16 %
Hamdan et al [6]	L-shaped aluminum fins	8.9%
Hasan [36]	Rectangular aluminum fins	13.2%
Farhan et al [7]	Longitudinal aluminum fins	15.3%
Akyol et al [37]	Aluminum fins	8.77%
Zhao et al [11]	Fins cooling	16%

7.1 Energy Performance Results

Fig. 4(a) and Fig. 4(b) show the hourly variations of ambient air temperature and solar radiation intensity between 08:00 and 16:00 on two clear days, February 24 and 27, 2025.



(a)



(b)

Fig.4 Variation of ambient temperature and solar irradiance on the (a) 24th Feb. day and (b) 27th Feb. day.

The ambient temperatures are low. The intensity of solar radiation peaks between 11:30 and 13:30, then diminishes prior to nightfall.

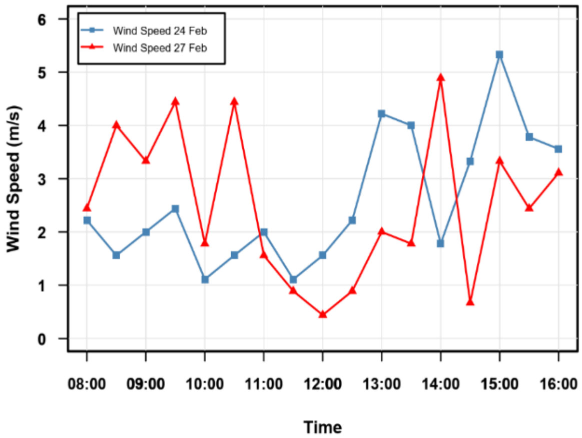
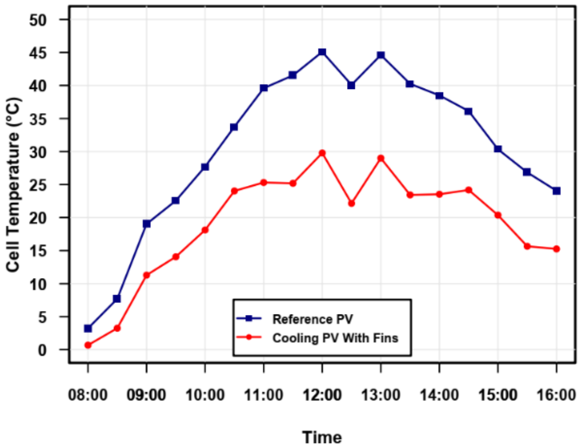


Fig. 5 Variation in wind speed on the 24th Feb. and 27th Feb. test day.

Fig. 5 depicts the wind velocities from 08:00 to 16:00 over two days. The wind speed varied between 0.5 and 5 m/s as a result of the installation of the experimental apparatus on a tall building.

Fig. 6 depicts the temperature variations of PV panels over time for Scenarios I and II. In Scenario I, both the reference and fin-cooled panels begin at low temperatures at 08:00, 3°C and 1°C, respectively. Maximum sun irradiation causes temperatures to peak between 12:00 and 13:00. The reference panel reaches 45°C, while the cooled panel reaches 29.78°C. The L-shaped fins lower the temperature by up to 15.31°C due to improved heat dissipation, natural convection, and greater surface area. The smallest decrease seen is roughly 5°C. Fig. 6(a) shows the largest temperature difference at midday. In Scenario II, depicted in Fig. 6(b), both the reference and cooled panels begin at low temperatures. By 11:00, the reference panel reaches 40°C, whereas the cooled panel with fins and reflector achieves 27°C, representing a 13°C decrease. Although Scenario II shows a somewhat lower decrease than Scenario I due to greater irradiation from the reflector, cooling remains successful, with temperature gaps averaging 10°C throughout the afternoon.



