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Performance optimization of photovoltaic panels using hybrid nanofluid cooling with titanium oxide and aluminium oxide

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ABSTRACT

High operating temperatures, particularly under high solar irradiance, significantly reduce the efficiency of photovoltaic (PV) modules. The performance of PV systems declines as cell temperatures rise, underscoring the need for effective cooling mechanisms, particularly in regions with extreme thermal conditions. Hybrid nanofluids have emerged as a promising solution for thermal management in photovoltaic systems due to their enhanced thermophysical properties. Superior heat dissipation, convective heat transfer, light trapping, and thermal stability are all coupled with relatively low production costs. The effect of different concentrations of titanium oxide (TiO_2) and aluminum oxide (Al_2O_3) hybrid nanofluids on the thermal and electrical performances of photovoltaic modules is investigated in this study. An experimental setup was set up with five identical PV modules of which one was a reference. Meanwhile, the other four were subjected to various nanofluid concentrations on their rear surface. Real-time backside temperature profiles were recorded using K-type thermocouples, and electrical output parameters were measured using a data logger. Findings showed that, compared to the control, nanofluid coating improved the performance of the modules. In the absence of Al_2O_3, the optimal enhancement was found to be 0.4% TiO_2, which led to a 14.98% increase in output power and a 15.56% increase in efficiency. The results demonstrated here suggest that hybrid nanofluids may be a means to improve photovoltaic cooling strategies and increase the overall energy conversion efficiency.

Keywords: hybrid nanofluids, photovoltaic cooling, thermal management, titanium oxide, aluminium oxide.

INTRODUCTION

With rising industrial, agricultural, and domestic energy demands, diversifying key energy sources is essential for increased fossil fuel consumption. The mass production of energy derived from fossil fuels releases harmful greenhouse gases such as those that cause global warming and climate change [Alktranee and Bencs, 2020]. According to Bayrak et al. [2017] these problems are being solved by alternative and sustainable energy sources which are solar, wind, geothermal, and tidal energy. The current energy paradigm has seen significant advances in renewable power technologies, which can provide both clean and sustainable solutions for climate protection and meet rising energy demands [Yaghoubirad et al., 2022]. Solar and wind energy solutions have been widely chosen as renewable options since they present electricity generation capability as well as a reduced environmental footprint [Shoaei et al., 2022]. The technology for solar energy production has been used globally both for electricity generation and heat production. Among the technologies in this field, the photovoltaic (PV) system is the main one that has spread through different applications [Firoozzadeh et al., 2021]. The PV cells are based on semiconductor materials, which transform a fraction of the incident solar irradiation into electricity by physical mechanisms [Jamal et al., 2019]. According to Al-Amri and Abdelmagid [2021], the total efficiency of PV modules depends on solar radiation intensity in conjunction with ambient temperature, cell material composition, and PV unit dimensions.

Thermal investigations in solar photovoltaic have been actively studied over the years, and cooling was found to be the third major barrier to the performance enhancement of such systems. The combination of a photovoltaic/thermal (PVT) device and a thermoelectric cooler was proposed in research by Dimri et al. [2017]. The performance of thermoelectric cooled collectors was compared to PV modules that had no cooling treatment and showed a 4.723% and 7.266% increase in performance. A PVT system integrated with PCMs was studied by researchers Preet et al. [2017], who found that it increased electrical output by up to 10.66%. Haidar et al. (2018) have conducted an experimental study to show that evaporative cooling improves PV panel temperatures by 20 °C leading to a 14 % increase in electrical efficiency. A PVT system incorporating microencapsulated paraffin showed improved electrical performance from enhanced melting dynamics and resulted in a 3.23% peak exergy efficiency improvement according to Yu et al. [2019] numerical simulation.

Nanofluids, composed of suspended nanoparticles in base fluids, have attracted much attention because they exhibit superior cooling properties via enhanced thermal transport. Three major factors affect the performance capabilities of these fluids: nanoparticle size distribution base fluid selection, and thermal conductivity and material properties of the system. Nanoparticles provide better thermal conductivity than conventional base fluids due to their high surface-to-volume ratio [Sheikholeslami et al., 2023].

