

ORIGINAL ARTICLE OPEN ACCESS

Experimental Enhancement of Thermal and Electrical Efficiency in Concentrator Photovoltaic Modules Using Nanofluid Cooling

Yasser Elhenawy^{1,2,3}  | Kareem Fouad⁴ | Ahmed Refaat⁵ | Osama A. Al-Qabandi⁶ | Monica Toderaş⁷ | Mohamed Bassyouni⁸ 

¹Mechanical Power Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt | ²School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, South Africa | ³Center of Excellence in Membrane-Based Water Desalination Technology for Testing and Characterization, Port Said University, Port Said, Egypt | ⁴Civil Engineering Department, Higher Future Institute of Engineering and Technology, El Mansoura, Egypt | ⁵Electrical Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt | ⁶College of Engineering and Technology, American University of the Middle East, Egaila, Kuwait | ⁷Department of Physics, Faculty of Informatics and Sciences, University of Oradea, Oradea, Romania | ⁸Department of Chemical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia

Correspondence: Mohamed Bassyouni (m.bassyouni@eng.psu.edu.eg)

Received: 6 May 2024 | **Revised:** 19 November 2024 | **Accepted:** 2 December 2024

Funding: This work was supported by the University of Oradea pays the Article Processing Charges (APC).

Keywords: Al₂O₃ nanofluids | concentrator photovoltaic panels | efficiency improvements | environmental impact | heat transfer

ABSTRACT

Electricity production from photovoltaic panels is a clean and promising technology. However, increased panel temperatures resulting from solar intensity notably reduce productivity. Cooling these panels through diverse technologies becomes essential to enhance power generation and extend cell lifetime. In this study, electricity generation for concentrated photovoltaic (CPV) panels was enhanced by cooling with Al₂O₃/water nanofluid. An experimental analysis of the thermal and electrical efficiency of cooled and uncooled CPV was employed. Various loadings (0.3–0.9 wt%) of Al₂O₃ were utilized to investigate the effect of Al₂O₃ on overall performance. Each run was carried out at a flow rate of 1.0 L/min. The results showed that Al₂O₃/water nanofluid at a loading of 0.9 wt% resulted in a significant decrease in photovoltaic surface temperature. The temperature at the surface of CPV was significantly decreased by 52%. The electrical yield reached its maximum at 45 and 46 W/h using CPV without and with cooling water, respectively. The electricity generation was remarkably enhanced up to 54 W/h at 0.9 wt% Al₂O₃/water nanofluid. Electrical and thermal efficiency improved by 21% and 65%, respectively using 0.9 wt% of Al₂O₃. The total daily savings in CO₂ reached 0.35 kg/kW for 0.9 wt%, Al₂O₃.

1 | Introduction

Photovoltaic (PV) systems are highly sensitive to temperature increases which can significantly reduce their electrical efficiency and lifespan [1]. As solar intensity rises, the heat generated in PV modules leads to performance degradation, presenting a major challenge in optimizing solar energy production [2]. Effective thermal management is crucial for

maximizing the potential of solar energy, a key renewable resource in reducing reliance on fossil fuels and combating climate change [3]. Recent innovations including the use of nanofluids for cooling have shown considerable promise in mitigating these temperature-related issues, thereby enhancing the efficiency and durability of PV systems [4]. There are several strategies to generate power using solar energy. One method is to employ solar thermal power mechanisms, which heat a

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Authors. *Energy Science & Engineering* published by Society of Chemical Industry and John Wiley & Sons Ltd.

working fluid using solar energy and then use the heated fluid to operate a turbine engine [5]. Utilizing PV systems, which produce power entirely from sunlight, is a promising option. Since significant cost reductions in PV systems and improvements in component efficiency, the utilization of PV systems has expanded significantly over the past few decades [6]. However, only 12%–20% of the solar energy is transformed into electricity with the remainder raising the temperature of the panel. The module effectiveness is reduced by this greater temperature [7]. The PV panel's productivity is influenced by the solar cell's temperature, the weather, and other factors. A very small amount of sunlight reaching the panel is transformed into energy; the majority is lost as heat. Solar PV energy systems, first utilized in space applications are now widely applicable wherever electricity is needed [8, 9].

The worldwide demand for solar PV systems for generating power has grown significantly in recent years. According to the most recent data available, 102.4 GW of grid-connected PV panels were installed worldwide in 2018 which is equal to the total PV capacity available in the globe at the time (100.9 GW). Due to this outcome, there will be more than 500 GW of solar energy capacity available globally in 2018 [10]. As a result, as solar cells' temperature rises, their efficiency declines, and the panel becomes damaged [11]. High temperatures have a major negative influence on the effectiveness of solar techniques. As a result, many cooling procedures are used in the literature to lower PV panel temperatures and boost power yield. These cooling methods can be divided into six categories: evaporation, jet impingement, heat pipe, phase change material, spray, pipe, thermoelectric, fin, and PV/thermal systems [12]. Therefore, developing an efficient cooling method for PV panels is vital. Numerous studies have concentrated on the detrimental impact of temperature rise on PV panel efficiency decline. These studies have demonstrated that a 1°C increase in panel temperature can result in a 0.5% reduction in electrical efficiency [13]. Reduced operating temperature increases the solar cells' electrical output as mentioned before. The total quantity of electricity generated will also increase if the lifespan of P.V.s is also enhanced. It is widely believed that the bandgap of the material and the wavelength of the sun have a considerable impact on the PV panel's efficiency [14]. Owing to its enhanced thermal conductivity and improved specific surface area with the volume of fluid as compared to base fluids, nanoparticles in fluids are involved in diverse thermal applications. In thermal processes, thermal oil, water, deionized water, and mixtures of ethylene glycol are often used fluids. When it comes to enhancing the thermal performance of thermal purposes, nanofluids seem to be more effective. Although numerous nanoparticles are frequently utilized in thermal apparatus, their constancy and life cycle analysis are still up for debate [15]. In the nanofluid cooling strategy, the base fluid (BF) is incorporated with particles on a dimension of 10^{-9} m (nano-meter size) using the proper approach; the resultant fluid is denoted as the nanofluid, and as a consequence, the nanofluid's k value increases compared to the BF [16]. With better thermal properties (a higher heat transfer ratio), working fluids known as nanofluids enable the production of more usable heat. The use of nanofluid has become more prevalent in recent years, particularly in solar panels [17]. Graphene particles (GNP) were employed as a nanosized material for the cooling of PV panels.

According to this research, GNP nanofluids cooling exhibits the best effective performance, measured at about 42% when evaluated with water cooling with a solution flowing at a flowrate of 1.11 L/min, and a 54% improvement when referred to non-cooling at operating temperatures below 45°C [18].

TiO₂ and Al₂O₃ and water-based mixtures with varied volume flow rates and concentrations (0.01%, 0.05%, and 0.1%) by weight were utilized as the two sorts of nanofluids. TiO₂ nanofluids showed the most excellent performance at the examined concentration (0.1 wt%) [19]. Two nanofluids, SiO₂/water, and Al₂O₃/water were employed as cooling fluids for multijunction solar cells. The performance assessment, temperature distribution, and heat transfer efficiency were investigated. By employing SiO₂/water 2 at 5%, the device's total efficiency is enhanced by 3.82% at a Re of 8.25 [20]. Another study has investigated the performance of a coolant nanofluid containing zirconium oxide (ZrO₂) nanoparticles. The experimental study showed a reduction in the PV section by 10.2°C. Additionally, the PV module temperature has dropped by 5.1 C as a result of the DI water cooling. In comparison to PV units cooled by DI water, the total performances gradually rose with an improvement in volume concentration by 8.9%, 18.8%, and 24.4%, respectively. Exergy efficiency could be improved by 66.8% by using ZrO₂ nanofluids with 0.0275 vol%, while exergy losses and entropy invention could be decreased by 7% and 26%, respectively [21].

A study into the use of carbon black nanoparticles in water was conducted for PV cooling, and concentrations between 0 and 0.4 wt.% were evaluated. The carbon black/water nanofluid's cooling performance was remarkable, according to the results. This led to the ideal concentration being determined to be 0.21 wt%. This concentration resulted in the production of 7% greater electricity output when using pure water as the coolant and 54% extra power yield when using a conventional solar panel [22]. In another study, copper oxide-based nanofluid was employed for the cooling of a PV device. Uncooled PVT equipment had an average electrical performance of 12.98% and an elevated panel temperature of 68.4 C at noon. The PVT technique's water and nanofluid cooling significantly lowered the panel temperature at noon by 15 C and 23.7 C, respectively. The average electrical performance of the water- and nanofluid-cooled PVT systems improved by 12.32% and 35.67%, respectively, to achieve 14.58% and 17.61%, in comparison to the uncooled PVT device. Owing to the greatest heat absorption capacity of nanoparticles, when compared to water cooling, the thermal efficiency of the nanofluid-cooled PVT system (71.17%) was much higher [23]. Previous studies have explored the use of various nanomaterials as coolant agents for PV systems, demonstrating their potential to enhance thermal management and improve electrical efficiency. However many of these materials are associated with high costs, limiting their practical application. Among the different nanomaterials studied, Al₂O₃ stands out due to its favorable balance of cost-effectiveness and high thermal conductivity. These properties make it a promising candidate for PV cooling. While the benefits of nanofluids in improving PV performance have been documented, there is a need for more detailed investigations into the specific impacts of different nanofluid on concentrator PV (CPV) modules. Moreover, previous research often lacks a comprehensive

comparison between cooled and uncooled systems under controlled conditions leaving gaps in our understanding of the true efficiency gains achievable through nanofluid cooling.

Among the several nanomaterials investigated, Al_2O_3 stands out for its favorable cost-effectiveness and better thermal conductivity. These characteristics make it a good candidate for PV cooling. While the benefits of nanofluids in increasing PV performance have been reported, many studies lack full comparisons of cooled and uncooled systems under controlled settings generating gaps in an understanding of the efficiency. This work filled these gaps by proposing a unique cooling method in which the Al_2O_3 nanofluid was cooled by ambient air before being recirculated via the CPV system. This innovative technology was intended to improve cooling efficiency while reducing energy consumption providing a more sustainable and practical option for CPV thermal management. This study addressed these gaps by conducting an experimental analysis of CPV module performance using Al_2O_3 nanofluid at various concentrations. The cooling process included a novel approach where the nanofluid was cooled by atmospheric air before being recirculated through the CPV system. A direct comparison between cooled and uncooled CPV modules was performed to quantify the efficiency improvements in electrical output providing critical insights into the practical application of Al_2O_3 nanofluid for PV cooling.

2 | Experimental Test Rig

To explore the effect of the nanofluid on the overall effectiveness of CPV in an approach for direct contact cooling, a testing setup was established. Figures 1 and 2 show the photo of the employed PV system and a schematic representation of the testing operation. In the experimental study, ambient conditions were explored using a CPV unit with a V-shape that circulates nanofluid within the cooling conduits under the surface of the module. A 60-W polycrystalline conventional PV, made by Heckert Solar, Germany, was employed. The characteristics and electrical characteristics of the PV panel being tested under standard testing conditions are described in Table 1.



FIGURE 1 | Photograph of the experimental setup.