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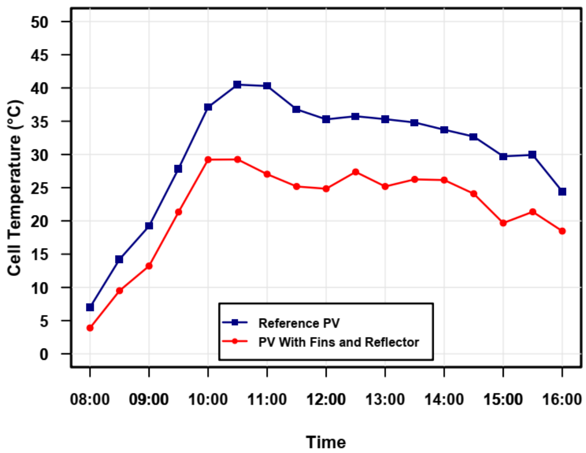
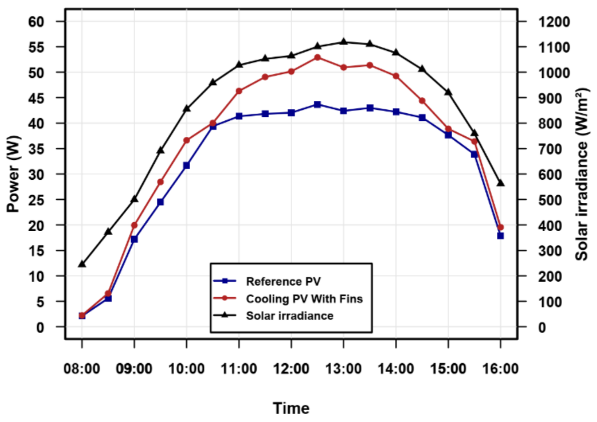


(b)

Fig. 6 Variations of PV module temperature on the (a) 24th Feb. day and (b) 27th Feb. day.

Fig. 7(a) and Fig. 7(b) present the variation in power output of photovoltaic (PV) modules between 8:00 and 16:00 for two enhancement methods, cooling fins alone and cooling fins combined with a reflector, compared with a reference PV module. In Scenario I (Fig. 7a), the cooled PV panel consistently delivers higher power output than the reference module throughout the test period, with the most significant improvement occurring between 11:00 and 14:30. In Scenario II (Fig. 7b), the PV panel equipped with both cooling fins and a reflector also outperforms the reference module during the entire period, again with the most notable difference between 11:00 and 14:30, and surpassing the performance achieved by fins alone. The maximum output powers recorded were 45.4 W for the reference PV, 52.91 W for Scenario I, and 55.03 W for Scenario II, corresponding to increases of 14.2% and 17.5% for the fins only and fins with reflector configurations, respectively. The improvement in Scenario I is attributed to temperature reduction via fins, which helps sustain higher voltage and current, thereby enhancing power output. In Scenario II, the reflector increases the incident solar irradiance, leading to greater photon energy and higher photocurrent generation, further boosting performance beyond cooling alone.



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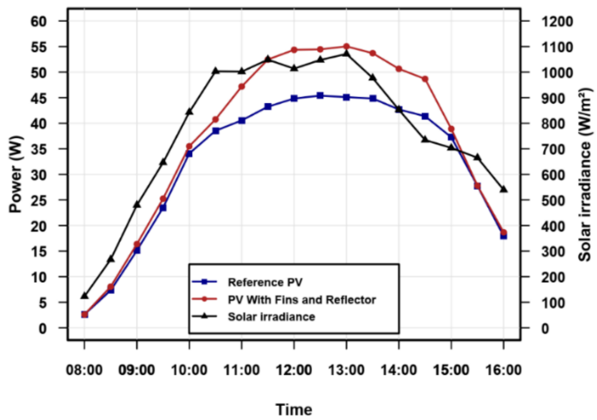
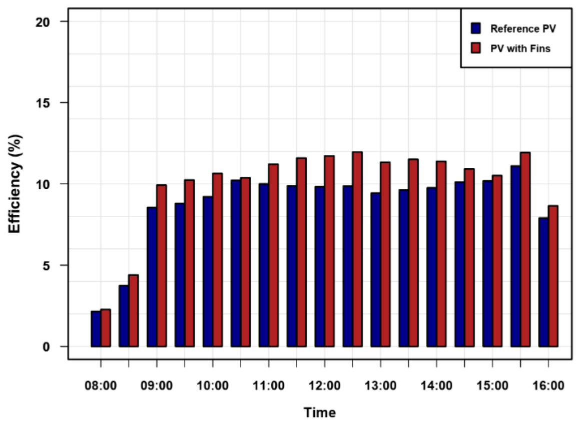


