



A comprehensive review of solar photovoltaic thermal technology: Performance evaluation and recent discoveries

Monaem Elmnifi¹ · Hasan A. Al-Asadi² · Karrar A. Hammoodi³ · Erdem Cuce^{4,5,6} · Duyun Tatyana Aleksandrovna¹ · Hala J. El-Khozondar^{7,8} · Yasser F. Nassar⁹ · Shahad A. Salih¹⁰

Received: 22 March 2026 / Accepted: 12 June 2026
© Akadémiai Kiadó Zrt 2026

Abstract

In the field of simultaneous electricity generation and thermal energy recovery, photovoltaic thermal (PVT) systems represent a promising solution; however, their performance is strongly dependent on the strategy used for recovering the heat, the choice of the working fluid, the stability of the materials, and the operating conditions. This structured critical review fills the gap in previous review literature, which tended to consider phase change materials (PCM) integration, nanofluid cooling, the design of the absorber, and the use of air-/water-based collectors separately. The novelty of this review is to build a comparative framework that categorises the recent developments in PVT into air-based, water-based, nanofluid-enhanced, PCM-integrated, and hybrid PVT systems and correlates the performance indicators with technical limitations, reliability, cost, and scalability. A review of approximately 250 published papers from 2000 to 2024 found that the following systems are compared, thermal management strategies are reviewed, and operating conditions and reported performance trends are discussed. The synthesis reveals that air-based PVT systems are still the simplest and costliest systems, with the reported efficiency range of 30–45%. Water-based and nanofluid-based systems are better at heat removal, with electrical efficiencies of 12–16% and thermal efficiencies of 50–75%, primarily because of the enhanced convective heat transfer and decreased PV cell temperature. Currently, PCM-integrated systems have been found to have thermal efficiency of 55–80% and offer passive thermal stabilisation; however, their long-term feasibility is compromised by low thermal conductivity, degradation, leakage risk, cost, and cycling reliability. Hybrid systems with the combination of nanofluids, absorber optimisation, and PCM generally exhibit the best overall performance, with some studies reporting overall efficiencies of up to 88.86% under optimal operating conditions. However, the advantages do not appear in all studies and are influenced by pressure drop, pumping power, and stability of the nanofluid, degradation of the PCM, testing conditions, and definitions of efficiency. Standardised testing, long-term outdoor validation, techno-economic assessment, durable low-cost materials, and intelligent monitoring and control strategies for scalable PVT deployment should be prioritised for future research.

Keywords Photovoltaic thermal (PVT) · Phase change materials · Nanofluids · Water collector · Air collector

Abbreviations

Abbreviations

Ag	Silver
Al	Aluminium
Al ₂ O ₃	Aluminium oxide
Au	Gold
CFD	Computational fluid dynamics
CNTs	Carbon nanotubes
C-PVT	PVT with circular absorber tubes
C-PVT-PCM	C-PVT with nano-PCM
Cu	Copper

CuO	Copper oxide
DPD	Dissipative particle dynamics
Fe	Iron
Fe ₂ O ₃	Iron (III) oxide
Fe ₃ O ₄	Magnetic iron oxide
FEM	Finite element method
GO	Graphene oxide
ICEs	Internal combustion engines
MgO	Magnesium oxide
MLP	Multi-layer neural network
MOF	Metal–organic framework
NpCF	Nanoparticle colloidal fluids
PCM	Phase change materials
PEMFCs	Proton exchange membrane fuel cells

Extended author information available on the last page of the article

PV	Photovoltaic
PVT	Photovoltaic thermal
RF	Random forest
S2S	Surface-to-surface
SiC	Silicon carbide
SVR	Support vector regression
TiO ₂	Titanium oxide
T-PCT-PCM	T-PVT with nano-PCM
T-PVT	PVT with twisted absorber tubes
W/EG	Water/ethylene glycol mixture
Zn	Zinc
ZnO	Zinc oxide

Roman symbols (unit)

MFR	Mass flow rate (kg s^{-1})
Ra	Rayleigh numbers (-)

Greek symbols

γ	Friction factor (-)
φ	Nanoparticle volume fraction (-)

Introduction

Over the recent past, there has been a significant rise in demand for solar energy due to high population density, resulting in higher costs of non-renewable energy sources [1]. The world population has been on the rise, and the standard of living of countries in terms of per capita income has improved, hence, a faster rate of depletion of primary resources such as fossil fuels and non-renewable resources [2]. These resources are being rapidly exploited, resulting in environmental depletion and climate shifts, including global temperature rise, glacier melting, and ozone layer depletion [3]. Thus, climate and environmental questions concerning our world can be solved by using photovoltaic (PV) solar cells to convert sun radiation into electricity in countries having the highest irradiation levels [4]. Due to the above factors, PV technology is a suitable solution to the challenges arising from the utilisation of fossil fuels since light is clean and freely assimilated [5]. The technology has a low cost of operation and ease of maintenance as compared to other forms of renewable energy sources [6]. It is also unlimited and is available in most regions of the world, which makes it possibly the solution to the challenges resulting from the utilisation of fossil fuels [7]. Due to the advantages accorded to renewable energy in the aspects of economics and the environment, energy researchers and policymakers alike [8] can no longer ignore solar technology. The methods used to capture light and use solar energy for heating and electricity, including PV technology, are discussed with a specific focus on PVT systems. In solar PV, incoming sunlight is transformed into electricity with efficiencies from 5 to 25%. As a result, most of the solar

radiation absorbed by the solar cells is converted to heat, causing the solar cells to heat up and reducing their electrical output [9]. Either only 20 per cent of the remaining solar energy is trapped by PV cells, or the energy dissipates into surrounding areas. Hence, it is essential to determine the suitable working temperature of PV arrays to maximise performance parameters and efficiency to sustain an ever-increasing global energy demand [10]. Numerous studies have addressed the thermal–electrical modelling of air-based PVT collectors [11–13]. Extensive studies have been conducted to evolve these systems to better serve consumers. An innovative hybrid PVT system was developed by fusing a PV panel and a conventional flat-plate air-heating solar collector for the simultaneous increase of electrical as well as thermal energy out, yielding unique benefits for agricultural applications such as fodder drying [13]. It was shown that the energy extraction is at its maximum in case the PV panel covers 25% of the total length of the flat-plate collector. A complete classification of PVT systems is provided in the study, and a stringent review of theoretical and experimental research in the field is conducted. PVT systems are evaluated based on the technology, previous fields of application, performance characteristics, and overall efficiency. Recent trends in efficiency have further sharpened thermal collector designs regarding the fluid mass flow rate (MFR), ambient temperature, solar cell material, heat-absorbing medium, and glazing. While most of the existing literature provides a better understanding of heating principles, it is evident that thermal design in PVT systems offers the greatest room for improvement in thermal performance; this study indicates that thermal collector designs directly influence the performance of the whole system. However, little research has investigated the impact of nanofluid concentration in PCM and various MFRs on the performance of hybrid PVT collectors [14, 15].

This review thus intends to do a comprehensive and comparative review of recent advances in PVT technology with special emphasis on the incorporation of nanofluids and PCM for thermal management and performance enhancement. The study in the present work compares the air-based, water-based, nanofluid-enhanced, and PCM-integrated PVT systems in a single framework and compares them in accordance with previous reviews, which were mainly focused on individual cooling techniques, specific working fluids, or isolated PCM-based PVT configurations. The review addresses the issue of how the selection of the working fluid, the concentration of nanoparticles, integration of the PCM, the design of the absorber, the MFR, and the operating conditions of the system all affect the thermal efficiency, electrical output, reduction of temperature, cost, environmental impact, and durability of the system. This review aims to fill the identified gap of a comprehensive comparison between material innovation and operating parameters, performance

indicators, and practical deployment issues. While there are many reports on the use of nanofluids and PCM as effective enhancement strategies, the previous studies often report the effects of these materials separately, under different experimental conditions and with various performance metrics. It is hard to determine the best configuration for a real application. In response to this, the present review compiles some 300 studies published in the period 2000 to the present and categorises them by collector type, cooling method, material enhancement, the performance outcome, and the applicability for future use. Furthermore, the manuscript goes beyond performance reporting to address the requirements of standardisation, long-term field testing, cost analysis, environmental impacts, and finally, the potential of artificial intelligence and machine learning in PVT system optimisation. Numerous review articles have been written on PV systems, phase change refrigeration, and design optimisation or heat transfer using nanofluids; however, these articles are scattered. Most previous reviews cover individual optimisation techniques without a comprehensive comparison of material selection, operating fluid type, PCM integration, nanofluid concentration, absorber geometry, MFR, operating conditions, efficiency definition, uncertainties, cost, and scalability. Consequently, it is difficult to determine the optimal PV system design for specific climatic, economic, and application conditions. To bridge this gap, this review provides a classification and framework for the critical comparison of advanced PV systems. The review studies were categorised into five main groups: air thermal PV (APR) systems, hydrothermal PV (HPR) systems, nanothermal PV (NPR) systems, thermal PV systems combined with PCMs, and hybrid thermal PV (PPR) systems (PCMs and nanofluids). In addition to summarising the reported efficiencies, this review critically analyses the operating conditions, limitations, long-term reliability, technical and economic feasibility, scalability barriers, and future research priorities. This analysis is timely, as recent years have seen advancements in PCMs, hybrid nanofluids, machine learning-based prediction, and intelligent thermal management of PPR technologies, all of which require a unified assessment to guide future experimental design and commercialisation of these technologies.

Methodology of literature review

A structured literature search and screening approach was used to conduct this review in an open and transparent manner. The goal of the methodology was to locate, classify, and critically discuss studies on PVT systems, focusing on air-based, water-based, nanofluid-enhanced, PCM-integrated, and hybrid PVT systems.

Literature search strategy

Literature search was conducted during 2000–2025. The primary electronic databases utilised were ScienceDirect, SpringerLink, Taylor & Francis Online, and Google Scholar. Manual screening of reference lists of relevant review papers, journal papers, conference papers, book chapters, and highly cited papers in the field of solar PVT technology was performed to identify additional records. The combination of the following keywords was used in the search strategy:

PVT system, PV/T system, PVT collector, PVT thermodynamics, photovoltaic thermal, PVT processor, PVT machine, PVT system design, PVT modelling, PVT optimisation, PVT simulation, PVT efficiency, PVT solar, PVT solar thermal, PVT overall efficiency, PVT electrical efficiency, PVT mass flow rate, PVT absorber design, PVT machine learning, PVT techno-economic, PVT solar thermal management, PVT system efficiency, PVT techno-economic analysis, PVT solar thermal management system, PVT modelling, PVT optimisation, PVT simulation, PVT efficiency, PVT system, and PVT thermodynamics. Boolean combinations were used as needed, e.g.:

PVT AND nanofluid, PVT AND PCM, PVT AND thermal efficiency, and PVT collector AND mass flow rate, VT AND machine learning, Use PVT AND techno-economic analysis.

Inclusion criteria

The studies considered in this review were those that fulfilled at least one of the following criteria:

1. They explored the PVs Thermal systems experimentally, numerically, analytically, or based on validated modelling.
2. They gave out the electrical efficiency, thermal efficiency, overall efficiency, exergy efficiency, PV temperature reduction, heat transfer performance, or any indicator related to PVT performance.
3. They studied air-based, water-based, nanofluid-based, PCM-based, and PVT hybrid PV systems.
4. They spoke about the design of the absorber, the choice of working fluid, the mass flow, the operating temperature, the cooling method, or thermal storage integration.
5. They offered technical, environmental, and economic or scalability input to advanced PVT deployment.
6. They have been published in peer-reviewed journals, conference proceedings, book chapters, or in a recognised scientific source.

Exclusion criteria

Studies were excluded if they fulfilled any of the following:

1. They only took into consideration standalone PV modules and nothing about thermal recovery or PVT relevance.
2. They talked of general solar energy systems with no analysis of PVT.
3. They did not have enough technical data about the configuration of the system, operating conditions, or performance indicators.
4. They duplicate publications, or they use the same dataset without further contribution.
5. They were in languages other than English or provided insufficient methodological detail to be assessed.
6. They did material synthesis only and did not relate the material to PVT thermal management performance.

Screening and selection procedure

This screening was done in steps. The selected keywords and database searches were used to identify the records. Secondly, titles and abstracts were reviewed to exclude irrelevant studies. Third, the full text of potentially relevant studies was reviewed based on the inclusion/exclusion criteria. Finally, the selected studies were categorised based on collector type, cooling medium, enhancement technique, working fluid, PCM integration, absorber design, performance metrics, and practical limitations. About 250 studies were chosen for final evaluation. The studies were categorised into major groups such as PVT systems with air, water, nanofluids, PVT systems integrated with PCM, optimisation of absorber design, prediction using machine learning, and techno-economic evaluation. The classification was not intended to be a stand-alone literature summary, but to facilitate comparative analysis.

