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Research Article

Experimental and machine learning-based electro-thermal performance enhancement of PV/T renewable energy systems with advanced cooling and power optimization techniques for sustainable buildings

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Abstract. The electrical power output and conversion efficiency of photovoltaic (PV) systems decrease significantly due to increased thermal losses at elevated module temperatures. Unlike conventional PV/T enhancement approaches, this study integrates recycled porous media, hybrid nanofluid PCM cooling, and data-driven optimization within a unified electro-thermal framework. This work experimentally investigates and optimizes the electro-thermal performance of a PV/T renewable energy system under real climatic conditions of Madinah, Saudi Arabia. An extreme gradient boosting (XGBoost) machine learning model was employed to predict PV/T electrical and thermal performance and identify the dominant parameters affecting power generation and system efficiency. Four modified PV/T configurations were developed and compared with a conventional PV unit: Al_2O_3 /water nanofluid cooling, recycled copper porous media, PCM containing recycled copper filings, and Cu/water nanofluid integrated with PCM. These configurations significantly enhance heat transfer coefficients and thermal dissipation, leading to improved electrical performance. The results revealed that the mean surface temperatures of PV/T@ Al_2O_3 , PV/T@ Al_2O_3 +CP, PV/T@ Al_2O_3 +CPPCM, PV/T@Cu+CPPCM were reduced by 6.08% (3.16 °C), 10.30% (5.15 °C), 15.31% (8.17 °C), 17.38% (11.98 °C) compared to standard PV, respectively. Consequently, electrical energy production increased by 7.57%, 18.85%, 27.85%, and 31.49%, respectively, compared with the standard PV unit (610 Wh). The PV/T@Cu+CPPCM configuration achieved the highest electrical and thermal efficiencies of 15.90% and 24.85%, respectively, with an electrical efficiency improvement of up to 22.39%. Techno-economic analysis indicates significant improvements in LCOE and payback period by 47.37, 55.56, 64.71, and 86.67%, respectively. The XGBoost model demonstrated high predictive accuracy and robustness, confirming its capability for real-time performance prediction and system level optimization. The results demonstrate a strong coupling between thermal regulation and electrical output enhancement, confirming the effectiveness of the proposed electro-thermal optimization strategy. This work presents a novel integrated electro-thermal optimization approach that combines hybrid cooling techniques with data-driven modeling to maximize PV/T system performance under real operating conditions for sustainable buildings in Saudi Arabia.

Keywords: Photovoltaic/thermal (PV/T) systems; Renewable energy systems; Electrical power generation; Machine learning; Sustainable buildings; Techno-economic analysis.



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1. Introduction

The challenge posed by energy crisis, erratic pricing in fossil fuel-based sources, and global warming makes renewable energy sources critical in generating electricity for buildings and decentralized power sources (Tazay, 2020; Tazay, 2026). Out of all the sources of energy, solar energy has emerged to be among the most significant due to its extensive availability and use, especially in Saudi Arabia (Mohammed *et al.*, 2024; Abdelkrim *et al.*, 2024). The technology associated with solar energy can be used for several different applications, ranging from electricity production (Harby *et al.*, 2025) to heating applications (Shabahat *et al.*, 2026), water distillation (Wu, 2024) to solar cooling applications. Photovoltaic (PV) technology is an effective technology capable of converting solar energy directly into electricity; thus, it is being used increasingly by low to mid-

energy consumption industries located in remote locations. However, the efficiency of photovoltaic systems drops during hot weather conditions since high temperatures lead to a decrease in their electrical yield (Attia *et al.*, 2024). The surface temperature of solar PV cells can reach 60 to 80°C (Abdelkrim *et al.*, 2023), which is one of the most common problems that must be resolved while the system is working (Abd Elnaby *et al.*, 2024). From an electrical engineering perspective, PV temperature rise directly affects the current voltage characteristics, maximum power point, fill factor, and electrical efficiency of the module. Therefore, temperature control should not be treated only as a thermal-management problem; it is also an electrical power-generation problem that influences maximum power extraction, energy yield, and power-conditioning stability (Mohan & Chiranjeevi, 2026).

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Recently, there has been a trend towards using hybrid photovoltaic/thermal (PV/T) technology to minimize the module surface temperature and convert solar intensity into heat and electrical energy simultaneously (Mohammed *et al.*, 2024). The solar cell is cooled using a solar collector and takes advantage of the excess thermal energy while minimizing the surface temperature of the cell and thus increasing the electrical energy production (Shahsavari *et al.*, 2022; Alshibil *et al.*, 2022). Abdelkrim *et al.*, (2024) presented a new cooling system to reduce the surface temperatures of a solar PV/T unit by introducing a new skeleton-fin heat exchanger. This system creates a double pass natural heat rejection allowing for improved overall system performance. They concluded that the average daily electrical production produced by the proposed cooling system was about 2.03 kWh with an improvement of about 55.2% over the traditional system. The energy cost and payback period lowered by 11.77% and 34.8%, respectively. Othman *et al.*, (2005) introduced a modern design of a double-pass PV/T unit integrated with extended surfaces to reduce the PV surface temperature and enhance system performance. They demonstrated that using PV/T combined with CPC and fins can significantly reduce the module temperatures, boost the power output, and lower the cost of electricity output. Teo *et al.* (2012) provided experimental research to improve the performance of PV/T unit using fins in an air channel behind a PV. They concluded that applying the suggested cooling technique caused a significant drop in temperature, increasing the overall system efficiency by 12%-14%. Fudholi *et al.*, (2019) introduced an experimental and simulation study on the thermal efficiency of PV/T unit combined with air channels for cooling process. Experimental and energetic analysis on the performance of PV/T unit coupled with a flat plate unit utilized as a solar collector was conducted by Jha *et al.* (2019). The addition of wavy plates is expected to accelerate the dispersal process of fluid flow and increase the pace of heat removal. They found that electrical energy, thermal energy, and net energy increased significantly. Özakin & Kaya (2019) provided an investigation on the use of fin inside an air-cooled channel to minimize the temperatures of monocrystalline and polycrystalline cells PV/T module. Several fin arrangements were tested to achieve maximum system performance including sparse and redundant. They discovered that applying fins in the air channel improved the exergy efficiency of the solar cell by 30.22% and 70.22%, respectively. Energy efficiency is also enhanced by 55.1% and 70.1%, respectively. The PV surface temperatures dropped by 10 to 15.1°C. Diwania *et al.*, (2021) performed experimental study on the usage of air collectors prepared by V-groove in the air channels to minimize the surface temperatures of PV/T unit. The research was conducted under variety of weather parameters of Ghaziabad, India. They found that performance of the PV/T unit ranged between 10.38-10.25% for electrical efficiency, 41.77-41.67% for thermal efficiency, and 52.16-51.82% for overall efficiency. Vajedi *et al.*, (2022) evaluated a PV/T unit coupled with a converging collector for cooling reasons. They showed a 12% improvement in overall system efficiency as compared to a traditional system collector. Arslan *et al.*, (2020) performed practical and simulation study on the functioning of a PV/T unit in conjunction with fine-grained air channels. L-shaped fins were used at the bottom of the PV/T module. The mass of air ranged from 0.032 to 0.046 kg/s. They concluded that the proposed PV/T module provided about 13.98% electrical efficiency and 49.5% thermal efficiency. There was an increase in energy efficiency with 0.42% in contrast to the PV/T module used as reference.

Phase-change materials (PCMs) have also been widely used for PV/T thermal regulation because they absorb excess heat during periods of high solar radiation and delay PV temperature rise. However, paraffin-based PCMs usually suffer from low thermal conductivity, which restricts charging and discharging rates and limits their effectiveness under rapidly varying outdoor conditions. To address this limitation, previous studies have incorporated fins, nanoparticles, metal foams, heat pipes, and thermoelectric units to improve heat diffusion inside the PCM region. Although these approaches improve thermal storage behavior, the integration of PCM with recycled conductive porous media remains insufficiently explored, particularly for outdoor PV/T operation in hot-arid climates. Some other studies investigated the use of PCM for better heat transfer and reducing the temperature of PV panels. Wongwuttanasatian *et al.*, (2020) found that the utilization of PCM along with fins helped increase the area for heat transfer and reduce PV modules temperature by 6.2°C, leading to a 9.40% gain in electrical efficiency and 4.79% improvement in overall efficiency. Khanalizadeh *et al.*, (2023) introduced the utilization of TEG unit, air and water as cooling fluids, and PCM to reduce the module temperature. They showed that the combined units achieved about 23.1% reduction in PV/T surface temperature and overall efficiency of 55.7%. Ji *et al.*, (2023) presented an investigation to enhance the performance of a PV/T unit using a Y-shaped heat pipe installed beneath the cell. Vajedi *et al.*, (2022) presented a cooling system consisting of a collector and two fans to enhance the performance of PV/T unit. This method increased the value of heat transfer coefficient by 12-38%. Saeed *et al.*, (2025) made comparisons between standard PV unit and the modified one with the using PCM and aluminum fin on the rear side of PV/T unit. They showed an increase in the efficiency of the panels by about 1.7%. Tyagi & Kumar, (2024) investigated the use of PCM enhanced by nanofluid to raise the performance of PV/T units. They found an increase in electrical and thermal efficiencies of about 13.04% and 56.66%, respectively. Different studies also used PCMs with conductive materials to improve their thermal conductivity, including the use of nanoparticles (Amir *et al.*, 2022), fins (Fang *et al.*, 2023), and metal foam (Hamid *et al.*, 2022). Recently Rajamony *et al.*, (2024) used graphene nanoparticles (0.7 wt%) to enhance the conductivity of paraffin wax. They found that thermal conductivity enhanced by 75.07%.

Nanofluids have also been applied in PV/T collectors because suspended nanoparticles can improve thermal conductivity and convective heat transfer. Practical nanofluid use depends on stability, nanoparticle concentration, pumping requirements, long-term degradation, and cost. The nanofluids were used because of their high thermal conductivity and heat capacities. Abadeh *et al.*, (2018) indicated that nanofluids can lead to raise the efficiency of PV/T by 7.1% compared to standard PV unit. In another study, Ghadiri *et al.*, (2015) conducted experimental work to enhance the electrical and thermal performances of a PV/T unit with the use of iron nanoparticles. They found that the overall efficiency increased by 79%. Karami & Rahimi (2014) reported the effect of using boehmite nanofluids on the performance of PV/T unit. They concluded that the module temperature decreased in a range between 18.32 and 24.23 °C for various concentrations of nanofluids. Moreover, Al-Waeli *et al.*, (2017) used silicon carbide nanofluids to reduce surface temperature of PV/T unit. They achieved an enhancement in efficiency by 88.9%. Fudholi *et al.*, (2014) showed a maximum efficiency of energy savings of up to 91% from a PV/T unit. Bassam *et al.*, (2023) demonstrated an enhancement in the electricity output up to 44.5% by employing

a silicon carbide/water nanofluid with nano-enhanced PCM inside a grooved fined tube. Shakir *et al.*, (2023) performed a similar experimental work by using Cu nanofluid and TiO₂ nanofluids to enhance the performance of a PV/T unit. They showed that higher electric efficiency was achieved by Cu nanofluid with 11.81%. Jarimi *et al.*, (2016) also carried out comparative experiments with air, water, and hybrid air-water cooling techniques with energy efficiency results of 62.33% for water and 58.12% for air cooling methods. According to Attia *et al.*, (2024), the system proposed in the study significantly enhanced energy efficiency by improving thermal efficiency by approximately 47.62%. Recent reviews have discussed the importance of dielectric nanofluids as promising materials with enhanced thermal properties and stability due to surfactants (Farade *et al.*, 2025). Recent high-impact reviews have highlighted that the stability, thermal properties, and sustainable composition of nanofluids are critical factors affecting their long-term applicability (Farade *et al.*, 2025). However, in practical renewable energy systems, PV modules are rarely used as isolated components; they are commonly connected to DC-DC converters, maximum power point tracking (MPPT) controllers, batteries, or inverter-based power conditioning units. Any fluctuation in PV temperature changes the voltage, current, and power available to these interfaces, which can affect MPPT accuracy, converter operating points, and the stability of downstream renewable energy systems.

Previous researchers have introduced many methods to maximize performance reduction due to high temperature in PV modules. According to the previous studies, different types of nanofluids have been tested in combination with heat exchangers for PV/T cooling, although there are few comparative studies regarding them. Phase-change materials (PCMs) have been also employed in some studies for increasing the heat storage capacity by capturing the latent heat behind PV module. To increase the thermal conductivity of PCMs, as well as reducing costs, is necessary for the effective implementation of PCMs in large-scale industry PV/T units. Despite the extensive literature on PV/T cooling using PCM, nanofluids, fins, and porous media, three important gaps remain. First, limited studies have simultaneously combined recycled porous metallic media, PCM enhancement, and nanofluid-based cooling in a single experimentally validated PV/T configuration. Second, most studies focus on thermal improvement without explicitly linking temperature regulation to electrical power stability and renewable power-conditioning requirements. Third, relatively few studies integrate outdoor experimental data with explainable ML models to predict electro-thermal performance and identify the most influential operating parameters under hot-arid climatic conditions.

Therefore, the main objectives of this study are as follows:

1. Development and outdoor experimental assessment of four PV/T configurations integrating nanofluid cooling, recycled copper porous media, and PCM thermal storage.
2. Evaluation of the effect of thermal regulation on PV electrical output, electrical efficiency, and energy production under real hot-arid conditions.
3. Application of XGBoost with cross-validation to predict PV/T electro-thermal performance using experimental data.
4. Use of SHAP and sensitivity analyses to identify the most influential parameters affecting power generation and thermal behavior.
5. Discussion of the suitability of the enhanced PV/T system for renewable energy applications in Saudi Arabia.

Unlike previous studies related to the optimization of PV/T that primary depends on either experimental improvement or only predictive models, the novelty of this study lies in integrating experimental electro-thermal enhancement, techno-

economic evaluation, and interpretable ML within a unified framework. This approach combines experimental modification, mainly nanofluid cooling, PCM, and recycled porous media with XGBoost-based prediction and SHAP interpretability analysis to (1) simultaneously enhance PV/T performance, (2) illustrate nonlinear variables interactions, and (3) determine dominant operating parameters. This integrated framework provides both physical understanding and intelligent performance optimization under real climatic conditions, which ensures a more comprehensive methodology for sustainable PV/T system design and operation. This framework also confirms the possible use of recycled materials in sustainable energy applications.