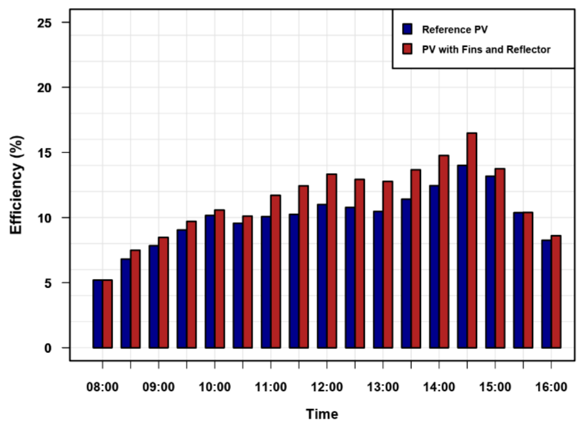
(b)

Fig. 7 Variations in the output electrical power on the (a) 24th Feb.day and (b) 27th Feb.day.

Fig. 8 (a) and Fig. 8 (b) show the variation of the electrical efficiency of photovoltaic (PV) panels over time for two scenarios, from 08:00 to 16:00. With the use of cooled-fins, the efficiency of PV panels improves, compared to the reference PV panel. For the reference PV panel, electrical efficiency increases at 10:30 AM and remains relatively constant until 15:30. The cooled-fins improve the PV panel's electrical efficiency to about 12 % from 11:30 to 14:30. PV efficiency decreases with rising temperature, which affects the current-voltage characteristics. Cooling panels improve conversion efficiency by maintaining cell temperature near 25°C, reducing losses. Furthermore, in Fig 8 (b), the improved PV system with fins and reflectors reaches a significant efficiency peak of 16.5 %, indicating that the addition of the fins and reflector enhances the efficiency of the PV panel by about 3 % during the time 11:00 to 14:00. The reflector enhances the incident power; however, if the output power does not increase appropriately (due to thermal losses), efficiency may plateau or decline.



(a)



(b)

Fig. 8 Variations of the electrical efficiency with the time on the (a) 24th Feb. day and (b) 27th Feb. day.

The energy performance indices (panel temperature, output power, and electrical efficiency) are compared for two scenarios under varying solar irradiation (200 to 1100 W/m²), as seen in the Fig. 9. The cooling fins substantially lower the temperature of the photovoltaic cell across all solar irradiation levels. In scenario I, illustrated in Fig. 9 (a), the cell temperature decreases by roughly 3.5°C at 200 W/m², and 8.5°C at 700 W/m², then increases to around 15°C at a higher intensity of 1100 W/m². This behaviour indicates that the fins play a crucial function in dissipating heat from the panel over time, and the fluctuation in the panel temperature reduction results from the impact of additional meteorological data. In scenario II, the fins facilitate heat dissipation, hence lowering the panel temperature, whereas the reflector elevates the panel temperature due to its reflectivity. The average temperature decline varies from 2.5°C to 10°C, contingent upon the level of irradiance. Fig 9 (b) illustrates the impact of cooled-fins on the photovoltaic power output under varying solar irradiation intensities for scenario I. The fins improve efficiency and result in a power boost by effectively reducing the panel temperature throughout all solar irradiations (200 – 1100 W/m²). This improvement achieves approximately a 16% enhancement compared to the reference photovoltaic system at 1100 W/m².

In scenario II, the power output of the photovoltaic panel with fins and a reflector is compared to that of the reference photovoltaic panel as solar irradiance increases from 200 to 1100 W/m². The reduced cell temperature of the fin and the reflector increase the incident solar radiation on the panel, hence enhancing power generation. The improved system exceeds the benchmark photovoltaic (PV) system at all solar irradiance levels, attaining almost 18% advantage at 1100 W/m². In scenario I, Fig. 9 (c), the photovoltaic reference electrical efficiency varies between 9% and 10%. The cooled-fins improved electrical efficiency to 12% under high irradiation circumstances. Cooling fins reduce efficiency degradation caused by heat by decreasing the module's temperature. In scenario II, it is shown that the PV panel with fins and a reflector demonstrates significantly more efficiency than the reference, with efficiency improving more rapidly as irradiance escalates. At high irradiation levels, the incorporation of cooling fins and a reflector significantly improves photovoltaic efficiency. by approximately 0.5% to 1% within the 400 - 700 W/m² spectrum, escalating to about 2.5% when solar radiation exceeds 900 W/m².