Data extraction and synthesis

The following parameters were extracted from each selected study, if available: parameters of the system, type of collector, type of cooling medium, type and concentration of the nanoparticles, type of PCM, MFR, irradiance level, ambient temperature, inlet and outlet fluid temperatures, the design of the absorber, electrical efficiency, thermal efficiency, overall efficiency, exergy efficiency, PV temperature reduction, uncertainty information, and any limitations reported. Data were extracted and analysed thematically through a comparative method. The studies were not considered separately, but were classified based on the technical approach and assessed on the basis of performance enhancement, operating environment, practical

implementation, long-term durability, cost and budget considerations, scalability, and technical challenges that were not resolved.

It is a review of the methodology used to review that is provided; it is the nature and limitations of the review methodology that are provided

The review is organised and transparent in the use of the literature. The study should be called a structured critical review; however, because a full PRISMA flow diagram with exact numbers of records identified, screened, excluded, and included at each stage is not presented, the study does not constitute a systematic review. For this reason, the terms 'systematic review' and 'systematic comparison' should only be used when a systematic PRISMA-style workflow is included. One of the biggest drawbacks of the methodology is that there are significant differences between the experimental conditions, collector size, climate, flow rates, efficiencies, and reporting standards in the studies reviewed. This restricts the ability to make direct quantitative comparisons between all studies. However, the present review focuses on critical comparative synthesis, operating condition interpretation, and practical feasibility, rather than merely on reported peak efficiency values, to overcome this limitation.

A graphical depiction in Fig. 1 shows the classification of research topics from the studies in the field. The synthesis demonstrates how PVT technology has progressed while showing the increasing importance of implementing nanofluids because they enhance system efficiency. The results demonstrate organised attempts to handle solar energy sustainability and efficiency challenges, which will guide upcoming developments in hybrid solar systems.

Distribution of Research Papers by Type

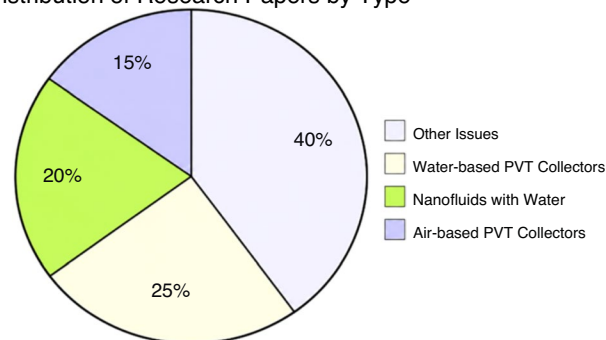


Fig. 1 The subject classification of the reviewed articles in this study

Classification of PVT systems

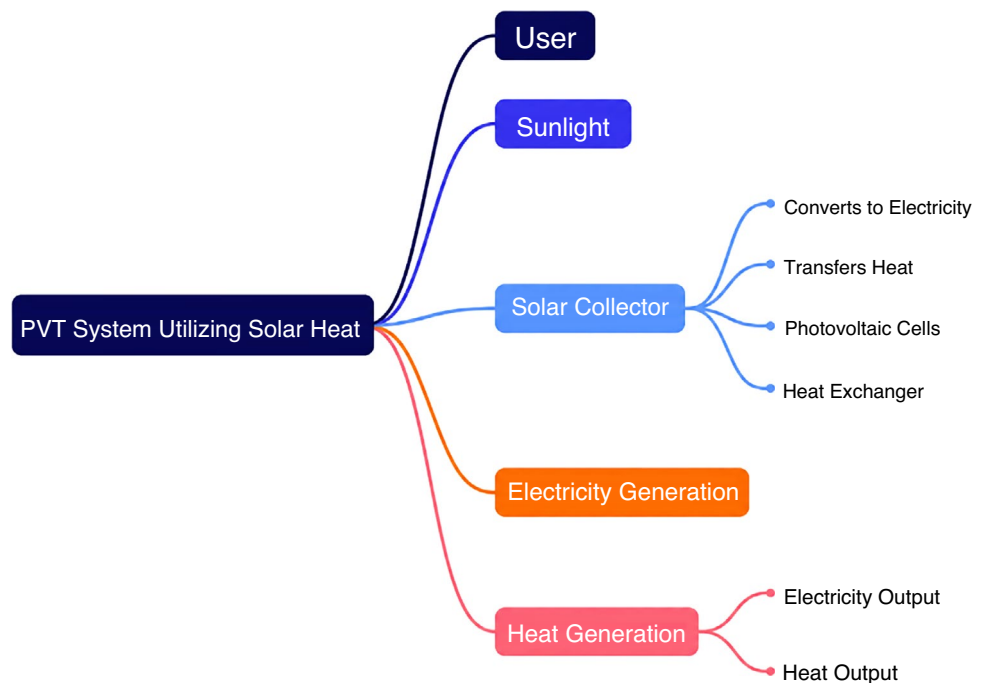
The challenge of efficiency decrease in solar energy conversion at increased solar cell temperatures was recognised in the mid-1970s [7]. If not properly released, over 80% of incident solar energy is transformed into heat, which has adverse effects on the performance of the PV cell, particularly if it is utilised for an extended period of time without a thermal collector [8]. A PVT system capturing solar energy for electric and thermal usages is shown in Fig. 2. Many theoretical and experimental works have been performed in recent years with a strong emphasis on two types of collectors, namely air-based and water-based collectors for harvesting heat from PV modules [16]. However, while the benefits of PVT technology are clear, investment has yet to fully materialise in optimising the technology. In the last decade, significant research has been conducted to promote PVT system technology and develop directives for future solar systems. Solar energy usage can be determined as solar thermal energy systems that transform solar radiation into heat or PV systems that convert solar radiation into electricity. In this context, a PVT collector is a unit equipped to recover heat utilising multiple technologies embedded in different classes of thermal collectors. In these types of systems, a liquid or gas absorbs the heat in the thermal collector that is then circulated through a set circuit designed to heat up a home or business. Silicon wafer-based PV cells are an essential component of the PV systems used to convert solar

energy into electricity. A system in which solar thermal collectors and PV cells are operating together is referred to as a PVT hybrid or PVT power system [5]. A PVT system is composed of solar thermal collectors, which include PV cells in an absorber plate to produce electrical and thermal energy. The current method enhances the performance of PV systems as a whole by converting the surplus heat generated by the solar panels into low-temperature thermal radiation, thus decreasing the adverse effects of elevated temperatures on the PV modules and improving their electrical output [8]. The dual conversion of solar energy allows for the more effective use of solar energy than the use of only PV or thermal systems, allowing greater energy production per unit area [10]. A double-glazed outer wall covering the PV cells has been proven capable of capturing thermal energy for use in domestic sectors if air is flown inside [6]. If both air and water are used in conjunction under the PV module for the generation of electric and thermal energy, this system is referred to as a PVT hybrid or combination panel system [17].

History of PVT solar collectors

Combining PV and thermal solar collectors for the simultaneous supply of electrical and thermal energy is not a novel concept, but it received little attention in the past. Due to the growing concerns about energy sources and their utilisation, the area of PVT has attracted more interest. The impression of the area-around has been studied from the mid-1970 to the early 1980. Wolf [18] was the first to prototype a flat-panel

Fig. 2 PVT system that utilises solar heat for both electricity production and heat generation



solar collector machine, monitoring the performance of a device that combined heating with PV electricity generation for homes. Bergene and Løvvik [19] reported on a numerical model for a flat-panel solar collector with an embedded solar cell array in 1995. They have created a suite of algorithms to make quantitative predictions of the electrical and thermal performance of a PVT system. They observed that a device comprising each additive attained efficiencies ranging from 60 to 80%. In 2001, Huang et al. [20] developed a PVT machine using a polycrystalline solar panel, which was mixed with a thermal collector. The collector is installed immediately on a commercial PV panel using a thermal cloth to enhance the relationship. The grid-connected PVT gadget became constructed on a rooftop as a case for the software of the solar collector [21].

Figure 3 shows three cooling approaches applied to PV panels to enhance their efficiency while reducing the increase in temperature from solar radiation absorption. Different techniques characterise the three designs, which work to improve heat dissipation. An air-cooled system within the design allows air entry through dedicated vents to collect heat during internal fin passage, thus ensuring better system cooling. This basic design works well yet appears to have less efficiency than systems which make use of

heat-absorbent materials or fluids. The nanofluid cooling system employs a fluid circulation through dedicated channels, below a PV panel for heat absorption from entering and exiting channels. Due to the enhanced thermal properties of nanofluids, the cooling efficiency becomes superior to traditional air-based cooling methods. The efficient operation of this system depends on supplementary equipment, particularly pumps, which manage fluid movement. The PCM functions as the primary component in the third design framework under the placed PV panel. The material transforms into a liquid because it absorbs heat during temperature increases. At lower temperatures, the material reverts to its original state, allowing heat from storage to be released in a controlled manner. The implementation of this design benefits from temperature stabilisation features, though finding appropriate PCM components with high thermal storage capacity becomes critical to deliver maximum performance across different climate zones. Air cooling systems maintain easy operation and affordable costs, yet struggle for peak efficiency because air has low thermal capacity. More efficient cooling performance emerges with nanofluid cooling technology, although the system includes additional requirements for pumps and controllers. The innovative PCM cooling system provides effective thermal stability through the

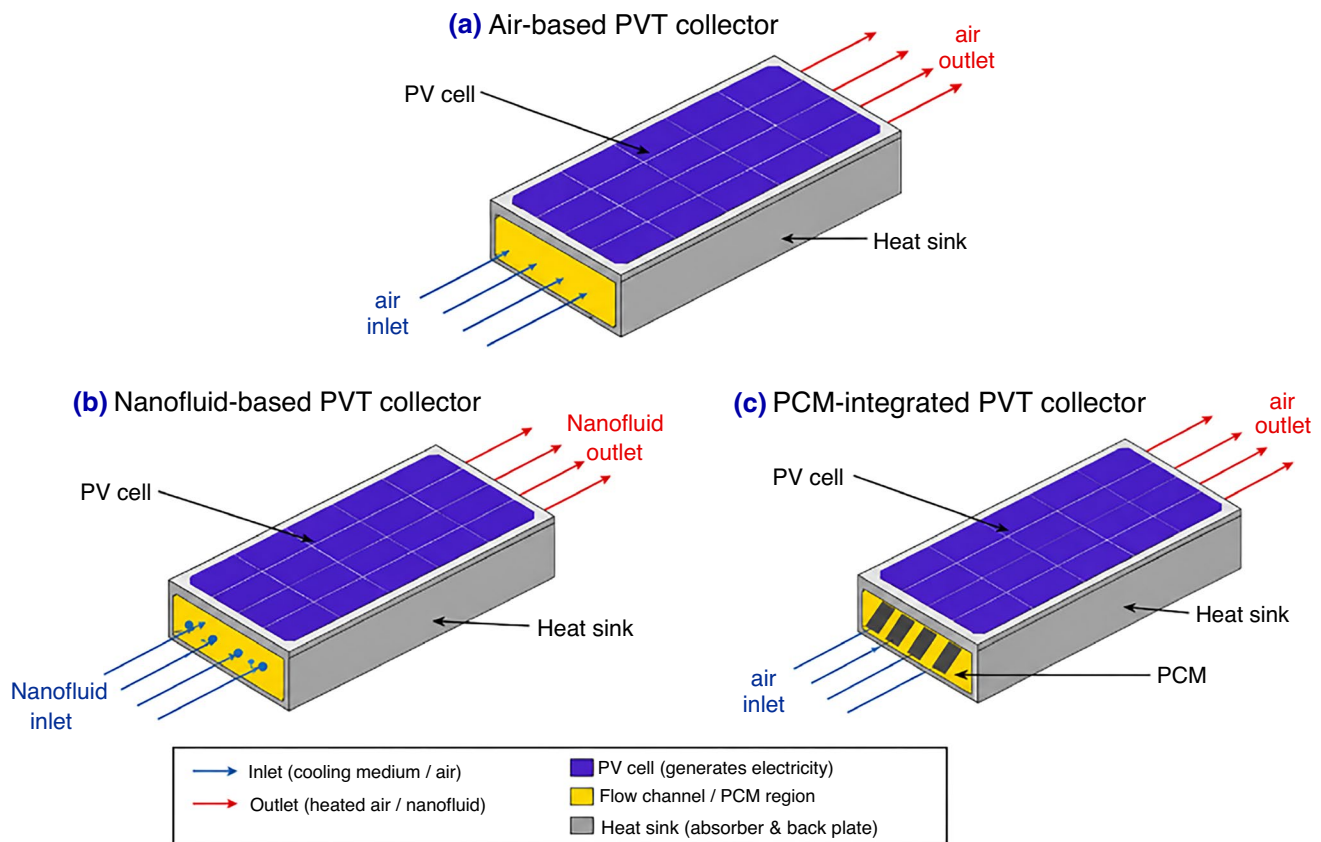


Fig. 3 PVT system, water-based, air-based, and PCM

proper choice of PCMs for optimal performance. The right cooling system selection relies on environmental conditions, together with cost factors and maintenance needs to achieve complete solar panel usage and operational enhancement.

