Maximizing PV Efficiency:A Combined Approach Using Reflectors and Heat Exchanger

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Abstract. The Solar energy is a globally prominent renewable resource, particularly in regions like ADRAR, South Algeria, which experiences high irradiation (around 5.8 kWh/m2). The efficiency of photovoltaic (PV) systems is often limited by their non-linear electrical characteristics and high operating temperatures. This study investigates the effectiveness of an integrated Photovoltaic/Thermal (PV/T) system combining concentrator Bi-reflector to increase solar flux and a plate heat exchanger for active cooling and heat recovery. Experiments conducted under real-world ADRAR conditions demonstrated that the Bi-reflectors enhanced illumination while the cooling system absorbed excess heat. This dual approach successfully maintains electrical efficiency by keeping the panel temperature low and simultaneously provides a useful thermal output (heated water). The results conclusively show that the integrated Bi-reflector and heat exchanger system significantly increases the overall electrical and thermal performance of the PV generator, representing a promising strategy for optimizing PV energy generation and developing efficient PV/T systems in high-irradiance desert environments.

Keywords: Photovoltaic/Thermal (PV/T), Solar Concentration, Bi-reflector, Active Cooling, Heat Exchanger, PV Efficiency, Desert Environment, Thermal Management.

1 Introduction

The inevitable depletion of fossil fuels mandates the urgent shift to alternative energy sources [1]. Solar photovoltaic (PV) systems are a key, rapidly expanding component of the sustainable energy market, offering clean power generation. While solar radiation intercepted by Earth is vast, making solar the most promising resource of the 21st century, its current conversion efficiency limitations make solar-generated electricity more costly than conventional power. Conventional PV modules convert only about 20% of incident solar radiation into electricity, dissipating over 50% as excess heat [2]. Since the electrical output is proportional to solar radiation intensity, solar con-

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centration systems are a promising approach to enhance efficiency and reduce the cost of electricity. However, integrating optical concentrators, like bi-reflectors, to augment solar flux leads to elevated operating temperatures, which negatively impacts performance [3]. Research shows that a one-degree Celsius increase in cell temperature reduces efficiency by about 0.5%. Excessive heat also causes thermal stress, reducing the PV system's operational lifetime [4].
To address this, we propose a dual approach: combining optical concentration using bi-reflectors (which increases photocurrent and power output) with an active cooling system for temperature management. Building on validated research of planar reflectors, this study integrates a concentrator bi-reflector system with a plate heat exchanger to create a photovoltaic/thermal (PV/T) hybrid system. This system is specifically optimized for high-irradiance desert environments, such as the ADRAR region in southern Algeria.