2. Experimental Setup and Methodology

2.1 System assembling process

In this study, four PV/T configurations incorporating different thermal-management strategies were designed, fabricated, and experimentally evaluated to improve electrical power output, thermal energy recovery, and overall electro-thermal performance. The outcomes were compared with those of a standard PV system without modifications. Fig. 1 presents a photograph and schematic diagram of the proposed setup used in this work. The experimental platform consisted of a reference PV module, a modified PV/T module, a DC electrical collection unit, charge controller, battery storage, inverter/load interface, circulation pump, water storage tank, data logger, and electrical sensors. The electrical side of the system was arranged to monitor the voltage, current, and output power of both the reference PV and modified PV/T modules. This arrangement allowed the thermal effect of each cooling configuration to be linked to electrical power generation and

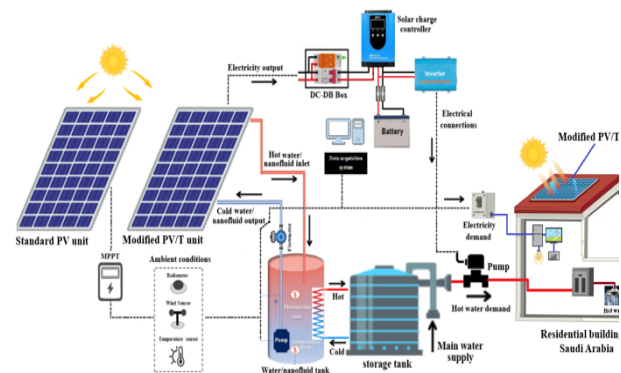
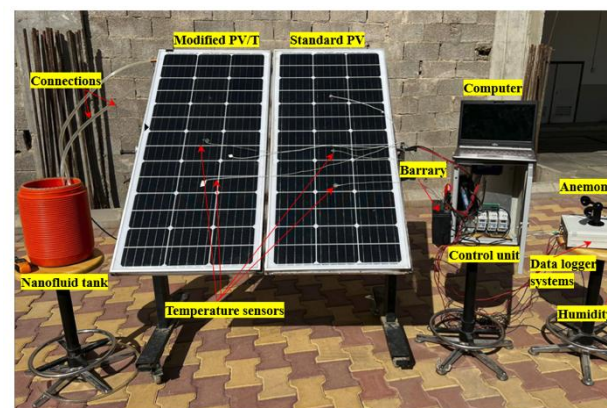


Fig. 1. a) Experimental and b) Schematic representation of the whole proposed setup.

Table 1
Electrical specifications of the monocrystalline PV.

Element	Characteristics	Symbol	Value	Units
PV solar module	Maximum energy	P_{max}	115	W
	Open circuit voltage	V_{oc}	21.06	V
	Short circuit current	I_{sc}	6.49	A
	Maximum voltage	V_{maxp}	18.06	V
	Maximum current	I_{maxp}	5.55	A
Battery	Capacity	Cap	110	Ah
		I	12	V
Charge Controller	Current		6	A
			12	V

conversion efficiency. The inclusion of a charge controller, battery storage, and inverter/load connection reflects a practical renewable-energy architecture in which PV output variations influence DC-bus behavior, and downstream power conditioning. Both PV modules were installed at a fixed tilt angle of 24.5° from the horizontal to match the local solar-collection conditions in Madinah, Saudi Arabia (latitude 24°28'12"N 39°36'36"E). In order to get comparable and consistent outcomes from the proposed PV/T systems, they were set up under similar climatic conditions. The setup was mounted on a steel support platform with an adjustable tilt angle.

Each PV module had dimensions of 1200 × 540 × 30 mm and consisted of 42 monocrystalline silicon cells connected in series-parallel configuration. Under standard test conditions, the rated maximum power was 115 W, with open-circuit voltage, short-circuit current, maximum power voltage, and maximum power current of 21.06 V, 6.49 A, 18.06 V, and 5.55 A, respectively. The PV panel comprises cells connected either in series, in parallel, or in to achieve specific requirements for power generation. The PV cell functions as a p n junction semiconductor device that translates sunlight into electricity. Table 1 shows dimensions and specifications of the PV units used. As indicated, open-circuit voltage (V_{oc}) of the modules was 21.06 V, short-circuit current (I_{sc}) was 6.49 A, maximum power

voltage (V_{maxp}) of the modules was 18.06 V, while maximum power current (I_{max}) of the modules was 5.55 A. These electrical parameters were used as the baseline for evaluating changes in output power, electrical efficiency, and operating point shift under outdoor conditions. Since PV voltage and maximum power are temperature dependent, direct measurement of voltage and current during operation was necessary to quantify the effect of thermal regulation on electrical performance.

An absorber made of aluminum contains 9 tubes made of copper (D_{out} = 8.5 mm) spaced by about 6 cm is designed and used as nanofluid-cooled PV/T collector, as shown in Fig. 2. The copper tubes are connected with two manifolds with a larger outer diameter of about 12 mm, which are used to distribute and collect nanofluid water behind the proposed PV/T system. The tubes have been made of copper because of its high thermal characteristics (see Table 2). The design makes sure that there is even heat distribution of the nanofluid in the PV/T module, making it even and homogeneous. In addition, the design helps in preventing any heat concentration at any point and helps eliminate any variance of heat. To prevent any kind of leakage, the copper tubes were connected with manifolds through welding, while an air pump seal was used for ensuring proper sealing. The back part of the parallel tubes was also provided with insulation with a thickness of 15 cm. The copper manifolds are attached to the nanofluid tank that has the spent nanofluid through insulating pipes. The nanofluid is drawn and circulated from the nanofluid tank to the manifolds under the PV/T module through a DC submersible pump fitted inside the nanofluid tank. Nanofluids are employed to enhance heat transfer efficiency and hence reduce cell temperatures rapidly.

2.2 Proposed configurations

To maximize energy productivity, four proposed configurations with different designs for modified PV/T units were proposed, compared, and tested as follows:

- Modified PV/T@ Al_2O_3 unit. In this system, H_2O/Al_2O_3 nanofluid-cooled PV/T collector was used to cool the back of the PV/T module. The spaces between the copper tubes were left empty. Leaving the space between the nanofluid-cooled PV/T collector empty is the general and standard practice used in most previous studies. The H_2O/Al_2O_3 nanofluid was employed as the working fluid in the PV/T absorber, aiming at reducing the surface temperature of the PV/T system. The used aluminum oxide/water nanofluid had a wt. concentration of 0.3%, which is in line with previous work that produced maximum performance (Sundar *et al.*, 2018; Said *et al.*, 2016). Table 2 demonstrates the previous specification of the utilized H_2O/Al_2O_3 nanofluid in the experiments. It should be noted here that a constant nanofluid mass flow rate of 0.005 kg/s was considered for all cases to ensure fair comparisons between all

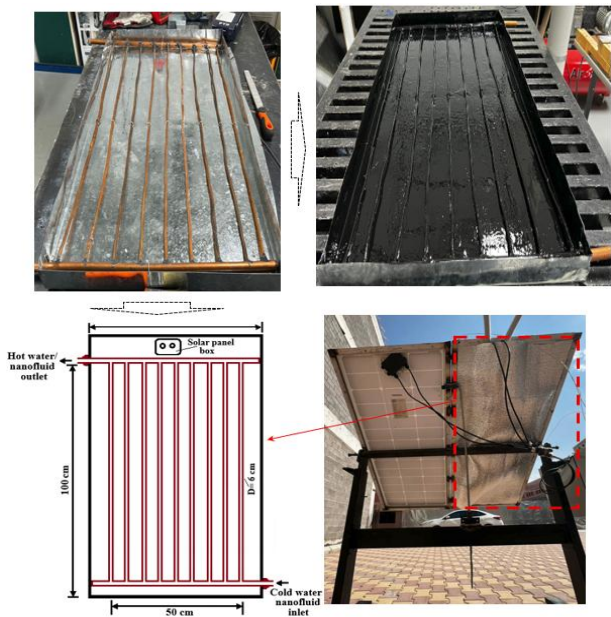


Fig. 2. Pictorial views and schematic with dimensions of the proposed nanofluid-cooled PV/T solar collector.

Table 2.

Characteristics of the materials used (Adeel *et al.*, 2021; Ahmad *et al.*, 2026; Fayaz *et al.*, 2019).

Elements	Specifications	Measurements	Units
Copper tube	Melting temperature,	1084 -273	°C
	Thermal conductivity	403	W/m.°C
	Thermal capacity	0.391	kJ/kg.°C
	Density	886	kg/m ³
Cu nanoparticles	Thermal conductivity	381	W/mK
	Density	8978	kg/m ³
	Thermal capacity	388	J/kgK
	Size	<50	nm
Al₂O₃ nanoparticles	Concentration	0.05	%
	Thermal conductivity	17.65	W/mK
	Density	3970	kg/m ³
	Thermal capacity	525	J/kgK
H₂O	Size	<50	nm
	Concentration	0.03	%
	Thermal conductivity	0.061	W/m.°C
	Density	998.3	kg/m ³
Paraffin wax	Thermal capacity	4183	J/kgK
	Dynamic Viscosity	0.001	Pa.s
	Thermal conductivity	0.20	W/m.°C
	Melting area	41-48	°C
Recycled porous media/ filings	Density solid/liquid	880/770	kg/m ³
	Thermal capacity	2150	J/kgK
	Melting temperature,	660	°C
	Thermal conductivity	238	W/m.°C
	Heat capacity	897	J/kg.°C
	Density	2385	kg/m ³

proposed configurations. The value of 0.005 kg/s was applied based on nanofluid mass flow rates of most previous studies on performance of PV/T units that had varied between 0.002 to 0.006 kg/s (Yazdanpanahi *et al.*, 2015; Jarimi *et al.*, 2016). This rate of flow can easily be achieved using a small pump. As higher flow rates increase convection but also pressure drop and pumping power, this choice was taken in order to examine solely the impact of recycling the metal scraps on the heat transfer augmentation. The preparation method of Al₂O₃-nanofluid was done using two-step process outlined by Yu and Xie (2012) and Babar and Ali (2019). Initially, the required mass of Al₂O₃-NPs (≤50 nm in diameter) was weighed using an electronic balance (0.1 mg accuracy) to prepare 0.3% concentration, as considered in previous works. Table 2 details the properties of the Al₂O₃-NPs used in this work. Then, Al₂O₃-NPs were gradually added to demineralized water (the base liquid) with continuous magnetic stirring to ensure initial mixing. Subsequently, surfactant (CTAB solution) was then incorporated into the mixture to prevent agglomeration, and the mixture was subjected to ultrasonication for approximately 60 minutes to obtain a homogeneous and stable nanofluid (Shaalan *et al.*, 2025).

- Modified PV/T@Al₂O₃+CP unit. In this system, porous medium made of recycled copper filings were employed between the spaces of the PV/T collector tubes. This can further enhance thermal contact area and promote between tubes and the back of the PV/T module. Recycled copper filings are able to absorb/dissipate heat because of their high thermal conductivity and capacity (see Table 2) (Abdullah *et al.*, 2026), which makes the heat transfer rate from the module surface higher. In addition, they are inexpensive and can be found in abundance, and recycling such material provides a solution to environmental issues related to their landfilling. This proposed arrangement can help to augment the evenness of heat distribution under the PV surface, thus avoiding overheating in some places.

- Modified PV/T@Al₂O₃+CPPCM unit. In this system, paraffin wax of about 4000 g enhanced by recycled copper filings was used between the spaces of the PV/T collector cooled with nano-liquid H₂O/Al₂O₃. PCM has a very high heat capacity, which allows it to absorb and store a lot of thermal energy. PCM helps in heat management through absorption of additional heat on the back of the PV/T module, which makes the PV cell cooler and increases efficiency. In PCM, heat is stored as latent heat due to melting, and therefore, the cell does not heat as fast as in other cases when there is a lot of solar irradiations. The addition of recycled copper filings with good thermal conductivity in PCM focuses on increasing their low thermal conductivity. As a result, PCM will absorb heat faster and hence cool down the rear surface of the PV/T module. The copper filings help in increasing the paths for heat transfer in PCM, hence the fast charging and discharging processes. Consequently, the copper filings-enhanced PCM will extract more heat from the rear end of the PV/T module faster. The copper filings have good thermal conductivity properties, availability, and extremely low cost, making them environmentally friendly.

- Finally, modified PV/T@Cu+CPPCM unit. In this system, paraffin wax (PCM) enhanced by recycled copper filling (10 wt %) was used between the spaces of the PV/T collector cooled with nano-liquid H₂O/Cu (see Table 2). In this case, the Cu nanoparticles were used in the nanofluid-cooled PV/T collector instead of Al₂O₃ nanofluid. A PCM type Rubitherm RT-47 was used based on its melting temperature (Rubitherm, 2026) as shown in Table 2.

2.3 Data gathering process

This section describes the methodology and arrangement used to test the proposed modified units (PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, and PV/T@Cu+CPPCM) explained in Section 2.2, during the experimental days. Also, as mentioned earlier in section 2.1, two

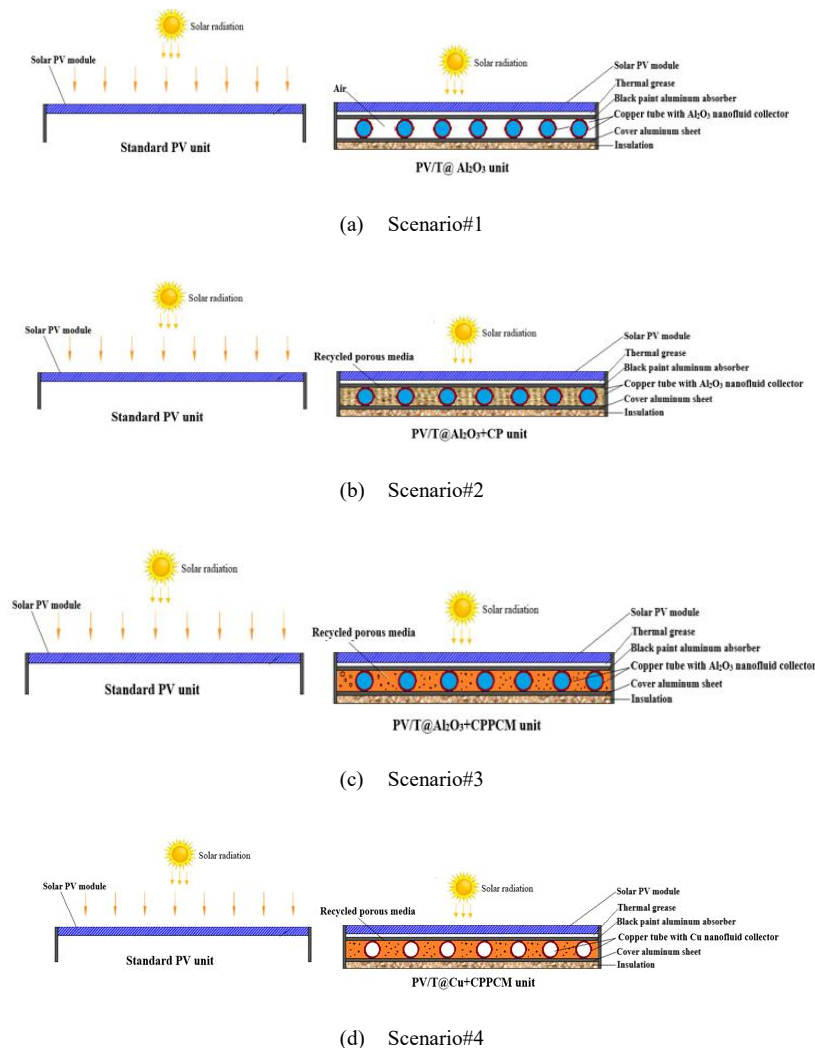


Fig. 3. Schematic diagram of various experimental scenarios conducted through the experiments.

main photovoltaic (PV) units were designed and implemented. The first unit was the modified PV/T module, and the second unit was the reference PV module without any modifications. Therefore, with four modified PV/T units, the experiments were conducted under four different scenarios compared to the reference PV module, as shown in Fig. 3. In Scenario#1, standard PV unit was tested with the modified PV/T@ Al_2O_3 unit. In Scenario#2, standard PV unit and modified PV/T@ Al_2O_3 +CP units were tested. In Scenario#3, standard PV unit was tested with the modified PV/T@ Al_2O_3 +CPPCM unit. Finally, in Scenario#4, standard PV unit was tested with the modified PV/T@Cu+CPPCM unit.