The repeated melting and solidification process of the PCM is the thermodynamic condition of PCM-integrated PVT systems. The hotter the PV module during high solar irradiance, the more heat will be transferred from the back surface of the PV panel to the PCM layer. PCM absorbs latent heat due to melting approximately its melting point without a significant change in temperature. This thermal buffering effect minimises PV temperature fluctuations and may increase electrical output by minimising the losses due to temperature changes, which cause efficiency reductions in PV devices. When irradiance decreases or when the system is operating at night, the PCM solidifies and cools the system, which results in heat recovery when irradiance is lower than it was, and in part heat regulation. The effectiveness of this process, however, is strongly reliant on the match of the PCM melting temperature with the PV module operating temperature range. Lower melting point will mean that the PCM can melt earlier in the day; thereby, it will not have the heat storage capacity during the times of peak solar radiation. Excessively high melting temperature may result in partial melting of PCM, which may affect the latent heat utilisation. Therefore, besides latent heat capacity, the selection of PCMs should also consider the melting range, thermal conductivity, cycling stability, encapsulation material compatibility, and climate and thermal load temperature. Low thermal conductivity is a major thermodynamic constraint of most PCMs. This will reduce the heat transfer rate between the PV module and the PCM volume, which will result in non-uniform melting and delayed solidification. Consequently, only a portion of the PCM can be effective in heat storage, particularly in the case of large thicknesses of the PCM or less than optimum absorber geometry. This limitation has been suggested to be addressed with enhanced heat spreading materials such as fins, metallic foams, graphite additives, heat sinks, nanoparticles, and bio-inspired absorber structures. However, these improvements make the system more complex, heavier, costlier, and sometimes can decrease the amount of PCM. Another process that influences the long-term reliability is called melting–solidification cycling. Phase segregation, supercooling, volume change, leakage, encapsulated failure, and loss of latent heat capacity may occur after repeated thermal cycles. Organic PCMs (paraffin-based materials) are typically chemically stable, but the low thermal conductivity and flammability are concerns. The inorganic salt hydrates provide higher thermal conductivity and volumetric storage capacity, but can supercool and corrode, and can suffer from phase separation. Although thermal properties such as melting temperatures can be tailored using eutectic PCMs, their long-term

durability and price need to be assessed. Another important problem for PCM-integrated PVT system is the thermal degradation. The PCM properties such as melting temperature, latent heat, viscosity, and thermal conductivity can change with time with repeated exposure to high temperature. These changes will diminish ability of the PCM to control PV temperature and can lead to a gradual degradation of system performance. Thus, any increase in efficiency would only be worthwhile in the short term. Accelerated thermal cycling tests, DSC tests before and after thermal cycling, leakage tests, durability assessment of the encapsulation, and long-term outdoor monitoring under realistic solar conditions should be included in the future studies. Practical considerations are the reliability of the PVT system, which rely on the balance of thermal performance enhancement versus system penalties in the integrated system. The advantages of PCM integration are thermal efficiency and temperature stability of PV systems, while the disadvantages are mass, cost, structural load, maintenance, and complexity. Furthermore, the recovered heat is frequently low-grade heat, and thus, the practical application of the PCM storage depends on the type of heat demand, such as the preheating system, drying system, space heating system, or domestic water heating system.

Photovoltaic thermal collector (water-based)

Water is the most commonly used working fluid in liquid-based PV thermal collectors. This section discusses the class of water-based PV thermal collector structures, overall performance parameters, absorber design in these systems, and electricity performance analysis.

Advanced absorber designs for liquid-based PVT

Dubey and Tay [22] provided a comprehensive study on PVT module configurations through their research. The experiments happened under standardised conditions where researchers utilised typical tropical weather with MFRs between 0.03 and 0.06 kg s⁻¹. The evaluation of PVT module efficiency required fundamental energy balance equations together with design parameters to calculate the complete system efficiency. The PVT modules showed precise temperature distribution measurements in different layers to study how heat waves spread and how thermal energy affects overall performance. The PVT module achieved a superior electrical efficiency compared to standalone PV modules with an average boost of 0.4%. The effective heat dissipation systems built into PVT designs maintained electrical efficiency by reducing losses as temperatures rise. The research evaluated different PVT collector designs by testing their thermal–electrical performance under the same tropical environmental

conditions. The research indicated that the leaf-and-tube collector produced superior performance levels compared to the movable parallel plate collector in thermal and electrical measurements. The findings emphasise how properly designed collectors serve as a fundamental factor for improving PVT system performance, specifically in hot operating conditions that require efficient thermal control. Sultan et al. [23] studied and designed a PVT collector with a spiral flow absorber while also analysing its performance under different climatic conditions in Malaysia. Based on the above assumptions, the study analysed the effect of inlet water temperature on the thermal, electrical, and overall efficiencies of the PVT system in several different weather conditions (sunny and cloudy days). The results from the simulation showed that thermal efficiency was at its highest at one hour at 61.3% on sunny days but slightly lower (59.6%) on cloudy days. Electrical efficiency was 12.89% during sunshine and rose slightly to 13.03% during cloudy conditions. The overall efficiency of the system was appreciable, having a maximum performance of 74.1% during sunnier days and a minimum of 72.63% on cloudy days, indicating the system successfully reduces variations due to the cloudy weather. Baloch et al. [24] investigated a new solar PV cooling method named converging channel cooling via experimental and numerical studies. The main objective of this method is to maintain a low, constant surface temperature of the PV panel, thereby indirectly increasing the PV system's efficiency. Their findings focused on how ensuring optimum temperature conditions could enhance the functioning of solar PV technologies. This research has conducted a comparison between an uncooled PV system and a converging channel cooled PV system under Saudi Arabia's extreme climatic conditions during June and December. Compared to conventional passive cooling methods, the introduction of a cooling inclination angle resulted in the temperature distribution across the PV module being highly uniform ($STDEV = 0.91$), while a holistic system characterisation enabled the computational examination of the performance of PV systems by incorporating optical, radiation, thermal, computational fluid dynamics (CFD), and electrical models. The temperature of the uncooled PV module reached 71.2 °C in June and 48.3 °C in December, as measured thermally. On the other hand, the implementation of converging channel cooling was able to drop PV module temperature to 45.1 °C during the month of June and 36.4 °C during December. The cooling technique also led to 35.5% higher maximum power output and 36.1% higher conversion efficiency, compared to the uncooled PV system. For a grid-connected PVT system to harvest thermal energy, Kazem [25] studied field tests carried out in Sohar, Oman. In this system, a direct flow type thermal collector was used as a rectangular absorber.

The results showed that compared to conventional solar panels, the water-based PVT collectors generated higher electrical output at the end of the study period. In fact, it was noticed that the changing temperature influenced the electric potential energy curve of the solar cells, while at the same time, the heat exchanger from the solar panel to the thermal collector also changed, increasing the heat transfer. The study also confirmed that higher cell temperatures yielded higher short-circuit current, which is also consistent with previous observations in the literature on the subject. These findings underscore the significance of effective thermal regulation in PVT systems to improve electrical and thermal performance simultaneously. The square absorber form additionally proved powerful in decreasing the temperature of the solar panels because it covered a larger region, which allowed for prolonged warm temperature switching. They concluded that the proposed PVT gadget showed advanced electric-powered overall performance at some stage in the check duration, with the very best electric power achieving about 67 watts and a voltage of 18.9 V. The not-unusual energy output from the PVT panel became 6% higher than the common strength output from traditional panels. This look highlights the benefits of water-based PVT structures in producing warmth and warm water in climatic conditions, which include those located in Oman. Senthilraja et al. [26] developed and constructed a new design for a sun-assisted hydrogen-manufacturing machine, which was then analysed experimentally using air and water at three specific MFRs (0.008, 0.01, and 0.011 kg s⁻¹). The findings of the study revealed numerous essential consequences. First, the power output of the device extended with the mass drift rate, with the best enhancement of 11.8% determined inside the PVT/water creditors at a flow charge of 0.011 kg s⁻¹ and a time of 12:00. Additionally, the temperature of the panel surface reduced as the waft charge elevated, with the best discount of 20.01% stated for the PVT/water solar collector on the same drift charge and time. Moreover, both varieties of PVT solar collectors tested increased thermal efficiency with rising mass glide ratios. The average thermal performance for the PVT/water and PVT/air creditors was 27.17% and 24.44%, respectively, between 8:00 and 16:00. The highest thermal efficiency of 33.8% was accomplished via the PVT/water collector at a drift fee of 0.011 kg s⁻¹ at 12:00. In terms of electrical performance, the common efficiencies of the PV module and the PVT collectors were observed to be 4.9%, 5.18%, and 5.41% all through the identical length. The highest electrical performance recorded was 8.5% for the PVT/water collector at 0.011 kg s⁻¹, while the PV module exhibited the lowest efficiency of 7.5% at noon. Finally, the hydrogen-manufacturing rate is shown to grow with the power output of the PVT solar collectors. Under peak solar radiation and

at the best mass waft charge, the hydrogen-manufacturing charges have been 8.19 mL min^{-1} for the PV module, 13.9 mL min^{-1} for the PVT/air collector, and $17.12 \text{ mL min}^{-1}$ for the PVT/water collector. Menon et al. [27] developed a PVT system that consisted of a serpentine coil-configured thermosiphon heat pump and evaluated it by recording the electrical and thermal performance of the device connected to both water and nanofluid. A detailed analysis evaluated cooling approaches for PVT technology by studying water and nanofluid-based heat exchange systems. The uncooled PVT system operated at an average electrical efficiency of 12.98% while maintaining an average panel temperature of 57°C . The peak solar radiation period (12:00 p.m.) witnessed substantial temperature decreases when using water cooling, which reduced temperatures by 15°C , yet nanofluid cooling produced an even greater temperature reduction of 23.7°C . Water cooling as a system implementation method increased electrical efficiency by 12.32%, which brought overall system efficiency to 14.58% when compared to the uncooled design. The nanofluid cooling technology exceeded water cooling by providing superior heat transfer properties to boost electrical efficiency by 35.67% over the uncooled system, which resulted in a total efficiency rate of 17.61%. The nanofluid-cooled system delivered superior thermal performance because it operated at 71.71% thermal efficiency at high-concentration ratios, while the water-cooled system maintained only 58.77% thermal efficiency. The superior heat absorption and conduction properties of nanoparticles in the nanofluid resulted in a significant improvement of heat transfer and dissipation processes. The nanofluid-cooled system achieved better performance than the water-cooled system by 21%. The primary energy savings reached 97.15% for water cooling and 117.53% for nanofluid cooling, which establishes nanofluid-based cooling methods as more efficient than water cooling. The research supports using PVT modules with serpentine coil-configured thermal absorbers cooled by nanofluids because this setup optimises both electrical output and thermal performance to enhance PVT system efficiency. Tiwari et al. [28] carry out experimental and numerical studies aimed to enhance heat switch efficiency of water primarily based PVT systems. The analysis concerned adjusting numerous variables, which include collector pipe diameter, base plate thickness, and Reynold's quantity, to look at their effect at the thermal, electrical, and general performance of PVT system. The average thermal, electrical, and ordinary efficiencies for the gadget of PVT estimated at 10%, 20%, and 30%. Of the copper tube, diameters examined (8 mm, 12 mm, and 16 mm); the 16 mm tube demonstrated the good cooling properties under equal operation conditions. Moreover, increasing the tube diameter and decreasing the thickness of lower back plate gave a

maximum mobile temperature reduction of 6°C . Moreover, the observer found out that improved Reynolds numbers, led to 10% enhance in thermal transition performance of water-based PVT device. The researchers also finished numerical simulations to validate their experimental records, which confirmed a strong correlation between the numerical and experimental consequences, with a maximum relative error of just 3.96%.