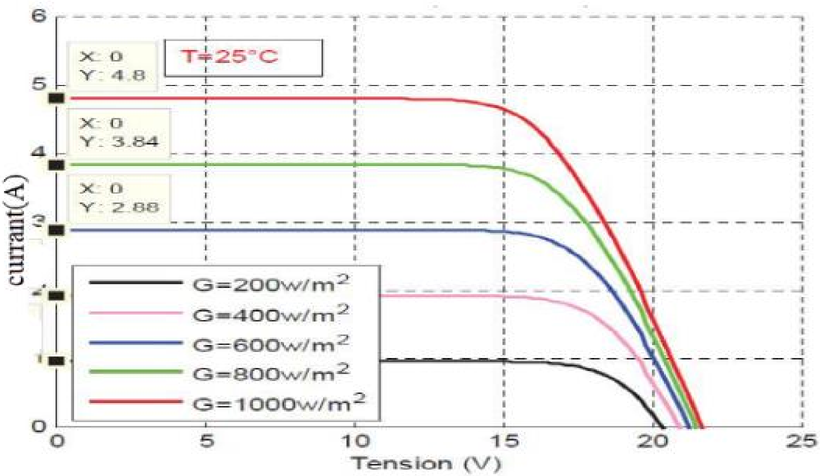

Fig. 1. I–V Characteristic as a Function of Illumination

While optical concentration enhances incident radiation, it simultaneously causes PV module temperatures to rise, leading to a decrease in power output and conversion efficiency, with sensitive crystalline silicon cells experiencing a significant loss of 0.4% to 0.5% per degree Celsius [5]. Consequently, an effective thermal management system is crucial to counteract the heat from concentrated sunlight. This study conducted a comprehensive experimental comparison of three PV configurations under real-world conditions in the high-irradiance ADRAR region: (1) a Baseline PV panel; (2) a Concentrator PV system with bi-reflectors (using cost-effective aluminum foil [6]); and (3) an Integrated PV/T System combining bi-reflectors with dual cooling mechanisms. The research aimed to define the optimal operational strategy for high-irradiance desert environments by comparing the output power, current-voltage characteristics, and thermal behavior across these three setups.

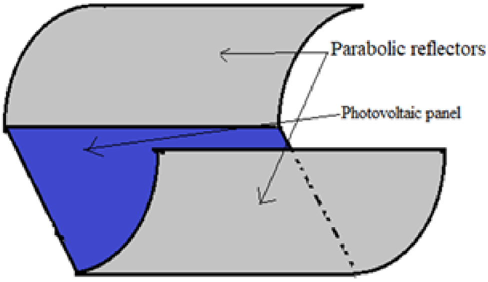

Fig. 2. Bi-Reflector Geometry

2 Proposed Cooling Techniques

The temperature sensitivity of PV cells stems from semiconductor physics: elevated operating temperatures reduce the bandgap energy [7]. This reduction primarily causes a drop in open-circuit voltage (Voc), which outweighs the slight increase in short-circuit current (Isc), resulting in a net reduction in cell efficiency. Therefore, effective thermal management is essential to maintain optimal operating temperatures and maximize electrical output. This investigation employs a dual, complementary cooling system applied to the PV panel's rear surface, combining passive and active mechanisms (Figure 3).

2.1 Integrated Passive and Active Cooling System

Thermal management systems are classified as passive (relying on natural heat transfer without external power) or active (requiring auxiliary power for superior, precise heat removal) [8, 9]. This study utilizes a synergistic integrated approach: the Passive Cooling Component consists of aluminum heat sinks mounted on the PV panel rear, providing power-free, foundational cooling by increasing the surface area for convective and radiative heat dissipation [10]. This is complemented by the Active Cooling Component: a closed-loop water circulation system using highly conductive copper tubing (≈400 W/m·K) [11], which is thermally bonded to the heat sinks. A pump circulates water to efficiently absorb heat, creating a Photovoltaic/Thermal (PV/T) hybrid system that both generates electricity and recovers usable thermal energy in the form of heated water, offering enhanced heat removal capacity and thermal energy recovery [12] [13].

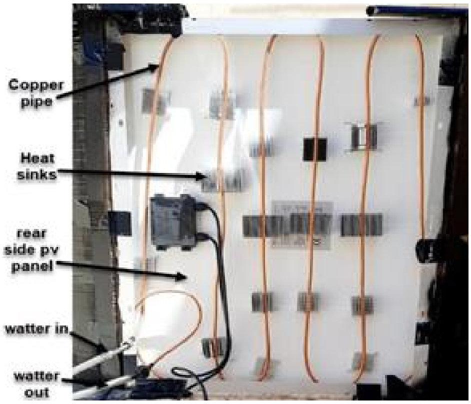

Fig. 3. Rear View of PV Module with Heat Sinks and Copper Cooling Pipes

3 Experimental Setup

3.1 Photovoltaic Module Specifications

The study utilized a commercially available polycrystalline silicon PV module with a nominal peak power (Pmax) of 150 Wp. The module's performance under Standard Test Conditions (STC) (1000 W/m2, AM 1.5, 25∘C cell temperature) is detailed in Table 1 [14], serving as the baseline reference for the experimental evaluations.