Each of the scenarios was replicated four times with similar conditions of operation (4 consecutive days) in August 2025 in order to check the precision of measuring equipment and readings. During the operation process, the top surface of the PV/T units will receive the sun's rays, which are subsequently transferred to the bottom absorber surface. As this happens, some of the incoming rays of the sun will be converted to electricity by the PV cells, with most being transformed to heat, leading to a reduction in the produced electrical power. However, because of the proposed nanofluid-cooled PV/T collector, most of the heat absorbed by the absorber will be transferred to the nanofluid and PCM enhanced by porous media that are situated below the solar PV panels.

2.4 Measuring instrument

The experimental system was instrumented to measure environmental, thermal, hydraulic, and electrical variables required for electro-thermal performance evaluation as presented in Table 3. Electrical voltage and current were measured at the output terminals of both PV modules to calculate instantaneous DC power. A power meter was used to verify output power, while the charge controller and battery interface represented the practical DC-side power-conditioning stage of the renewable-energy system.

A solar meter was used to measure the intensity of the solar radiation and was installed adjacent to the setup. Different K-type thermocouples were also used to measure the temperatures in various places. A thermocouple is used to measure ambient temperatures. Three thermocouples were placed to measure module temperature. Three thermocouples are used inside the nanofluid tank to measure the nanofluid temperatures. The performance of the setup was conducted on various days in August 2025 in Madinah, Saudi Arabia. Sunny weather prevailed, and all day we had consistent weather. Measurements were made between 8:00 a.m. and 6:00 p.m. Every 30 minutes, data was recorded, and those presented here represent the average data.

Table 3.
Measurement instruments with operating ranges and uncertainty.

Device	Accuracy	Range	Uncertainty [%]
Solar meter [Wm ⁻²]	± 10	100-1251	1.5
Thermocouple [°C]	± 0.1	-200-1300	0.12
Ammeter [A]	± 0.9	2-20	1.1
Voltameter [mV]	± 0.9	200-1000	1.1
Power meter [W]		0-4500	
Anemometer [m/s]	±2.4	0-30	

2.5 Uncertainty Evaluation

Maximum uncertainties of the analyzed and determined parameters of the studied systems are determined as follows (Holman, 2012):

$$V_L = \sqrt{\left[\left(\frac{\partial L}{\partial x_1} R_1\right)^2 + \left(\frac{\partial L}{\partial x_2} R_2\right)^2 + \left(\frac{\partial L}{\partial x_3} R_3\right)^2 \dots + \left(\frac{\partial L}{\partial x_n} R_n\right)^2\right]} \quad (1)$$

where V_L , x_1 , ..., x_n , R_1 , ..., R_n and L stand for total uncertainty, independent parameters, uncertainty of independent parameters and the provided function, respectively.

The electrical side of the system was monitored through voltage, current, and power measurements so that the influence of thermal regulation on PV operating point, power output, and renewable-energy power conditioning could be directly assessed. The error analysis is provided in Appendix I.

3. Electro-thermal and Techno-economic Performance analysis

3.1 Performance Analysis

The electro-thermal performance of the tested PV/T configurations was evaluated under steady outdoor operating conditions to quantify electrical power generation, thermal energy recovery, and overall renewable-energy utilization. The electrical analysis focuses on the DC power available at the PV output terminals, which represents the input power supplied to downstream power-conditioning interfaces such as MPPT controllers, DC DC converters, battery storage, and inverter-based loads (Harby *et al.*, 2025):

$$P_{dc}(t) = I_{dc}(t) \times V_{dc}(t) \quad (2)$$

where $P_{dc}(t)$, $I_{dc}(t)$, and $V_{dc}(t)$ are the instantaneous DC output power, current, and voltage of the tested PV/T module, respectively.

When the module operates near the maximum power point, the output power is calculated as:

$$P_{max} = I_{p,max} \times V_{p,max} \quad (3)$$

Where, $I_{p,max}$ and $V_{p,max}$ represent the maximum power current and voltage, the values are given in Table 1.

The PV/T energy is given as:

$$E_{el} = \sum_{j=1}^m P_{dc,j} \Delta t \quad (4)$$

where E_{el} is the daily electrical energy output, $P_{dc,j}$ is the measured DC power at time step j , and Δt is the measurement interval.

The ratio of maximum power output to the product of open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) will give us the fill factor (FF) of a solar panel (Opoku *et al.*, 2020):

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} \quad (5)$$

where V_{oc} , I_{sc} , and P_{max} are the open-circuit voltage, short-circuit current, and maximum power, respectively.

The fill factor was used as an indicator of the electrical quality of the PV module and the effect of cooling on the operating point. The electrical efficiency (η_{ele}) of the tested PV/T units can be calculated using (Harby *et al.*, 2025):

$$\eta_{ele} = \frac{P_{max}}{I \times A_{pv}} \quad (6)$$

Here, I represents sun intensity, while A_{pv} denotes the area of a PV.

The thermal efficiency (η_{ther}) of the standard design and modified designs of PV units is (Abdelkrim *et al.*, 2024):

$$\eta_{ther} = \frac{Q_t}{I \times A_b} \quad (7)$$

where A_b is the PV/T area and Q_t is the rate of useful thermal energy, given by (Harmailil *et al.*, 2024):

$$Q_t = \dot{m}_c \times C_{p,c} \times (T_{c,o} - T_{c,i}) \quad (8)$$

Where, $\dot{m}_c$, $C_{p,c}$, $T_{c,o}$ and $T_{c,i}$ are nanofluid mass, thermal capacity, and temperature at outlet and inlet, respectively.

3.2 Economic evaluation

The economic assessment was conducted to compare the financial viability of the modified PV/T configurations with the reference PV system from a sustainable-building perspective. The economic analysis will be based on the evaluation of their competitive advantages over the standard PV unit. The LCC of the tested PV/T units could be formulated using the following equation (Alazwari *et al.*, 2024; Rajamony *et al.*, 2025):

$$LCC = C_p + \sum_{n=1}^N MS_p - [E_s \times KF \times T_E] \quad (9)$$

Where, N is the lifecycle period (assumed N= 25 years), C_p is the annual capital price, MS_p is the annual maintenance and servicing price (assumed $MS_p = 3\%$), E_s is the annual energy saving, KF is the capital recovery parameter, and T_E is the energy tariff (in accordance with the Saudi residential tariff: 17 halalas/kWh for monthly usage up to 6000 kWh).

Capital recovery factor will be computed using formula (Zainab *et al.*, 2024) as follows:

$$KF = \frac{i}{1 - (1 + i)^{-n}} \quad (10)$$

Where i stands for interest rate and in this case, we consider an approximate interest rate of 10% (according to Saudi government) while n represents the average lifespan of the photovoltaic modules (n= 25 years).

Levelized cost of energy (LCOE) for the tested PV/T units can be determined by using the following equation (Khelifa *et al.*, 2024; Farade *et al.*, 2025) as follows:

$$LCOE = \frac{\sum_{n=1}^N \frac{CF_y}{(1+i)^n}}{\sum_{n=1}^N \frac{E_s}{(1+i)^n}} \quad (11)$$

Where, N represents the lifetime (assuming N= 25 years) (Tazay, 2020), CF_y refers to the cash flow per year.

Simple payback period (Pp) in years can be computed using the following equation (Tazay, 2020):

$$Pp = \frac{C_c}{\sum_{t=1}^N C_s} \quad (12)$$

Where CC refers to the initial costs including PV/T elements, and N stands for PV/T lifetime, and C_s is the yearly price savings compared with standard PV unit.

4. Machine Learning-based Electro-thermal Prediction

In this study, extreme gradient boosting (XGBoost) was developed as a supervised regression model to predict the electro-thermal performance of the tested PV/T configurations. This model is difficult to capture using traditional statistical methods or classical ML algorithms with high accuracy, as shown in Fig. 4. This algorithm characterizes with a gradient

boosting framework that provides management of missing values, efficient capturing of heterogeneous data types, and achieving robust predictions even with the limited datasets. Unlike other models, such as ANN and LSTM that require large datasets, the XGBoost model characterizes with its demonstrated robustness with small experimental dataset. This model uses L1/L2 regularization, subsampling, and learning rate to achieve stable generalization on limited dataset. Furthermore, while other models such as random forest provides ensemble averaging, the explicit regularization and iterative optimization of the XGBoost model led to lower variance and higher predictive accuracy.

The input parameter of the model involves four key physical parameters: solar irradiance (W/m^2), input coolant temperature ($^{\circ}C$), PV cell surface temperature ($^{\circ}C$), and configuration. The selection of these factors was based on their physical effect in the system performance, in addition to their strong correlation with the target variables. The models were developed using 55 high-fidelity data points representing the results of all configurations and operational conditions. The datasets were split using an 80/20 ratio, with 80% (44 data points) allocated to training and validation, and 20% (11 data points) to an unbiased final test to estimate the generalization performance of the model. A five-fold cross-validation was applied during the training phase to prevent overfitting, a common issue for limited data, and to ensure the robustness of the model.

The XGBoost algorithm was fine-tuned using carefully optimized hyperparameters to balance the model's complexity and predictive accuracy, as shown in Fig. 4. A learning rate of 0.05 with a set of 500 decision trees ($n_estimators = 500$) was used, adjusting the contribution of each tree to the final prediction. This low rate with a maximum tree depth of 4 ($max_depth = 4$), allows the model to learn meaningful patterns and prevents the model from picking up noise in the training data. During the development of each tree about 80% subsampling ($subsample = 0.8$) was used at the column (coefficients) and row (data states) levels, which produces an element of randomness that decreases variance and improves generalization. Cascade boosting sequentially operates, with each subsequent tree considering correcting residual errors resulting from the previous tree model. This iterative optimization technique along with stepwise descent optimization decreases the differential loss function while incorporating regularization terms (L_1 and L_2) that penalize complexity of the model.

To improve interpretability, SHAP analysis was used to quantify the contribution of each input feature to the predicted

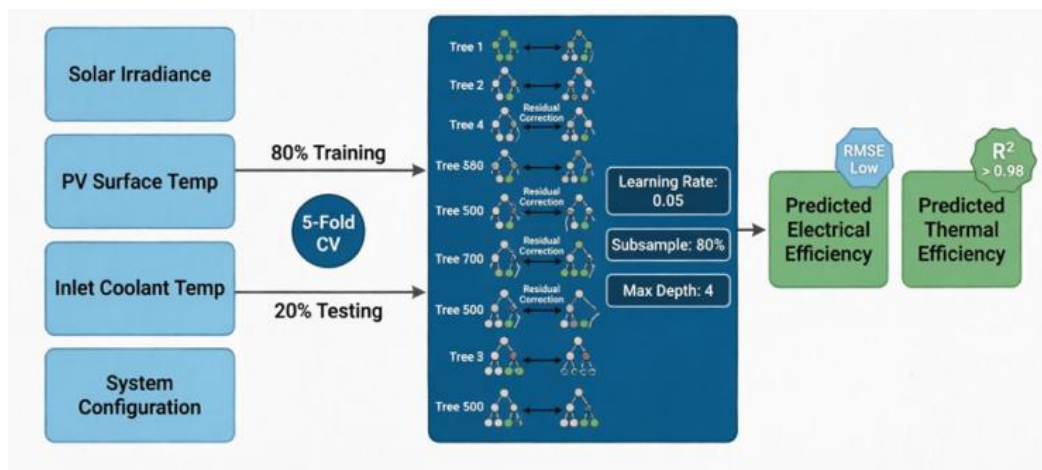


Fig. 4. The setting and structure of XGBoost model used for PV/T system prediction.

output. This is particularly important for PV/T systems because the model should not only predict efficiency but also explain whether irradiance, module temperature, coolant temperature, or system configuration dominates the prediction. The SHAP values were computed using TreeExplainer, which is specifically designed to explain tree-based ensemble models such as XGBoost (Lundberg *et al.*, 2020).

5. Results and Discussion

5.1 Outdoor Experimental Evaluation of Electro-thermal Performance

5.1.1 Atmospheric Parameters Throughout Tests

Outdoor climatic conditions strongly influence PV/T electro-thermal performance because solar irradiance governs photocurrent generation, while ambient temperature affects heat dissipation, module voltage, and the maximum power point. Increased irradiation of the sun results in increased electrical currents produced by the module, hence resulting in an increase in power production as the irradiation level enhances. However, high temperatures tend to lower the efficiency of PV modules and the amount of power generated. It should be noted that it is very important to have reliable atmospheric measurements during various working days for experiments related to electricity generation and the performance of energy usage. It can be seen in Fig. 5 that changes in temperature and solar radiation occur hourly in different situations in August 2025 from 08:00 h to 18:00 h. As indicated in the mentioned figure, the initial values for the solar radiation were lower, being 438, 436, 433, and 435 W/m² at 08:00 h. As more working hours elapse, solar irradiance increases progressively throughout the morning, reaching its peak at noon at 12:00 h where it registered 1000, 998, 999, and 996 W/m² respectively on the experimental days. It later decreases gradually to reach 45, 45, 50, and 49 W/m² at 18:00 h. On average, the daily solar radiation intensity was approximately 656.23, 656.86, 658.5, and 655.32 W/m².