The CPV system was built by using two plan reflector mirrors 3 mm placed on both borders of the traditional PV module. The nanofluid cooling procedure was formed by folding a single 1.25 mm copper sheet and was then directly contacted underneath the CPV module. The angles of both reflector mirrors are set according to the basis of experimental research by both Tanaka [24] and Kostić [25], to achieve the appropriate estimate of the concentration of irradiance on the surface of the CPV module. The upper reflector was then located at almost a right angle with the horizontal axis, while the lower reflector was situated at a horizontal angle of 30°. Throughout the experiments, the solar panel was installed in a south-facing position and the inclination of the panel was positioned with respect to the earth at a 30° angle, to increase the level of irradiance knocking the solar unit exterior.

To eliminate the extra heat produced by the concentrating of solar radiation, Al_2O_3 /water nanofluid with varying concentrations of nanoparticles circulates via the cooling conduits beneath the V-CPV module, Figure 3. The Al_2O_3 /water nanofluid can control the operational temperatures of the CPV panel by providing continuous direct contact cooling, thus significantly enhancing the heat removal from the CPV module at the rear side. The heated nanofluid Al_2O_3 /water leaves the CPV system and is then guided to the 90 L reservoir for later usage. The heated Al_2O_3 /water nanofluid is transferred in a closed nanofluid loop to the inlet of the BHE where it can exhaust the thermal energy, which could launch a closed cooling process again for the CPV module. The AHE vertically, consists of 20 equivalent part 5 cm copper pipes designed to serve as a normal basin to dissipate the extra temperature of the heated Al_2O_3 /water nanofluid. A rotameter and an appropriate centrifugal pump are utilized to circulate the nanofluid of Al_2O_3 /water from a 90 L reservoir to the AHE entrance, and the flow rate varies in a closed circle through a series of by-pass regulation valves.

The rotameter was adapted utilizing a stopwatch as the standard weighting method and then using the approximate nanofluid density in the current research to achieve a precise nanofluid mass flow rate, the mass flow rate of the nanofluid also is accessed. The pre-cooled nanofluid leaving the AHE is subsequently directed to the entrance of the cooling conduit system for continuous cooling of the CPV module, the existing nanofluid is subsequently ordered back to the nanofluid tank entrance once again. The pre-cooled nano Al_2O_3 /water fluid leaving from the AHE is afterward directed to the cooling channel entry system for continuous cooling of the CPV module, and the nanofluid is subsequently redirected after leaving the cooling conduits, to the nanofluid tank inlet once again.

The dimensions of the rectangular cross-shaped cooling ducts were (150 × 90 × 12) mm and were entirely installed on the rear of the LCPV panel to guarantee uniformly effective cooling, the Al_2O_3 /water nanofluid inlet was positioned at the lower end and the outlet was positioned on the top border to ensure constant supplying of the conduits with circulated cooling fluid. Using 0.02 m thickness of polypropylene fibers, the cooling conduits used at the LCPV panel are isolated from its back to avoid transfer of heat with the atmospheric; epoxy resin is utilized to firmly connect the cooling transmit frame's

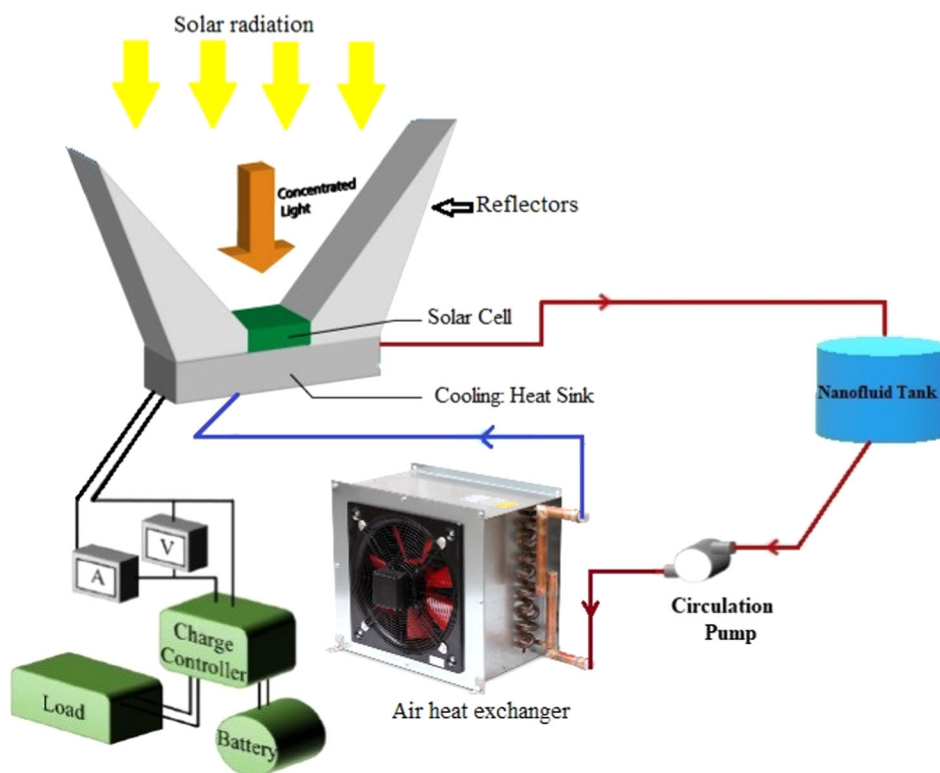


FIGURE 2 | Experimental system schematic diagram.

TABLE 1 | PV module electrical standards over STC.

Specification under STC	Value
MPP power	60 W
PV module area	0.42 m ²
Module efficiency	13.71%
MPP voltage	19.01 V
MPP current	3.16 A
OC voltage	22.61 V
SC Current	3.38 A
Temperature coefficient of OC voltage	−0.38%/°C
Temperature coefficient of SC Current	0.04%/°C

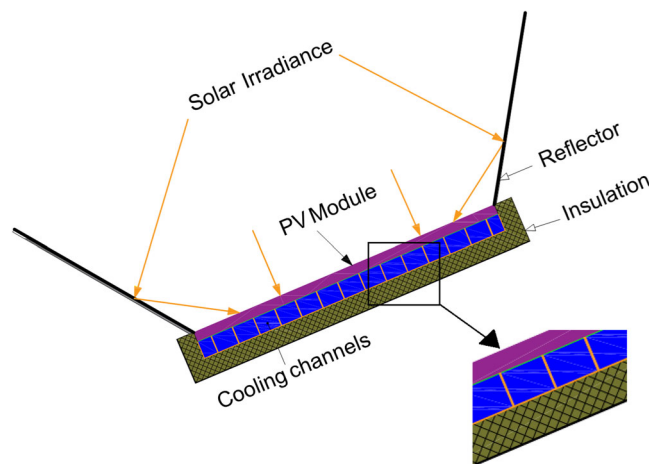


FIGURE 3 | Cooling channels cross-section.

side edges, creating a leak-proof shield to avoid Al₂O₃/water nanofluid leakage.

3 | Materials and Procedures

3.1 | Materials

All of the chemical materials included in the experimental testing were reagent grade, Al₂O₃ nanoparticles imported from (Sigma-Aldrich GmbH) were dispersed in the distilled water as base fluid with 99.98% purification with an average diameter of 30–60 nm. One of the primary reasons for choosing Al₂O₃ is its high thermal conductivity. It has significantly higher thermal conductivity than conventional cooling fluids like water or ethylene glycol making it highly effective at transferring heat

away from the PV modules. Aluminum oxide nanofluid helps maintain lower operating temperatures which is essential for optimizing the electrical efficiency of the CPV system. This ability to manage heat effectively is crucial in preventing the temperature-related degradation that often slow down the performance of PV modules. In addition to its thermal properties, Al₂O₃ nanoparticles exhibit exceptional stability when dispersed in water which considered as a critical factor for ensuring consistent nanofluid properties over time. The stability of the Al₂O₃ nanofluid as confirmed by its zeta potential value prevents the aggregation and sedimentation of nanoparticles. This stability is particularly important for long-term applications where maintaining the thermal properties of the nanofluid is essential for sustained cooling efficiency. Aluminum oxide

nanofluid has low density which contributes to the overall lightweight nature of the cooling system. The high specific surface area of Al_2O_3 nanoparticles also may enhance heat transfer by increasing the interaction between the fluid and the nanoparticles further improving the cooling efficiency through greater surface contact. Economic viability also plays a role in the selection of Al_2O_3 . While it may not match the thermal performance of more expensive nanomaterials like silver or carbon nanotubes, Al_2O_3 offers a good balance between cost and efficiency. This makes it a practical choice for large-scale applications where budget constraints are a consideration, without significantly compromising on the thermal management capabilities of the cooling system [26]. Sulfonate (SDBS), and sodium dodecyl benzene, were used as natural surfactants to diffuse Al_2O_3 via the distilled water (DW) as the base fluid and also to increase the constancy of nano Al_2O_3 /water fluid as SDBS provides the highest degree of stability for the nanofluid [27]. Table 2 details the physical characteristics of base water and nanoparticles.

The key nanofluid properties taken into account when calculating the usable thermal energy generated via the cooling cycle are density ρ_{nf} and heat efficiency C_{nf} , which can differ considerably from the base water. Due to the authors' lack of calculation of both the density and heat capacity of Al_2O_3 -nanofluids at various concentrations of nanoparticles, the formulas estimated via Pak and Cho [29] and Xuan and Roetzel [30] are utilized to determine density and heat capacity as:

$$\rho_{nf} = (1 - \psi)\rho_{bf} + \psi \rho_p, \quad (1)$$

$$(\rho \cdot C)_{nf} = (1 - \psi)(\rho \cdot C_p)_{bf} + \psi(\rho \cdot C_p)_p, \quad (2)$$

where subscriptions f , p , and nf are allocated to base fluid, nanoparticle, and nanofluid. The thermal conductivity K_{nf} of the nanofluid is evaluated utilizing the Hamilton–Crosser estimated model [31] as:

$$K_{nf}/k_f = k_p + (n - 1)k_f + (n - 1)\psi(k_p - k_f)/k_p + (n - 1)k_f - \psi(k_p - k_f), \quad (3)$$

TABLE 2 | Physical properties of Al_2O_3 nanoparticles and water [28].

	Density, kg/m^3	Specific heat, J/kg K	Thermal conductivity, W/m K
Al_2O_3	3980	892	35.5
Water	997	4180	0.62

TABLE 3 | Nanofluid thermo-physical properties.

Volume concentration Ψ , (% vol.)	Density ρ , kg/m^3	Specific heat C_{nf} , J/kg K	Thermal conductivity k , W/m.K
0.3	1030	4052	0.638
0.6	1060	3935	0.661
0.9	1090	3817	0.682

where n is the component of particle form factor defined as $n = 3/\psi$ in which ψ shows the sphericity of the particle. The sphericity factor for both cylindrical and spherical particles is 0.5 and 1, respectively. Therefore, considering the spherical shape of the Al_2O_3 nanoparticles, the value of n is considered to be 3 in the current work. As a function of the volume concentration of nanoparticles, the measured thermophysical properties of Al_2O_3 -nanofluids are presented in Table 3.