Abdel-Aziz et al. [2025] have conducted research to utilize Al_2O_3/water nanofluids as a coolant in concentrated photovoltaic (CPV) and improve the electrical output of these systems. The investigation was performed in two parts, measuring the electrical and thermal power from CPV panels in cooled and non-cooled conditions. System performance testing involved aluminum oxide nanoparticles introduction using flow rate of 1.25 L/min examined at concentrations between 0.2 wt% and 0.5 wt%. The research showed maximum thermal cooling effects when using a 0.5 wt% concentration of Al_2O_3/water nanofluid, which resulted in a 55% reduction in panel surface temperatures compared to an uncooled panel. Under maximum solar conditions, the uncooled panel produced 43.22 Wh and the water cooled panel produced 48.87 Wh of electrical energy. As Al_2O_3/water nanofluid concentration increased to 0.2 wt% and 0.5 wt%, the system output improved to 51.01 Wh and 54.30 Wh, respectively. Moreover, when using a 0.5 wt% nanofluid, the electrical and thermal efficiencies of the nanofluid-cooled panel reached 34.80 % and 64.42%, respectively.

Two identically designed parabolic trough solar collector systems used in Amman, Jordan were evaluated by Al-Oran et al. [2024]. A hydraulic nanofluid mixture comprised of multi-walled carbon nanotubes (MWCNTs), Y_2O_3 nanoparticles, soluble gum Arabic (additive) in distilled water as a base heat transfer medium were used by the system at 0.01%, 0.025%, 0.05%, and 0.1% solution ratios. To generate the nanofluid solution and establish parameters for the preparation, the performance of the nanofluid (stability of the solution and its measurements compared against distilled water) was evaluated. Research results showed that hybrid nanofluid heat transfer was superior to single nanoparticle fluid heat transfer and achieved a thermal efficiency of 44% at a concentration of 0.1%. The maximum possible efficiency was provided by this concentration according to the Clausius Clapeyron relation. Tests indicate that distilled water by itself, without the oil, results in 19% heat transfer efficiency while by adding oil, this can increase up to 24%. At a volume concentration of 0.1%, the hybrid nanofluid had its maximum optical efficiency. The predicted collector's outlet temperature and thermal efficiency were accurate and consistent with the experimental data with an average deviation of 0.03% and a span in the efficiency measurements of 0.9%.

The potential of MWCNT/ZnO nanofluid to increase thermal regulation and enhance the overall operational performance of the PVT system was investigated by Sharaby et al. [2024]. The influence of MWCNT/ZnO nanofluid on the three performance measures electrical efficiency, thermal efficiency, and exergy performance were evaluated in this study. By improving the thermal properties of the base fluid, the MWCNT/ZnO nanofluid considerably enhanced the electrical and thermal output levels. However, in the nanofluid-cooled surface, the surface showed a superior performance by reducing the panel temperature by 14.9oC, enhancing electrical efficiency by 16.8%, and attaining a maximum thermal efficiency of 51.3% which was higher than the maximum thermal efficiency of water-cooled operation at 45.5%. Overall performance corresponded to an average efficiency of 58.7% of the nanofluid cooled system. The maximum exergy efficiency of the MWCNT/ZnO nanofluid was higher than conventional systems (7%) and water-cooled systems (27%). A 3.5% cut in entropy generation and exergy destruction was shown in the experimental setup compared to the conventional cooling systems.