The rising trend for the ambient temperature was also predictable and was influenced largely by the rising sun irradiation intensity, with a rapid increase occurring throughout the morning period. On average, the ambient temperature starts off at 33.5°C at about 08:00 h, then gradually rises until 46.5°C is reached between 13:00 h and 14:00 h. In the afternoon period, the ambient temperature drops somewhat to level at an average of 40.5 °C at 18:00 h. On average, the daily ambient temperature

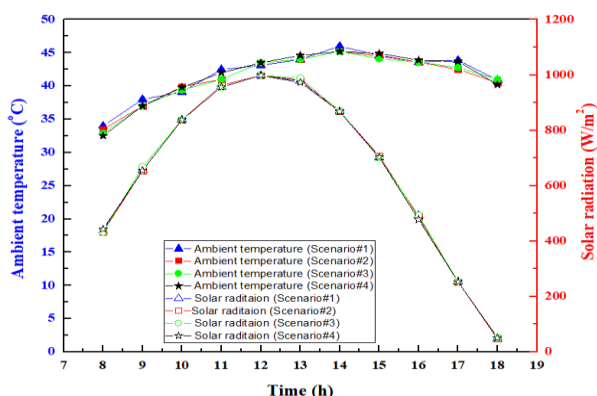


Fig. 5. Hourly changes in climatic condition of Madinah, Saudi Arabia during the testes Scinarios 1 to 4.

was approximately 41.79, 41.38, 41.32, and 41.57 °C. It is obvious that values of both ambient temperature and sun intensity display a stable pattern with minor changes, which is typical for stable weather through the different scenarios from 1 to 4.

5.1.2 PV/T Surface and Fluid Outlet Temperatures

Fig. 6 displays the hourly variations of PV surface temperature as a function of the tested PV/T units (standard PV, PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM) from 08:00 h to 18:00 h. As shown, a significant decrease in panel temperature throughout the day was achieved by the proposed techniques. The average panel temperature of all tested systems at the beginning of test at 08:00 h was 39.1, 39.4, 38.6, 37.9, and 36.8°C, respectively. As time goes on, it increases until it attains maximum value at 13:00 h, after which it decreases until it gets minimum value towards the end of testing period at 18:00 h with 41.2, 42.10, 42.51, 43.34, and 43.01 °C, respectively. The maximum panel temperature of standard PV, PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units was 69.01, 63.5, 58.3, 54.12, and 52.3 °C, respectively, around 13:00 h. This can be attributed to the intensity of solar radiation, which attained peak at around 12:00 h, as already discussed in Fig. 5. At 13:00 h, maximum panel temperature was achieved with 5.5 °C, 11°C, 15°C, and 17 °C by PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units. Additionally, it is quite evident from the results obtained that the average panel temperature of proposed systems is lower than that of standard PV system during the day.

The average panel temperature of standard PV, PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units was 55.19, 52.03, 50.04, 47.86, and 47.02, respectively. This illustrates that the mean temperature of the panels for PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units was 6.08%, 10.30%, 15.31%, and 17.38% lower compared to that of standard PV unit, respectively. Employing H₂O/Al₂O₃ nanofluid-cooled PV/T collector placed at the back side of the PV/T module in PV/T@Al₂O₃ model improves the thermal conductivity rate and hence the heat absorption and dissipation of heat outside, which caused a temperature drop of 6.08% (3.16 °C). Furthermore, the addition of recycled porous media in PV/T@Al₂O₃+CP unit around the tubes of nanofluid-cooled PV/T collector further enhance the thermal conductivities rate and thus enhanced the heat absorption inside recycled porous media. This led to improvement of heat dissipation and reduced the generation of hotspots, as a result, reducing the temperature by 10.30% (5.15 °C). In PV/T@Al₂O₃+CPPCM unit, adding PCM enhanced by recycled copper filings around the tubes of H₂O/Al₂O₃ nanofluid-cooled PV/T collector further enhances the heat absorption by the PCM and the recycled porous media, leading to further improved heat absorption and better temperature distribution, resulting in a 15.31% (8.17 °C) temperature reduction. This will also avoid heat accumulation at the junction where the tubes meet the surface of the cells, an important feature of this existing configuration. Finally, in PV/T@Cu+CPPCM unit, using Cu nanofluid instead of Al₂O₃ nanofluid in PV/T collector results in increased values for heat transfer coefficient, since Cu nanofluid has higher thermal conductivity than Al₂O₃ nanofluid, which in turn leads to increased heat absorption coefficient, giving rise to temperature reduction by 17.38% (11.98 °C).

Figs. 7 (a and b) presents the hourly variation in nanofluid temperatures within the H₂O/Al₂O₃ nanofluid-cooled PV/T

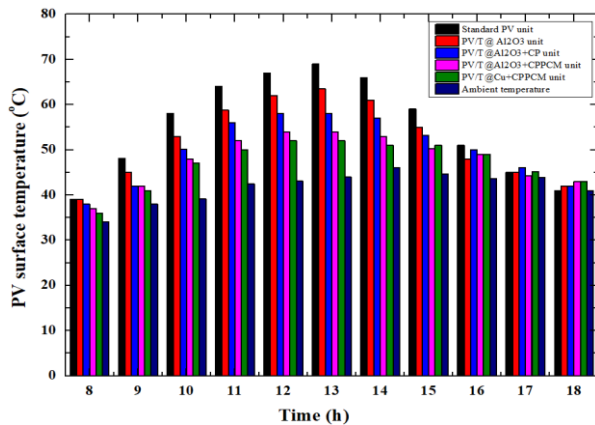


Fig. 6. Changes of hourly PV surface temperature as a function of the proposed PV/T systems.

collector as a function of the proposed PV/T systems. As seen, the outlet nanofluid temperature steadily rises from 08:00 h until it reaches its peak value at 13:00 h, after which it falls sharply to its lowest value at 18:00 h. This is due to the intensity of the solar radiation striking the PV surfaces as seen earlier in Fig. 5. It can be observed that all the four proposed cooling methods behave the same behavior throughout the beginning and end parts of the test period, because of sun intensity. Increased amount of solar intensity on the PV/T module raises its surface temperature, and consequently, the outlet nanofluid temperatures. The highest temperatures of the outlet nanofluid at the outlet were observed to occur around 13:00 h and were measured to be 57.2, 56.3, 55.4, and 53.9°C for PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units, respectively.

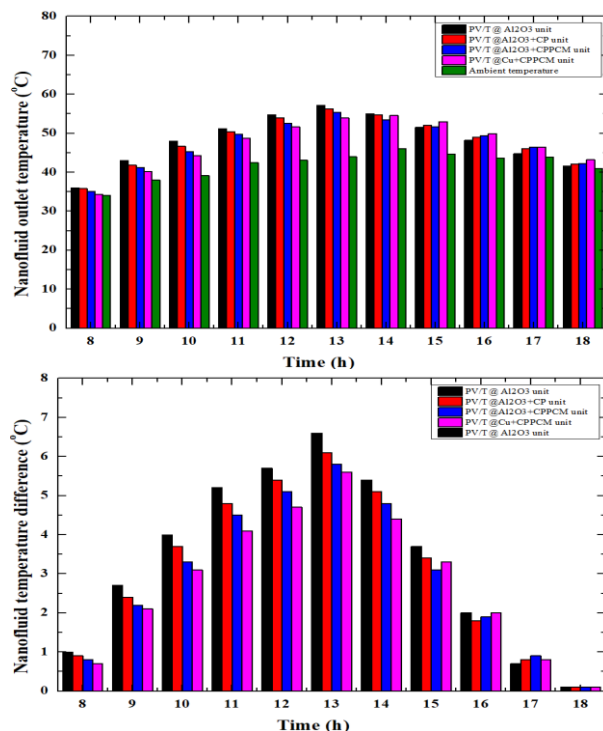


Fig. 7. Hourly temperature changes of nanofluid as a function of the proposed PV/T systems.

The rise in nanofluid temperatures shows the effectiveness of the suggested PV/T collectors to absorb and retain the energy produced by the PV/T systems. The different PV/T collectors with various configurations collect the absorbed heat in sensible by PV/T@Al₂O₃ and PV/T@Al₂O₃+CP units, while others retain it in latent by PV/T@Al₂O₃+CPPCM and PV/T@Cu+CPPCM units, and then release it into the surroundings. The average temperatures of the nanofluids at the collector exit were recorded as follows: PV/T@Al₂O₃ = 48.29, PV/T@Al₂O₃+CP = 48.07, PV/T@Al₂O₃+CPPCM = 47.51, and PV/T@Cu+CPPCM = 47.3°C. The highest exit temperatures were found in PV/T@Al₂O₃, followed by PV/T@Al₂O₃+CP with the porous media, and then PV/T@Al₂O₃+CPPCM with PCM, and lastly with the PV/T@Cu+CPPCM unit with Cu nanofluid. This is because, when the PV/T modules heat up during peak hours, the porous media and PCM absorb a significant amount of heat energy from PV/T; consequently, the outlet temperatures of nanofluid decrease, and temperature uniformity is maintained. It can be also seen from Fig. 7(b) that the temperatures of the nanofluids at the exit were always greater than their temperatures at the inlet during the entire experiment. Also, the application of PCM results in the increase in outlet nanofluid temperature in situations where there is low solar irradiance (at 17:00 and 18:00 h) because the heat stored is discharged in the evening period. Moreover, the inclusion of recycled copper materials in PCM has proven to be a good way of maintaining the outlet nanofluid temperature constant because the heat is easily discharged in such cases. This is due to the high thermal capacity (897 J/kg.°C) and thermal conductivity (about 238 W/m.°C) of the copper materials used, as already explained previously in Table 2. Furthermore, better thermal properties associated with Cu nanofluid used in PV/T@Cu+CPPCM rather than Al₂O₃ result in improved heat transfer coefficient. During late afternoon, the PCM-assisted systems maintained more stable outlet temperatures as stored heat was gradually released. This behavior is useful for sustainable building applications, where hot-water demand may not coincide exactly with peak solar irradiance.

5.1.3 Short-circuit Current/open-circuit Voltage Measurements

The short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) determine the electrical limits of the I-V characteristics of a PV unit, thus significantly affecting the electricity production. I_{sc} is governed by irradiance, whereas V_{oc} is strongly affected by cell temperature. The higher the value of I_{sc} , the more current will be made available to be used when connected to a load; hence, more electricity can be generated, provided that the voltage remains constant. A high value V_{oc} permits a long series stringing of panels, making it possible for the inverter to operate within its voltage range. Figs. 8 (a and b) display the hourly changes in a) short-circuit current (I_{sc}) and b) open-circuit voltage (V_{oc}) as a function of the proposed PV/T systems. As shown, short circuit current in each system demonstrates an evident rise trend till it starts at 10:00 h, peaks at 13:00 h and decreases progressively till 16:00 h. This trend corresponds to the electrical power produced by the PV/T units, which is related to solar radiation intensity striking the PV/T unit. It exhibits a slight increase when the cell temperature rises. Moreover, it is shown that the short-circuit current of standard PV unit demonstrates a higher value compared to the modified PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units through the whole day period. The value of the short-circuit current (I_{sc}) depends greatly on the level of solar radiation falling on the module and thus its temperature. At around 10:00 hours, the values of the short circuit currents were 4.25, 4.2, 4.1, 3.62, and 3.8A respectively

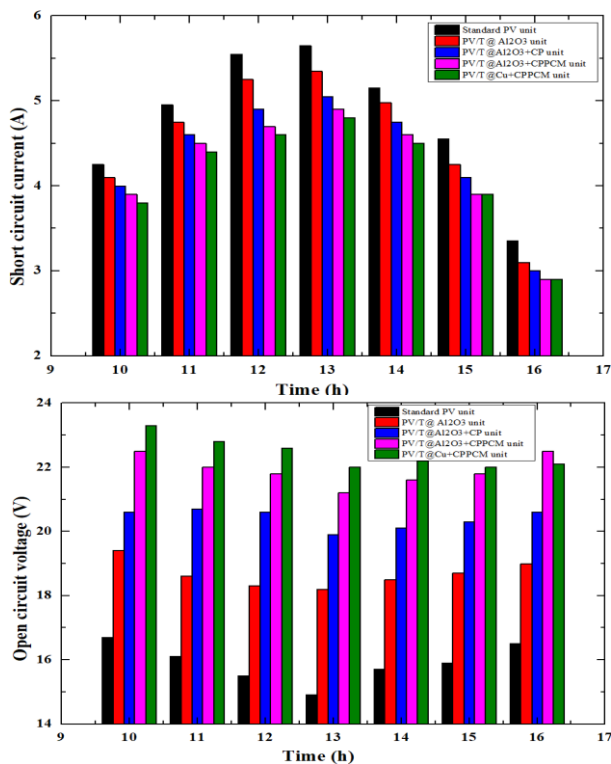


Fig. 8. Hourly changes in a) short-circuit current (I_s) and b) open-circuit voltage (V_o) as a function of the proposed PV/T systems.

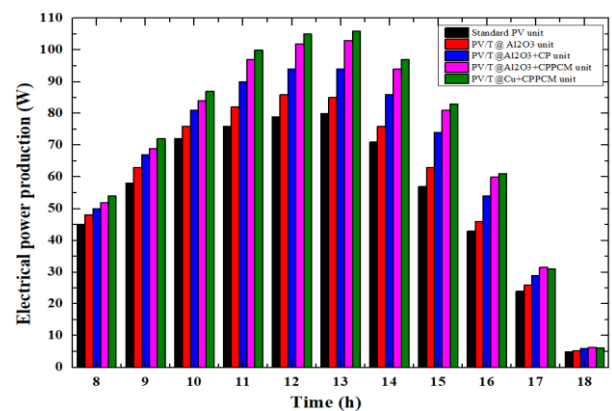
for the standard PV, PV/T@ Al_2O_3 , PV/T@ Al_2O_3 +CP, PV/T@ Al_2O_3 +CPPCM, PV/T@Cu+CPPCM units. These currents reached the peak at around 13:00 hours, with 5.65, 5.36, 5.05, 4.91, and 4.52 A respectively. As the day progressed, the values of short-circuit current dropped to reach the value of 3.35, 3.11, 3.1, 2.92, and 2.9 A at 16:00 h, respectively. With the proposed cooling units employed, panel temperature is lowered, which slightly reduces the I_{sc} , particularly when the intensity of irradiation is high, because I_{sc} increases slightly with cell temperature. Among all the tested modified units, the PV/T@Cu+CPPCM unit performs better than all other modified units (PV/T@ Al_2O_3 , PV/T@ Al_2O_3 +CP, and PV/T@ Al_2O_3 +CPPCM) throughout the experimental periods.