3.2 | Preparation of Nanofluid

Throughout the present experimental research, the Al_2O_3 /water nanofluid was produced using two sequential processes, steric stability, and the sonication technique. The base liquid is first formulated by utilizing a magnetic stirrer (MtopsMs300hs Spectrum Scientific Co. Ltd.) to attach sodium dodecylbenzene sulfonate (SDBS) as a surfactant to purified water, and is carefully blended magnetically at 1500 rpm for 30 min. After the first stage, nanofluids of different volume concentrations as per Equation (4) were weighed accurately various amounts of Al_2O_3 particles and distributed as a base fluid in the DW-SDBS solution (at 2:1 surfactant mass ratio of Al_2O_3 nanoparticles to SDBS), as this ratio showed improved stability [31]. The specified Al_2O_3 /water nanofluid is formulated at concentrations of 1%, 2%, and 3%, respectively. Formulated stability of nanofluids is the crucial factor that expresses concern and evaluates the effectiveness of nanofluids in the cooling procedure [32]. Nanofluid is carefully blended via a magnetic stirrer to preserve constancy. Afterward, it is sonicated for an additional 2 h to prevent agglomeration by an ultrasonic processor to obtain stable dispersed surfactant Al_2O_3 /water nanofluid. The cooling fluid within the storage basin was agitated in two consecutive experimental tests for around 20 min, to prevent the possibility of sedimentation with nanoparticles. Nanoparticles' volume concentration, Ψ , in Al_2O_3 /water was determined by the following equation:

$$\% \Psi = (W_{np}/\rho_{np})/[(W_{np}/\rho_{np}) + (W_{bf}/\rho_{bf})], \quad (4)$$

where w_{np} and ρ_{np} are the weight and density of w_{np} and ρ_{np} nanoparticles, and for the base fluid are w_{bf} and ρ_{bf} .

3.3 | Nanofluids Characteristics

Malvern Zeta sizer was used to measure the hydrodynamic particle size distribution and zeta potential of cooling fluid NPs dispersed in an aqueous solution. As illustrated in Figure 4, the secondary Al_2O_3 's average particle size was measured at 150 nm. The major and supplementary sizes that were noted of the prepared NPs are described in Table 3. As the proportion of

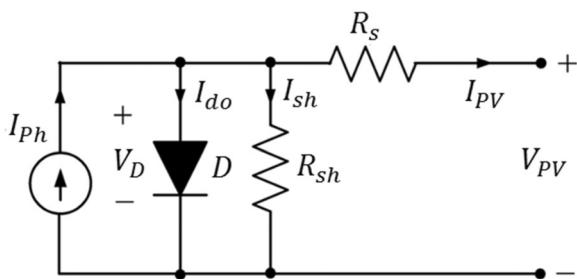


FIGURE 4 | Single exponential model of a PV module.

TABLE 4 | Particle sizes and Zeta potentials of Al_2O_3 /water nanofluid at $\Psi = 0.9\%$.

Primary specified particle size (nm)	Secondary particle size (nm)	Particle size ratio	Zeta potential (mV)
60	135	2.3	-39.2

the supplementary size to the major stated size is below 5 [33], the prepared nanofluid is believed to be stable. To further affirm our nanofluid stability, zeta potential measurements were performed as one of the most significant experiments to validate the durability of nanofluid stabilities. The stability of the Al_2O_3 /water nanofluid was investigated by measuring its zeta potential and particle size distribution. Nanoparticle stability is an important aspect in determining the efficiency and lifetime of nanofluid cooling systems, since agglomeration or sedimentation can damage the fluid's thermal properties. The zeta potential is a significant measure of nanoparticle stability. It was reported that values over ± 28 mV indicated electrostatic repulsion between particles preventing agglomeration and ensuring dispersion stability [34, 35]. In this study, the zeta potential of the Al_2O_3 /water nanofluid was measured to be -39.2 mV as listed in Table 4. This large negative value showed that the nanofluid exhibited substantial electrostatic repulsion between particles resulting in exceptional stability. Such a high zeta potential indicated that the Al_2O_3 nanoparticles are well-dispersed in the water base fluid reducing particle agglomeration over time. As a result, the nanofluid is predicted to sustain its improved thermal characteristics over time helping to provide constant cooling performance for CPV modules. Furthermore, the particle size analysis showed that the Al_2O_3 nanoparticles had a primary particle size of 60 nm and a secondary particle size of 135 nm, for a particle size ratio of 2.3. This suggests that, while there was some particle aggregation, the overall distribution is still controllable for effective heat transmission. The acceptable stability shown by the zeta potential guarantees that these particles do not form bigger clusters, which might impair the fluid's capacity to circulate through the CPV cooling system.

3.4 | Devices and a Data Collection Procedure

During the present research, the effect of the key parameters on the operation of the CPV unit was recorded using various

equipment. Six type k thermocouples placed at the entrance and the end of the cooling technique and the underground heat exchanger, respectively, to record the temperatures of the circulating Al_2O_3 /water at various positions. A rotameter (Model: LEMA-01-A3, Dwyer) is employed to measure the nanofluid flow rates across the examined system. The CPV module operational surface temperatures were also recorded with an infrared thermometer (Testo 825-T4). At the CPV surface, the irradiance intensity is registered using an LP02 Hukseflux Pyranometer that is placed at the same inclination angle as the CPV module. By utilizing a records acquisition module (Model: GL820ABS, Graphtec Co. Japan) the data were collected for later analysis. All the experiments were performed, and measurements were continuously collected during 1-h periods from 8:00 a.m. to 6:00 p.m. and displayed on graphs. The associated voltage and current were monitored throughout the experiment utilizing a digital multimeter over the suggested LCPV module. CPV module thermal productivity is determined through the thermal efficiency defined as an extra thermal benefit for receiving the solar energy (5).

$$\eta = \frac{Q_u}{AG}. \quad (5)$$

The valuable benefits of heat through the cooling fluid, Q_u (W), were estimated using the following equation:

$$Q_u = m_f C_p (T_{f,\text{out}} - T_{f,\text{in}}), \quad (6)$$

where m_f is the cooling fluid mass flow (kg/s) and C_p (J/kgK) is the specific heat of the cooling nanofluid, whereas $T_{f,\text{in}}$ is the cooling fluid inlet temperature and $T_{f,\text{out}}$ is the cooling fluid outlet temperatures of the LCPV system, respectively.

3.5 | Uncertainty Analysis

Table 5 points out the characteristics of each of the measurement instruments and the standard uncertainty. Equation (7) is used to establish the uncertainties for the equipment utilized in the experimental investigation [36].

$$u = a/\sqrt{3}, \quad (7)$$

where a is the device accuracy [37, 38].

The uncertainties in the experimental measurements are listed in Table 5. They were carefully considered during the calculation of thermal efficiency and other derived quantities. Each measurement device has its associated standard uncertainty which contributes to the overall experimental uncertainty.

The pyranometer used to measure incident solar intensity has a standard uncertainty of $2.88 \times 10^{-2} \text{ W/m}^2$. This uncertainty impacted the calculation of the incident solar power which was crucial for determining the thermal efficiency of the CPV system. Given the significant role of solar intensity in these calculations, its uncertainty can affect the accuracy of the overall thermal efficiency measurement.

TABLE 5 | Device precision and uncertainty.

Devices	Measured parameter	Accuracy	Limit	Standard Uncertainty
Pyranometer	Incident solar intensity	0.05 W/m ²	0–2500 W/m ²	2.88×10^{-2} W/m ²
Thermocouples	Nanofluid temperatures	$\pm 0.15^\circ\text{C}$	(0–200) $^\circ\text{C}$	$8.6 \times 10^{-2}^\circ\text{C}$
Infrared thermometer	LCPV surface temperature	$\pm 0.1^\circ\text{C}$	(–20–300) $^\circ\text{C}$	$5.77 \times 10^{-2}^\circ\text{C}$
Rotameter	Nanofluid flow rate	0.05 L/min	0.5–4 L/min	0.028 L/min
Digital Voltmeter	Loaded voltage	± 0.015 V	0–100 V	8.6×10^{-3} V
Digital Ammeter	Loaded current	± 0.015 A	0–16 A	8.6×10^{-3} A

For nanofluid temperatures, measured using thermocouples, the standard uncertainty is $8.6 \times 10^{-2}^\circ\text{C}$. This uncertainty affected the calculation of heat transfer rates and temperature differences, which were integral to determining thermal efficiency. Variations in temperature measurements due to this uncertainty can influence the final efficiency values.

The infrared thermometer used to measure the CPV surface temperature has a standard uncertainty of $5.77 \times 10^{-2}^\circ\text{C}$. This uncertainty affected the accuracy of surface temperature readings which were critical for calculating heat dissipation and thermal performance. Variations in surface temperature measurements contributed to the overall uncertainty in thermal efficiency.

The nanofluid flow rate measured with a rotameter has an uncertainty of 0.028 L/min. This parameter was essential for calculating the convective heat transfer rate within the CPV system. The flow rate uncertainty has an impact on the precision of heat transfer calculations and consequently the thermal efficiency.

The loaded voltage and current measured with a digital voltmeter and ammeter respectively have uncertainties of 8.6×10^{-3} V and 8.6×10^{-3} A. These measurements were critical for calculating the electrical power output and efficiency of the CPV system. Any uncertainty in these measurements directly affected the accuracy of the electrical performance calculations.

To quantify the impact of these uncertainties on the final thermal efficiency values, standard error propagation methods were applied. This process involved combining the uncertainties from each measurement device to determine the overall uncertainty in the derived efficiency values. The comprehensive analysis ensured that the reported results accurately reflected the precision of the measurements and provided a clearer understanding of the reliability of the experimental data.

4 | Results and Discussion

As aforementioned, this research presented two sets of experimental works: one on the CPV module with cooling known as CPV, and compared with an uncooled equivalent module. From the viewpoint of the system performance, the results of each system are then compared. It should be noted that the experiments were conducted to investigate the influence of the cooling technique on the operation of each PV concentrator under

the outdoor solar insolation for various operating parameters. At the beginning of each test, the nanofluid flow was adjusted to the appropriate rate utilizing bypass valves. Therefore, to maintain a stable condition, the whole system was given a reasonable period of around 20 min before recording the measurements. During this time, measurements of the CPV temperatures were recorded at the module surface at different positions. Besides, the CPV module's current and voltage, solar radiation, ambient temperature, and temperatures of the circulated nanofluid at the entrance and exit of the CPV and AHE were recorded.

4.1 | Electrical Output Characteristics of PV Module

Constructing an accurate model of a PV generator (cell, module, or array) is a crucial research issue in PV systems, particularly when studying the output characteristics of the PV module, predicting power output, and designing systems for maximum power extraction. The problem with creating a model for PV modules is the nonlinear relationship between the resultant voltage and the resultant current. Modeling of PV modules concerns the estimation of the output characteristics curves to emulate the actual behavior of the PV module under various atmospheric states. The most popular method to simulate the PV module is to employ the electrical equivalent circuit, which is mainly constructed on a diode [39].

The ideal equivalent circuit of a PV module is usually denoted by a current supply connected in parallel with an ideal diode. However, the ideal model of a PV module does not represent the output characteristics of a practical PV panel. To acquire a more accurate model, series, and shunt resistances are incorporated in the ideal model to form the single exponential model (also known as the five-parameter model) as presented in Figure 4. The resultant current of the PV module can be expressed using the following equation [40, 41]:

$$I_{PV} = I - I_0 \underbrace{\left\{ \exp \left[\frac{q(V_{PV} + I_{PV}R_s)}{m V_t} \right] - 1 \right\}}_{I_{d0}} - \underbrace{\frac{V_{PV} + I_{PV}R_s}{R_{sh}}}_{I_{sh}}, \quad (10)$$

where I_{PV} is the module resultant current (A), V_{PV} is the module resultant voltage (V), I_{ph} is the photo-generated current, I_{d0} is the Shockley diode equation, I_{sh} is the saturation current due to diffusion, I_0 is the dark saturation current, q is the electron charge ($1.6022 \times 10^{-19}\text{C}$), $(V_t = n_s K T_m/q)$ is the thermal

voltage of the unit, n_s the number of series-connected cells in the PV module, K is the Boltzmann constant ($1.3806 \times 10^{-23} \text{ J/K}$), T_m is the module working temperature (K) and m is the diode ideality factor.