Ibrahim et al. [2023] conducted a comparative study wherein they simultaneously operated three conventional polycrystalline solar panels under identical weather conditions. The electrical and thermal performance of a photovoltaic thermal system composed of a flat plate thermal absorber, Al_2O_3 nanofluid, and water as cooling agents, was evaluated using a serpentine coil arrangement. The results illustrated that PV modules benefited from improvements in Isc and Voc, and overall conversion efficiency for elevated nanoparticle concentrations and mass flow rate conditions. A 15.5% improvement in electrical efficiency was demonstrated in the PVT system. A combination of 0.05% nanoparticle concentration and a flow rate of 0.07 kg/s enhanced the PVT panel surface temperature by 22.83% compared to the reference panel. The uncooled PVT system achieved its maximum surface temperature at midday, which reached 75.5 °C while maintaining an average electrical efficiency of 12.156%. Peak sunshine hours resulted in a 10.0 °C drop in panel temperature when using water as a cooling agent, while nanofluid cooling produced an additional temperature reduction of 20.0 °C.

The goal of this research is to determine the optimum mixture ratio of aluminium oxide and titanium oxide nanoparticles that provide maximum efficiency when used in water based nanofluid cooling of photovoltaic panels in Amman area, Jordan under the Amman climate conditions. The research project examines the impact of varying Al_2O_3 and TiO_2 nanoparticle amounts on the thermal management capabilities of PV modules. The research employs nanofluid coatings on the backside surfaces of photovoltaic panels to evaluate temperature reductions and efficiency improvements.

EXPERIMENTAL SETUP AND PROCEDURE

Experiment setup

Figure 1 depicts the experimental setup, which contains various essential components designed to measure photovoltaic panel thermal properties and electrical behavior when using nanofluid as a coolant. Five polycrystalline PV panels, each rated at 155 W, were installed on iron frames that maintained a 27° tilt position, representing optimal solar access for Amman, Jordan. The experiment included one reference panel and four treatment panels, which received hybrid nanofluid applications.

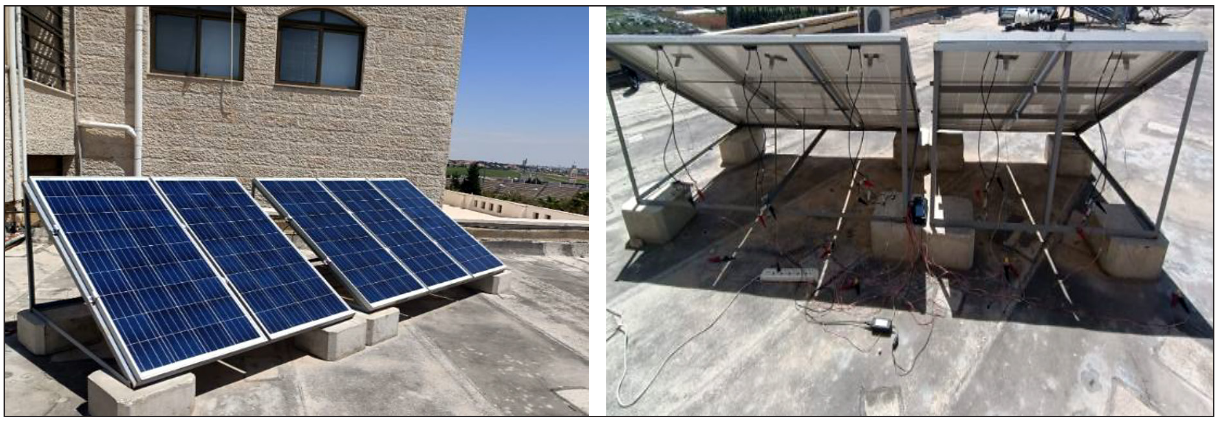

Figure 1. Experiment setup

A combination of titanium oxide and aluminium oxide nanoparticles suspended in distilled water made up the cooling fluid. US Research Nanomaterials provides nanoparticles containing Al_2O_3 with 30 nm particles, while TiO_2 nanoparticles exist between 30–50 nm. These nanoparticles exhibit pure forms and large surface areas.

The GL220 Graphtec midi data logger operated in conjunction with DATAQ Instruments software for the detection of electric and thermal data. A total of three K-type thermocouples were mounted on the rear surface of each PV panel to measure its backside temperature throughout each hour. Permanent data recorders tracked temperature measurements to determine how environmental changes affected overall performance.