While the I_{sc} increased as the intensity of sun intensity increased, the V_o showed a slight reduction due to the rising surface temperature of the solar cells. The increase in the I_{sc} because of the increase in temperature brought about by the modified system caused a slight reduction in the V_{oc} . A rise in the panel surface temperature causes an increase in the concentration of the charge carriers hence resulting in a reduction in the V_{oc} . As indicated, the V_{oc} in the standard PV unit is lower compared to that in the modified PV/T units during the day. The V_{oc} decreases slightly from 10:00 h to 13:00 h before it begins to increase, and this corresponds to the highest temperature recorded during the day in the cells. At 13:00 h, the open-circuit voltage was 14.9 V, 18.2 V, 19.9 V, 21.2 V, and 22 V in standard PV, PV/T@ Al_2O_3 , PV/T@ Al_2O_3 +CP, PV/T@ Al_2O_3 +CPPCM, PV/T@Cu+CPPCM units. Among the modified units tested in the experiment, the open-circuit voltages recorded for PV/T@Cu+CPPCM are higher compared to those of the other tested modified units (PV/T@ Al_2O_3 , PV/T@ Al_2O_3 +CP, and PV/T@ Al_2O_3 +CPPCM). As a result of using the proposed cooling methods, the temperature of the cells will be reduced, thus leading to increased open-circuit

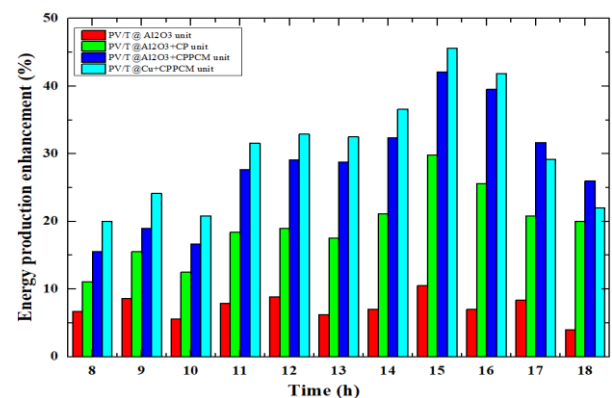
voltage, particularly at high solar intensity levels (at 13:00 h). This is because the heat capacity of PCM is very high, and the thermal conductivity of the recycled copper filings and copper nanoparticles helps in absorbing heat energy, thus reducing the temperature and increasing the open-circuit voltage. The improved voltage stability of PV/T@Cu+CPPCM is particularly relevant for renewable-energy systems because DC DC converters and inverter front-end stages require sufficient input-voltage margin for stable operation. Therefore, the proposed cooling configuration supports both efficiency enhancement and more reliable MPPT-based power extraction.

5.1.4 Electrical Production Evaluation

Figs. 9 (a and b) present the hourly DC electrical power output and the corresponding power enhancement ratio of the modified PV/T configurations relative to the standard PV module. Electrical power increased from morning to midday with increasing irradiance and declined in the late afternoon as solar input decreased. As shown, the electricity produced through the day hours are higher for the proposed units compared to standard PV unit, especially at midday, due to the lower surface temperatures achieved by using the different proposed cooling techniques. Additionally, it is observed that electricity production increases with the daylight hours as a result of the increased intensity of solar radiation, see previously Fig. 5. The electrical power generated peaked at midday in all cases. The units produce a relatively similar amount of electricity in the morning hours, around 8:00 h. Productivity increases with working hours and reaches its highest value at 13:00 h, when the solar intensity arrives at its maximum value with 80, 85, 94, 103, and 106 W for standard PV, PV/T@ Al_2O_3 ,



(a)



(b)

Fig. 9. a) Electrical power changes and b) Electrical power enhancement through the day using the proposed PV/T systems.

PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units.

As shown in Fig. 9 (a), the mean value of electrical energy produced per day is estimated to be 55.45, 59.65, 65.90, 70.9, and 72.92 W, respectively, for normal standard PV, PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM. In other words, using an H₂O/Al₂O₃ nanofluid-cooled PV/T collector in PV/T@Al₂O₃ unit increases the thermal conductivity and heat transfer rates, resulting in a 7.57% increase in energy production, as shown in Fig. 9 (b). Moreover, utilizing recycled porous media with PV/T@Al₂O₃+CP unit among the tubes of the nanofluid-cooled PV/T collector increases the thermal conductivities and thus enhances heat transfer. This causes a significant improvement in heat dissipation and prevents hotspots formation, resulting in 18.85% electricity enhancement. The incorporation of PCM reinforced by the recycled copper filings around the tubes of H₂O/Al₂O₃ nanofluid-cooled PV/T collector results in further improvement in heat transfer rates, heat absorption capacity of the PCM, and recycled porous media. Additionally, the temperature distribution becomes much better, leading to 27.85% increase in energy production. Moreover, it will prevent heat concentration in the region where tubes contact the absorber, which is one major benefit of this configuration. In the last case of PV/T@Cu+CPPCM unit, Cu nanofluid is used as the nanofluid in the PV/T collector. This will result in a higher heat transfer coefficient because Cu nanofluid has higher thermal conductivity than that of Al₂O₃ nanofluid. Therefore, higher values of heat transfer rates and cycle performance are expected in this case, causing an enhancement of about 31.49% in energy production.

The higher and more stable DC output power is directly relevant to power-conditioning systems. In building-integrated renewable-energy systems, this behavior can reduce thermal-induced power fluctuations during peak solar hours and improve inverter-side energy delivery.

5.1.5 Electrical Efficiency

Fig. 10 shows the hourly electrical efficiency of the standard PV module and modified PV/T configurations. Electrical efficiency was calculated from measured DC power, incident

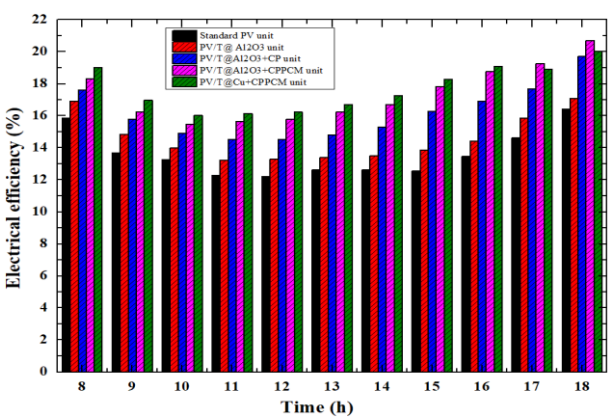


Fig. 10. Hourly changes in electrical efficiency as a function of the proposed PV/T systems.

irradiance, and PV area; therefore, it reflects the ability of each configuration to convert available solar energy into usable electrical power. Fig. 10 displays the changes in electrical efficiency of the proposed modified units and those of the standard PV unit. As observed, at 08:00 h, the mean electrical efficiency generated from PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units, as well as the standard PV system, was approximately 16.91, 17.62, 18.32, 19.03, and 15.85%, respectively. Over time, the electrical efficiency of standard PV, PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units reduced, reaching its lower values at 16.61, 13.40, 14.82, 16.24, and 16.71 %, respectively. This means that the proposed PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, PV/T@Cu+CPPCM units provided an enhancement in electrical efficiency of approximately 7.31, 20.01, 29.15, and 31.34%, respectively higher than that of standard PV unit. This is a direct result of the increase in electrical energy production (see Fig. 9) in the proposed systems due to the decrease in panel temperatures through the proposed cooling systems, which were explained in detail above. From an electrical engineering perspective, efficiency improvement is mainly associated with better voltage retention under high irradiance and high temperature. This is beneficial for MPPT operation because a more stable voltage power characteristic reduces thermal drift

Table 4. A comparison of energy efficiency enhancement with previous related studies.

Ref.	The used technique	Enhancement in energy efficiency
Özakin & Kaya, (2019)	Utilized fins inside an air-cooled channel to minimize the temperatures of monocrystalline and polycrystalline cells PV/T module	55.1-70.1
Diwania <i>et al.</i> , (2021)	Used air collectors prepared by V-groove in the air channels to minimize the surface temperatures of PV/T unit.	10.38-10.25%
Vajedi <i>et al.</i> , (2022)	PV/T unit coupled with a converging collector for cooling reasons	12%
Wongwuttanasatian <i>et al.</i> , (2020)	Used PCM along with fins to increase the area for heat transfer and reduce PV modules temperature.	9.40
Tyagi & Kumar, (2024)	Used PCM enhanced by nanofluid to raise the performance of PV/T units.	13.04%
Jarimi <i>et al.</i> , (2016)	Carried out comparative experiments with air, water, and hybrid air-water cooling techniques	62.33%
Current study	PV/T@Al ₂ O ₃	7.31
	PV/T@Al ₂ O ₃ +CP	20.01
	PV/T@Al ₂ O ₃ +CPPCM	29.15
	PV/T@Cu+CPPCM	31.34

of the maximum power point and supports more reliable DC-side power conversion.

Table 4 presents a comparison of energy efficiency enhancement with previous related studies. As shown, the energy efficiency enhancement in this study ranged between 7.31-31.34%. While the enhancement in energy efficiency with other related study ranged between 9.40-70.1%. It should be noted that the comparison is not direct due to changes in operating and design conditions.

5.1.6 Thermal Power Recovery and Thermal Efficiency

Fig. 11 (a and b) present the hourly useful thermal power recovered by the circulating nanofluid and the corresponding thermal efficiency of the proposed PV/T configurations. This analysis is important for sustainable building applications because the recovered heat can support low-temperature thermal demands, such as domestic hot-water preheating, while the PV module simultaneously generates electricity. As shown, a significant enhancement in thermal energy and efficiency is observed over time, particularly from 11:00 h to 14:00 h. This is related to the increase in solar irradiance. At 08:00 h, the thermal energy was 41.83, 37.65, 33.46, and 29.28 W, respectively for PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, and PV/T@Cu+CPPCM units. Over time, amount of thermal energy enhanced with the rise in solar intensity and reaches the maximum values at 13:00 with 276.08, 255.16, 242.61, and 234.25 W, then decreased over time until reaching of about 4.18 W at 18:00 h.

The highest absorbed thermal energy (141.08 W) and thermal efficiency (30.36%) are achieved by PV/T@Al₂O₃ with only using Al₂O₃/water nanofluid-cooled PV/T collector. Introducing recycled porous media made of copper between the collector tubes in PV/T@Al₂O₃+CP unit, results in the absorption and storage of thermal energy produced by the system. Additionally, increases the amount of heat dissipation to the environment, thus reducing the thermal energy and efficiency of the system to 7.54% (131.19 W) and 6.39% (28.54 %), respectively compared with that of PV/T@Al₂O₃ unit. Additionally, introducing PCM enhanced by recycled copper material between the collector tubes in PV/T@Al₂O₃+CPPCM results in higher absorption and storage of thermal energy generated by PV/T unit. Additionally, enhances the amount of heat dissipation to the surrounding, thus further reduce the thermal energy and efficiency of the system by 14.15% (123.59 W) and 11.12% (27.32%), respectively compared with that of

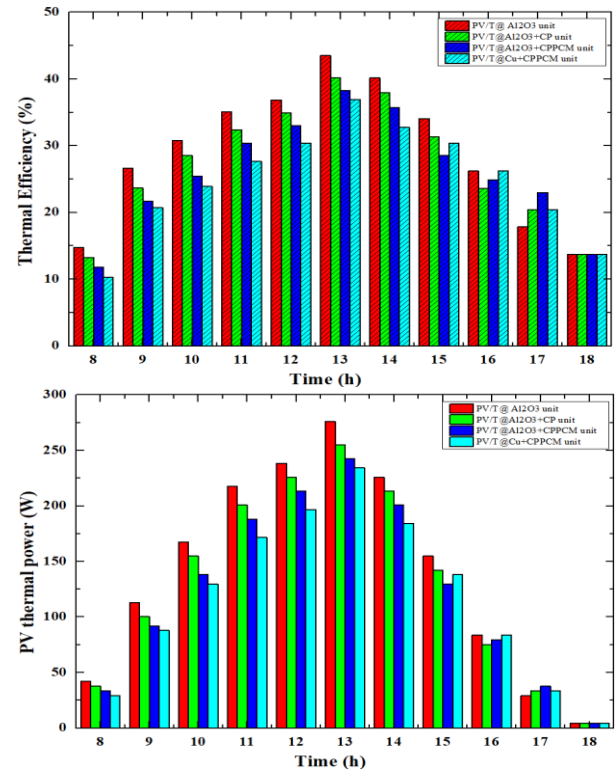


Fig. 11. Hourly changes in a) thermal output and b) thermal efficiency as a function of the proposed PV/T systems.

PV/T@Al₂O₃ unit. Finally, introducing the same PCM enhanced by recycling copper material between the collector tubes but replacing Al₂O₃ by Cu nanofluid in PV/T@Cu+CPPCM results in higher heat transfer rates and enhances heat storage and dissipation and further reduces the thermal energy and efficiency of the system by 20.06% (117.50 W) and 16.01% (26.17 %), respectively compared with that of PV/T@Al₂O₃ unit.

5.2 Economic Evaluation

Table 5 gives the average cost of investments incurred in relation to various elements used in the proposed modification in comparison with standard PV unit. The total capital cost (CtC) of the components is around \$81.24 for the standard PV unit,

Table 5.
Investment cost details of the tested units.

Description	Units	Standard PV	PV/T@Al ₂ O ₃	PV/T@Al ₂ O ₃ +CP	PV/T@Al ₂ O ₃ +CPPCM	PV/T@Cu+CPPCM
PV system	\$	80	80	80	80	80
PV/T collector	\$	-	20	20	20	20
Al ₂ O ₃ nanofluid	\$	-	5	5	5	-
Cu nanofluid	\$	-	-	-	-	5
Copper filings	\$	-	-	1	1	1
PCM	\$	-	-	-	2	2
Manufacturing cost	\$	5	10	10	10	10
Residual cost	\$	3.76	7.22	7.22	7.22	7.22
Total investment price	\$	81.24	107.78	108.78	110.78	110.78

Table 6.
Economic and LCC analysis of the suggested unit with reference to the conventional PV unit.

Description	Standard PV	PV/T@Al ₂ O ₃	PV/T@Al ₂ O ₃ +CP	PV/T@Al ₂ O ₃ +CPPCM	PV/T@Cu+CPPCM
Total investment cost [\$]	81.24	107.78	108.78	110.78	110.78
Maintenance value [\$]	1.885	1.714	1.714	1.714	1.714
Replacement value [\$]	3.97	7.33	7.33	7.33	7.33
Manufacturing price [\$]	3	10	10	10	10
Annual energy productivity (kWh)	146.4	529.94	520.35	513.45	504.81
Interest rate i [%]	15	15	15	15	15
Degradation rate [%]	0.5	0.5	0.5	0.5	0.5
Lifetime [N]	25	25	25	25	25
Life cycle cost, LCC [\$]	118	167	168	170	170
LCOE [\$/kWh]	0.540	0.192	0.197	0.204	0.207
Simple payback [year]	8	5	5.5	4.7	4.8

\$107.78 for PV/T@Al₂O₃, \$108.78 for PV/T@Al₂O₃+CP unit, \$110.78 for PV/T@Al₂O₃+CPPCM unit, and \$110.78 for PV/T@Cu+CPPCM unit. The expected increase in energy generation by the proposed modified units will offer an immediate payback due to increased production levels compared to the standard PV unit.