The temperature of the PV unit (T_m) varies from the ambient temperature (T_{amb}) and could be calculated by the following equation [42]:

$$T_m = T_{\text{amb}} + \frac{\text{NOCT} - 20}{800} \times G, \quad (11)$$

where G is the solar irradiation and NOCT is the symbolic operational cell temperature at an irradiation level of 800 W/m^2 and the ambient temperature is 20°C .

To build a more realistic model, the changes in solar radiation and module operating temperature concerning standard test conditions (STC: $T_{\text{ref}} = 25^\circ\text{C}$, $G_{\text{ref}} = 1000 \text{ W/m}^2$) must be considered in the models (12–15) [40, 43].

$$I_{\text{ph}} = \left[I_{\text{ph}, T_{\text{ref}}} + \alpha_I (T_m - T_{\text{ref}}) \right] \left(\frac{G}{G_{\text{ref}}} \right), \quad (12)$$

$$I_{\text{ph}, T_{\text{ref}}} = \frac{R_{\text{sh}} + R_s}{R_{\text{sh}}} I_{\text{sc}, T_{\text{ref}}}, \quad (13)$$

$$I_0 = \frac{I_{\text{sc}, T_{\text{ref}}} + \alpha_I (T_m - T_{\text{ref}})}{\left\{ \exp \left(\frac{V_{\text{oc}, T_{\text{ref}}} + \alpha_V (T_m - T_{\text{ref}})}{m V_t} \right) - 1 \right\}}, \quad (14)$$

$$V_{\text{oc}} = V_{\text{oc}, T_{\text{ref}}} + \alpha_V (T_m - T_{\text{ref}}) + m V_t \ln \left(\frac{G}{G_{\text{ref}}} \right), \quad (15)$$

where $I_{\text{ph}, T_{\text{ref}}}$ is the module photo-generated current at STC, $I_{\text{sc}, T_{\text{ref}}}$ is the module short-circuit (SC) current at STC, $V_{\text{oc}, T_{\text{ref}}}$ is the module open-circuit (OC) voltage at STC, α_I is the temperature coefficient of the SC current and α_V is the temperature coefficient of the OC voltage.

The electrical competence of the concentrated PV unit can be calculated by Equation (16) [44].

$$\eta_{\text{el}} = \frac{I_m \times V_m}{A_m \times G \times \text{CR}}, \quad (16)$$

where I_m and V_m are the PV module current and voltage at highest power point (MPP), A_m is the module area, and CR is the concentration ratio of solar irradiance.

Figure 5 shows the influence of solar irradiance variation on the electrical characteristics of a CPV module at a constant cell temperature of 25°C . As is evident, the SC current increases significantly with an increase in solar radiation, while the OC voltage is enhanced slightly. Theoretically, the resultant power of the CPV unit can be doubled for CR of 200%, if the module temperature is held constant at 25°C . Unfortunately, the resultant power of the CPV unit may decrease due to the undesirable influence of the module temperature on the OC

voltage, where 80% of the solar energy is transformed into heat [45]. Figure 6 presents the influence of module temperature on the resultant characteristics at constant solar radiation of 1 kW/m^2 . As can be seen, the OC voltage increases remarkably with a decrease in module temperature, while the SC current decreases slightly. Hence, compared to a hotter CPV module a cooler one generates extra output energy [43, 44].

Figure 7 illustrates the critical importance of aligning the load line with the Maximum Power Point (MPP) load line in PV systems. When these two lines do not match, a substantial amount of power is lost. This loss can have significant implications for the overall efficiency and performance of a solar PV system. The MPP represents the ideal operating point at which a solar panel generates the maximum amount of power for a given set of environmental conditions, such as sunlight intensity and temperature. However, these conditions are not static and can vary throughout the day and across seasons. Additionally, the power requirements of the connected load may change. To address these variations and optimize power generation, the use of a Maximum Power Point Tracker (MPPT) is indispensable. The MPPT continually adjusts the load to ensure that it operates at the MPP, maximizing power output and minimizing energy wastage.

4.2 | Distribution of Solar Irradiance

The hourly difference between solar intensity and ambient temperature for CPV with and without reflectors is illustrated in Figure 8. Observations have been daily monitored from 9.00 a.m. to 6.00 p.m. As shown, the ambient temperature has steadily increased from 28° to 33°C from 9.00 a.m. to 2.00 p.m., respectively before decreasing to 28°C at the end of observations at 6.00 p.m. For uncooled CPV, the solar intensity increased from 620 to 980 W/m^2 at noon before steadily decreasing to about 200 W/m^2 at 6.00 p.m. However in cooled CPV, the solar intensity significantly increased from 760 to 1820 W/m^2 at noon before reaching 200 W/m^2 at 6.00 p.m. This trend is in accordance with a previous study by Kabeel and Abdelgaied [46].

4.3 | Temperature Distribution of PV and CPV Module

An excellent test for determining whether a cell works within its permissible temperature range is the utmost cell temperature. However, the cell temperature distribution consistency is an additional parameter. Figure 9 shows the temperature contours for CPV and PV at the surface without cooling. For PV, the maximum temperature contour was homogeneous and refers to a temperature range between 46°C and 48°C . However, the maximum temperature contour for CPV has ranged between 67°C and 72°C . The contours also demonstrate that there are reduced hot spots and a more equal temperature distribution. This results trend is similar to a previous study by Jowkar et al. [47]. The influence of $\text{Al}_2\text{O}_3/\text{water}$ nanofluid for cooling CPV using different concentrations of nano Al_2O_3 is illustrated in Figure 10. The $\text{Al}_2\text{O}_3/\text{water}$ was without, 0.3, 0.6, and 0.9 wt%, respectively. As shown, with water only, the maximum temperature contour ranged from 38°C to 42°C . By

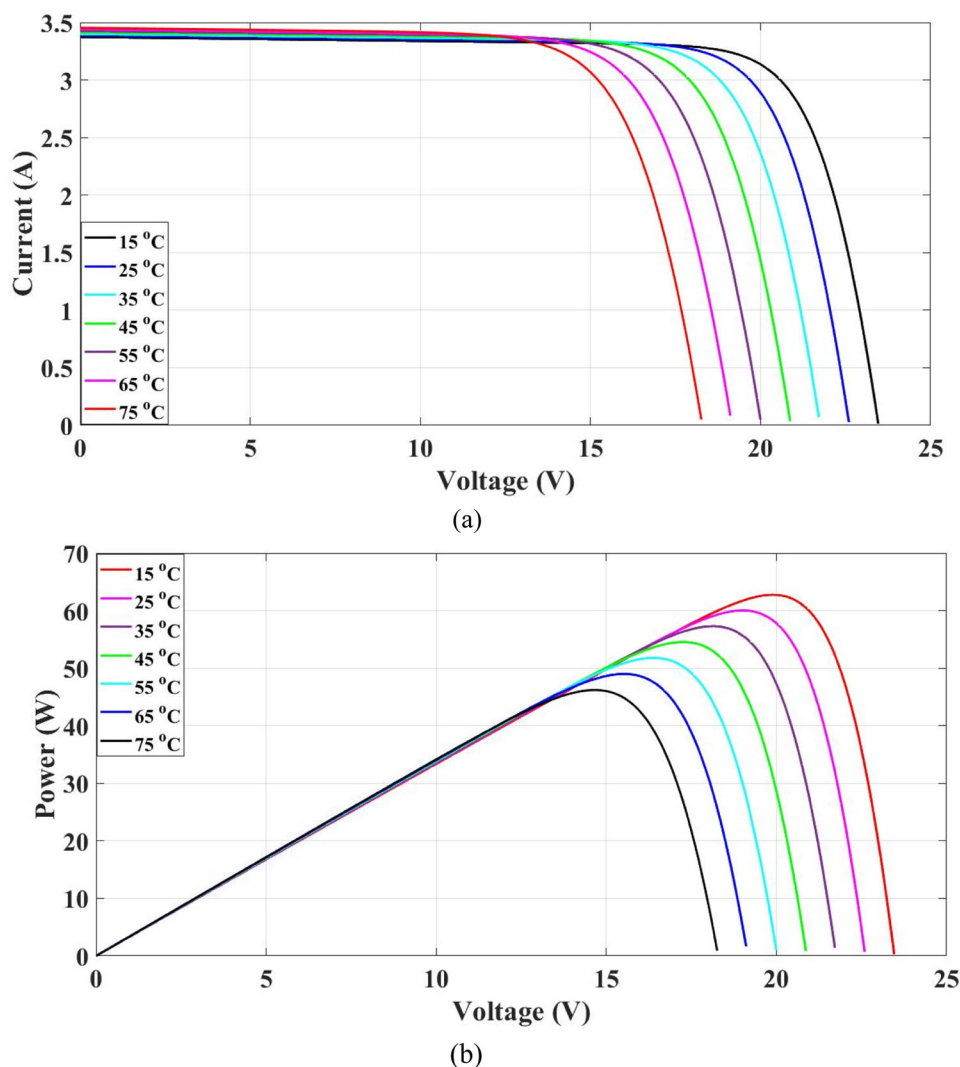


FIGURE 5 | The electrical characteristics of CPV module at different solar radiation levels and a constant module temperature: (a) I-V curves and (b) P-V curves.

employing 0.3% Al_2O_3 /water nanofluid, the maximum temperature contour decreased and ranged from 35° to 40°. Moreover, increasing the Al_2O_3 /water nanofluid ratio to 0.6% has decreased the maximum temperature contour between 33°C and 38°C. At an Al_2O_3 /water nanofluid ratio of 0.9%, the maximum temperature contour has significantly reduced between 25°C and 33°C.

The enhanced cooling performance observed with higher concentrations of Al_2O_3 nanoparticles in the nanofluid can be attributed to several interconnected factors. As the concentration of Al_2O_3 nanoparticles increases, the thermal conductivity of the nanofluid rises. This is because Al_2O_3 has a high thermal conductivity which enhanced the fluid's ability to transfer heat away from the CPV surface. Consequently, this improved thermal conductivity facilitated more efficient heat dissipation resulting in lower surface temperatures of the CPV module.