A precision nano-spray gun was used to distribute the nanofluid solution evenly on the rear surfaces of the PV panel. A system was designed to dispense solutions from internal tanks, which produced homogeneous coverage across every treated module.

Procedure

Five photovoltaic panels were installed adjacent to each other to receive equivalent exposure from weather elements. The rear surfaces of each panel were equipped with K-type thermocouples for precise temperature measurement during thermal behavior monitoring. The GL220 midi data logger operated continuously to record and save performance data metrics about temperature readings, current measurements, voltage measurements, and power production measurements.

A GRWS100 weather station monitored environmental parameters, including ambient temperature and wind speed, to investigate the performance impacts on photovoltaic panels. A testing procedure consisted of applying diverse nanofluid concentrations from the Al_2O_3 and TiO_2 mixture to four PV modules using a nano-spray gun across their entire surface area. Each panel received a nanofluid application on its rear surface through a nano-spray gun for uniform paneling. The tested nanofluid concentrations were as follows:

- 0.4% Al_2O_3 – 0.4% TiO_2,
- 0.1% Al_2O_3 – 0.3% TiO_2,
- 0.3% Al_2O_3 – 0.1% TiO_2,
- 0.4% Al_2O_3 – 0.2% TiO_2.

The fifth panel, left untreated, served as the reference control. The performance of all panels was monitored under real-time operating conditions, and data were analyzed to determine the impact of hybrid nanofluid concentration on cooling effectiveness and overall PV module efficiency.

RESULTS AND DISCUSSION

Figure 2 illustrates the hourly solar irradiance recorded on April 18, 2024, in Amman, Jordan, demonstrating the expected diurnal variation characteristic of clear-sky conditions. Solar irradiance began at a low level in the early morning hours and progressively increased, The intensity of sunlight achieves 560 W/m² at its maximum during the middle

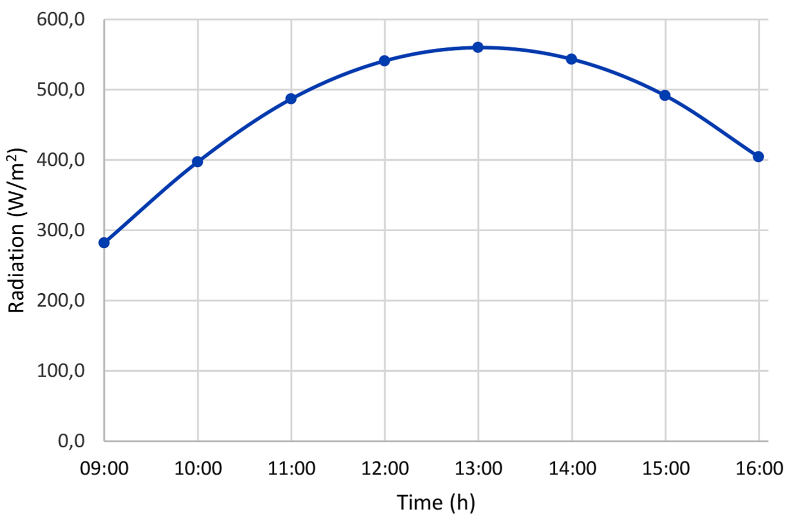

Figure 2. Hourly distribution of solar radiation on April 18th, 2024

of the day. This peak corresponds to the period when the sun's position is closest to being directly overhead, maximizing the incident solar radiation on the PV surfaces. Following this maximum, irradiance levels declined gradually throughout the afternoon, eventually tapering off to minimal values by late evening.

This temporal profile reflects the typical influence of solar zenith angle on irradiance levels, highlighting the natural daily cycle of solar energy availability. While this data offers valuable insights into the irradiance conditions under which the PV modules were tested, it is essential to acknowledge that the observed pattern is specific to the geographical and seasonal context of Amman in May.