Table 6 presents a comparison of levelized cost of electricity (LCOE), annual energy production, and payback period for the tested units in comparison with that of standard PV unit. As shown, LCOE for the tested standard PV unit, PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, and PV/T@Cu+CPPCM units was 0.28, 0.19, 0.18, 0.17, and 0.15 \$/kWh, respectively. This means that, for the proposed configurations PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, and PV/T@Cu+CPPCM, the value of LCOE is lower than the value of LCOE for the standard PV system by 47.37, 55.56, 64.71, and 86.67 %, respectively. The low value of LCOE is obtained by the PV/T@Cu+CPPCM unit, which shows that the produced energy could cover the total cost for the lifecycle of the suggested systems. When comparing the values of LCOE with values found from the relevant previous studies, they were near the values obtained in this present research, which were \$0.12-0.16/kWh (Tazay, 2020), \$0.42-0.2/kWh (Shabahat *et al.*, 2026) and \$0.16/kWh (Wu, 2026). On the other hand, the payback period P_b for the proposed units PV/T@Al₂O₃, PV/T@Al₂O₃+CP, PV/T@Al₂O₃+CPPCM, and PV/T@Cu+CPPCM is 60% (5 years), 45.45% (5.5 years), 81.82% (4.4 years), and 73.91% (4.6 years) shorter than the PV/T (8 years). There is a great prospect of taking them into account for their novelty and cost effectiveness for use in thermal management, which seeks to optimize the performance of solar photovoltaic energy systems. The economic value of the proposed PV/T units is not limited to annual energy yield.

5.3 Machine Learning Prediction

Fig. 12 shows the scatter plots for overall thermal efficiency, PV temperature, and outlet temperature the target outputs of the XGBoost model. The figure reveals varying degrees of agreement between actual and predicted values. A strong clustering of points around the ideal regression line was observed for overall efficiency and outlet temperature, which indicate a higher value of the coefficient of determination (R^2), that was primarily employed to estimate the ability of the model to explain the variance in the experimental results. The obtained high values of R^2 , greater than 0.95 for all target outputs, confirmed that the ability of the model to successfully capture the nonlinear relationships between operating conditions and

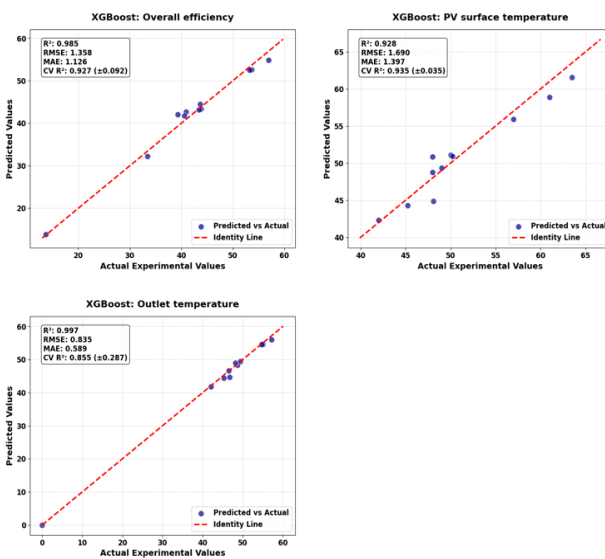


Fig. 12. The scatter plot of overall efficiency, PV and outlet temperature.

PV/T system responses. The RMSE and MAE indicators were also used for further examination to identify the average prediction deviations between experimental and predicted values. The relatively low RMSE (0.835-1.69) and MAE values (0.589-1.397) revealed that the prediction errors remained within a narrow range, which emphasizes the reliability and stability of the XGBoost model. Additionally, RMSE exhibited slightly higher values than MAE values because RMSE provides greater weight to larger deviations, which illustrates the presence of a lower number of outlier predictions resulted from fluctuations in experimental operating conditions. Quantitatively, variables with a high R^2 are associated with low CV values (less than 5%), which indicate the stability of the model and predictive accuracy. This difference between CV and R^2 is due to various reasons: most notably the heterogeneity and nature of the input data, the effect of nonlinear parameters that may not be fully considered in some sub-models, and the possible presence of outliers or noise that directly raises the relative variance even if the overall trend remains positive. Combining R^2 and CV ensures a more comprehensive evaluation of the performance of the model, with demonstrating the overall fit quality, as well as the stability and accuracy of predictions across different cases.

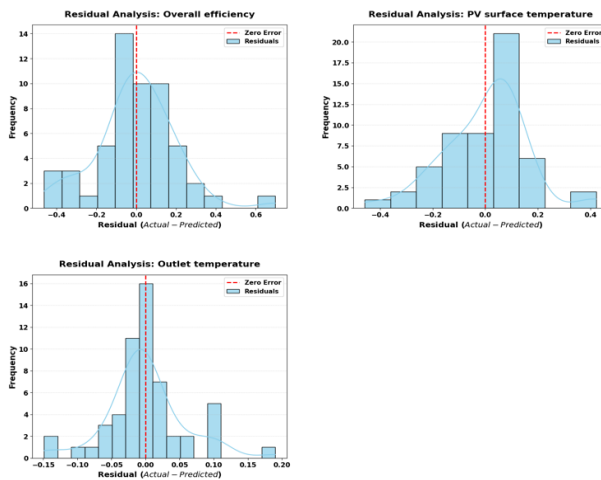


Fig. 13. The residual analysis for overall efficiency, PV and outlet temperature.

The residual histograms for different parameters developed using XGBoost model are presented in Fig. 13. The residual across different cases highlights statistical behavior that indicates predictive accuracy and the model's performance. The residuals are nearly symmetrically distributed around zero with around 70–85% concentrated within the range of -0.02 to $+0.02$. This reflects the absence of systematic underprediction or overprediction behavior. Furthermore, the low standard deviation values approximately 0.01 – 0.015 and relatively narrow residual spread demonstrate strong generalization capability of the model and limited uncertainty in predictions. The slight dispersion observed in the prediction of the PV temperature compared to the other two outputs, was due to the higher sensitivity of PV temperature to transient fluctuations in environmental conditions, mainly changes in ambient temperature and rapid changes in solar irradiance during experimental measurements. This illustrates the slightly lower R^2 value obtained for PV temperature prediction. This variation between cases is owing to the nature of each case in terms of the complexity of the relationships between the input variables. Cases with sharp variation in data or nonlinear behavior result in wider distributions and larger residuals. Overall, a residual distribution approaching a symmetric normal with a narrow range is a strong indicator of model quality.

Fig. 14 shows the results of Shapley Additive Explanations (SHAP) analysis that applied to the XGBoost model. This analysis estimates the relative importance of each input parameter in predicting the performance of the PVT system. These results were calculated based on determining Shapley values, which estimates the marginal contribution of each variable to the target outputs throughout all possible combinations of parameters. The analysis revealed that solar irradiance was the most influential parameter, with an average Shapley value of $+0.42$. This is expected as it directly controls the quantity of incident energy available for both electrical conversion and thermal accumulation within the PV/T system. The rise in solar irradiance increases the absorption of photon and electrical generation; however, it simultaneously increases thermal loading on the PV surface, which illustrates its powerful contribution to both positive and negative performance changes. The PV cell surface temperature comes next with a value of -0.31 , which reflects the inverse relationship between electrical efficiency and cell temperature. Physically, the increase in PV temperature narrows the semiconductor band-gap and increases losses of electron-hole recombination, which

results in a decrease in voltage and lower electrical output. This behavior is strongly aligned with the experimental findings, where the reduction in PV temperature using proposed cooling methods significantly improved electrical output and efficiency. The temperature of inlet coolant also had a negative Shapley value of -0.18 , because the reduced coolant temperatures enhance the temperature gradient between the cooling fluid and PV surface, consequently promoting convective heat transfer rates and increasing the heat extraction from the PV surface. This finding demonstrates the thermodynamic needs of preserving effective thermal dissipation within the collector. The configuration variables, including porous medium, nanofluid type, or PCM achieved a value of $+0.27$, which emphasizes the significant effect of these modifications. The results of SHAP analysis revealed that the improvement mechanisms are not independent but thermally coupled. PCM, for instance, acts as latent heat storage, recycled porous media promotes heat transfer and thermal pathways, while Cu nanofluids improve convective heat transfer due to their superior thermal conductivity. Their integration produces synergistic thermal management impact that ultimately enhance electrical performance. The previous values were estimated by applying the SHAP algorithm to a trained model, the calculated values are then ranked in descending order of the absolute mean, and analyzing the direction of the impact, positive or negative based on the distribution of the value. High positive values indicate optimal operating conditions, high irradiance and low temperature, while negative values indicate unfavorable conditions.

The results of tornado analysis are presented in Fig. 15, this analysis assesses the sensitivity of the system's performance to different modifications using the XGBoost model. The influence of each factor was estimated by determining the variation in expected performance value when each factor was separately varied, keeping other parameters constant. For the overall efficiency (baseline: 40.45%), the results elucidate that the use of Al_2O_3 nanofluid was the most influential parameter, with an

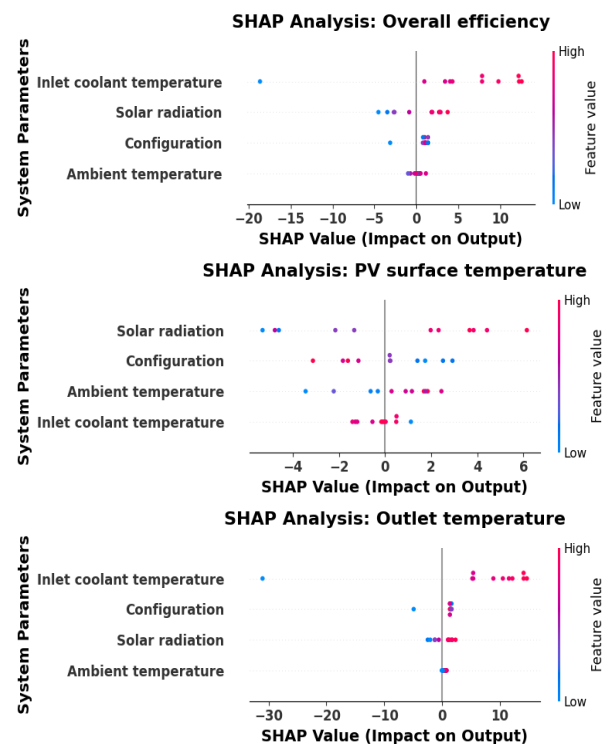


Fig. 14. The results of SHAP analysis.

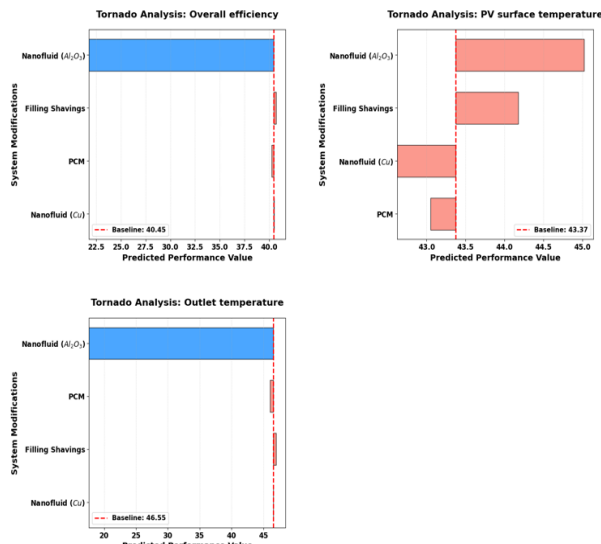


Fig. 15. The results of tornado analysis for overall efficiency, PV and outlet temperatures.

effect of approximately 40%, which emphasize its crucial role in improving heat transfer. PCM and copper shavings exhibited minor positive influences, while copper nanofluid exhibited a slight negative impact on overall efficiency. As for the PV surface temperature (baseline: 43.37°C), Al_2O_3 nanofluid also recorded the highest expected value of approximately 45°C, followed by shavings at 44.2°C. PCM and copper nanofluid achieved a decrease in temperature of around 43.2°C and 43.1°C, respectively, demonstrating their effectiveness in the cooling of PV surface. Regarding the outlet temperature (baseline: 46.55°C), Al_2O_3 nanofluid also had a significant impact in the range of 45–46°C, while the effects of PCM, shavings, and copper nanofluid were less pronounced. These findings indicated that the integration of Al_2O_3 with recycled porous materials and PCM achieves an optimal balance between electrical efficiency and thermal control. It should be noted that the results of tornado analysis indicate an apparent methodological difference with the previous experimental findings. The analysis elucidated that the Al_2O_3 nanofluid had the largest single impact on the overall efficiency, while the Cu

nanofluid had a marginally lower influence when isolated from other factors, however, this difference does not conflict with the superiority of the PV/T@Cu+CPPCM design. This discrepancy results from the nature of the Tornado analysis, which estimates the influence of each variable individually. While, the experimental results reveal the synergistic impact resulting from the combination of different modifications, nanoparticles, porous materials, and PCM, which produces a combined thermal pathway that surpasses the sum of the individual component impacts. Therefore, experimental and analysis results complement each other rather than contradict each other, as tornado analysis explains the reliance of the model on individual inputs, while experiment proves the overall integration is the critical variable for actual performance optimization.

Fig. 16 shows the optimization response surface that was developed to interactively map the input operational parameters and their corresponding electrical, thermal, and economic performance indicators. The global optimum point on this surface was identified by applying systematic numerical search algorithms that scanned the operational variables and determined the configuration that exhibited the highest value for the target function based on decreasing leveled costs and maximizing output. The results illustrated that optimal conditions are achieved at a stable PV surface temperature of 43.2°C, a solar irradiance of a 990–1000 W/m^2 , and an inlet coolant temperature of 38.5°C, with the application of the PV/T@Cu+CPPCM configuration, where the system achieved a peak performance with an electrical efficiency of 15.90% and thermal efficiency of 24.85%, a 31.49% increase in electrical output, and a 17.38% (11.98°C) reduction in surface temperature compared to the standard model. These values were precisely determined by combining a trained prediction model. These quantitative results demonstrate that the generated optimization surface accurately indicates the complex nonlinearity between operating conditions and actual performance. It provides a robust mathematical approach for the optimal operational design of PV/T systems in areas with arid and hot climatic conditions, while ensuring the reliability of predictions by verifying surface stability at parametric edges and avoiding local optimum.