A solar PVT system with a symmetric grid float heat exchanger underwent experimental testing at Vellore, India's typical climate, according to Rao et al. [29]. Performance analysis included core thermodynamic evaluations of energy, exergy, and entropy to measure PVT system performance against standard solar PV devices. The testing was conducted at different solar radiation levels between 220 and 850 W m^{-2} and fluid flow rates from 0.5 to 2.0 L min^{-1} . The PVT system operated at 0.5 L min^{-1} achieved its maximum electrical power output of 285.5 W, which represented a 3.21% increase in performance compared to the reference PV module. The system achieved its highest electrical efficiency of 3.25% while operating at a 1.5 L min^{-1} flow rate. The PVT system operated with a midday average cell temperature of 56.15°C at 2.29°C lower than typical PV module temperature levels. Thermally, the system achieved its best thermal efficiency of 63.09% at 1.5 L min^{-1} while producing water at 47°C at 0.5 L min^{-1} , where the temperature exceeded the 1.5 L min^{-1} measurement by 12.55°C . The PVT system achieved maximum overall energy efficiency of 55.28% and maximum exergy efficiency of 21.15% at 1.5 L min^{-1} flow rate conditions. The high end of entropy generation reached 2.8 W K^{-1} at 0.5 L min^{-1} , and the main exergy loss point occurred at 0.03 at 2.0 L min^{-1} . The PVT system's electrical and thermal performance reached optimum levels at specified flow rates due to the symmetric grid float heat exchanger, which successfully controlled temperature rises, especially during daytime peak hours. The arrangement shows substantial promise to enhance solar energy system efficiency because it provides better thermal regulation and energy conversion capabilities.

Yildirim and Cebula [30] carried out a very extensive experimental and computational analysis of a newly developed water-based PVT system. The resultant thermal and electrical efficiencies were systematically tested under a variety of operating conditions, such as varying conditions along inlet MFRs, inlet temperatures, and heat fluxes. In the independent cooling configuration, a thermal efficiency of $85.54 \pm 1.12\%$ is obtained at an inlet MFR of 0.0542 kg s^{-1} , an inlet temperature of 21.70°C , and a heat flux of 1184.4 W m^{-2} . Decreasing MFR from 0.0542 kg s^{-1} to 0.0325 kg s^{-1} resulted in approximately 4% improvement in thermal efficiency, while increase MFR up to 0.1417 kg s^{-1} gave about 13% improvement in thermal performance. An advanced 3D MPL-based CFD modelling was developed

that showed a very close correlation with experimental results, with an average error of 1.51%. The optimum flow rates and inlet temperatures at maximum thermal efficiency were $96.47 \pm 1.40\%$ and 19.12% at maximum electrical efficiency, with the records taken at a MFR of 0.0458 kg s^{-1} , an inlet temperature of 11.90°C , a heat flux of 592.89 W m^{-2} , and a temperature gradient of 40.72°C across the PV cell layer. Thus, these results indicate that the new PVT system has outclassed all the rest through improved thermal management and better optimised operation parameters, proven by accurate computer modelling. Research was conducted on ML algorithms to improve PVT solar thermal device efficiency predictions since experimental results deviated from theory because of practical implementation limitations. Researchers, including a multi-layer neural network (MLP), used three machine learning approaches and random forest (RF) methods together with support vector regression (SVR). This study utilised over 380 datasets that researchers retrieved from various water-based working fluid research. Through its RF model, researchers attained a $0.9862 R^2$ value with minimal RMSE error that produced the most efficient prediction of PVT panel electrical efficiency. The (Size 1) next-worst follower was the MLP model with $R^2=0.8775$, yet the SVR model came in second with $R^2=0.7639$. The SHAP method investigated RF model variables to determine the MFR and wind speed, with the inner tube diameter acting as the principal influencing aspect. Researchers tested the created models on 46 datasets, which exceeded the established development criteria. RF model outperformed SVR for electric efficiency predictions when testing cell absorption along with inlet fluid temperature changes, but SVR proved better at solar radiation value prediction outside training boundaries, according to Gharaee et al. [31].

Recently, machine learning has been shown to be a potentially powerful solution to predict and optimise PVT system performance, especially when the experimental results do not match with the theoretical or numerical results due to the complex interactions of solar radiation, ambient temperature, inlet fluid temperature, MFR, wind speed, absorber geometry, and working fluid properties. The prediction reliability, however, is very sensitive to the dataset preparation, validation strategy, hyperparameter optimisation, uncertainty assessment, and input-feature selection, which all rely on ML models. Preparing the datasets is a crucial step in the PVT modelling using ML. The experimental data obtained from various studies are usually characterised by non-uniform operating conditions, collector size variations, variations in measurement units, and various definitions of electrical, thermal, and overall efficiency. Thus, it is imperative to thoroughly clean, normalise, and standardise the dataset prior to using it for ML model training. Data should be checked for missing data, duplicated operating points, outliers, and inconsistent units. For an accurate and efficient

design, some key input variables are solar irradiance, ambient temperature, wind speed, inlet fluid temperature, outlet fluid temperature, MFR, collector area, tube diameter, absorber geometry, type of working fluid, nanoparticle concentration, and PCM characteristics (where applicable). The variables produced can be PV temperature, electrical efficiency, thermal efficiency, overall efficiency, exergy efficiency, and net power output. Model validation is crucial since model accuracy in prediction can be an error if trained and tested on non-independent or narrowly distributed data. A well-formulated ML workflow should incorporate data partitioning (during training into training, validation, and testing sets) and ideally use k-fold cross-validation. Model validation is especially critical for PVT systems, as performance can vary for new climates or collector shapes and/or use ranges. Besides the coefficient of determination, R^2 , it is important to report RMSE, MAE, MAPE, the distribution of the residuals, and prediction uncertainty. This is required because a high R^2 value does not necessarily indicate the reliability of the model, particularly when used for prediction beyond the range of the data that were used to create the model. As far as prediction accuracy is concerned, the random forest models have performed well in predicting PVT efficiency, since it is possible to capture the nonlinear interaction between operating parameters without a predefined relationship between them. The RF model gave the highest prediction accuracy for the electrical efficiency ($R^2=0.9862$), better than the MLP model ($R^2=0.8775$) and the SVR model ($R^2=0.7639$) in the studied work. This high accuracy, however, should be used with caution. RF models can be good for interpolating values within the range of the data and not so good for extrapolating beyond the range that it was trained on. Prediction accuracy thus needs to be analysed for interpolation and extrapolation problems and more particularly for extreme solar radiation, unusually high inlet temperature, different geometry of the absorber, and new configuration of nanofluid and PCM. Model optimisation must also be discussed with reference to the practical operation of PVT. The number of trees, the depth of the trees, the learning rate, the kernel function, the regularisation parameters, and the structure of the hidden layers are examples of hyperparameters that can have an impact on the model's performance. These can be done using grid search, random search, Bayesian optimisation, or evolutionary algorithms to find optimal model parameters. Furthermore, optimisation should not be based only on the maximisation of thermal or electrical efficiency. Incorporating multi-objective optimisation targets in PV systems, such as PV temperatures, net electrical gains, thermal output, exergy efficiency, pumping power and pressure drop, system cost, and long-term reliability, should be considered using the ML-based optimisation framework. To make the interpretability of ML models better, feature importance analysis is crucial. For instance,

SHAP can be used to determine the most important factors that affect PVT performance. MFR, wind speed, inlet fluid temperature, and tube diameter are some factors that significantly influence the electrical efficiency as they are used to control the heat removal of the PV module. Feature importance should be used in conjunction with physical reasoning, however. A variable may have a statistical significance due to the structure of the datasets but the effect of the variable should be substantiated through experiment. Thus, ML should not be used as a substitute for physical understanding; rather it can be used alongside thermodynamic modelling and experimental analysis. However, there are still significant challenges in the application of ML in PVT systems. The majority of the available data is small, heterogeneous and comes from short-term experiments. Data imbalance can result if there are many data in certain ranges of irradiance or flow rate. Furthermore, most of the studies do not provide enough information regarding sensor uncertainty, experimental repeatability, or data pre-processing. This restricts the generalisation capability of the ML models. Open benchmark datasets, standardised definitions of features, uncertainty-aware modelling, physics-informed ML methods, and real-time control strategies for adaptive flow-rate regulation, fault detection, and predictive maintenance for PVT systems should then be developed in the future studies.

Design of absorber for PVT water collector

The literature illustrates numerous studies that used solar PVT collector configurations to find out an overall performance based on electrical, thermal, and overall efficiencies to determine a suitable model for optimal design of these systems. Harby et al. [32] investigated the performance characteristics of an optimised bi-fluid PVT solar system incorporating a wire-on-tube serpentine heat exchanger with simultaneous water cooling and natural-convection air cooling. A 3D numerical model developed in ANSYS Fluent and validated against experimental data was used to compare three cooling system materials, namely stainless steel, aluminium, and copper. The results showed that the proposed bi-fluid configurations reduced the average PV surface temperature by 1.62–5.27%, increased the average daily electrical output by 7.66–16.04%, and improved the electrical efficiency by 9.14–17.93%. Among the tested designs, the copper-based system exhibited the best overall techno-economic performance, yielding the lowest levelised cost of energy and the shortest payback period. Zheng et al. [33] optimised the structure and filling ratio of a flexible separate heat pipe (FSHP) applied in a tracking-type PVT system. The study experimentally examined the effects of key design and operating parameters, including the diameter and material of the adiabatic pipe, evaporator–condenser height difference, filling ratio, solar irradiance, and

side-altitude inclination angle, on the thermal performance of the FSHP. The findings indicated that incrementing the adiabatic pipe diameter improved the internal temperature distribution, reduced pressure differences, and enhanced both MFR and thermal efficiency. In particular, increasing the diameter from 10 to 17 mm increased the MFR and thermal efficiency by up to 1.62 and 1.27 times, respectively. The evaporator–condenser height difference also had a clear influence on performance, especially under moderate and high solar irradiance, where increasing the height difference from 0.74 m to 1.06 m improved thermal efficiency by approximately 5.00–12.48%. The filling ratio was identified as another critical parameter, with 25% being relatively unsuitable, while stable operation was observed between 35 and 75%. The optimum performance was achieved at a 45% filling ratio, where the thermal efficiency remained within the range of 69.37–79.71% under the tested conditions. Overall, the study demonstrated that structural optimisation of FSHPs can significantly improve the thermal behaviour of tracking-type PVT systems and provides a promising strategy for broader solar energy utilisation. Rejeb et al. [34] were conducted, a comparative economic analysis between PVT collectors of several designs (plates and tubes) and conventional solar thermal collectors and PV modules was carried out under the climatic conditions of Monastir (Tunisia). The study worked at a fixed MFR of $0.00552 \text{ kg s}^{-1}$ and found that decreasing the number of tubes decreased spacing while increasing thermal resistance between the absorber plate and tubes, which decreased electrical performance. Moreover, the thermal efficiency was reduced due to the smaller number of tubes. The comparative economic analysis also showed the uncovered PVT collector to exhibit the best electrical performance, payback period, and overall economic efficiency. Rosli et al. [35] compared the thermal efficiency to the electrical efficiency and overall efficiency of the PVT solar collector, with various designs of absorber tube. The work titled uses ANSYS Fluent software to model the thermodynamic performance of the system through CFD simulations. The heat transfer medium is water. The CATIA V5R20 software was utilised to create the engineering model, which was subsequently imported into the ANSYS software to generate the mesh model. Various settings were defined in the simulation, including the airflow model, radiation model, the properties of the materials, and the surface-to-surface (S2S) radiation model, which was applied for analysing the performance of the systems. Rao et al. [36] conducted an experimental analysis of a PVT system using a heat absorber with a double-sided spiral flow configuration and PCM. The PCM enabled latent heat discharge during nocturnal periods, enhancing thermal energy storage capacity. The experimental configuration employed water as the working fluid, with an MFR ranging from 0.0085 to 0.067 kg s^{-1} . The ideal MFR was determined

to be 0.033 kg s^{-1} , resulting in a peak heat gain of 757 W and an average energy-saving efficiency of 69% . The results verified a $3\text{--}5\%$ enhancement in accessible energy when utilising the PVT-PCM system in comparison with a standard PV module under equivalent environmental conditions. The investigation revealed that the overall efficiency of the PVT system was enhanced with the incorporation of heat absorbers and PCM, while the thermal performance relied on the thermophysical characteristics of the working fluid. Al-Aasam et al. [37] investigated the thermal performance of a twist absorber tube PVT collector with the addition of nano-PCM inclusions.