Table 1. PV Module Electrical Specifications (STC)

Parameter	Symbol	Value	Unit
Short-circuit current	I_sc	8.98	A
Open-circuit voltage	V_oc	22.54	V
Maximum power point voltage	V_mp	18.00	V
Maximum power point current	I_mp	8.34	A
Maximum power output	P_max	150	W
Standard Test Conditions	STC	AM 1.5, 25°C, 1000 W/m²	—

The module dimensions are 1480 mm × 680 mm, providing an active area of approximately 1.006 m². Electrical output parameters (voltage and current) were measured using precision digital multimeters with appropriate measurement ranges and accuracy specifications [15].

3.2 Mechanical Support Structure and Tilt Adjustment

The PV module was mounted on a custom-fabricated adjustable mechanical support structure consisting of a fixed base frame and a movable upper section. This configuration enables precise angular adjustment of the module inclination relative to the horizontal plane, with tilt angles ranging from 0° to 90°. The adjustable mounting system facilitates optimization of the solar incidence angle and allows investigation of reflector performance across various orientations [16].

3.3 Bi-Reflector Configuration

The experimental setup utilized two reflectors (1480 mm×600 mm each), constructed by adhering aluminum foil to rigid substrates. The foil provides diffuse solar reflection, redirecting both direct and scattered radiation onto the PV module surface [17]. Mounted symmetrically using adjustable positioning brackets (Figures 4 and 5), the reflector geometry was selected to ensure a quasi-uniform flux distribution and minimize optical losses [18]. This bi-reflector configuration successfully increases the concentration ratio, augmenting incident solar irradiance beyond ambient levels, thereby enhancing current generation and electrical output power.

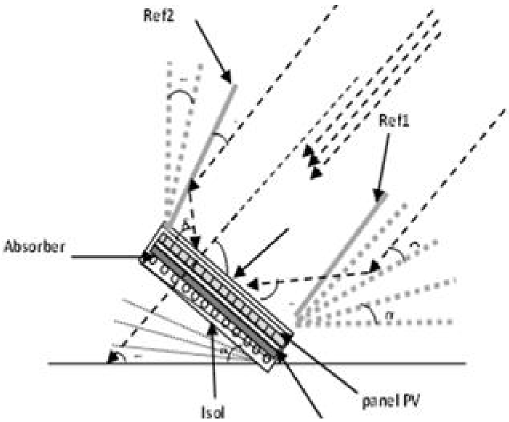

Fig. 4. Schematic of Integrated PV/T System with Bi-Reflectors and Cooling.

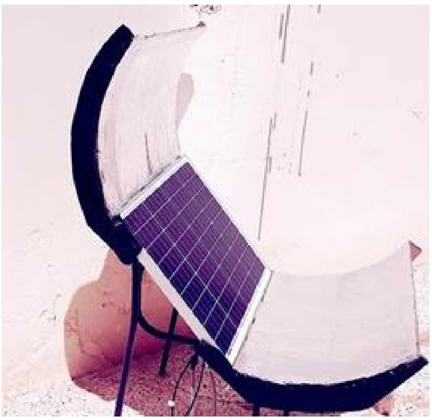

Fig. 5. Outdoor Experimental Setup with Bi-Reflectors

3.4 Experimental Configurations and Measurement Protocol

The experimental evaluation compared the performance of three distinct system configurations simultaneously under identical environmental conditions (Figure 6): (1) Baseline: Standard PV panel without reflectors or cooling; (2) Optical Enhancement: PV panel with bi-reflectors; and (3) Integrated PV/T: PV panel incorporating bi-reflectors and the dual cooling system (heat sinks + water circulation). Comprehensive measurements were acquired at regular intervals throughout the diurnal cycle to capture performance across varying irradiance and temperature conditions in the ADRAR desert region. The monitored parameters included: Module surface temperature (Tpv) (via K-type thermocouples), output current (I) and voltage (V), ambient temperature (Tamb) and solar irradiance (G) (via meteorological sensors), and the water inlet (Tin) and outlet (Tout) temperatures for the cooling system in the Integrated PV/T configuration.