5.4 Comparison with Previous PV/T Cooling Studies and Engineering Implications

Fig. 17 compares the PV module temperature reduction achieved in the present study with selected PV/T cooling studies reported in the literature. Since PV/T performance is strongly affected by module type, cooling configuration, irradiance level, ambient temperature, flow rate, and climatic conditions, this comparison should be interpreted as a performance benchmark rather than a direct one-to-one ranking. As discussed before, there were no prior works that had tested these modified methods for minimizing the surface temperature of PV/T units. As seen in Fig. 17, this work is well-aligned with prior literature. Compared with the selected studies in Fig. 17, the present configurations provide competitive temperature reductions, particularly the PV/T@ Al_2O_3 +CPPCM and PV/T@Cu+CPPCM systems, which achieved reductions of approximately 15 °C and 17 °C, respectively. On average, the reduction in temperature of panels with the current cooling technique was between 5.5 and 17 °C. This reduction is important because lower module temperature mitigates voltage degradation, improves the maximum power operating region, and supports higher DC power availability. Therefore, the present cooling strategy should be viewed not only as a thermal

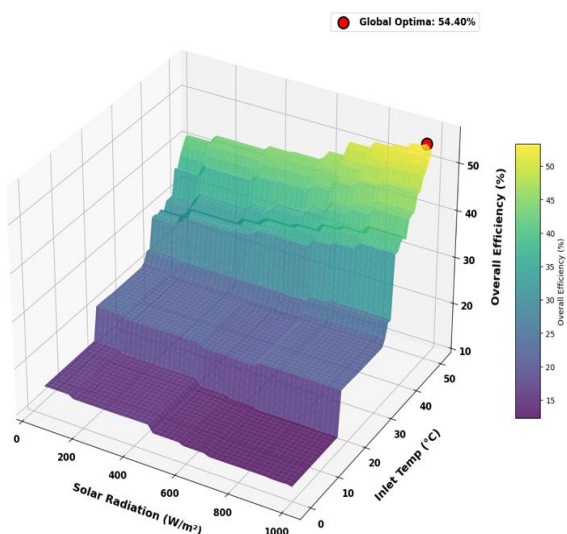


Fig. 16. The optimization surface with global optima.

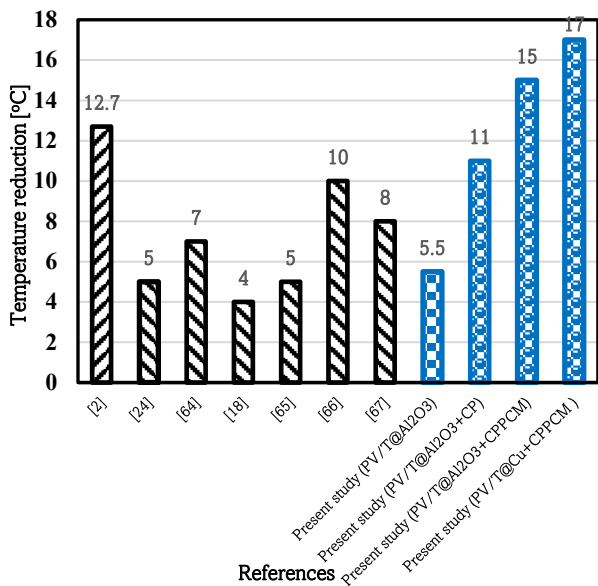


Fig. 17. Comparisons of the reduction in the panel temperature of the present study with earlier studies.

enhancement method but also as an electro-thermal approach for improving building-integrated renewable-energy performance under hot-climate operation.

6. Conclusion

The electrical power production of a PV system decreases as the module surface temperature increases. This study experimentally evaluated four modified PV/T configurations for sustainable building applications in Madinah, Saudi Arabia throughout August 2025. The tested configurations combined Al₂O₃/water nanofluid cooling, recycled copper porous media, PCM enhanced with recycled copper fillings, and Cu/water nanofluid cooling. An XGBoost-based machine learning model was developed to predict electro-thermal performance and support data-driven interpretation of the dominant operating variables. From an electrical engineering and power electronics perspective, the improved thermal regulation can support more stable PV operating voltage and reduce thermal drift of the maximum power point. Overall, this work demonstrates that integrating recycled porous media, PCM, nanofluid cooling, and machine learning provides a promising pathway for improving PV/T renewable-energy systems in hot climates. The outcomes showed that the use of the proposed modified units led to a decrease in surface temperatures of 3.16°C - 11.98°C, which in turn led to an increase in electrical power output of 7.57% - 31.49%, compared to standard photovoltaic cells (610 Wh). The LCOE and payback period values for proposed PV/T units have shown to be more advantageous at 136-160% and 160-181%, respectively, compared to the standard PV unit. The XGBoost model demonstrated high predictive accuracy with $R^2 > 0.98$ and low RMSE, confirming its ability to accurately simulate system performance under diverse operating conditions. Tornado analysis elucidated that using Al₂O₃ nanofluid had the highest effect on overall efficiency, around of 40%, while PV/T@Cu+CPPCM exhibited the best temperature decrease, around of 17°C.

However, it is recommended that future studies include analysis of exergy energy, investigation of the rheological properties and long-term durability of the Al₂O₃ nanofluid, PCM cycle behavior, pressure drop effects, real-time coupling with

MPPT, DC-DC converters, and grid-connected inverter systems. Investigate the thermal properties of the used porous medium made from recycled copper filling. Finally, evaluate the performance of the proposed PV/T configurations throughout the whole year. Evaluate and consider the hydraulic losses, pressure drop, and pump energy demand to determine the net benefit of nanofluid circulation.

Ethics approval

The author declares that the submitted manuscript is original. The author acknowledges that the research has been conducted ethically and approves the final version of the manuscript.

Consent to participate.

The author consents to participate in this research study.

Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

Symbols

A_b	Module area (m ²)
E_n	Energy saving
g	Gravity (m ²)
I_s	Solar irradiation (Wm ⁻²)
h	Convection heat transfer coefficient
i	Discount rate (%)
I	Current (A)
KF	Capital recovery factor

Abbreviations

PV/T	Photovoltaic/Thermal unit
M_s	Maintenance and service cost
n	Lifetime (year)
C_c	Initial cost (year)
T	Temperature (K ⁻¹)
T_0	Initial temperature (K ⁻¹)
T_E	Energy tariff
T_s	Panel temperature (°C)
V	Voltage (V)
V_m	Voltage at the higher power

amb	Ambient
ins	Insurance
Elec.	Electrical
max	Maximum

Greek symbols

η_{ele}	Electrical efficiency (%)
η_t	Thermal efficiency (%)
LCC	Life cycle price
LCOE	Levelized price of energy
CF_n	Cash flow in year
V_{oc}	Voltage of open circuit (V)
I_{sc}	Short circuit current (A)
P_p	Payback period (year)

References

- Abadeh, A., Rejeb, O., Sardarabadi, M., Menezo, C., M. Passandideh-Fard, A. Jemni. (2018). Economic and environmental analysis of using metal-oxides/water nanofluid in photovoltaic thermal systems (PVTs), *Energy*, 159, 1234-1243, <https://doi.org/10.1016/j.energy.2018.06.089>.
- Abd Elnaby, K., Abdelkrim, K., Mohammed, E. Attia., Mohamed, A., Müslüm, A., Moataz, M. A. (2024). Optimal Design and Orientation of Cooling Technology for Photovoltaic Plants: A Comparative Simulation Study. *Solar Energy*, 269, 112362. <https://doi.org/10.1016/j.solener.2024.112362>.

- Abdelkrim, K., Kabeel, A.E., Mohammed, E. A., Mohamed, E. Z., Mohamed, A. (2023). Numerical analysis of the heat transfer and fluid flow of a novel water-based hybrid photovoltaic-thermal solar collector integrated with flax fibers as natural porous materials. *Renewable Energy*, 217, 119245. <https://doi.org/10.1016/j.renene.2023.119245>.
- Abdelkrim, K., Mohammed E. A., Harby K., Abd Elnaby, K., Moataz, M. A., Mohamed, A. (2024). Experimental and economic evaluation on the performance improvement of a solar photovoltaic thermal system with skeleton-shaped fins. *Applied thermal engineering*, 248 123180. <https://doi.org/10.1016/j.applthermaleng.2024.123180>
- Abdelkrim, K., Mohamed, A., Harby, K., Mohammed E. A. (2024). Performance improvement of photovoltaic/thermal collectors based on the optimized design of efficient innovative multiple-impinging slot jets. *Solar Energy*, 283 112992. <https://doi.org/10.1016/j.solener.2024.112992>.
- Abdelkrim, K., Mohammed E. Attia, Harby K., Abd Elnaby, K., Moataz, M. A., Mohamed, A., (2024). Experimental and economic evaluation on the performance improvement of a solar photovoltaic thermal system with skeleton-shaped fins, *Applied Thermal Engineering*, 248 123180. <https://doi.org/10.1016/j.applthermaleng.2024.123180>
- Abdullah, A.S., Hegazy, R., Omara, Z.M., Harby, K. (2026). Comprehensive evaluation of hybrid solar distillation systems using spiral base copper fins, waste copper shavings-enhanced PCM, and external condenser coupled with PV-thermoelectric system. *Solar Energy Materials and Solar Cells*, 303, 114375. <https://doi.org/10.1016/j.solmat.2026.114375>
- Adeel, A., Mark, J., Lei, S., Yuying, Y. (2021). Thermophysical characteristics and enhancement analysis of carbon-additives phase change mono and hybrid materials for thermal management of electronic devices. *J. Energy Storage* 34, 102231. <https://doi.org/10.1016/j.est.2020.102231>
- Ahmad, F. T., Shima, Barakat, B., Aykut, F.G., Heba, I., Mohamed, M. S. (2026). Techno-Economic Optimization of a Hybrid Renewable Microgrid for Electric Vehicle Charging: A Comparative Study in Egypt and Türkiye. *Results in Engineering*: 109938. <https://doi.org/10.1016/j.rineng.2026.109938>
- Ahmad, F. Tazay. (2026). Experimental performance and economic analysis of a hybrid PVT system with H₂O/CuO nanofluid and recycled waste materials, *Results in Engineering*, 29, 109413. <https://doi.org/10.1016/j.rineng.2026.109413>
- Alazwari, M. A., Basem, A., AL-bonsrulah, H. A. Z., Almitani, K. H., Abu-Hamdeh, N. H., Albdeiri, M. S., AlQemlas, T., & Egami, R. H. (2024). Assessment of photovoltaic system in existence of nanomaterial cooling flow. *Results in Engineering*, 24, 103264. <https://doi.org/10.1016/j.rineng.2024.103264>
- Alshibil, A. M., Farkas, I., Vig, P. (2022). Multi-aspect approach of electrical and thermal performance evaluation for hybrid photovoltaic/thermal solar collector using trnsys tool. *Int. J. Thermofluids*, 16100222. <https://doi.org/10.1016/j.ijft.2022.100222>
- Al-Waeli, A.H., Sopian, K., Chaichan, M.T., Kazem, H.A., Hasan, H.A., Al-Shamani, A.N. (2017). An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system, *Energy Convers. Manag.* 142, 547e558, <https://doi.org/10.1016/j.enconman.2017.03.076>.
- Amir, K., Alibakhsh, K., Fathollah, P., Mohammad, A. V. (2022). Evaluation of a nanofluid-based concentrating photovoltaic thermal system integrated with finned PCM heatsink: an experimental study. *Renew. Energy*, 201, 1010–1025. <https://doi.org/10.1016/j.renene.2022.11.025>
- Arsan, E., Aktas, M., Can, O. (2020). Experimental and numerical investigation of a novel photovoltaic thermal (PV/T) collector with the energy and exergy analysis. *J. Clean. Prod.* 276, 123255. <https://doi.org/10.1016/j.jclepro.2020.123255>
- Aste, N., Del Pero, C., Leonforte, F. (2014) Water flat plate PV thermal collectors: a review. *Sol. Energy*, 102 98–115, <https://doi.org/10.1016/j.solener.2014.01.025>.
- Attia, M.E., Khelifa, A., Abdelgaied, M., Harby, K., (2024). The efficient strategy of operating the active cooling systems incorporated with photovoltaic panels for the three climatic regions: A case study. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 46, 14219–14245. <https://doi.org/10.1080/15567036.2024.2405065>
- Babar, H., Ali, H.M. (2019). Towards hybrid nanofluids: Preparation, thermophysical properties, applications, and challenges, *J. Mol. Liq.* 281. 598–633. <https://doi.org/10.1016/j.molliq.2019.02.102>.
- Bassam, A.M., Sopian, K., Ibrahim, A., Al-Aasam, A.B., (2023). Dayer M., Experimental analysis of photovoltaic thermal collector (PVT) with nano PCM and micro-fins tube counterclockwise twisted tape nanofluid. *Case Studies in Thermal Engineering*, 45, 102883.
- Chandrasekar, M., Suresh, S., Senthilkumar, T., karthikeyan G. (2013). Passive cooling of standalone flat PV module with cotton wick structures. *Energy Conversion and Management*, 71, 43. <https://doi.org/10.1016/j.enconman.2013.03.012>
- Diwania, S., Siddiqui, A. S., Agrawal, S., Kumar, R. (2021). Performance assessment of PVT-air collector with V-groove absorber: a theoretical and experimental analysis. *Heat Mass Tran.* 57, 665–679. <https://doi.org/10.1007/s00231-020-02980-0>
- Fang, W., Zhenfei, L., Mengwei, L., Xianfei, L., Dongqing, P., Weifeng, D., Xiaoqian, C., Yichi, Z., Wenliang, G.
- Farade, R. A., Abdul Wahab, N. I., Rafiq, M., & Mansour, D.-E. A. (2025). Cutting-edge dielectric nanofluids: A review of factors influencing stability and thermo-dielectric properties. *Journal of Thermal Analysis and Calorimetry*, 150, 18917–18965. <https://doi.org/10.1007/s10973-025-14631-9>
- Farade, R. A., Wahab, N. I. A., Said, Z., Khan, T. M. Y., & Saleel, C. A. (2025). Toward green and sustainable dielectric nanofluids: Surfactant impacts on stability, properties, and regulations. *Advances in Colloid and Interface Science*, 346, 103668. <https://doi.org/10.1016/j.cis.2025.103668>
- Fayaz, H., Rahim, N.A., Hasanuzzaman, M., Rivai A., Nasrin R. (2019). Numerical and outdoor real time experimental investigation of performance of PCM based PVT system. *Sol. Energy* 179, 135–150. <https://doi.org/10.1016/j.solener.2018.12.057>
- Fudholi, A., Sopian, K., Yazdi, M.H., Ruslan, M.H., (2014). Ibrahim A., Kazem H.A., Performance analysis of photovoltaic thermal (PVT) water collectors, *Energy Convers. Manag.* 78, 641e651, <https://doi.org/10.1016/j.enconman.2013.11.017>.
- Fudholi, A., Zohri, M., Rukman, N. S., Nazri, N. S., Mustapha, M., Yen, C. H., Mohammad, M., Sopian, K. (2019). Exergy and sustainability index of photovoltaic thermal (PVT) air collector: a theoretical and experimental study, *Renew. Sustain. Energy Rev.* 100 44–51. <https://doi.org/10.1016/j.rser.2018.10.019>
- Ghadiri, M. M., Sardarabadi M., Pasandideh-fard, Moghadam, A.J. (2015). Experimental investigation of a PVT system performance using nano ferrofluids, *Energy Convers. Manag.* 103 468–476, <https://doi.org/10.1016/j.enconman.2015.06.077>.
- Hamid, S., Sadeh, A., Afshar, S., Behnam, S. (2022). Utilization of a phase change material with metal foam for the performance improvement of the photovoltaic cells. *J. Energy Storage*, 51, 104466. <https://doi.org/10.1016/j.est.2022.104466>
- Harby, K., Mohammed, A., Abdelkrim, K., Majidi, A., Erdem, C., & Mohamed, A. (2025). Performance characteristics of optimized bi-fluid photovoltaic-thermal solar system: A comparative study of innovative cooling system made of different materials. *Applied Thermal Engineering*, 278, Article 127283. <https://doi.org/10.1016/j.applthermaleng.2025.127283>
- Harmaili, I. O., Sultan, S. M., Tso, C. P., Fudholi, A., Mohammad, M., & Ibrahim, A. (2024). A review on recent photovoltaic module cooling techniques: Types and assessment methods. *Results in Engineering*, 22, 102225. <https://doi.org/10.1016/j.rineng.2024.102225>
- Holman, J.P. (2012). *Experimental Methods for Engineers*, eighth ed., McGraw-Hill, New York.
- Jarimi, H., Abu Bakar, M.N., Othman, M., Din, M.H. (2016). Bi-fluid photovoltaic/thermal (PV/T) solar collector: Experimental validation of a 2-D theoretical model. *Renew. Energy*, 85 1052–1067. <https://doi.org/10.1016/j.renene.2015.07.014>
- Jarimi, H., Abu Bakar, M.N., Othman, M., Din, M.H. (2016). Bi-fluid photovoltaic/thermal (PV/T) solar collector: experimental validation of a 2-D theoretical model. *Renew. Energy*, 85 1052–1067, <https://doi.org/10.1016/j.renene.2015.07.014>.
- Jha, P., Das, B., Gupta, R. (2019). An experimental study of a photovoltaic thermal air collector (PVTAC): a comparison of a flat and the wavy collector. *Appl. Therm. Eng.* 163 114344. <https://doi.org/10.1016/j.applthermaleng.2019.114344>
- Ji, Y., Zhou, J., Yu, M., Zhong, W., and Yuan, Y. (2023). A novel multi-function “Y-shape” heat pipe photovoltaic/thermal (PVT) system:

- Experimental study on the performance of hot water supply and space heating. *Renewable Energy*, 218, 119327, 0960-1481. <https://doi.org/10.1016/j.renene.2023.119327>
- Karami, N., Rahimi, M. (2014). Heat transfer enhancement in a hybrid microchannelphotovoltaic cell using Boehmite nanofluid, *Int. Commun. Heat Mass Tran.* 55, 45-52, <https://doi.org/10.1016/j.icheatmasstransfer.2014.04.009>.
- Kazem, H.A., Al-Waeli, A.A., Chaichan, M.T., Sopian, K., Ahmed, A., and Roslam, W.I.W.N. (2023). Enhancement of photovoltaic module performance using passive cooling (Fins): A comprehensive review. *Case Studies in Thermal Engineering*, 49, 103316, ISSN 2214-157X. <https://doi.org/10.1016/j.csite.2023.103316>
- Khanalizadeh, A., Astaraei, F. R., Heyhat, M. H., and Rad, M.A. (2023). Experimental investigation of a PVT system containing a TEG section between water-based heat exchanger and air-based heat sink. *Thermal Science and Engineering Progress*, 42, 101909, 2451-9049. <https://doi.org/10.1016/j.tsep.2023.101909>
- Khelifa A., Mohamed A., Mohammed, E. A., Harby, K., Müslüm, A. (2024). Development and optimization of dual-objective PVT modules for a smart residential building using inclined fins. *Journal of Building Engineering*, 97, 110893. <https://doi.org/10.1016/j.jobbe.2024.110893>
- Lundberg, S. M., Erion, G., Chen, H., DeGrave, A., Prutkin, J. M., Nair, B., Katz, R., Himmelfarb, J., Bansal, N., Lee, S.-I. (2020). From local explanations to global understanding with explainable AI for trees. *Nature Machine Intelligence*, 2, 56-67. <https://doi.org/10.1038/s42256-019-0138-9>
- Mohammed, E. A., Abd Elnaby, K., Abdelkrim, K., Mohamed, E. Z., Moataz, M. A. (2024). Numerical analysis and design of a novel solar photovoltaic thermal system using finned cooling channel structures embedded with air/TiO₂-water nano bi-fluid. *Solar Energy*. 269, 112368. <https://doi.org/10.1016/j.solener.2024.112368>.
- Mohammed, E. A., Harby, K., Abdelkrim, K., Mohamed, A. (2024). The effect of the impinging angle of multi-rectangular air jets on the performance improvement of passive solar photovoltaic-thermal systems. *Arab J Sci Eng*. 50, 13899-13914 (2025). <https://doi.org/10.1007/s13369-024-09595-1>
- Mohan, C. C., and Chiranjeevi, C. (2026). Experimental investigation on the hybrid PVT-solar still with rotating cylinder for enhanced electrical power and freshwater production, *Results in Engineering*. 29, 109185. <https://doi.org/10.1016/j.rineng.2026.109185>
- Opoku, R., Obeng, G.Y., Adjei, E.A., Davis, F., Akuffo F.O. (2020). Integrated system efficiency in reducing redundancy and promoting residential renewable energy in countries without net-metering: a case study of a SHS in Ghana, *Renew. Energy*, 155 65-78, <https://doi.org/10.1016/j.renene.2020.03.099>.
- Othman, M. Y. H., Yatim, B., Sopian, K., Abu Bakar, M. N. (2005). Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins. *Renew. Energy* 30, 2005-2017. <https://doi.org/10.1016/j.renene.2004.10.007>
- Özakın, A. N., Kaya, F. (2019). Effect on the exergy of the PVT system of fins added to an air-cooled channel: a study on temperature and air velocity with ANSYS Fluent. *Sol. Energy*. 184 561-569. <https://doi.org/10.1016/j.solener.2019.03.100>
- Rajamony, R. K., Sridhar, K., Kalidasan, B., Mishra, R., Farade, R. A., Megalingam, A., Abedin, T. (2025). Cut-ting-edge cooling techniques for photovoltaic systems: A comprehensive review. *Hyperfine Interactions*, 246, 41. <https://doi.org/10.1007/s10751-025-02267-y>.
- Reji, K. R., Johnny, K. S., Pandey, A. K., Yaw, C. T., Jagadeesh, P., Sieh, K. T., Talal, Y., Samykano, M., Sofiah, A. G., Kalidasan, B., Oday, A. A., & Kadrigama, K. (2024). Energizing the thermophysical properties of phase change material using carbon-based nano additives for sustainable thermal energy storage application in photovoltaic thermal systems. *Materials Today Sustainability*, 25, Article 100658. <https://doi.org/10.1016/j.mtsust.2023.100658>
- Rubitherm. RUBITHERM® RT47 Datasheet. https://www.rubitherm.eu/media/products/datasheets/Techdata_RT47_EN_09102020.PDF.
- Saad, S., Abid, H., Imran, A., Hanzla S., Muhammad A., Hafiz, M. A. (2025). Photovoltaic module efficiency enhancement system by novel cooling techniques: effect of phase change material and fins. *Process Saf. Environ. Prot.* 194, 1056-1066. <https://doi.org/10.1016/j.psep.2024.06.105>
- Said, Z., Saidur, R., Sabiha, M.A., Hepbasli, A., Rahim, N.A., (2016). Energy and exergy efficiency of a flat plate solar collector using pH treated Al₂O₃ nanofluid. *J. Cleaner Prod.* 112, 3915-3926. <https://doi.org/10.1016/j.jclepro.2015.07.115>
- Shaalán, Z.A., Hussein, A.M., Abdullah, M.Z. (2025). Numerical-experimental study to improve photovoltaic panel cooling by using hybrid ZnO/Al₂O₃ nanofluids. *Case Studies in Thermal Engineering* 70, 106053. <https://doi.org/10.1016/j.csite.2025.106053>
- Shabahat, H. Q., Zafar, S., Dawid P. H., Majid, A., Abdullah, N., (2026). Hybrid solar PVT systems for renewable energy in dairy farming: A performance and economic analysis in Belgium, *Energy Conversion and Management: X* 29, 101555. <https://doi.org/10.1016/j.ecmx.2026.101555>.
- Shahsavari, A., Jahangiri, A., Qatani, A., Ahmadi, G. (2022). Energy and exergy analysis and multi-objective optimization of using combined vortex tube-photovoltaic/ thermal system in city gate stations. *Renew. Energy*. 196 1017-1028. <https://doi.org/10.1016/j.renene.2022.07.057>
- Shakir, A.K., Hajidavalloo, E., Daneh-Dezfuli A., Abdulhaleem S.M., Obayes O.K. (2023). Experimental study on the performance of different photovoltaic thermal collectors with nano-technology. *Energy Sources Part A* 45, 8458-8477. <https://doi.org/10.1080/15567036.2023.2227123>
- Sundar, S., Manoj, K., Singh, V. Punnaiah, Sousa, Antonio C.M., (2018). Experimental investigation of Al₂O₃/water nanofluids on the effectiveness of solar flat-plate collectors with and without twisted tape inserts. *Renew. Energy* 119, 820-833. <https://doi.org/10.1016/j.renene.2017.10.056>
- Tazay, A. (2020). Techno-economic feasibility analysis of a hybrid renewable energy supply options for university buildings in Saudi Arabia. *Open Engineering* 11, 39-55. <https://doi.org/10.1515/eng-2021-0005>.
- Teo, H. G., Lee, P. S., Hawlader, M. N. (2012). An active cooling system for photovoltaic modules. *Appl. Energy*. 90 309-315. <https://doi.org/10.1016/j.apenergy.2011.01.017>
- Tyagi, P. K., Kumar, R. (2024). Performance enhancement of nanofluid-based photovoltaic/thermal system with a novel finned multi-block container of phase change material in the summer season of northern India. *J. Energy Storage* 90, 111733. <https://doi.org/10.1016/j.est.2024.111733>
- Vajedi, H., Dehghan, M., Aminy, M., Pourrajabian, A. (2022). Experimental study on an air-based photovoltaic-thermal (PV-T) system with a converging thermal collector geometry: a comparative performance analysis. *Sustain. Energy Technol. Assessments*, 52, 102153. <https://doi.org/10.1016/j.seta.2022.102153>
- Vajedi, H., Dehghan, M., Aminy, M., Pourrajabian, A. (2022). Experimental study on an air-based photovoltaic-thermal (PV-T) system with a converging thermal collector geometry: a comparative performance analysis. *Sustain. Energy Technol. Assessments* 52 102153. <https://doi.org/10.1016/j.seta.2022.102153>.
- Wang, F., Li, Z., Liu, M., Liu, X., Pang, D., Du, W., Cheng, X., Zhang, Y., & Guo, W. (2023). Heat-dissipation performance of photovoltaic panels with a phasechange-material fin structure. *J. Clean. Prod.* 423, 138756. <https://doi.org/10.1016/j.jclepro.2023.138756>
- Wongwuttanasatian, T., Sarikarin, T., and Suksri, A. (2020). Performance enhancement of a photovoltaic module by passive cooling using phase change material in a finned container heat sink. *Solar Energy*, 195, 47-53, 0038-092X. <https://doi.org/10.1016/j.solener.2019.11.053>
- Wu, R., Teresa, A. (2026). Techno-economic and environmental assessment of an integrated PVT-based solar-assisted heat pump with seasonal thermal storage for public housing decarbonization. *Applied Thermal Engineering*. 298 130860. <https://doi.org/10.1016/j.applthermaleng.2026.130860>.
- Yazdanpanahi, J., Sarhaddi, F., Mahdavi, M. Adeli. (2015). Experimental investigation of exergy efficiency of a solar photovoltaic thermal (PVT) water collector based on exergy losses. *Sol. Energy*, 118 197-208, <https://doi.org/10.1016/j.solener.2015.04.038>.
- Yu, W., Xie, H. (2012). A Review on Nanofluids: Preparation, Stability Mechanisms, and Applications, *J. Nanomater.* 2012. <https://doi.org/10.1155/2012/435873>.
- Zainab, M. M., Ali, N. Al-Shamani, A., Hazim, A. A., Raed, A., Sopian, K., Ali, A. (2024). Enhancing photovoltaic thermal (PVT) performance

with hybrid solar collector using phase change material, porous media, and nanofluid. *Solar Energy*, 283 112983
<https://doi.org/10.1016/j.solener.2024.112983>



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Appendix I. Error analyses

Uncertainties for measurement of climate data such as the ambient temperature and sun's intensity using experimental devices are evaluated through use of the Gauss' law of error propagation. According to this law, given $S=f(y_1, y_2, y_3, \dots, y_n)$, the uncertainty for S will be as follows:

$$U_S = \sqrt{\left(\frac{\partial S}{\partial y_1}\right)^2 \sigma_{S_{y1}}^2 + \left(\frac{\partial S}{\partial y_2}\right)^2 \sigma_{S_{y2}}^2 + \dots + \left(\frac{\partial S}{\partial y_n}\right)^2 \sigma_{S_{yn}}^2} \quad (I.1)$$

Where, σ_{y1} represents the standard deviation of y_1 ; σ_{y2} the standard deviation of y_2 ; etc.

The parameters associated with inaccuracies in temperature and sun intensities include temperature sensing accuracy (E_{r1}), solarimeter accuracy (E_{r2}), data logger accuracy (E_{r3}), and connection accuracy (E_{r4}). To determine the total uncertainty of temperature (U_{Tem}) and solarimeter (U_{Sol}), we use the following formulas:

$$U_{Tem} = \sqrt{E_{r1}^2 + E_{r3}^2 + E_{r4}^2} \quad (I.2)$$

$$U_{Sol} = \sqrt{E_{r2}^2 + E_{r3}^2 + E_{r4}^2} \quad (I.3)$$

The greater errors for temperature and solar intensity were established to be 1.1% and 0.46%, respectively, using Equations I.2 and I.3.