The investigation conducted experimentally by Al-Aasam et al. [5] evaluated the performance of a unique PVT system that integrates features like a twisted absorber tube, an enhanced PCM (nano-PCM) vessel, and a PV panel. The testing took place under indoor solar simulator conditions, maintaining constant solar irradiance of 800 W m^{-2} with a mean error of 1.51% . Five configurations were analysed in the study:

1. A reference PV panel
2. A PVT with circular absorber tubes (C-PVT)
3. A PVT with twisted absorber tubes (T-PVT)
4. A C-PVT with nano-PCM (C-PVT-PCM)
5. A T-PVT with nano-PCM (T-PVT-PCM)

The T-PVT-PCM configuration exhibited the best performance in terms of electrical, thermal, and overall efficiency among all the tested configurations achieving 9.46% , 79.40% , and 88.86% electrical efficiency, thermal efficiency, and overall efficiency, respectively, for a MFR of 0.04 kg s^{-1} , solar irradiance of 800 W m^{-2} , and ambient temperature of 27°C . The values, however, should be considered as laboratory results under standard and best operating conditions and not as field efficiencies. Likewise, the maximum thermodynamic efficiency of $96.47 \pm 1.40\%$ and electrical conversion efficiency of 19.12% were obtained for a particular inlet MFR of 0.0458 kg s^{-1} , inlet temperature of 11.90°C , and heat flux of 592.89 W m^{-2} . Hence, the practical significance of the high-efficiency values will rely on the repeatability of the operating conditions, uncertainty of measurements, auxiliary pumping power, long-term stability of the cooling medium, and the PCM and the effective use of the recovered thermal energy. The enhanced thermal performance is attributed to the twisted tubing design, which significantly improves convection heat transfer between the working fluid and the wall of the tube. The other great advantage of nano-PCM was its temperature regulation capabilities, which resulted in a drop of the PV surface temperature by 30°C when compared to the standard reference PV panel and approximately 10°C compared to the C-PVT-PCM system. Of

the very high PV performances mentioned above, T-PVT-PCM attained an extraordinary 34.5% relative efficiency compared to the base PV panel. These results highlight the reason for performance increasing phenomena based on twisting the absorbers, while nano-PCM enhances this phenomenon and conducts the improvement in the electrical efficiency of the liquefied gas using heat transfer. The advanced conception associated with T-PVT-PCM has indeed helped improve the design in terms of heat transfer and temperature management, bringing forth enormous improvements in energy conversion efficiency for solar PVT applications. El Alami et al. [38] studied the performance of a water-based PVT hybrid solar collector with a new heat exchanger via numerical simulations. In this article, a newly designed channel-box PVT-C was introduced, and the performance was investigated numerically through COMSOL Multiphysics software and finite element method (FEM). The 3D numerical model was validated with existing numerical and experimental results in the literature to guarantee the accuracy of the current computational approach. The results showed that as the flow rate of the cooling fluid increased, the electrical efficiency and power output improved. The optimal cooling water flow rate of $\approx 180 \text{ L h}^{-1}$ was reached, above which the additional increases of local heat transient extraction showed diminishing returns. The PV system delivered electrical power outputs of 37.06 W and 140.08 W , while the PVT-C system achieved an initial performance of 38.45 W , extending to 187.02 W ; thus, indicating that the proposed PVT-C design is capable of facilitating thermal regulation and achieving superior power conversion efficiency.

Figure 4 displays the overall PVT collector performance trends over the past few decades. In 1995, Bergene and Løv-vik [19] presented a simple flat-plate collector design with a maximum thermal efficiency of 20% . Zondag et al. [39] extended this design to a PV (sheet and tube) configuration, improving thermal performance significantly to 35% . To further enhance the design, Fan et al. [40] used CFD to optimise the flow through the parts, resulting in 50% thermal efficiency. Ibrahim et al. [41] refined the design with a spiral flow absorber, achieving a thermal efficiency of 63.55% , which was in good agreement with experimental data. Sardarabadi and Passandideh-Fard [42] studied the performance of metal oxide/water nanofluids in augmenting the cooling performance of PVT systems using an experimental and numerical research approach. It studied three categories of nanoparticles, aluminium oxide (Al_2O_3), titanium oxide (TiO_2), and zinc oxide (ZnO), in deionised water at a mass 0.2% concentration to reach 79% efficiency. Finally, Zhou et al. [43] examined the three-generation system (cooling/heating/electricity) using the roll-to-roll PVT heat pump with an efficiency of 65% . Incorporation of similar

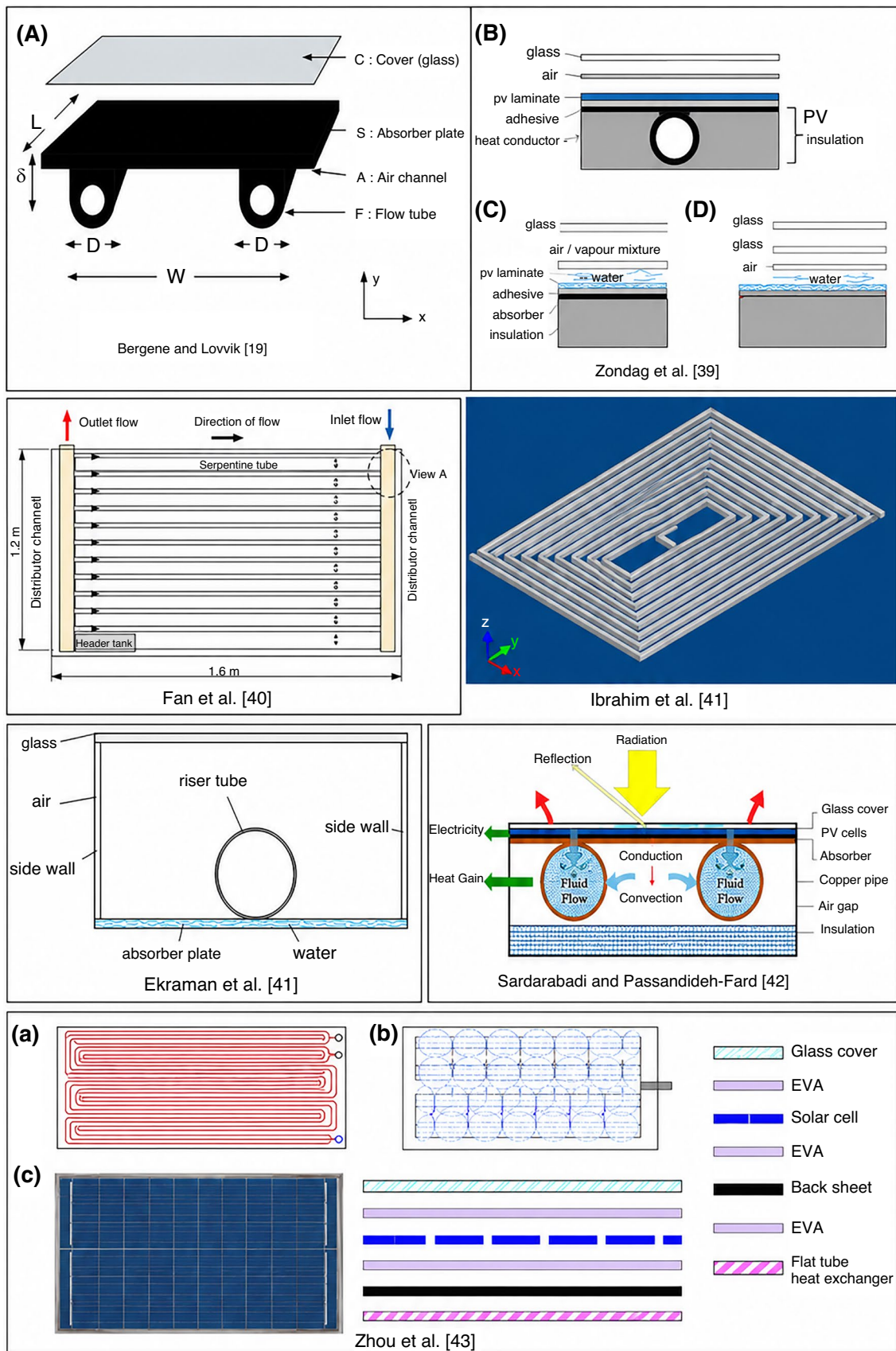


Fig. 4 Performance improvements of PVT collectors over the past two decades

Comparison of Thermal and Electrical Efficiencies of PVT Systems

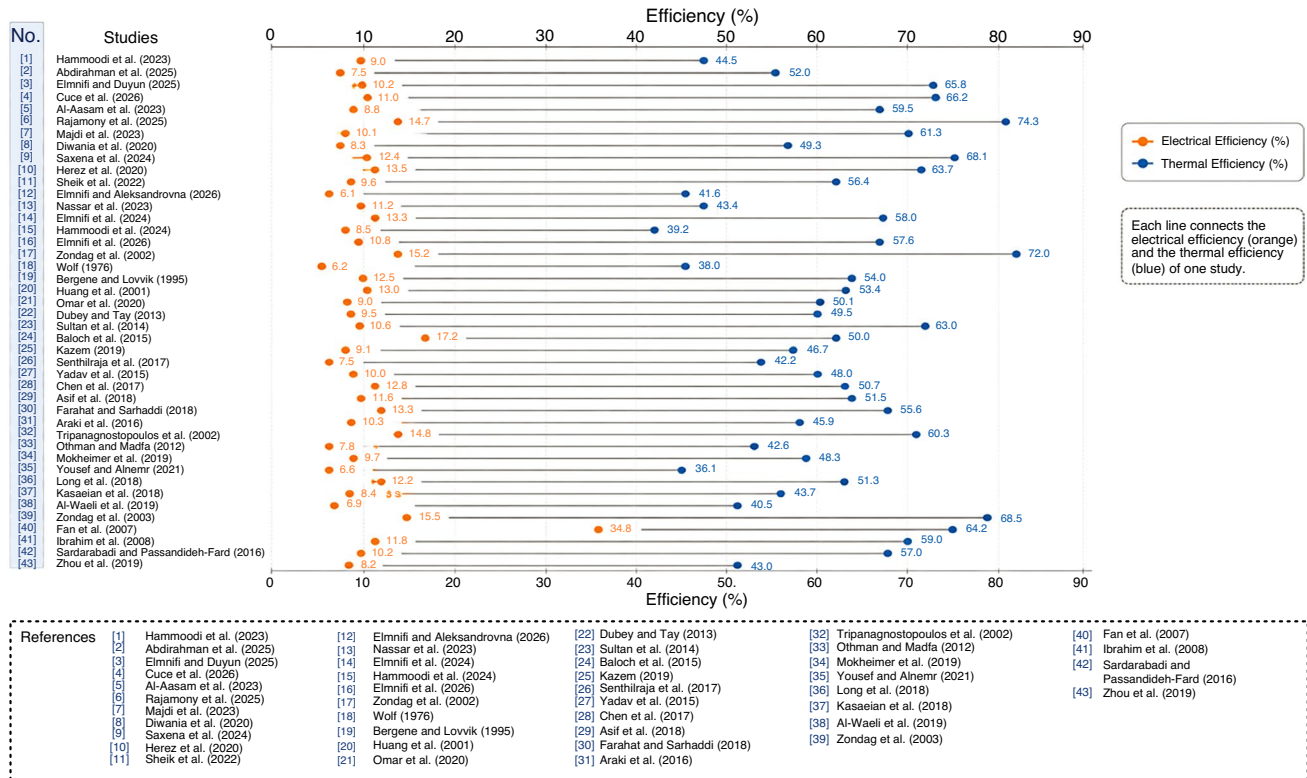


Fig. 5 PVT studies from 2000 to 2022

approaches is evident in studies demonstrating the gradual and continuous evolution of PVT collector designs, highlighting continuous and gradual enhancement in both thermal and electrical efficiency over the years.

Figure 5 displays the evolution of the efficiency of PVT structures through various studies carried out over the years. It suggests that thermal efficiency exceeds electrical efficiency in maximum systems, indicating a high performance in converting solar power to warmth in comparison with producing energy. Over time, there appears to be an upward trend in enhancing normal efficiency, specifically with technological innovations, new designs of thermal collectors, the usage of advanced materials, and dynamic technology such as oscillating heat floats and heat pumps. Recent studies in 2015 and 2024 show widespread development because of the focus on improving the gadget's overall performance and the use of integrated electricity garage solutions. Variations in efficiency are also found based on geography, with international locations with high solar radiation, including Malaysia and India, attaining better performance because of favourable environmental conditions. Experimental research shows more accuracy in comparison with theory, with theories specialising in exploring design possibilities and assessing financial feasibility. The evaluation shows that the destiny of PVT structures depends on the combination of technologies

and the development of building materials to improve typical performance and make those systems more powerful in meeting thermal and electrical power needs sustainably.