Furthermore, higher nanoparticle concentrations led to an increase in the rate of heat transfer. With more nanoparticles

present, there were more particles in contact with the heat transfer surfaces. This increased contact enhanced the heat transfer coefficient making the cooling process more efficient. The additional nanoparticles effectively increased the heat transfer efficiency of the fluid. Additionally, a higher concentration of nanoparticles created a denser network of conductive pathways within the fluid. This network improved thermal conduction within the nanofluid allowing for more effective heat removal from the CPV module. The increased number of conductive pathways provided better heat conduction from the CPV surface to the fluid enhancing the overall cooling performance. The specific surface area available for heat exchange also increased with higher nanoparticle concentrations. As the concentration of nanoparticles increased, the available surface area for heat absorption and transport increased further improving the fluid's cooling capability. This larger surface area allows for more effective heat exchange between the CPV module and the cooling fluid. Moreover, the Brownian motion of nanoparticles which helped to keep them dispersed within the fluid was more pronounced at higher concentrations. This improved dispersion ensured that nanoparticles were uniformly

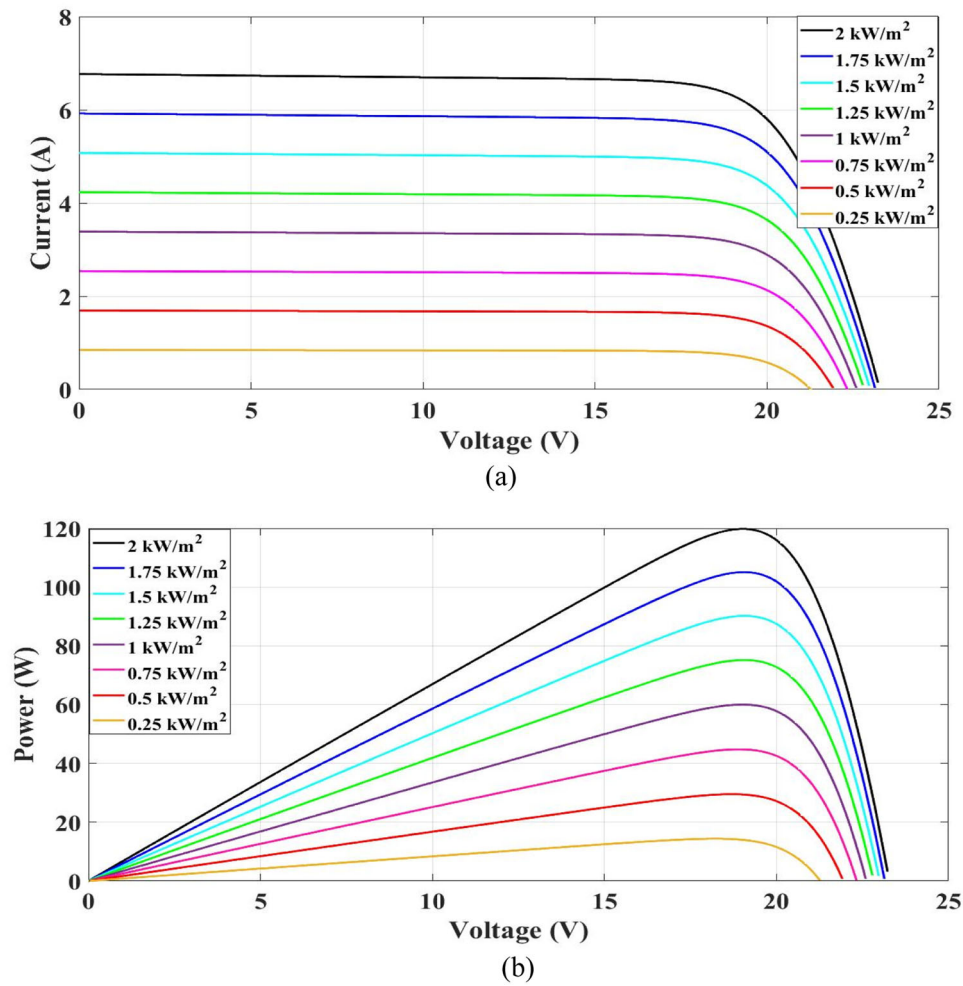


FIGURE 6 | The electrical characteristics of CPV module at different module temperature and a constant solar radiation level: (a) I-V curves and (b) P-V curves.

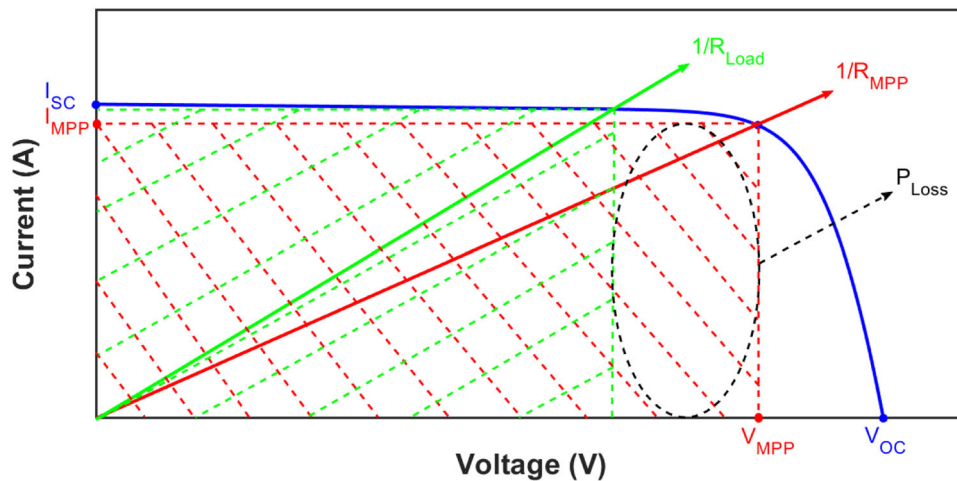


FIGURE 7 | Illustration of the power losses on the V-I curve of the PV panel that occurs when the load line is not properly aligned with the MPP load line.

distributed preventing sedimentation and maintaining the nanofluid's effectiveness over time. The stable dispersion of nanoparticles contributed to a consistent and efficient cooling process. These results show that increasing the nanofluid ratio has a superior influence on the cooling of the CPV which

enhanced the electrical productivity of the CPV. By boosting the thermal conductivity and causing processes like microlayer evaporation and reformation of the thermal boundary layer, employing nanoparticles in the fluid can increase the efficiency of heat transmission [48].

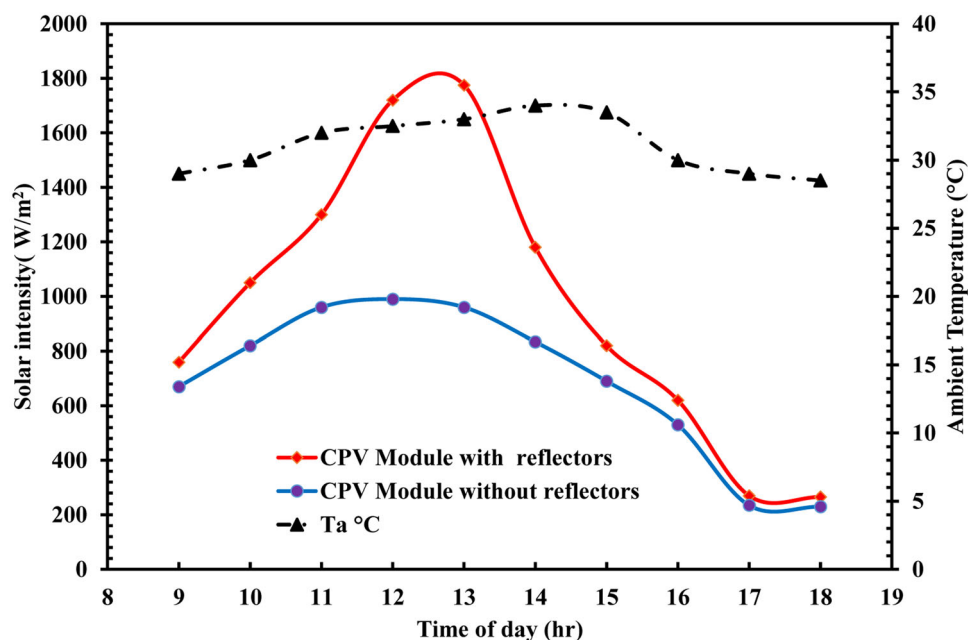


FIGURE 8 | Solar intensity and air ambient temperature.

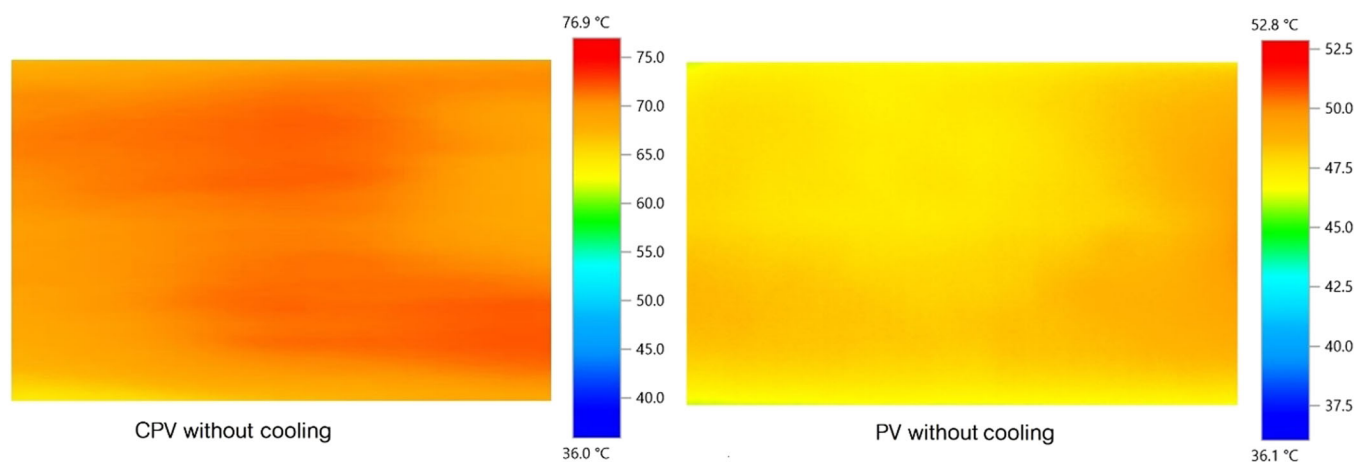


FIGURE 9 | Temperature variation for the CPV and PV without cooling.

4.4 | Performance of CPV Module

The electrical output of the CPV unit is illustrated as presented in Figure 11. The electrical yield was measured under various conditions without cooling, cooling with water only, 0.3, 0.6, and 0.9 wt% Al_2O_3 /water, respectively. The cooling flow was discharged at 1.0 L/min. The electrical yield was monitored between 9.00 a.m. and 6.00 p.m. As shown, without cooling the electrical yield has increased from 30 to 45 W/h at noon before decreasing to 18 W/h at the end of the day. At noon the electrical yield has reached its maximum as 45, 46, 48, 50, and 54 W/h for CPV without cooling, with cooling water, with 0.3% Al_2O_3 /water, 0.6% Al_2O_3 /water, and 0.9% Al_2O_3 /water, respectively. These results show that the electrical yield has increased by 20% for 0.9% Al_2O_3 /water. The output and effectiveness of PV cells rise as a result of cooling nanofluid, which has a greater heat transfer rate from the PV cell surface [19].

It's clear from Figure 13 that employing an Al_2O_3 cooling nanofluid has increased the electrical and thermal efficiency. Electrical efficiency as illustrated in Figure 12a has reached 15%, 17%, 18%, 19%, and 21% without cooling, with water only, 0.3, 0.6, and 0.9 wt% Al_2O_3 , respectively. This trend is due to the enhancement in heat transfer efficiency as aforementioned. At a nanoparticle loading concentration of 0.9 wt%, the Al_2O_3 nanoparticles are reported to have the maximum thermal efficiency as shown in Figure 12b. Compared to the result at a nanoparticle loading concentration of 0.9 wt%, thermal efficiency is marginally reduced for nanoparticle loading concentrations of 0.3 and 0.6 wt%. The extreme thermal competence reached its value after 2.0 p.m. which ranged between 54% and 65% for an Al_2O_3 mass concentration of 0.9%. In a previous study by Çiftçi et al., the thermal efficiency ranged between 50.25% and 55.83% [49].