7.2 Economic Results

This section utilizes actual climatic data to analyze a 5-kW power output from a photovoltaic solar system designed to generate electricity for a residence. It employs a reference photovoltaic module, a cooled-fins photovoltaic system, and a cooled-fins photovoltaic system with a reflector. The yearly electricity output per square meter for the reference, cooled-fins, and cooled-fins with reflector are 7705.9, 8756.3, and 9882.49 kWh/year, respectively.

Table 4 includes three solar systems: Case I (reference photovoltaic system), Case II (photovoltaic system with cooled-fins), and Case III (photovoltaic system with cooled-fins and reflector).

Table 4. PV module cost details.

Item	Cases		
	Case I	Case II	Case III
Initial cost, USD	5000	5200	5400
Salvage, USD	150	156	162
Maintenance and operation	13 USD/kW-year		
Yearly Energy production, MWh/year	7.706	8.756	9.883
Annual Revenue, USD/year	770.592	875.63	988.25
System Lifetime, years	20	20	20
Payback Period, years	6.5	5.9	5.5
Net Present value (NPV), USD	3731	4839.93	6043.42
COE, USD/kWh	0.053	0.048	0.044
Energy saving, %	-	13.63	28.25

According to Table 4, the startup and operational costs for the reference, cooled-fins, and cooled-fins with reflectors are $5,000, $5,200, and $5,400, respectively. The exclusive utilization of fins results in a notable 13.63% increase in energy generation relative to reference photovoltaic (PV) systems, whilst the combination of fins and reflectors yields a 28.25% improvement compared to baseline PV panels. The use of fins reduces working temperature, thereby improving efficiency, while the reflector intensifies incident solar energy; both factors contribute to increasing generation. Furthermore, annual revenue increases proportionately with energy production, ascending from $770.59 with baseline PV to $875.63 in Case II and $988.25 in Case III. The payback period decreases from 6.5 years (Case I) to 5.5 years (Case III) as more efficient systems recover their investments more swiftly. In Case III, the Net Present Value (NPV) is maximized at $6,043.42, indicaing it provides the highest economic value over the system's duration after considering the discounting and costs. Moreover, the economic analysis reveals that in Zakho city, the cost per kWh is around $0.053, $0.048, and $0.044 for scenarios I, II, and III, respectively. Fins improve the energy efficiency of PV panels by reducing their operating temperature, leading to a modest increase in annual output. On the other hand, reflectors amplify energy input, leading to a significant increase in output. Enhanced energy efficiency yields more savings or revenue, facilitating accelerated payback. However. the return on investment is maximized only if the heat generated by the reflector does not substantially reduce efficiency.

7.3 Environment Performance

Table 5 illustrates the decrease in CO_2 emissions attained through the utilization of solar photovoltaic (PV) modules in Case I, Case II, and Case III.

Table 5. CO_2 reduction results.

CO_2 reduction	Cases		
	Case I	Case II	Case III
Annual CO_2 reduction, tCO_2/year	4.62	5.25	5.93
Lifetime CO_2 reduction, tCO_2	92.4	105	118.6

As seen in Table 5, a large advantage arises from utilizing photovoltaic systems with cooled-fins, as well as those with both cooled-fins and reflectors. Increased energy output from the same panel area results in reduced reliance on fossil fuels. Augmented energy generation correlates with improved carbon mitigation. Research indicates that even little efficiency improvements (1–3%) during a 20–25-year system lifespan can markedly decrease lifecycle emissions per kWh. Particularly vital in areas where the electrical grid mostly relies on carbon-intensive sources, such as diesel or coal.

The energy payback time (EPBT) for the solar photovoltaic (PV) system was determined for three distinct configurations: Case I, Case II, and Case III. The results indicate that Case I has an EPBT of 3.2 years, which decreases to 2.9 years for Case II, and further to 2.5 years for Case III, illustrating enhanced energy efficiency in Case III.