Research has subsequently moved to India, China, and Malaysia, where innovative designs such as spiral channels and PCM have been tested, improving overall efficiency to over 70% [44]. In 2019, a study by Yang et al. [45] in China showed that PCM-based systems offer 27% higher long-term performance compared to conventional panels. More recently, in 2023 and 2024, research has focused on improving the integration of systems into buildings to meet sustainable energy requirements. In a study, parallel water pipe systems were developed to cool solar panels, achieving electrical efficiencies of up to 12.5%. In Europe, insulation materials and pipe designs have been improved to improve waste heat utilisation. This gradual evolution of PVT systems shows a marked shift towards sustainability and resource efficiency, making them suitable for use in modern buildings, while reducing environmental impact and improving overall system efficiency. It is best to interpret the reviewed studies not only based on the reported efficiency gains but also on other fundamental characteristics. Their practical utility depends on experimental conditions, system complexity, flow rate, pumping power, material stability, cost, and reliability in long-term outdoor applications.

Therefore, caution should be exercised when comparing field studies to laboratory studies indicating high efficiencies, as field studies are susceptible to additional losses due to dust deposition, variations in solar radiation, ambient temperature fluctuations, water quality, nanofluid instability, PCM degradation, and maintenance costs.

Comparative evaluation of air- and water-based PVT systems

While water-based PVT systems are particularly well researched, offering superior thermal performance, air-based systems also have unique advantages worth exploring, particularly when targeting residential deployments and small-scale systems. Air-based collectors are often unobstructed, less complex in structure, and require no pumps or heat exchangers, resulting in significantly lower installation and maintenance costs. They are also applicable in arid and water-scarce regions and are characterised by dry operation. However, the specific heat capacity and density of air are lower, and therefore, the thermal efficiency of air-based systems is typically lower than that of water-based systems. Furthermore, there is greater uncertainty in heat removal, especially when there is some variability in ambient conditions. Conversely, air-based systems maintain low maintenance costs, are easier to build, and have a longer operating life because they do not cause corrosion or calcification complications. Table 1 compares the main differences between air-based and water-based PVT systems to ensure a better comparison between them.

Table 2 shows a Summary of the previous studies on PV solar cell systems, starting from prototypes in the 1970s, to recent improvements in thermal and electrical performance using advanced materials and numerical simulation techniques.

Cooling techniques in PVT systems

The technological developments in material science centre on nanoparticles as one of their core innovations. These small components possess distinct physical and chemical

characteristics that standard materials lack. Multiple main classes of particles exist according to their chemical structures, together with their structural characteristics, as demonstrated by the classification diagram in Fig. 6. The classification system can be split into three central parts, including metal-based nanoparticles in addition to carbon-based nanoparticles, and nanocomposites. Every subcategory within these divisions controls the characteristics and chemical properties of the materials. The metallic nanomaterial classification consists of nanometals together with nanometal oxide varieties. The group of nanometals consists of aluminium (Al), iron (Fe), silver (Ag), copper (Cu), gold (Au), and zinc (Zn) elements, which play essential roles across industrial applications, electronic devices, and medical practices because of their distinct properties, which include high electrical conductivity as well as strong catalytic power. The group of nanomaterial metal oxides consists of Al_2O_3 , TiO_2 , SiO_2 , iron (III) oxide (Fe_2O_3), magnetic iron oxide (Fe_3O_4), copper oxide (CuO), ZnO, and magnesium oxide (MgO). These materials find extensive use in environmental, medical, and engineering applications because they demonstrate both chemical reaction catalytic ability and antimicrobial features. The three basic kinds of carbon nanomaterial consist of fullerenes, while carbon nanotubes, together with graphene, serve as the rest. The medical and electronic fields utilise fullerenes because of their special properties in their structure, which consists of a closed sphere or tube form created by carbon molecules. Single-walled and multi-walled represent the two categories of carbon nanotubes (SWCNT and MWCNT). Nanomaterials can serve advanced nanoelectronic and nanomedicine applications because of their exceptional mechanical behaviour and electrical performance. The advanced nanotechnology material grapheme stands out due to its atom-thin layers and flat dimensions that enable its use in creating next-generation technologies, solar power systems, and storage cells.

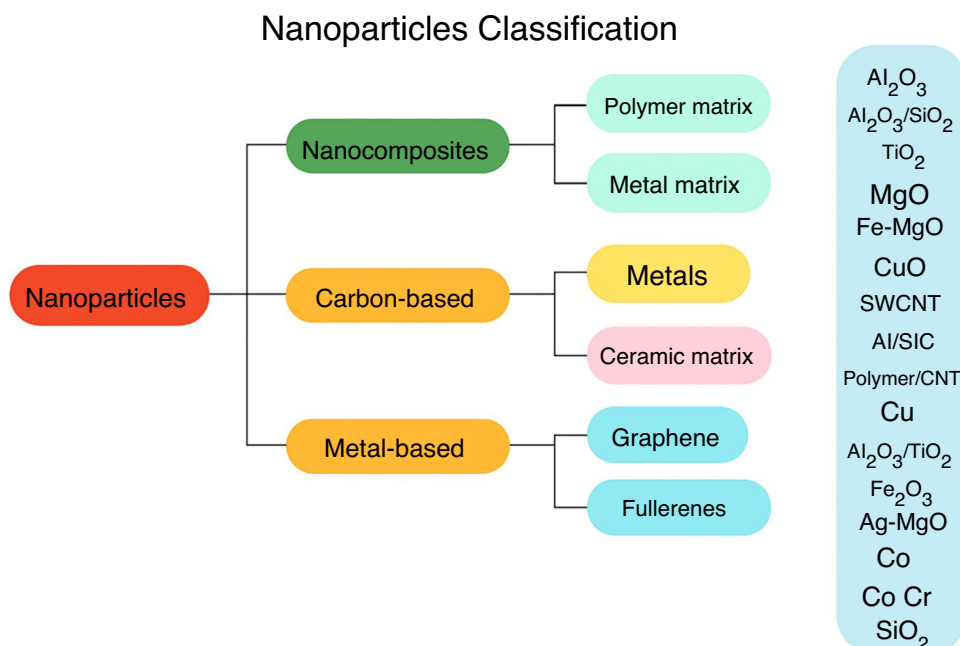
Nanocomposites represent nanomaterials composed of multiple components, which lead to properties exceeding conventional materials. The three primary types of nanocomposites exist as ceramic matrix, metallic matrix, and polymeric matrix nanocomposites. Advanced industrial applications require ceramic matrix nanocomposites due

Table 1 Comparison of the main differences between air-based and water-based PVT systems

Parameter	Air-based PVT system	Water-based PVT system
Thermal efficiency	Moderate to low	High
Installation cost	Low	Moderate to high
Maintenance requirements	Minimal	Moderate (requires pumping)
Climate suitability	Dry/cold regions	Mild/temperate regions
System complexity	Simple	Complex
Integration with PCM/Nano	Limited	Extensive
Ideal applications	Space heating, drying	Water heating, industrial use

Table 2 Summary of the previous studies on water-based PVT systems

Researcher(s)	Critical outcomes
Al-Aasam et al. [5]	Highest thermal efficiency 96.47%; ML modelling
Wolf [18]	Prototype of a flat-panel solar collector combining heating with PV
Bergene and Løvvik [19]	Numerical model of flat-panel PVT collector; 60–80% efficiency
Huang et al. [20]	PVT with polycrystalline panel; grid-connected rooftop system
Dubey and Tay [22]	PV sheet and tube config; 35% thermal efficiency
Sultan et al. [23]	Advanced absorber design; 0.4% electrical efficiency boost
Baloch et al. [24]	CFD optimisation of PVT flow; 50% efficiency
Kazem [25]	Spiral flow absorber; 74.1% overall efficiency
Senthilraja et al. [26]	Spiral flow absorber; 63.55% efficiency
Menon et al. [27]	Converging channel cooling; 36.1% higher efficiency
Tiwari et al. [28]	Direct flow collector in Oman; 6% better performance
Rao et al. [29]	Hydrogen generation with PVT/water collector; 33.8% thermal efficiency
Yildirim and Cebula [30]	Metal oxide nanofluids; 79% efficiency
Harby et al. [32]	Optimised bi-fluid PVT system with stainless steel, aluminium, and copper cooling designs; 7.66–16.04% increase in average daily electrical output; the copper-based design showed the best techno-economic performance with the lowest LCOE and shortest pay-back period
Zheng et al. [33]	Flexible separate heat pipe optimisation; 45% filling ratio; 69.37–79.71% thermal efficiency
Rejeb et al. [34]	Nanofluid vs water cooling; 17.61% total efficiency
Rosli et al. [35]	Three-generation PVT/heat pump system; 65% efficiency
Rao et al. [36]	Symmetric grid flow; 63.09% thermal efficiency
El Alami et al. [38]	Pipe vs plate absorber design; radiation major factor
Zondag et al. [39]	Economic study; uncovered PVT best in performance
Fan et al. [40]	Various absorber tube shapes; ANSYS simulation
Ibrahim et al. [41]	Dual-fluid model; better when fluids operate together
Sardarabadi and Passandideh-Fard [42]	Spiral flow + PCM; 69% energy-saving efficiency
Zhou et al. [43]	T-PVT-PCM design; 88.86% total efficiency
Yang et al. [45]	Channel-box PVT; 187.02 W output via COMSOL

Fig. 6 Nanoparticle classification

to their exceptional thermal and chemical characteristics that are achieved through compounds such as $\text{Al}_2\text{O}_3/\text{TiO}_2$, $\text{Al}_2\text{O}_3/\text{SiO}_2$, $\text{Al}_2\text{O}_3/\text{SiC}$, and $\text{Al}_2\text{O}_3/\text{CNT}$. Metal matrix nanocomposites consist of compounds including CO_2Cr , Fe-MgO , and Ag-MgO that engineers use in both environmental applications and construction for material durability enhancement. The field of biomedicine and thin-film technology utilises lightweight, flexible nanocomposites from the polymer matrix category, which consist of compounds such as Polyester/TiO_2 and Polymer/CNT . The scheme of classification shows exactly how the various categories connect with each other. The hierarchical structure of nanomaterial begins with the nanoparticle general category, followed by specific main categories, and then ending with sublevels that demonstrate each type's components. Each distinct main category possesses its separate colour scheme to create visual distinctions, and the levels feature an arrangement that reduces arrow overlap to help readers understand nanomaterial interconnections. The developed classification system serves as an effective method to understand nanomaterial diversity while exploring their potential applications across multiple fields, thus fostering innovative new applications.

Air-based cooling systems

Thermal conductivity is the prime factor in enhancing the capability of heat transfer devices to transfer heat through thermal conduction. Solid metals have much greater thermal conductivities compared to liquids; hence, solid particles are suspended in liquid as a heat transfer liquid to enhance heat conductance and heat transfer capacity. Nanofluids are generally prepared by putting nanoparticles in a base liquid. Many experimental investigations have been done to know more about these nanofluids, specifically for their thermal conductivity. Different techniques have been used for the measurement of thermal conductivity of nanofluids:

1. **Transient hot wire:** It uses a thin wire as both a heater and a temperature sensor. The wire is immersed in the nanofluid, and its transient temperature response is taped to get the thermal conductivity.
2. **Temperature fluctuation:** This method is a time-dependent measurement of the nanofluids. Such measurement of time-dependent temperature fluctuations provides the thermal conductivity of fluids.
3. **Steady-state parallel plate method:** Here, the nanofluid is sandwiched between parallel plates, and a steady-state heat flow is established. The thermal conductivity is derived from measuring the temperature difference between the plates.