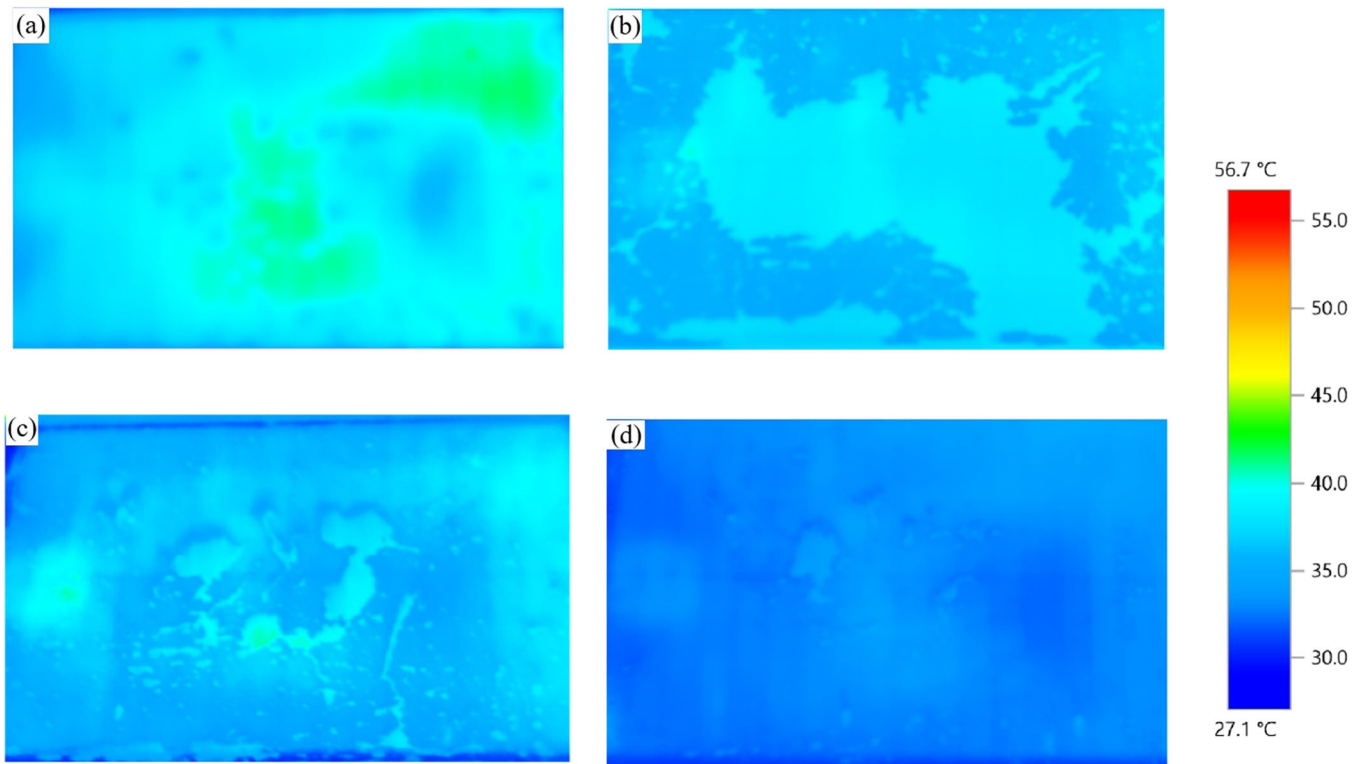


FIGURE 10 | Temperature variation for the CPV with different concentrations of $\text{Al}_2\text{O}_3/\text{water}$ nanofluid. (a) Temperature variation in the case of water. (b) Temperature variation in the case of 0.3% $\text{Al}_2\text{O}_3/\text{water}$ nanofluid. (c) Temperature variation in the case of 0.6% $\text{Al}_2\text{O}_3/\text{water}$ nanofluid. (d) Temperature variation in the case of 0.9% $\text{Al}_2\text{O}_3/\text{water}$ nanofluid.

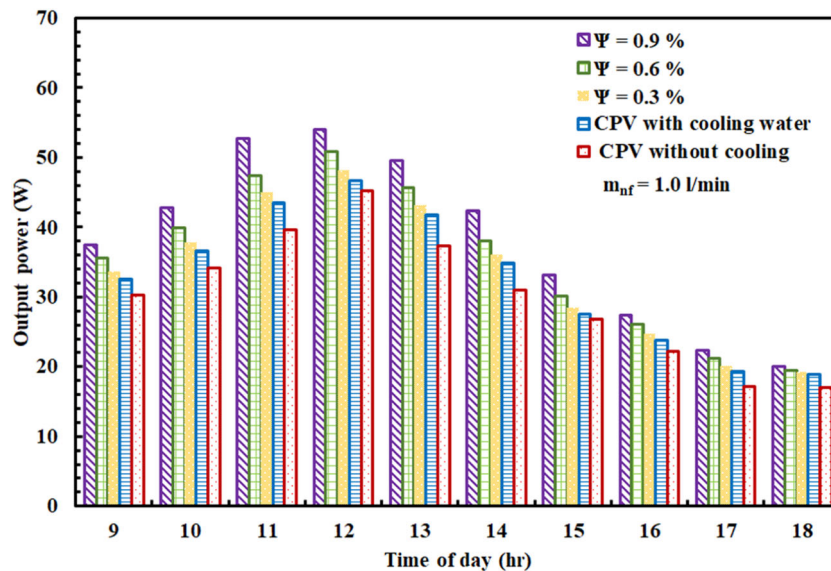


FIGURE 11 | Output power of CPV module.

4.5 | Efficiency Evaluation Between CPV Technique and the Published Works

A comparison has been attained, as stated in Table 6, between the present CPV procedure and the previously offered CPV systems. A close comparison of the present work findings with those of other studies described in Table 6 showed that the $\text{Al}_2\text{O}_3/\text{water}$ nanofluid performs a vital position in controlling

the corresponding operational temperature of the CPV module in the presence of cooling when applied directly to the backside of the LCPV. Again from the whole performance point of view of the CPV system, the current, voltage, and ultimately electrical provided power are markedly increased, while using nanofluid cooling, especially for the 0.9%-nanofluid status compared to other cooling methods and the uncooled CPV module without cooling. As per Table 6, the findings showed

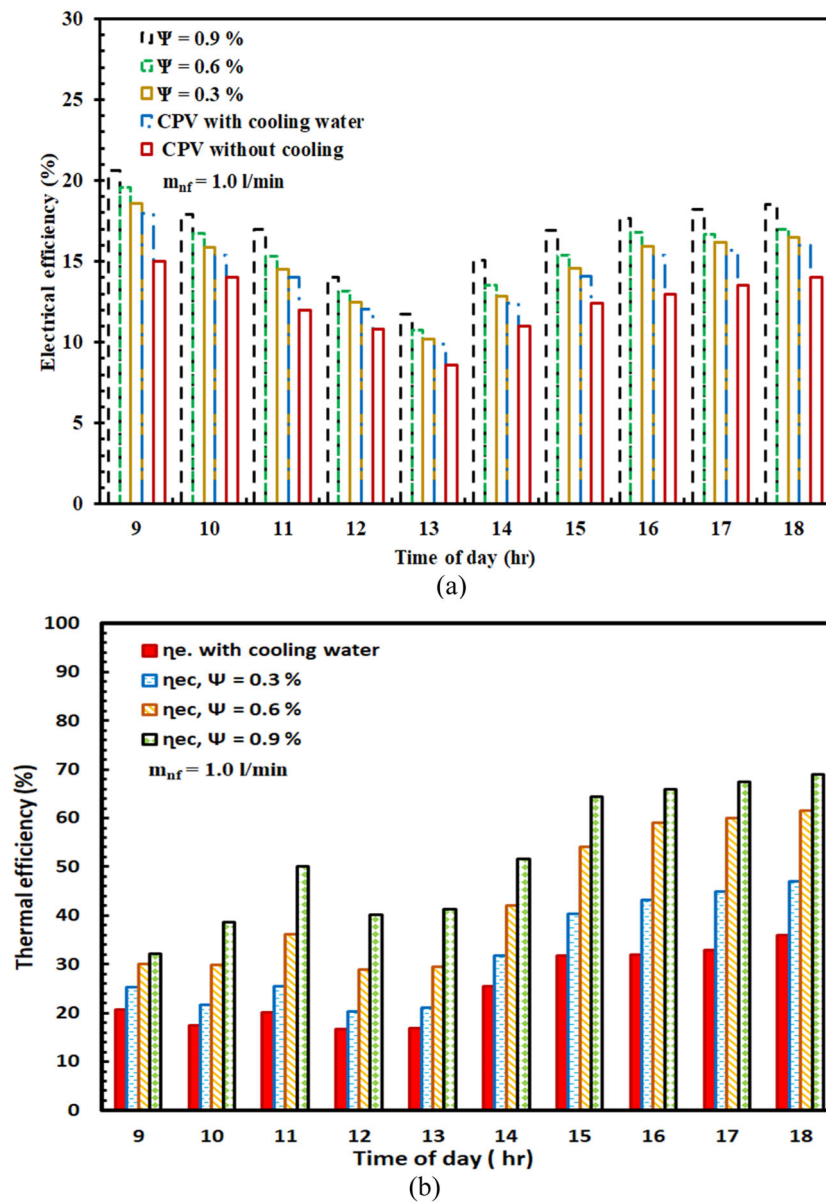


FIGURE 12 | Electrical and thermal efficiencies of CPV module. (a) Daily variation of Electrical efficiency (%). (b) Daily variation of thermal efficiency (%).

TABLE 6 | Contrasts the existing CPV setup with different alternatives.

Ref.	Coolant utilized	CR	η_e (%)	η_{th} (%)
CPV, Current study	Al_2O_3 /water nanofluid	1.45	14.90	45.77%
Radwan et al. [46]	CPV, Water cooling	< 1.95	13.90%,	—
Primož et al. [45]	CPV, Air cooling	—	10.5	21
Sardarabadi et al. [47]	CPV, Without cooling	1.5	9.3	—

the possibility of using Al_2O_3 /water nanofluid as an alternate cooling method for the CPV module, which might provide more apparent developments for PV systems. The present CPV module with the nano-cooling technology produced an average electric adeptness of 14.9% and an estimated thermal effectiveness of 45.77% at around the same concentration ratio, while the previous air-cooled CPV modules proved to have an

estimated electrical competence of about 10.5% and an estimated thermal efficiency around 21% [50].

Comparisons were performed with the present CPV module against the recently published work on cooling the CPV system showed about 8.10% better electrical efficiency than the previously investigated water-cooled CPV module achieved

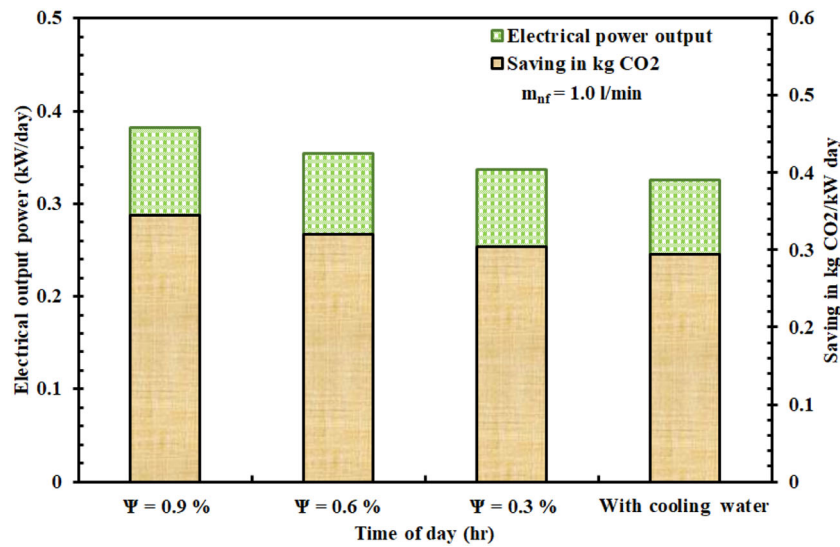


FIGURE 13 | Generated electricity and reduction in CO₂ emissions for each summer season.