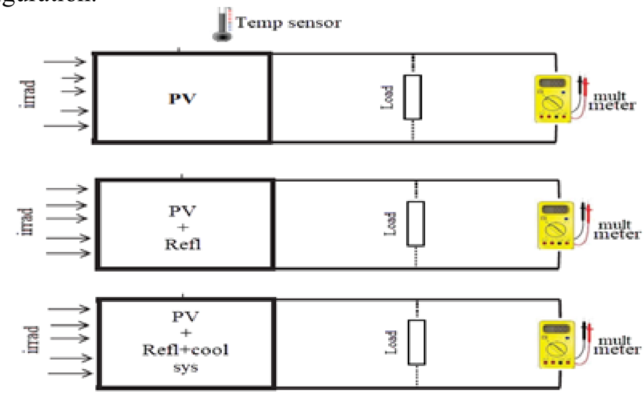

Fig. 6. Flowchart of Comparative Experimental Methodology

4 Results and Discussion

Comparative experimental measurements were conducted to evaluate the performance characteristics of the three system configurations under identical environmental conditions. The key performance parameters analyzed include module surface temperature, short-circuit current, open-circuit voltage, and electrical power output. The experimental results demonstrate significant performance variations among the baseline, optically enhanced, and thermally managed PV systems.

4.1 Thermal Performance Analysis

Figure 7 illustrates the temporal evolution of PV module surface temperature (Tpv) from 08:00 to 15:30. The Baseline configuration (no reflectors/cooling) showed a moderate temperature range, peaking at 45∘C around 13:00. The Bi-reflectors Only configuration resulted in substantially higher operating temperatures, reaching a maximum of 52∘C at peak irradiance, a 7∘C increase compared to the baseline. Crucially, the Integrated PV/T configuration (bi-reflectors + cooling) successfully controlled the temperature, maintaining Tpv within the range of 25∘C to 39∘C. At the critical 13:00 peak, the cooling system reduced the temperature from the 52∘C seen in the reflectors-only setup to 38∘C, achieving a significant temperature reduction of 14∘C. This conclusively demonstrates that the integrated thermal management approach effectively mitigates the adverse thermal effects induced by concentrated solar radiation.

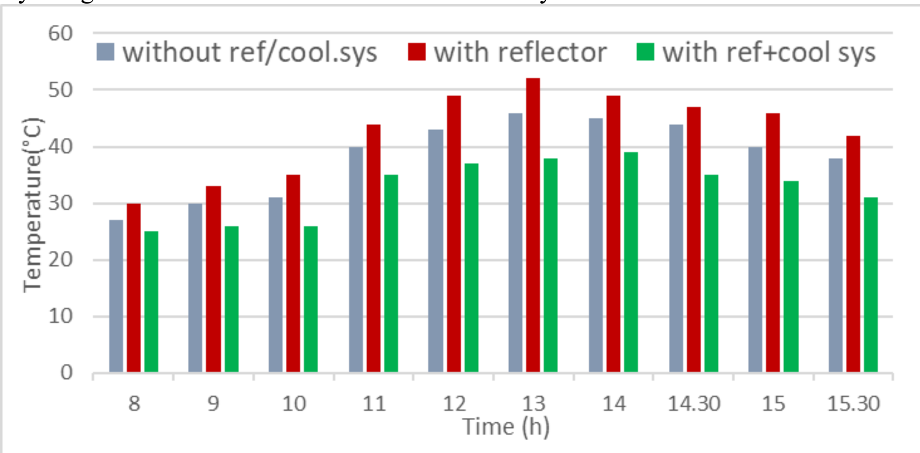

Fig. 7. Temporal Variation of Module Surface Temperature (Tpv)