These give important insights into thermal properties of nanofluids so that researchers can optimise their

formulations for improved heat transfer applications. Not only are nanoparticles improving thermal conductivity, but they also enhance heat transfer performance in many engineering applications. The most commonly used nanoparticles among these studies are SiO_2 , Al_2O_3 , and CuO . In any nanoparticle size and base fluid properties, experimental results showed the enhancement of thermal conductivity universally. It has been demonstrated that by using nanoparticle colloidal fluids (NpCF), nanoparticle mobility and stability are increased, and then, heat transfer efficiency is heightened because of the high surface area-to-volume ratio of nanoparticles. Choi and Eastman [46] researched thermal conductivity improvements of nanofluids made with Al_2O_3 and CuO nanoparticles. The study confirmed that nanofluids obtain enhanced thermal conductivity when used with smaller-sized nanoparticles instead of conventional base fluids. Nanoparticle thermal conductivity increases significantly because the surface area of each nanoparticle is greater than its overall volume. Irrigating the fluid with nanoparticles supports better fluid-particle contact, so the heat transfer performance of nanofluids gets strengthened. Better energy transfer occurs because of enhanced particle–fluid interaction, thus enabling more efficient thermal performance when heat transfer becomes critical. The study conducted by Choi et al. demonstrates that smaller nanofluid particles create opportunities for enhanced thermal conductivity and heat transfer effectiveness in different engineering systems. Zennifer et al. [47] investigated the thermal behaviour of CuO nanofluids prepared with ethylene glycol as the base fluid. Their study reported that CuO nanoparticles with a size range of 25–35 nm provided an enhancement of about 14.1% in thermal conductivity at 1 vol% and 50 °C. These findings confirm the potential of CuO /ethylene glycol nanofluids for advanced cooling and energy management systems where improved heat dissipation is required. Murshed et al. [48] investigated the thermal conductivity of TiO_2 nanoparticles dispersed in deionised water. Their study showed that thermal conductivity increased with increasing particle volume fraction and was strongly influenced by temperature. Using rod-shaped TiO_2 nanoparticles (10×40 nm) and spherical nanoparticles (15 nm), they reported thermal conductivity enhancements of nearly 33% and 30%, respectively, at a maximum concentration of 5 vol%. These outcomes demonstrate that TiO_2 /water nanofluids are promising for thermal systems requiring improved heat transport performance. Baheta and Woldeyohannes [49], this research focused on the effects of particle size on the thermal conductivity of Al_2O_3 and CuO nanofluids. The authors concluded that smaller particle sizes lead to higher thermal conductivity, which can significantly enhance the efficiency of thermal systems, making these nanofluids suitable for various industrial applications. Hwang et al. [50] investigated the thermal conductivity characteristics of water-based MWCNT

nanofluids. Their results showed that the thermal conductivity enhancement reached up to 11.3% at a volume fraction of 0.01, confirming that carbon nanotube-based nanofluids can effectively improve heat transport. The authors also noted that the degree of enhancement depends on the thermal conductivities of both the dispersed nanoparticles and the base fluid, highlighting the potential of MWCNT nanofluids for advanced heat transfer applications. Yu et al. [51] investigated the thermal conductivity of graphene nanosheets dispersed in ethylene glycol. Their results showed a substantial increase in thermal conductivity, reaching up to 86% at 5.0 vol% graphene loading. The authors attributed this improvement to the two-dimensional structure and high stiffness of graphene nanosheets, which favour efficient heat transport in the base fluid. These findings indicate that graphene-based nanofluids are promising candidates for advanced heat transfer applications requiring markedly improved thermal performance. Eastman et al. [52] investigated the effective thermal conductivity of Cu nanoparticle-based nanofluids prepared with ethylene glycol as the base fluid. Their results showed that dispersing approximately 0.3 vol% Cu nanoparticles with a mean diameter below 10 nm increased the thermal conductivity of ethylene glycol by up to 40%. These findings demonstrate the strong potential of copper-based nanofluids for improving heat transfer performance in advanced thermal management applications. Milyani et al. [53] investigated the effect of particle size on the thermal conductivity of SiO₂/deionised water nanofluids. Their results showed that thermal conductivity increased with increasing temperature and nanoparticle volume concentration, whereas increasing nanoparticle size led to a reduction in thermal conductivity under all tested conditions. These findings indicate that silica-based nanofluids can be promising working fluids for thermal applications, provided that particle size and concentration are carefully optimised. Urmi et al. [54] experimentally investigated the thermophysical properties of TiO₂–Al₂O₃ hybrid nanofluids prepared with a 40% ethylene glycol-based fluid. Their results showed that thermal conductivity increased with both temperature and nanoparticle concentration, and the hybrid nanofluids exhibited higher thermal conductivity than the corresponding single TiO₂ and Al₂O₃ nanofluids. A maximum thermal conductivity enhancement of 40.86% was reported at 0.1 vol.% and 80 °C, confirming the strong potential of Al₂O₃–TiO₂ hybrid nanofluids for advanced heat transfer and thermal management applications. Madas et al. [55] investigated the performance optimisation of a PVT system using CuO nanofluid using response surface methodology and single- and multi-objective optimisation. Their results showed that both nanofluid concentration and flow rate significantly affected PV cell temperature, electrical efficiency, thermal efficiency, and net electrical output. The study identified the optimum operating condition as 0.1% CuO concentration and 80 kg

h⁻¹ flow rate, demonstrating the suitability of CuO nanofluids for enhancing PVT thermal management and overall system performance. Sangeetha et al. [56], this study highlighted the synergistic effects observed in thermal conductivity improvements with MWCNT and Al₂O₃ nanofluids. The findings suggest that hybrid nanofluids could offer enhanced thermal performance, making them suitable for advanced cooling technologies. Kanti et al. [57] focused on hybrid graphene nanofluids and reported an enhancement in thermal properties. The combination of graphene with other nanoparticles effectively resulted in improved thermal control matrices, applicable to many engineering implementations. The increase in thermal conductivity was more pronounced at high temperatures and at small diameters. The experimental data from various research groups show significant discrepancies, as summarised in Table 3 [58]. It is reported that hybrid nanofluids have the potential to enhance the motion of nanofluids further and improve their thermal conductivity, but this may not always be true theoretically, considering how the resulting behaviour can differ from expectations, as shown in the study.

Recent interest in enhancing the efficiency of hybrid PVT systems has focused on the use of nanofluids due to their potential to simultaneously enhance thermal and electrical efficiency. Several studies in recent years have reported on the application of nanotechnology in this field, and their results have demonstrated significant gains in the thermodynamic performance of the system and a reduction in energy losses. In 2024, researchers investigated the latest trends in the use of nanofluids in PVT systems using several classes of nanoparticles, including Al₂O₃, TiO₂, and hybrid metal oxides. They demonstrated that the thermoelectric efficiency could be enhanced by using nanofluids enhanced at a rate ranging from 10 to 25% of that of plain water [60]. Regarding solar tracking systems, a pilot study was developed in 2024 to test the efficiency of fixed and mobile PVT systems equipped with spray cooling technology. The results demonstrated the highest performance level consistent with the dual-axis tracking system combined with a cooling system, increasing its production capacity by 26.1% and reaching a peak efficiency of 14%. When combined with cooling, the panel temperature remained within acceptable limits even with the increased energy absorbed due to cooling, demonstrating the effectiveness of this combination in enhancing the electrical and thermal performance of PV systems [61]. In the context of the development of solar-powered desalination devices, research was conducted in 2025 to improve the operation of a tubular solar still. This was enhanced by the need to integrate various technologies, including hot air injection through a parabolic basin collector, nanocoating, and nanofluid CuO. The results indicated that this composite configuration (which combines all of these factors) would be the most efficient, improving energy efficiency by 83.69%

Table 3 Summary of experimental studies on the thermal conductivity of nanofluids

Author	Particles	Size, nm	Fluids	Observations
Choi and Eastman [46]	Al ₂ O ₃ , CuO	20–50	Water	Observed significant thermal conductivity improvement with small particle size
Zennifer et al. [47]	CuO	25–35	Ethylene glycol	Approximately 14.1% thermal conductivity enhancement was reported at 1 vol% and 50 °C
Murshed et al. [48]	TiO ₂	10×40 (rod), 15 (spherical)	Deionised water	Thermal conductivity increased with particle volume fraction and showed strong temperature dependence; at 5 vol%, enhancement reached nearly 33% for rod-shaped particles and about 30% for spherical particles
Baheta and Woldeyohannes [49]	Al ₂ O ₃ , CuO	5–100	Oil	Higher thermal conductivity is observed with smaller particles
Hwang et al. [50]	MWCNT	–	Water	Thermal conductivity enhancement reached up to 11.3% at a volume fraction of 0.01; the enhancement depended on the thermal conductivities of both the nanoparticles and the base fluid
Yu et al. [51]	Graphene nanosheets	0.7–1.3 nm thickness; 0.2–2 µm lateral size	Ethylene glycol	Thermal conductivity increased dramatically, reaching up to 86% enhancement at 5 vol%; the effect of temperature on enhancement was reported to be limited
Eastman et al. [52]	Cu	< 10	Ethylene glycol	The thermal conductivity of ethylene glycol increased by up to 40% at approximately 0.3 vol% Cu nanoparticle loading, indicating strong heat transfer enhancement potential
Milyani et al. [53]	SiO ₂	Different particle sizes	Deionised water	Thermal conductivity increased with temperature and volume concentration, while larger particle size reduced the thermal conductivity of the nanofluid
Urmi et al. [54]	Al ₂ O ₃ , TiO ₂	–	40% ethylene glycol-based fluid	Thermal conductivity increased with temperature and concentration; the maximum enhancement reached 40.86% at 0.1 vol% and 80 °C, and the hybrid nanofluid showed higher thermal conductivity than the corresponding single nanofluids
Wang et al. [59]	Al ₂ O ₃ , CuO	10–100	Water	Improved thermal performance with hybrid nanofluids

and energy-emitting efficiency by 242.45%, with a 13.51% reduction in water production costs [62]. Another study conducted in 2025 involved the use of metal–organic framework (MOF) materials in a dual-slope solar still. Three scenarios were considered for use as nanofluid, atomic, and thin-film technologies. The latter technology outperformed the former by 103% in energy consumption, 162% in energy-emitting efficiency, and 92.12% in water production, with a low water production cost of 0.0122 L/L and low CO₂ emissions of 2.2 tons/year [63]. These changes in perovskite cell stability, observed in a 2025 study, include the instability of the

perovskite material under low stability, which reduces efficiency to 8%, with defect density increasing to 21.69% of the original stability and carrier lifetimes decreasing to between 0.002 and 20 microseconds, respectively. Effective humidity control in manufacturing has also been shown to raise efficiency levels to over 20% [64]. Considering the above studies, it can be argued that nanotechnology, as a means of linking PVT and desalination systems, could represent a successful approach to solving energy efficiency and water resource sustainability issues, achieving tangible environmental and economic benefits.

Nanofluids have been heavily reported as potential heat transfer media for PVT systems, but there are still some technical challenges that need to be addressed. In most of the reviewed works, the enhancement of the thermal conductivity, Nusselt number, heat transfer coefficient, and PV temperature reduction is highlighted, but this should be seen in the context of stability, hydraulic, economic, and long-term operation limitations. Nanofluid stability is one of the most crucial challenges. The van der Waals attraction, low surface charge, low dispersion quality, and thermal cycling during operation cause the nanoparticles to agglomerate over time. Agglomeration decreases the effective heat transfer surface area and can contribute to sedimentation, particularly in low flow or stagnant flows. Sedimentation is a potential problem in PVT systems because it can cause narrow channels to be choked and cause a lack of uniformity in heat removal, and can create local ‘hot spots’ on the PV module. Thus, a good laboratory performance does not necessarily imply good performance in an outdoor application over a prolonged period. Another significant constraint is the rise in viscosity as a function of the concentration of the nanoparticles. Increasing the loading of nanoparticles can usually increase the fluid viscosity and the resistance to flow, but it also increases the thermal conductivity. The direct effect of this is to raise the drop in pressure and the need for pumping power. This means that the net energy gain obtained from using nanofluid cooling could be diminished if the extra pumping energy is large enough. Thus, the thermal efficiency or electrical efficiency is not the only criterion for evaluating a PVT system using nanofluid; but it should also include pressure drop, pumping power, net electrical gain, and exergy efficiency. Sedimentation and clogging are especially significant in actual PVT collectors with small diameter tubes, serpentine channels, microchannels, or even with complicated absorber geometries. These configurations have better convective heat transfer, but are more susceptible to particle deposition and channel blockage. Long-term operation may lead to deposition on the channel walls, which decreases the flow area, increases friction losses, and decreases heat transfer performance. The importance of this issue is particularly significant for hybrid nanofluids and high-concentration suspensions, where the effect of interaction between particles increases. There are also practical trade-offs related to the type, size, concentration, base fluid, and surfactant of the nanoparticles. Smaller nanoparticles can provide better stability and thermal conductivity, but could be more costly and could need special chemical processing. Surfactants can improve dispersion stability, but they could become degraded at high temperatures, undergo changes in their thermophysical properties, and cause foaming and/or corrosion issues. Furthermore, there are health and environmental concerns if there is leakage, disposal, or accidental release of some nanoparticles. Thus, future

research is required to provide not only the thermal performance but also the colloidal stability, zeta potential and pH, sedimentation time, viscosity, corrosion behaviour, and environmental safety. Another drawback is that there are no uniform test protocols. Numerous studies have been reported for various preparation protocols, sonication time, particle size, particle concentration, flow conditions, and testing time. Therefore, it is difficult to compare studies directly. Furthermore, it is not possible to establish the suitability of a PVT system based on short-term thermal conductivity measurements. The stability and economic viability of nanofluids in regard to their lifetime in the PVT collector need to be judged in long-term tests under real solar radiation, repeated heating–cooling cycles, seasonal operation, and contamination in the outdoor environment.