The hourly backside temperature measurements for five photovoltaic panels operating under the same conditions are presented in Figure 3. The photovoltaic panel treated with the 0.4% Al_2O_3 – 0.4% TiO_2 hybrid nanofluid mixture maintained the lowest temperature levels across the entire day. Panels covered with 0.3% Al_2O_3 – 0.1% $TiO_2$and 0.1% Al_2O_3 – 0.3% TiO_2were treated sequence by temperature rise. On their backsides, the panel coated with 0.4% Al_2O_3 – 0.2% TiO_2, and the uncoated control panel showed the highest temperatures.

A 0.4% Al_2O_3 – 0.2% TiO_2 nanofluid mixture exhibited superior thermal performance, resulting in an 11.83% lower backside temperature compared to the control run. This demonstrates why a 0.4% Al_2O_3 – 0.2% TiO_2 mixture works best for heat dissipation. The base fluid's thermal conductivity increases, while convection and radiation improve, as nanoparticles disperse throughout the fluid. The PV module can dissipate heat more efficiently to its surrounding environment through these effects.

Thermal conductivity benefits from higher nanoparticle concentrations; however, concentrations exceeding optimal levels may cause aggregation problems that affect stability and sedimentation. The formation of agglomerations and sedimentation affects the stability of nanofluids and causes degradation of their heat transfer abilities over time. An appropriate amount of nanoparticles needs to be determined to ensure both efficient heat transfer capability and sustainable long-term operational durability.

The experimental results indicate that the nanofluid composed of 0.4% Al_2O_3 and 0.4% TiO_2 provides the most effective balance between enhanced thermal conductivity and fluid stability, making it the optimal formulation for passive backside cooling in PV applications.

Figure 4 presents the average hourly output power generated by each PV panel, enabling a direct comparison with the performance of the uncoated reference panel. The results reveal a clear trend: the panel coated with a hybrid nanofluid containing 0.4% Al_2O_3 and 0.2% TiO_2 achieved the highest power output throughout the observation period. This was followed by the panels treated with 0.3% Al_2O_3 – 0.1% TiO_2 and 0.1% Al_2O_3 – 0.3% TiO_2, and 0.4% Al_2O_3 – 0.2% TiO_2 nanofluids, respectively. The uncoated (control) panel consistently exhibited the lowest power generation.

The observed variation in output power is primarily attributed to the thermal regulation effects

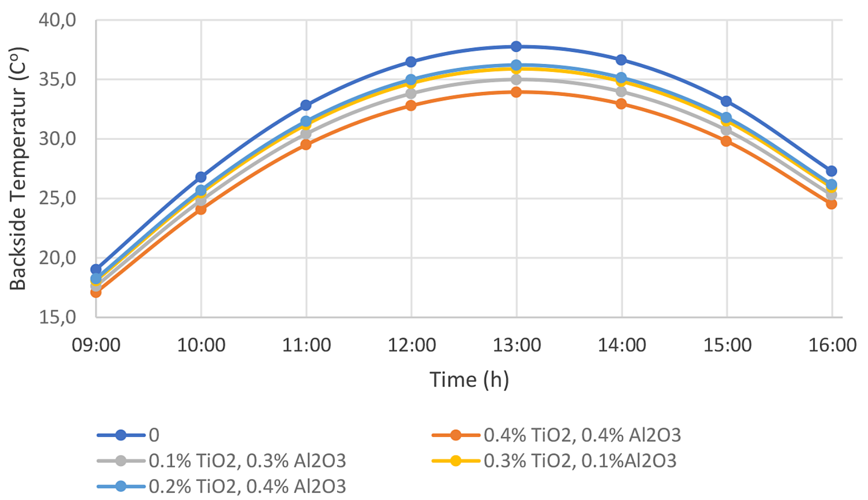

Figure 3. The hourly backside temperature measurement of a photovoltaic panel covered by a TiO_2 and Al_2O_3 hybrid mixture occurred on April 18th, 2024