The incorporation of fins reduces panel temperature, hence improving electrical efficiency and producing 8 to 9 percent more annual electricity. The inclusion of aluminum somewhat elevates embodied energy, yet it compensates for this with enhanced energy yield over time. Reflectors improve the amount of solar radiation incident on photovoltaic modules, resulting in an increase in electricity generation of up to 10%. Fins control thermal regulation, ensuring optimal efficiency. The integrated system can yield an annual gain of 20%, while the rise in embodied energy is only slightly greater than that of fins alone.

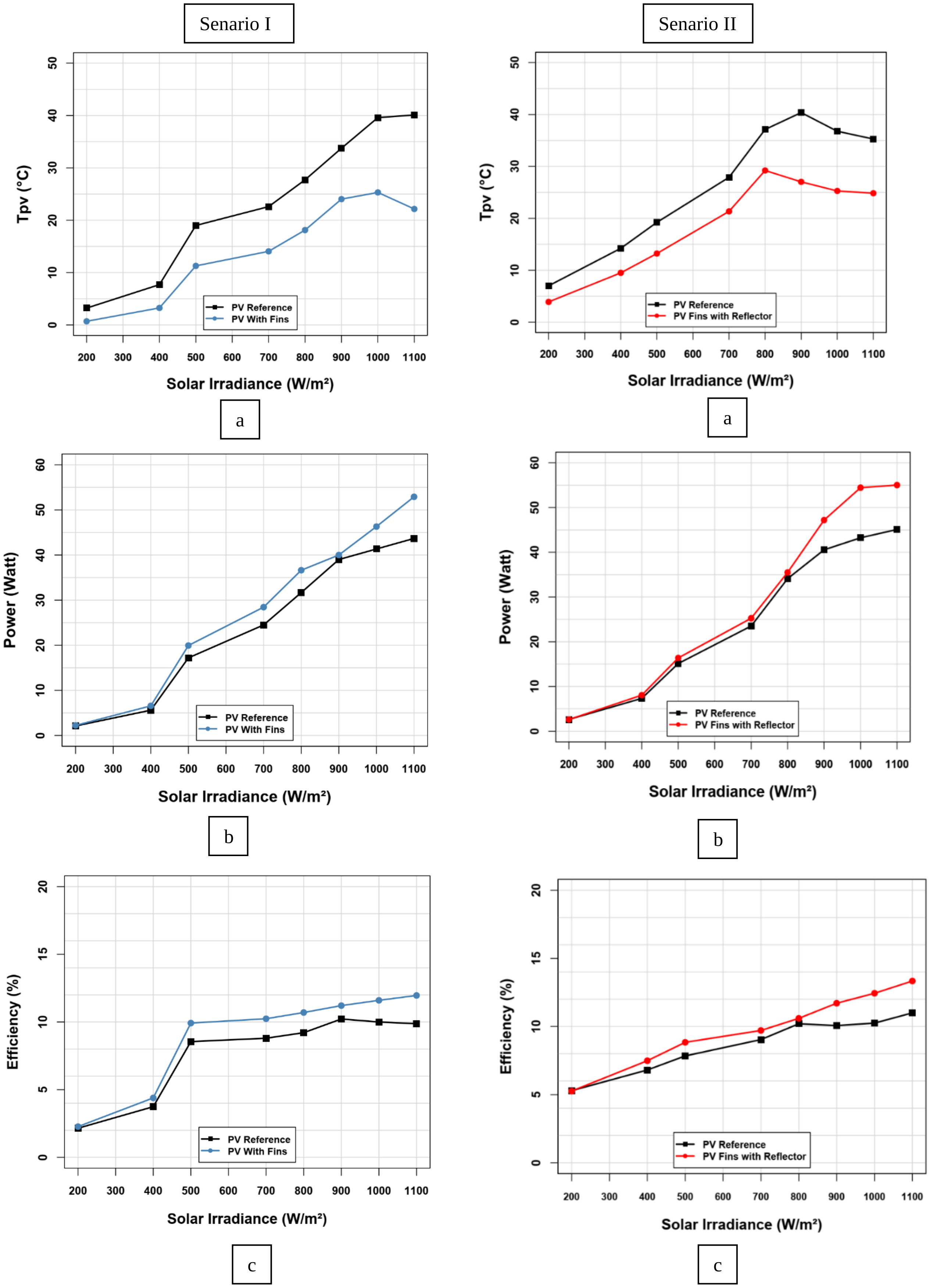


Fig. 9 Variation of the (a) Panel temperature, (b) power and (c) efficiency with solar irradiation