4.2 Infrared Thermography Analysis

Infrared thermal imaging (Figure 8) was used to visualize the spatial temperature distribution and quantify the effectiveness of the thermal management system. The thermographic images showed that the module with Bi-reflectors Only (Figure 8(b)) suffered from extensive high-temperature regions, with surface temperatures exceeding 37.5∘C across large areas and peak temperatures reaching the measured 52∘C. This confirmed non-uniform heating due to increased flux without adequate dissipation. In stark contrast, the Integrated PV/T System (Figure 8(a)) demonstrated substantially lower and more uniform module temperatures, with most of the surface remaining below 35∘C. The presence of cooler (blue-green) regions corresponding to the heat sink and copper tubing assembly clearly indicates enhanced heat removal and improved thermal uniformity. This uniformity is critical for both immediate performance enhancement and long-term module reliability by reducing thermomechanical stress.

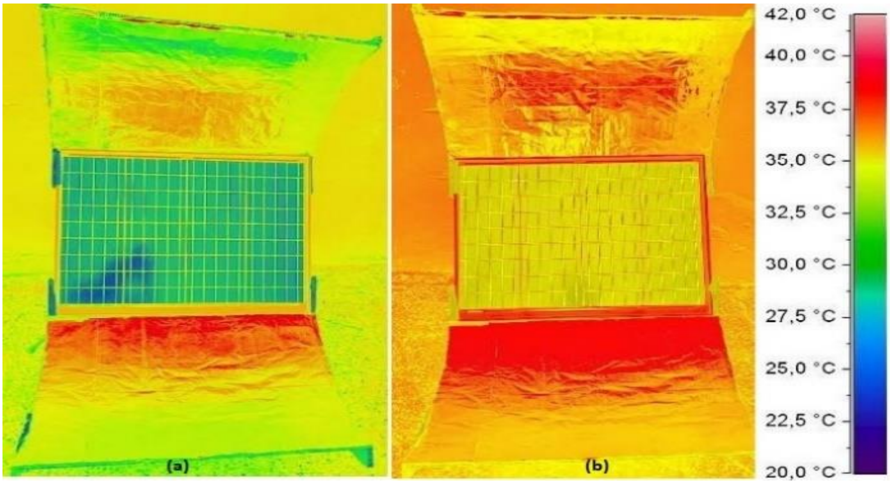

Fig. 8. Infrared Thermal Images: (a) Integrated PV/T vs. (b) Reflectors Only

4.3 Electrical Current Characteristics

Figure 9 shows the measured panel current (I) over time for the three configurations. The Baseline module (no reflectors) generated current between 0.5 A and 5.5 A. The addition of Bi-reflectors significantly enhanced current generation, raising the operating range to 1.5 A to 8.0 A. This substantial increase, approximately 45% at peak conditions, is a direct result of the augmented incident solar flux provided by the reflectors. The Integrated PV/T System (reflectors + cooling) showed nearly identical current characteristics, ranging from 1.5 A to 8.3 A. This confirms that the cooling system does not adversely affect photocurrent generation. The marginal improvement observed with cooling (8.3 A vs. 8.0 A) is attributed to enhanced carrier collection efficiency resulting from the reduced operating temperatures.