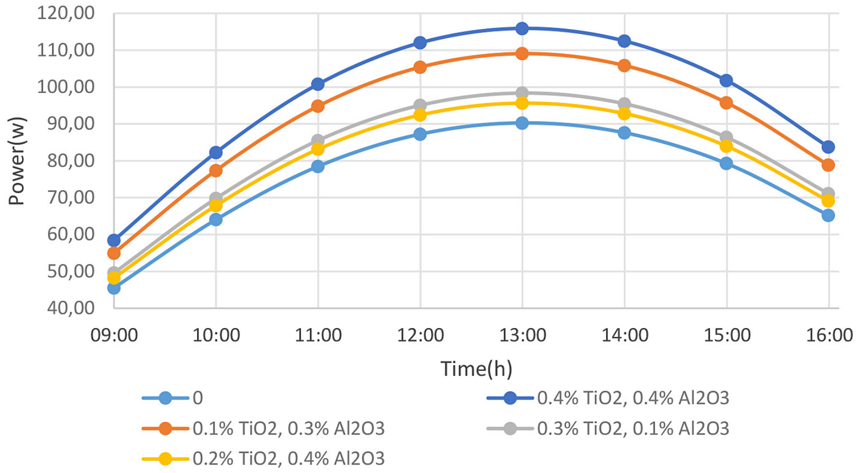

Figure 4. The hourly power output (W) of photovoltaic panels was recorded on April 18th, 2024, using a hybrid mixture of TiO_2 and Al_2O_3

of the nanofluids. As demonstrated in Figure 3, the application of nanofluids – particularly the 0.4% Al_2O_3-0.4 % TiO_2 mixture – effectively reduced the backside temperature of the PV panels. Since the electrical efficiency of PV cells is inversely related to their operating temperature, the cooling effect provided by the nanofluid coatings contributed to a significant reduction in thermal losses, thereby enhancing the photovoltaic conversion efficiency.

Electrical performance was enhanced by 14.98% when using panels treated with the 0.4% Al_2O_3 – 0.4% TiO_2 solution, indicating a direct relationship between thermal management and electrical output. The results demonstrate why nanofluid optimization plays a paramount role in achieving peak heat-dispersing capabilities without compromising fluid stability. Thermal analysis revealed temperature patterns that matched the improved power output observed in PV systems treated with hybrid nanofluids, thereby demonstrating that thermal regulation through hybrid nanofluids represents a valid method for PV enhancement.

Figure 5 illustrates the performance of the modified photovoltaic panel efficiency compared to the standard uncoated panel at each hour throughout the day. All nanofluid-coated panels demonstrated improved efficiency relative to the base panel, with the panel treated with a hybrid nanofluid containing 0.4% Al_2O_3 and 0.4% TiO_2 exhibiting the highest efficiency enhancement. Specifically, this configuration achieved an efficiency increase of

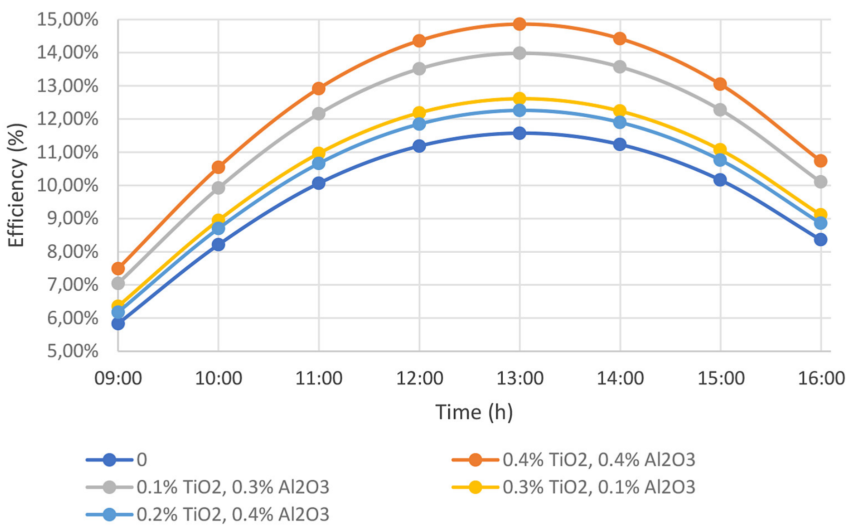

Figure 5. Hourly performance efficiency of photovoltaic panels using a hybrid mixture of TiO_2 and Al_2O_3 on April 18th, 2024

approximately 15.56%, indicating a substantial performance improvement.