8. CONCLUSION

This study aims to enhance the power performance of a polycrystalline photovoltaic module by employing a booster reflector and a passive cooling system. The study experimentally investigates two scenarios under the winter meteorological circumstances in Zakho, Iraq: the first utilizes fins for passive cooling, while the second incorporates fins with a booster reflector to concentrate sunlight and improve efficiency. An economic and environmental evaluation was performed on the power usage of a typical residence across the three scenarios. From the experimental results of this study, the following conclusions were derived:

1. In Scenario I, the L-shaped fins achieved a maximum temperature reduction of around 15.31°C and a minimum of about 5°C, indicating efficient heat dissipation due to enhanced natural convection facilitated by the fins. In Scenario II, which had fins with a booster reflector, the maximum temperature reduction was roughly 13°C, while the minimum was around 3°C.

2. The study found that passive cooling using fins significantly improved power output in Scenario I, with a maximum output of 52.91 W, surpassing the traditional PV module's output of 45.4 W. In Scenario II, the use of fins with a booster reflector resulted in a 17.5% increase in power output, reaching a peak of 55.03 W.

3. In Scenario I, the exclusive use of cooling fins improved electrical efficiency to around 12%, in contrast to 10% for the reference photovoltaic panel. Scenario II, which incorporated fins with a reflector, improved efficiency, reaching a high of 16.5% compared to 14% for the reference module.

4. The integration of changes into solar systems increases energy output by 13.63% with fins alone and by 28.25% when combined with reflectors, relative to the reference PV panel. Enhanced energy production leads to a higher yearly revenue: 770.6 USD for the reference photovoltaic panel, 875.6 USD with the inclusion of fins, and 988.25 USD when both fins and reflectors are utilized, resulting in a reduction of the payback period from 6.5 years to 5.5 years with the usage of fins and reflectors.

5. The cost per kWh decreases from 0.053 USD in the reference scenario to 0.048 USD for cooled-fins and 0.044 USD for both fins and reflectors, indicating improved cost-effectiveness.

6. The yearly CO_2 reduction increases progressively from 4.62 tCO_2/year for the reference case to 5.25 tCO_2/year for cooled-fins, and 5.93 tCO_2/year for both fins and reflectors, demonstrating that system improvements augment energy production while concurrently promoting greater carbon emissions reduction.

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DECLARATION OF COMPETING INTEREST
The authors declare that there are no conflicts of interest.

NOMENCLATURE
P_m Maximum Power Output (W).
I_m Maximum Current Output (A).
V_m Maximum Voltage Output (V).
I_{SC} Short circuit Current (A).
V_{OC} Open circuit Voltage (V).
G Solar radiation intensity (W/m^2).
A_P Module Area, (m^2).
w_V Voltage uncertainty (%).
w_I Current uncertainty (%).
w_P Power uncertainty (%).
w_G Solar irradiance uncertainty (%).
w_η Electrical efficiency uncertainty (%).
$C_{capital}$ Capital costs (USD).
$C_{operating}$ Operating costs (USD).
E_{PV} Annual energy production (kWh/year).
n_1 Number of hours (h).
P(n_1) Electrical output at hour n_1 (kW).
N The plant's lifespan (Years).
t Year.
i The interest rate (%).
GI Gas intensity (kgCO_2/kWh).

ABBREVIATIONS
PV Photovoltaics.
LCC Life cycle cost (USD).
COE Cost of energy (USD/kWh).
NPV Net present value (USD).
PBP The payback period (Year).
EPBT Energy payback time (Year)
STC Standard test conditions.
DOE Design of experiment.

GREEK SYMBOLS
η_{el} Electrical efficiency (%).
η Module efficiency (%).
β Temperature coefficient (%/ºC).

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