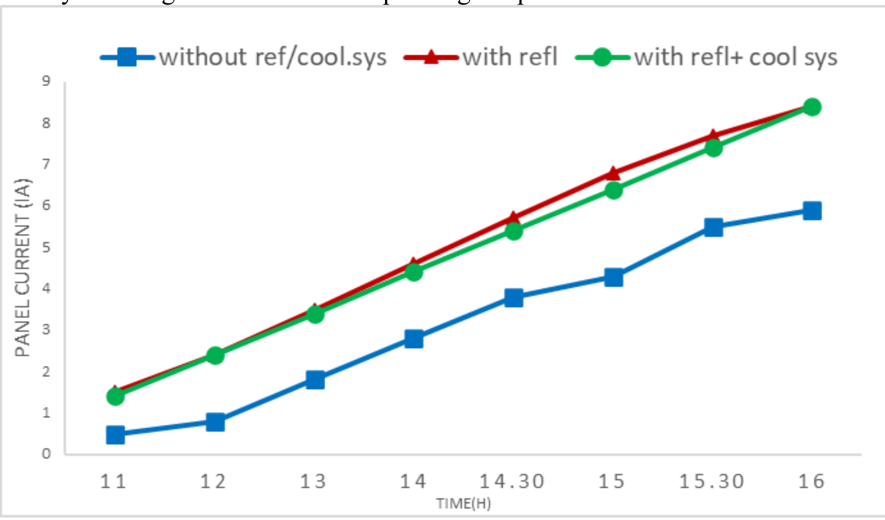

Fig. 9. Comparison of Panel Current Output (I)

4.4 Open-Circuit Voltage Analysis

The open-circuit voltage (Voc) measurements (Figure 10) show that thermal effects are the dominant factor affecting voltage. The Baseline configuration-maintained Voc between 17.5 V and 18.0 V. In sharp contrast, the Reflector-Only configuration exhibited severe voltage degradation, ranging from 10.5 V to 13.0 V, a 28%–33% reduction compared to the baseline. This voltage depression is directly caused by the elevated module temperature (up to 52∘C), which reduces the semiconductor bandgap in crystalline silicon cells. Crucially, the Integrated PV/T System (with cooling) dramatically reversed this degradation, recovering Voc to a range of 11.0 V to 18.0 V. During peak solar irradiance (13:00-15:00), the cooled system-maintained Voc above 15.0 V, yielding a 20%–40% voltage recovery compared to the uncooled reflector setup, proving the critical importance of thermal management in concentrator PV applications.

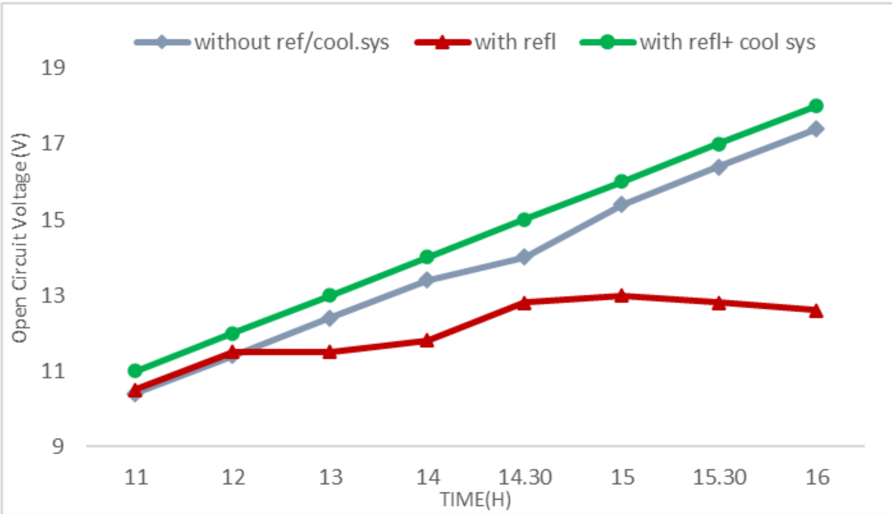

Fig. 10. Temporal Profile of Open-Circuit Voltage (Voc)

4.5 Power Output Performance

Figure 11, which integrates current and voltage behavior, provides the comprehensive metric for overall system performance. The Baseline PV module generated power between 105 W and 117 W. Implementing Bi-reflectors Alone improved the power output to 125 W to 139 W, an enhancement of 15%–19% over the baseline. However, this gain was significantly hindered by the substantial voltage degradation caused by elevated operating temperatures. The Integrated PV/T System (reflectors + cooling) achieved the most significant enhancement, maintaining power output between 139 W and 150 W. At peak solar conditions, this configuration nearly reached the module's rated capacity of 150 W, representing a performance improvement of approximately

25%–28% compared to the baseline and 8%–10% compared to the reflector-only setup.