[51]. The current CPV system achieved about 65.55% greater electrical efficiency when compared to the existing CPV procedure exclusive of cooling [52]. Thus, due to its elevated thermal conductivity compared to additional various coolants like base water or air. As shown in Table 6, it is more efficient to cool the CPV system with Al₂O₃/water nanofluid in the circumstance of direct interaction. This efficacy is explained by the variation among the Al₂O₃/water nanofluid convective heat transfer coefficient in the situation of direct interaction with the CPV rear exterior relative to extra traditional cooling techniques.

4.6 | Environmental Impacts

The environmental impact of the suggested cooled CPV system was also measured based on the period of the summer season. The cuts in CO₂ emissions owing to the utilization of the proposed cooled CPV methodology were measured as follows [53].

$$M_t = m_e \times dE \times t_{\text{life}}, \quad (17)$$

where m_e is the average CO₂ emission intensity (890 g/kWh) by a power station using coal-fired energy, m_t is the total decreased CO₂ (g) emission amount across its lifecycle [54], and dE is the gross energy saving resulting from the considered cooled CPV module during the summer season (kWh).

Figure 13 illustrates the average electrical power production accompanied by the cut in CO₂ releases while cooling the CPV with nanofluid daily at various capacity fractions of nanoparticles. It concluded from Figure 12 that the rise in volume concentration of nanoparticles from 0.3 to 0.9 wt% increases the electrical output of the CPV module compared with only water cooling. The total daily electrical power has achieved about 0.28 kW for 0.9% Al₂O₃ nanoparticles. This result shows that electrical output has raised by 7.7% compared with no cooling. Also, the total daily savings in CO₂ have been achieved at 1.0, 0.9, and 0.8 kg/kW for 0.9 wt%, 0.6 wt%, 0.3 wt% Al₂O₃.

The integration of nanofluids into PV systems presents a promising and cost-effective solution for both industrial and domestic power needs. Recent studies have highlighted the potential for significant reductions in energy consumption from conventional resources when employing these advanced systems. For instance, incorporating nanofluid receivers in a solar thermal power plant with a capacity of 100 MW could lead to annual savings of approximately \$3.5 million, as reported by Taylor et al. [55]. Nanofluids, known for their efficient heat transfer capabilities allow for more compact PV systems, thereby reducing overall costs [56]. Economic analyses have shown that the cost of energy produced by nanofluid-based PV/T systems can be up to 82% lower compared to current energy prices in Saudi Arabia, with a payback period estimated at just 2 years [57]. Future research should focus on a thorough cost-benefit analysis including long-term operational and maintenance costs, market variations, and the economic impacts of scaling up Al₂O₃ nanofluid-based concentrated photovoltaic (CPV) systems. This will provide a more robust evaluation of the potential financial benefits and challenges associated with implementing this technology.

5 | Conclusions

This study demonstrated that using Al₂O₃ nanofluid for cooling CPV modules significantly enhanced performance and sustainability. The optimal concentration of 0.9 wt% Al₂O₃ led to a 20% increase in electrical yield and improved the electrical efficiency from 15% to 21% compared to the uncooled CPV. Additionally, the study achieved a total daily CO₂ savings of 1.0 kg/kW with the 0.9 wt% nanofluid highlighting the environmental benefits of this cooling approach. In thermal efficiency, the highest range observed was between 54% and 65% for an Al₂O₃ of 0.9 wt% loading. The total daily electrical power achieved approximately 0.28 kW for 0.9% Al₂O₃ nanoparticles, resulting in a 7.7% increase in electrical output compared to no cooling. Furthermore, the use of 0.9% Al₂O₃ nanoparticles contributed to a total daily CO₂ emissions reduction of 1.0 kg/kW, indicating environmental benefits associated with

this cooling method. This study demonstrated the considerable potential of Al_2O_3 nanofluid cooling in enhancing both electrical and thermal efficiencies in CPV modules. The highest loading of 0.9% Al_2O_3 showcases significant advancements in electrical output, efficiency, and environmental impact, highlighting its promising role in improving the performance and sustainability of PV systems. The study focused on a single type of nanofluid and concentration range. Therefore, the development of the findings to other nanofluids or higher concentrations remains uncertain. Future research could explore the direct measurement of heat transfer coefficients to validate theoretical models and provide a more precise understanding of nanofluid performance. Additionally, investigating other types of nanoparticles and a broader range of concentrations could offer insights into optimizing nanofluid cooling for various CPV systems. Expanding the research to include long-term performance and economic feasibility assessments would also be valuable for practical applications.

Acknowledgments

This work was supported by the University of Oradea pays the Article Processing Charges (APC).

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Y. Elhenawy, K. Fouad, M. Bassyouni, and T. Majazi, "Design and Performance a Novel Hybrid Membrane Distillation/Humidification-Dehumidification System," *Energy Conversion and Management* 286 (2023): 117039, <https://doi.org/10.1016/j.enconman.2023.117039>.
2. Y. Elhenawy, M. Bassyouni, K. Fouad, A. M. Sandid, M. A. E. R. Abu-Zeid, and T. Majazi, "Experimental and Numerical Simulation of Solar Membrane Distillation and Humidification-Dehumidification Water Desalination System," *Renewable Energy* 215 (2023): 118915, <https://doi.org/10.1016/j.renene.2023.118915>.
3. Y. Elhenawy, K. Fouad, A. Mansi, et al., "Experimental Analysis and Numerical Simulation of Biomass Pyrolysis," *Journal of Thermal Analysis and Calorimetry* 149 (2024): 10369–10383, <https://doi.org/10.1007/s10973-024-12987-y>.
4. Y. Elhenawy, K. Fouad, M. Bassyouni, O. A. Al-Qabandi, and T. Majazi, "Yield and Energy Outputs Analysis of Sawdust Biomass Pyrolysis," *Energy Conversion and Management: X* 22 (2024): 100583, <https://doi.org/10.1016/j.ecmx.2024.100583>.
5. J. Liang, H. M. Morgan, Y. Liu, et al., "Enhancement of Bio-Oil Yield and Selectivity and Kinetic Study of Catalytic Pyrolysis of Rice Straw Over Transition Metal Modified ZSM-5 Catalyst," *Journal of Analytical and Applied Pyrolysis* 128 (2017): 324–334, <https://doi.org/10.1016/j.jaap.2017.09.018>.
6. F. Bayrak, H. F. Oztop, and F. Selimefendigil, "Effects of Different Fin Parameters on Temperature and Efficiency for Cooling of Photovoltaic Panels Under Natural Convection," *Solar Energy* 188 (2019): 484–494, <https://doi.org/10.1016/j.solener.2019.06.036>.
7. M. U. Siddiqui, O. K. Siddiqui, A. Al-Sarkhi, A. F. M. Arif, and S. M. Zubair, "A Novel Heat Exchanger Design Procedure for Photovoltaic Panel Cooling Application: An Analytical and Experimental Evaluation," *Applied Energy* 239 (2019): 41–56, <https://doi.org/10.1016/j.apenergy.2019.01.203>.
8. M. S. Chowdhury, K. S. Rahman, T. Chowdhury, et al., "An Overview of Solar Photovoltaic Panels' End-of-Life Material Recycling," *Energy Strategy Reviews* 27 (2020): 100431, <https://doi.org/10.1016/j.esr.2019.100431>.
9. R. Li, Y. Shi, M. Wu, S. Hong, and P. Wang, "Photovoltaic Panel Cooling by Atmospheric Water Sorption-Evaporation Cycle," *Nature Sustainability* 3 (2020): 636–643, <https://doi.org/10.1038/s41893-020-0535-4>.
10. V. Muteri, M. Cellura, D. Curto, et al., "Review on Life Cycle Assessment of Solar Photovoltaic Panels," *Energies* 13 (2020): 252, <https://doi.org/10.3390/en13010252>.
11. R. M., L. S., R. S., A. H., and D. A., "Experimental Investigation on the Abatement of Operating Temperature in Solar Photovoltaic Panel Using PCM and Aluminium," *Solar Energy* 188 (2019): 327–338, <https://doi.org/10.1016/j.solener.2019.05.067>.
12. F. Bayrak, H. F. Oztop, and F. Selimefendigil, "Experimental Study for the Application of Different Cooling Techniques in Photovoltaic (PV) Panels," *Energy Conversion and Management* 212 (2020): 112789, <https://doi.org/10.1016/j.enconman.2020.112789>.
13. A. Hadipour, M. Rajabi Zargarabadi, and S. Rashidi, "An Efficient Pulsed-Spray Water Cooling System for Photovoltaic Panels: Experimental Study and Cost Analysis," *Renewable Energy* 164 (2021): 867–875, <https://doi.org/10.1016/j.renene.2020.09.021>.
14. P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, and I. Kirpichnikova, "Advanced Cooling Techniques of P.V. Modules: A State of Art," *Case Studies in Thermal Engineering* 21 (2020): 100674, <https://doi.org/10.1016/j.csite.2020.100674>.
15. R. Sathyamurthy, A. E. Kabeel, A. Chamkha, A. Karthick, A. Muthu Manokar, and M. G. Sumithra, "Experimental Investigation on Cooling the Photovoltaic Panel Using Hybrid Nanofluids," *Applied Nanoscience* 11 (2021): 363–374, <https://doi.org/10.1007/s13204-020-01598-2>.
16. R. Kumar, V. Deshmukh, and R. S. Bharj, "Performance Enhancement of Photovoltaic Modules by Nanofluid Cooling: A Comprehensive Review," *International Journal of Energy Research* 44 (2020): 6149–6169, <https://doi.org/10.1002/er.5285>.
17. T. K. Murtadha and A. A. Hussein, "Optimization the Performance of Photovoltaic Panels Using Aluminum-Oxide Nanofluid as Cooling Fluid at Different Concentrations and One-Pass Flow System," *Results in Engineering* 15 (2022): 100541, <https://doi.org/10.1016/j.rineng.2022.100541>.
18. T. S. Y. Moh, T. W. Ting, and A. H. Y. Lau, "Graphene Nanoparticles (GNP) Nanofluids as Key Cooling Media on a Flat Solar Panel Through Micro-Sized Channels," *Energy Reports* 6 (2020): 282–286, <https://doi.org/10.1016/j.egy.2019.11.075>.
19. M. S. Y. Ebaid, M. Al-busoul, and A. M. Ghrair, "Performance Enhancement of Photovoltaic Panels Using Two Types of Nanofluids," *Heat Transfer* 49 (2020): 2789–2812, <https://doi.org/10.1002/hjt.21745>.
20. A. Ahmed, G. Zhang, K. Shanks, S. Sundaram, Y. Ding, and T. Mallick, "Performance Evaluation of Single Multi-Junction Solar Cell for High Concentrator Photovoltaics Using Minichannel Heat Sink With Nanofluids," *Applied Thermal Engineering* 182 (2021): 115868, <https://doi.org/10.1016/j.applthermaleng.2020.115868>.
21. M. Alktranee, M. A. Shehab, Z. Németh, P. Bencs, and K. Hernadi, "Effect of Zirconium Oxide Nanofluid on the Behaviour of Photovoltaic-Thermal System: An Experimental Study," *Energy Reports* 9 (2023): 1265–1277, <https://doi.org/10.1016/j.egy.2022.12.065>.
22. M. Firoozzadeh, A. H. Shiravi, M. Lotfi, S. Aidarova, and A. Sharipova, "Optimum Concentration of Carbon Black Aqueous Nanofluid as Coolant of Photovoltaic Modules: A Case Study," *Energy* 225 (2021): 120219, <https://doi.org/10.1016/j.energy.2021.120219>.
23. G. S. Menon, S. Murali, J. Elias, D. S. Aniesrani Delfiya, P. V. Alfiya, and M. P. Samuel, "Experimental Investigations on Unglazed Photovoltaic-Thermal (PVT) System Using Water and Nanofluid