This result aligns well with the previous findings discussed in Figures 3 and 4, where the same nanofluid formulation demonstrated superior cooling performance and the highest power output. The enhanced efficiency can be attributed to the effective reduction in thermal stress on the PV cells, achieved through improved heat dissipation by the nanofluid coating. By minimizing the operating temperature, thermal losses are reduced, allowing for more efficient conversion of incident solar radiation into electrical energy.

The remaining modified panels followed in descending order of efficiency improvement:
- 0.3% Al_2O_3 – 0.1% TiO_2,
- 0.1% Al_2O_3 – 0.3% TiO_2,
- 0.4% Al_2O_3 – 0.2% TiO_2.

Uncoated base panel

The trend confirms that optimal nanoparticle concentrations and ratios are crucial for maximizing heat transfer and maintaining the stability of nanofluids. Among the tested formulations, the 0.4% Al_2O_3 – 0.4% TiO_2 mixture provides the most effective thermal regulation, which directly translates into improved efficiency.

This demonstrates the viability of applications using hybrid nanofluid to enhance PV performance by employing passive cooling strategies. They also demonstrate the possibility that such coatings can be utilized in utility-scale photovoltaic systems, where enhanced thermal mitigation is critical for sustained stability, efficiency, and system longevity.

As can be seen in Figures 3, 4, and 5, the results collectively show that the hybrid nanofluid formulation of 0.4% Al_2O_3 – 0.4% TiO_2 yielded the most favourable overall results across all performance metrics. From the tested concentrations, this specific mixture is most effective at reducing backside temperatures, improving power output, and maximizing the efficiency of the photovoltaic panels. Due to its superior thermal conductivity and stability, this nanofluid blend consistently reduced panel operating temperatures, thereby increasing energy conversion efficiency and reducing thermal losses. It became evident in the 14.98% increase in power output and 15.56% increase in panel efficiency over the uncoated control.

The investigation reveals hybrid nanofluid coatings as a practical passive cooling approach for photovoltaic power systems installed in intense solar regions. The manipulation of nanofluid concentrations, combined with co position optimization, enables substantial a vancements in PV performance and extended system durability. The combination of 0.4% Al_2O_3 with 0.4% TiO_2 demonstrates peak performance potential in thermal conditions for maximizing solar energy collection.

CONCLUSIONS

The experimental findings that PV panel cooling effectiveness improves substantially when using nanofluids, which results in enhanced power generation and energy conversion performance at actual operating temperatures. The superior thermophysical properties of Al_2O_3 and TiO_2 nanoparticles within the nanofluid coatings achieved effective lower surface temperatures at PV module backside locations. The thermal load reduction directly addressed temperature-dependent electrical losses that significantly impact PV power generation output in high irradiance zones such as Amman, Jordan.

A hybrid solution that blended Al_2O_3 with TiO_2 at concentrations of 0.4% and 0.4% yielded the most efficient results for all performance metrics. The combination of optimized nanoparticle concentration at 0.4% Al_2O_3 and 0.4% TiO_2 resulted in 14.98% enhanced power generation and 15.56% improved overall efficiency compared to the uncoated reference panel. Results demonstrate that adjusting nanoparticle ratios enables scientists to create stable nanofluids with enhanced heat transfer capabilities.

The 0.4% Al_2O_3 and 0.2% TiO_2 coated panels delivered the minimal performance boost among all tested panels, yielding a power output improvement of 7.9% and an efficiency rise of 8.2%. The findings underscore the importance of optimizing nanofluid concentration, as inadequate ratios can lead to performance degradation due to particle aggregation or reduced thermal conductivity.

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