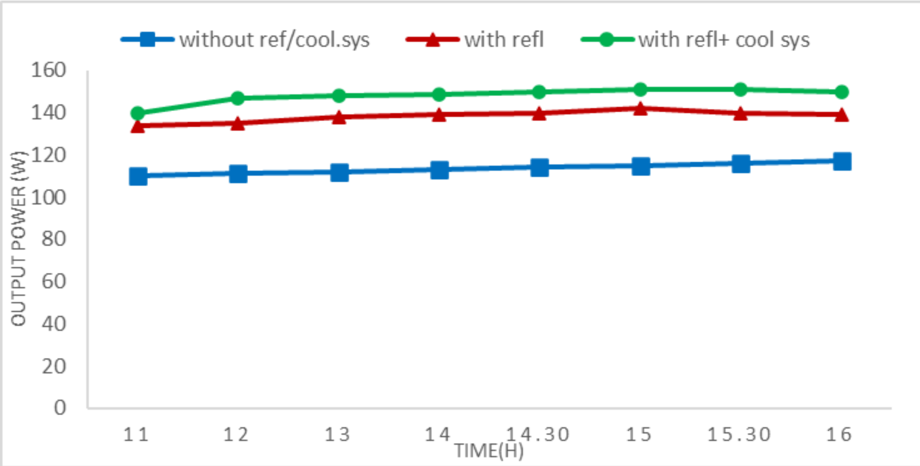

Fig. 11. Comparison of Electrical Power Output (P)

4.6 Performance Enhancement Summary

The experimental results conclusively validate the proposed integrated approach, which combines bi-reflectors with dual cooling (passive heat sinks and active water circulation), successfully resolving the inherent trade-off in concentrator photovoltaics between increased flux and elevated temperatures. Key findings demonstrated: Thermal Control by achieving a 14∘C temperature reduction (from 52∘C to 38∘C) at peak irradiance; Current Enhancement showing a 45% increase in photocurrent (from 5.5 A to 8.0 A) due to concentration; Voltage Preservation through thermal management, recovering 20%–40% of voltage loss and maintaining Voc above 15 V; and Power Output Optimization resulting in an overall electrical power improvement of 25%–28% compared to the baseline, nearly reaching the module's rated capacity under field conditions. Furthermore, the system provides the additional benefit of thermal energy recovery via heated water production, establishing a true PV/T hybrid system with dual energy outputs. This validates the approach as a promising strategy for optimizing solar energy generation in high-irradiance desert environments.

5 Conclusion

This investigation conclusively demonstrates the synergistic benefits of combining bi-reflectors (optical concentration) with an integrated dual cooling system (passive heat sinks and active water circulation) to enhance the performance of a 150 Wp crystalline silicon PV module in the high-irradiance desert environment of ADRAR, Algeria. While bi-reflectors alone achieved a substantial 45% photocurrent increase (from 5.5

A to 8.0 A), the resulting high temperature (52∘C) caused significant 28%−33% open-circuit voltage degradation, limiting the overall gain. The integrated cooling system provided remarkable thermal control, reducing peak temperature by 14∘C (to 38∘C) and effectively preserving voltage, leading to a maximal 28% overall electrical power improvement (reaching 150 W) compared to the baseline. This optimized output stems from the combined effect of enhanced current via concentration and preserved voltage via thermal management. Furthermore, the system functions as a true PV/T hybrid, generating both electricity and useful thermal energy (heated water), increasing overall energy utilization efficiency. This research validates a cost-effective, dual-benefit strategy for overcoming performance limitations in high-irradiance zones worldwide, with future work focusing on quantitative thermal analysis, long-term durability assessment, and system parameter optimization to advance the technology toward commercial deployment.

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