- Cooling Medium," *Renewable Energy* 188 (2022): 986–996, <https://doi.org/10.1016/j.renene.2022.02.080>.
24. H. Tanaka, "Tilted Wick Solar Still With Flat Plate Bottom Reflector," *Desalination* 273 (2011): 405–413, <https://doi.org/10.1016/j.desal.2011.01.073>.
 25. L. T. Kostić, T. M. Pavlović, and Z. T. Pavlović, "Optimal Design of Orientation of PV/T Collector With Reflectors," *Applied Energy* 87 (2010): 3023–3029, <https://doi.org/10.1016/j.apenergy.2010.02.015>.
 26. S. Alosious, S. S. R. A. R. Nair, and K. Krishnakumar, "Experimental and Numerical Study on Heat Transfer Enhancement of Flat Tube Radiator Using Al₂O₃ and CuO Nanofluids," *Heat and Mass Transfer* 53 (2017): 3545–3563, <https://doi.org/10.1007/s00231-017-2061-0>.
 27. P. K. Das, N. Islam, A. K. Santra, and R. Ganguly, "Experimental Investigation of Thermophysical Properties of Al₂O₃–Water Nanofluid: Role of Surfactants," *Journal of Molecular Liquids* 237 (2017): 304–312, <https://doi.org/10.1016/j.molliq.2017.04.099>.
 28. D. R. Lide, *CRC Handbook of Chemistry and Physics* (CRC Press, 2005), 85.
 29. B. C. Pak and Y. I. Cho, "Hydrodynamic and Heat Transfer Study of Dispersed Fluids With Submicron Metallic Oxide Particles," *Experimental Heat Transfer* 11 (1998): 151–170.
 30. Y. Xuan and W. Roetzel, "Conceptions for Heat Transfer Correlation of Nanofluids," *International Journal of Heat and Mass Transfer* 43 (2000): 3701–3707, [https://doi.org/10.1016/S0017-9310\(99\)00369-5](https://doi.org/10.1016/S0017-9310(99)00369-5).
 31. R. L. Hamilton and O. K. Crosser, "Thermal Conductivity of Heterogeneous Two-Component Systems," *Industrial & Engineering Chemistry Fundamentals* 1 (1962): 187–191.
 32. F. Abbas, H. M. Ali, T. R. Shah, et al., "Nanofluid: Potential Evaluation in Automotive Radiator," *Journal of Molecular Liquids* 297 (2020): 112014, <https://doi.org/10.1016/j.molliq.2019.112014>.
 33. D. Jing, Y. Hu, M. Liu, J. Wei, and L. Guo, "Preparation of Highly Dispersed Nanofluid and CFD Study of its Utilization in a Concentrating Pv/T System," *Solar Energy* 112 (2015): 30–40, <https://doi.org/10.1016/j.solener.2014.11.008>.
 34. Vadasz, P. "Heat Conduction in Nanofluid Suspensions," *ASME Journal of Heat and Transfer* 128, no. 5 (May 2006): 465–477, <https://doi.org/10.1115/1.2175149>.
 35. W. Daungthongsuk and S. Wongwises, "A Critical Review of Convective Heat Transfer of Nanofluids," *Renewable and Sustainable Energy Reviews* 11 (2007): 797–817, <https://doi.org/10.1016/j.rser.2005.06.005>.
 36. Mostafa Abu-Zeid, Yasser AbdEl-Rady, Mohamed Elhenawy, et al., "Performance Enhancement of Flat-Plate and Parabolic Trough Solar Collector Using Nanofluid for Water Heating Application," *Results in Engineering* 21 (2024): 101673.
 37. S. V. Gupta, *Measurement Uncertainties: Physical Parameters and Calibration of Instruments* (Springer Science & Business Media, 2012).
 38. L. Kirkup and R. B. Frenkel, *An Introduction to Uncertainty in Measurement: Using the GUM Guide to the Expression of Uncertainty in Measurement* (Cambridge University Press, 2006).
 39. A. Refaat, M. H. Osman, and N. V. Korovkin, "Current Collector Optimizer Topology to Extract Maximum Power From Non-Uniform Aged Pv Array," *Energy* 195 (2020): 116995, <https://doi.org/10.1016/j.energy.2020.116995>.
 40. Kalas, A. Daoud, and F. Bendary, "A Control Methodology of Grid-Connected PV System to Verify The Standard IEEE 929-2000," in *Proceedings of 15th International Middle East Power Systems Conference* (Egypt, 2012).
 41. M. Gharzi, A. Arabhosseini, Z. Gholami, and M. H. Rahmati, "Progressive Cooling Technologies of Photovoltaic and Concentrated Photovoltaic Modules: A Review of Fundamentals, Thermal Aspects, Nanotechnology Utilization and Enhancing Performance," *Solar Energy* 211 (2020): 117–146, <https://doi.org/10.1016/j.solener.2020.09.048>.
 42. A. G. Abo-Khalil, W. Alharbi, A. R. Al-Qawasmi, M. Alobaid, and I. M. Alarifi, "Maximum Power Point Tracking of Pv Systems Under Partial Shading Conditions Based on Opposition-Based Learning Firefly Algorithm," *Sustainability* 13 (2021): 2656, <https://doi.org/10.3390/su13052656>.
 43. M. K. Behera and L. C. Saikia, "A New Combined Extreme Learning Machine Variable Steepest Gradient Ascent MPPT for PV System Based on Optimized PI-FOI Cascade Controller Under Uniform and Partial Shading Conditions," *Sustainable Energy Technologies and Assessments* 42 (2020): 100859, <https://doi.org/10.1016/j.seta.2020.100859>.
 44. M. Sivashankar, C. Selvam, S. Manikandan, and S. Harish, "Performance Improvement in Concentrated Photovoltaics Using Nano-Enhanced Phase Change Material With Graphene Nanoplatelets," *Energy* 208 (2020): 118408, <https://doi.org/10.1016/j.energy.2020.118408>.
 45. A. Kouravand, A. Kasaiean, F. Pourfayaz, and M. A. Vaziri Rad, "Evaluation of a Nanofluid-Based Concentrating Photovoltaic Thermal System Integrated With Finned PCM Heatsink: An Experimental Study," *Renewable Energy* 201 (2022): 1010–1025, <https://doi.org/10.1016/j.renene.2022.11.025>.
 46. A. E. Kabeel and M. Abdelgaied, "Performance Enhancement of a Photovoltaic Panel With Reflectors and Cooling Coupled to a Solar Still With Air Injection," *Journal of Cleaner Production* 224 (2019): 40–49, <https://doi.org/10.1016/j.jclepro.2019.03.199>.
 47. S. Jowkar, X. Shen, G. Olyaei, M. Reza Morad, and A. Zeraatkardevin, "Numerical Analysis in Thermal Management of High Concentrated Photovoltaic Systems With Spray Cooling Approach: A Comprehensive Parametric Study," *Solar Energy* 250 (2023): 150–167, <https://doi.org/10.1016/j.solener.2022.12.032>.
 48. M. Zakaria, A. M. Sharaky, A. S. Al-Sherbini, M. Bassyouni, M. Rezakazemi, and Y. Elhenawy, "Water Desalination Using Solar Thermal Collectors Enhanced by Nanofluids," *Chemical Engineering & Technology* 45 (2022): 15–25, <https://doi.org/10.1002/ceat.202100339>.
 49. E. Çiftçi, A. Khanlari, A. Sözen, İ. Aytaç, and A. D. Tuncer, "Energy and Exergy Analysis of a Photovoltaic Thermal (PVT) System Used in Solar Dryer: A Numerical and Experimental Investigation," *Renewable Energy* 180 (2021): 410–423, <https://doi.org/10.1016/j.renene.2021.08.081>.
 50. P. Poredoš, U. Tomc, N. Petelin, B. Vidrih, U. Flisar, and A. Kitanovski, "Numerical and Experimental Investigation of the Energy and Exergy Performance of Solar Thermal, Photovoltaic and Photovoltaic-Thermal Modules Based on Roll-Bond Heat Exchangers," *Energy Conversion and Management* 210 (2020): 112674, <https://doi.org/10.1016/j.enconman.2020.112674>.
 51. A. Radwan, M. Ahmed, and S. Ookawara, "Performance Enhancement of Concentrated Photovoltaic Systems Using a Microchannel Heat Sink With Nanofluids," *Energy Conversion and Management* 119 (2016): 289–303, <https://doi.org/10.1016/j.enconman.2016.04.045>.
 52. M. Sardarabadi, M. Passandideh-Fard, and S. Zeinali Heris, "Experimental Investigation of the Effects of Silica/Water Nanofluid Onpv/T (Photovoltaic Thermal Units)," *Energy* 66 (2014): 264–272, <https://doi.org/10.1016/j.energy.2014.01.102>.
 53. S. K. Soni, M. Pandey, and V. N. Bartaria, "Energy Metrics of a Hybrid Earth Air Heat Exchanger System for Summer Cooling Requirements," *Energy and Buildings* 129 (2016): 1–8, <https://doi.org/10.1016/j.enbuild.2016.07.063>.
 54. Y. Elhenawy, G. H. Moustafa, A. M. Attia, A. E. Attia, T. Majazi Mansi, and M. Bassyouni, "Performance Enhancement of a Hybrid Multi Effect Evaporation/Membrane Distillation System Driven by Solar Energy for Desalination," *Journal of Environmental Chemical Engineering* 10, no. 6 (2022): 108855.
 55. R. A. Taylor, P. E. Phelan, T. P. Otanicar, et al., "Applicability of Nanofluids in High Flux Solar Collectors," *Journal of Renewable and Sustainable Energy* 3, no. 2 (2011): 023104.

56. A. H. Elsheikh, S. W. Sharshir, M. E. Mostafa, F. A. Essa, and M. K. A. Ali, "Applications of Nanofluids in Solar Energy: A Review of Recent Advances," *Renewable and Sustainable Energy Reviews* 82 (2018): 3483–3502, <https://doi.org/10.1016/j.rser.2017.10.108>.
57. S. Hassani, R. Saidur, S. Mekhilef, and R. A. Taylor, "Environmental and Exergy Benefit of Nanofluid-Based Hybrid PV/T Systems," *Energy Conversion and Management* 123 (September 2016): 431–444, <https://doi.org/10.1016/j.enconman.2016.06.061>.