Water-based cooling systems

Nanofluids are a new and advanced concept in heat transfer, distinctly characterised by their ability to augment thermal efficiency when compared with classical fluids. Added to a basic fluid, nanoparticles ultimately bring a much higher level of thermal performance, thus presenting themselves favourably for heating and cooling applications. Fotukian and Nasr Esfahany [65] studied turbulent convective heat transfer and the friction factor of aluminium oxide ($\gamma\text{-Al}_2\text{O}_3$) nanofluid in water through a circular pipe. The research looked into nanoparticle volume fractions below 0.2 mass% in the base fluid. The findings revealed that the wall temperatures in tubes carrying nanofluids dropped significantly when the base fluid passed through them. This average temperature reduction rendering was very sensitive to variations in the concentration of nanoparticles and the Reynolds number of the flow. Their research proved that a small portion of CuO nanoparticles, when added to water, could greatly boost the heat transfer characteristics of the resultant nanofluid. The researchers proposed a specific ratio that compared the heat transfer coefficient of the nanofluid with that of pure water. They showed that this has improved heat transfer significantly, even for low amounts of CuO nanoparticles. However, it was important to note that additional heat transfer was accompanied by increased pressure loss. A mass percentage of 0.135% of the nanofluid resulted in a virtually 30% increase in pressure loss compared to pure water at a Reynolds number of 20,000. A similar trend of increased pressure drop with increased concentration of nanoparticles was noted, suggesting that the flow resistance of the nanofluid was considerably higher than for the base fluid, even at lower concentrations of CuO. Overall, the research highlights the dual nature of using nanofluids for heat transfer applications: While they can significantly improve thermal performance, they also introduce challenges related to increased pressure losses that must be managed in practical

applications. In a related study, Sajadi and Kazemi [66] investigated the properties of turbulent heat transfer of TiO_2 nanofluids experimentally in a circular pipe up to 0.25 mass%. The results indicated that even minor amounts of TiO_2 nanoparticles in the fluid result in enhancement of the heat transfer coefficient. Specifically, an approximately 22% increase was registered properly at 5000 Reynolds and 0.25 mass% mass fraction of TiO_2 in the water, compared with pure water. In general, the higher the Reynolds number grew, the greater increase in the heat transfer coefficient observed before impairment at extremely high Reynolds numbers. However, the pressure drops because the friction increases with the increase in concentration of the nanofluid. At 0.25 mass% and 5000 Reynolds, the value reached 25% higher than that of pure water. Overall, both studies indicated the offsetting effects of enhancement of heat transfer and pressure drop due to the use of nanofluids, indicating the need for researchers to seek the best balance of these factors for good thermal performance in any practical application. Akhavan-Behabadi et al. [67] studied heat transfer of nanofluid flow in vertical helically coiled tubes. An isothermal boundary condition was imposed by keeping the tube wall temperature constant at 95 °C. Their analysis indicated that the heat transfer rates of helical coiled tubes were considerably greater than those of straight tubes. It was also found that the Nusselt numbers for nanofluid flows were higher than those for base fluid flows. When helical tubes were used with nanofluid flows, the heat transfer performance was greatly improved. Kayhani et al. [68] studied the convective heat transfer and pressure drop of turbulent TiO_2 -water nanofluid in a uniformly heated horizontal circular tube in their experimental study. The TiO_2 nanoparticles are spherical and have a 15 nm particle size and were chemically treated and mingled in distilled water to get suspension of 0.1, 0.5, 1.0, 1.5, and 2.0 mass volume concentration. They reported that the increment of the nanoparticles led to a more significant enhancement of heat transfer coefficients, irrespective of the Reynolds number. At 2 mass% TiO_2 concentration and Reynolds number of 11,780, we have up to an 8% increase in the Nusselt number. The experimental data were compared to the existing correlations for the convective heat transfer coefficients and the pressure drop and showed reasonable agreement. Ebrahimmia-Bajestan et al. [69] investigated the heat transfer characteristics of nanofluids for solar heat exchanger applications through both experimental and numerical modelling. They studied TiO_2 /water nanofluids flowing in uniformly heated pipes; they investigated the laminar convective heat transfer. The results showed that temperature and concentration of nanoparticles affected both the thermal conductivity and dynamic viscosity of the nanofluid. The average heat transfer coefficient increased by a maximum of 21% with TiO_2 /water nanofluids. The comparison between single-phase and two-phase models

also showed the difference between them. The single-phase model also overpredicted the heat transfer coefficient, and the two-phase model missed it even more (based on experimentally derived thermophysical properties).

A recent investigation by Abu-Nada [70] used the dissipative particle dynamics (DPD) method to study the heat transfer characteristics of nanofluids under natural convection in a differentially heated cavity. The average scale was that the viscosity and thermal conductivity of nanofluids were included as functions of temperature and nanoparticle volume fraction. The experimental data of these improving properties were incorporated into the DPD model; subsequently, the equilibrium DPD simulation of nanofluids heat transfer was incorporated. For Rayleigh numbers of more than 4%, deteriorated heat transfer in the enclosure, while lower nanoparticle volume fractions ($\phi \leq 4\%$) improved the heat transfer slightly. Further, for high Rayleigh numbers ($\text{Ra} \geq 10^5$), the DPD results indicated some effect of compressibility. Hamid et al. [71] improved by an experimental study on cool start heat transfer performance of TiO_2 - SiO_2 nanofluids at different composition ratios of the particles dispersed in water/ethylene glycol mixture (W/EG). The experiments were conducted in the turbulent flow regime, and their Reynolds numbers ranged between 3000 and 24,000. Experience was gained with five composite ratios of TiO_2 and SiO_2 nanoparticles at a total volume concentration of 1.0%: 20:80, 40:60, 50:50, 60:40, and 80:20. The outcomes showed that the 40:60 mixture proportion had the best total warmth exchange from general heat exchange, with a 35.32% advancement of warmth exchange at 70 °C, and the 50:50 proportion exhibited the minimal enhancement, which is a 9.02% expansion in warmth exchange at 30 °C. Comparatively, the divide factor for the nanofluids was little and countable less.

Baskar et al. [72] carried out a detailed study to investigate the convective heat transfer coefficient of propanol-based nanofluids, with the goal of their application in a refrigeration system. The researchers made and characterised stable suspensions of the nanofluid with two different volume fractions of 0.15% and 0.3%. In the process of experimentation, the density measurements were carried out, which showed that there was a slight increase in the density of the nanofluid with the increase in the concentration of the nanoparticles. This change of density is significant because it may affect the overall thermal properties of the fluid. In addition, the effect of specific heat of the nanofluid was found to be increased by increasing the nanoparticle concentration, which can store more thermal energy of the nanofluid that is beneficial for refrigeration applications. One of the most significant outcomes of the study was the significant increase in the convective heat transfer coefficient. The scientists witnessed a remarkable enhancement of up to 70% for the nanofluid with 0.3% carbon nanotubes.

This improvement indicates the carbon nanotubes addition significantly increases the heat transfer efficiency of the propanol-based nanofluid, and it has a great potential for more efficient refrigeration systems.

In other studies, Idris et al. [73] investigated the thermal control of proton exchange membrane fuel cells (PEMFCs), highlighting their potential as an alternative to internal combustion engines (ICEs) in automotive applications. The test focused on maintaining the most beneficial temperatures and uniform temperature distribution across the PEMFC stack and membranes. The researchers analysed the thermal enhancement provided by two types of cooling plates, using $\text{Al}_2\text{O}_3\text{:SiO}_2$ hybrid as the coolant within the distributor cooling plate. They tested water-based nanofluids with a concentration of 0.5%, including Al_2O_3 alone, SiO_2 alone, and $\text{Al}_2\text{O}_3\text{:SiO}_2$ hybrids at mixture ratios of 10:90 and 50:50. The effect of these nanofluids on enhancing the warm temperature transfer and fluid buoyancy over the Reynolds ranges from 400 to 2000. The results concluded that the 10:90 $\text{Al}_2\text{O}_3\text{:SiO}_2$ hybrid nanofluid is the most feasible choice, which was found by the 50:50 hybrid ratio, especially up to fluid buoyancy of Re 1000. These results indicate that the $\text{Al}_2\text{O}_3\text{:SiO}_2$ hybrid nanofluids complement the performance of the individual nanofluids and maintain tremendous performance for future programmes in PEMFC thermal control. Gelis et al. [74] experimentally investigated the effect of SiO_2 /deionised water nanofluids on the performance of a PVT system using the RSM approach. In their study, SiO_2 nanoparticles were dispersed in deionised water at volumetric concentrations of 0.1–0.3 vol%, and the effects of solar radiation, nanofluid flow rate, and volumetric concentration on the electrical and thermal efficiencies of the PVT system were analysed statistically. The results showed that radiation, flow rate, and concentration were the most influential parameters affecting system performance. Kazem et al. [75] experimentally investigated the effect of CuO–water–ethylene glycol nanofluids on the performance of a PVT energy system. Their results showed that the use of a 2.0% CuO nanofluid improved the cooling effectiveness of the PVT unit, leading to an enhancement of 6.76% in electrical efficiency and 39.6% in thermal efficiency compared with the base fluid. These findings demonstrate the potential of CuO-based nanofluids for improving the thermo-electrical performance of advanced PVT systems. Chen et al. [76] experimentally investigated the performance enhancement of a PVT system by using water-based paraffin PCM emulsions containing graphene oxide (GO). In their study, GO was added at concentrations of 0.01, 0.02, and 0.03 mass%, and the thermophysical as well as thermo-electrical characteristics of the working fluid were evaluated. The results showed that the emulsion containing 0.02 mass% GO exhibited a thermal conductivity of $0.505 \text{ W m}^{-1} \text{ K}^{-1}$ and delivered substantial PVT performance improvements,

including increases of 92.28% in thermal efficiency, 8.87% in electrical efficiency, and 45.75% in comprehensive efficiency, together with a 15.8% increase in heat collection compared with water. These findings demonstrate the strong potential of graphene oxide-based heat transfer media for advanced PVT thermal management applications. Murtadha [77] investigated the effect of 2 mass% $\text{Al}_2\text{O}_3\text{/TiO}_2$ hybrid nanofluid cooling on the performance of PV panels. The study compared three identical PV panels operated under hybrid nanofluid cooling, water cooling, and no cooling conditions at flow rates between 0.5 and 3 L min^{-1} . The findings generally confirm that $\text{Al}_2\text{O}_3\text{/TiO}_2$ hybrid nanofluids can effectively enhance PV thermal regulation and electrical performance. Sharaby et al. [78] investigated the impact of hybrid MWCNT-ZnO nanofluid cooling on the performance of a PVT system under realistic operating conditions. In their study, a 0.2 mass% suspension of MWCNT-ZnO circulated through a serpentine copper collector integrated with the PVT module. The hybrid nanofluid reduced the PV surface temperature by up to 16.6°C relative to the uncooled panel and enabled a peak thermal efficiency of 55.1%. Sangeetha et al. [79] experimentally investigated the use of MWCNT/water nanofluid as a coolant in a PVT system and compared its performance with $\text{Al}_2\text{O}_3\text{/water}$ and $\text{TiO}_2\text{/water}$ nanofluids at a constant concentration of 0.3 mass%. Their results showed that the MWCNT-based nanofluid delivered the best performance among the tested coolants, yielding a 45% increase in electrical power and a 47% improvement in electrical efficiency. From these studies and their summary listed in Table 4, it can be seen that the experimental data differ significantly from one study group to another (94). More studies are required to resolve these contradictions and clarify the performance and capabilities of nanofluids in thermal applications.

PCM and nanofluid-based enhancements

An energy balance is performed to determine how much of the incident solar radiation is converted into useful energy gain and how much is wasted as thermal and optical losses in the operation of a solar collector. Conduction, thermal expansion, and radiation account for the heating of the collector to the outside environment. Over the recent years, a lot of experimental and numerical work has been carried out to investigate the application of nanofluid in solar collectors. Numerous strategies have been proposed, including different solar collector designs and nanofluid formulations, as well as nanofluids mixed with aluminium foam [80]. Numerous experiments have been conducted that show a significant increase in thermal efficiency observed in solar collectors when nanofluids are used.

The increase in thermal conductivity up to October 2023 is attributed to the improved heat transfer through the

Table 4 Summary of experimental studies on thermal conductivity of nanofluids

Author	Particles size (nm)	Fluids	Observations
Fotukian and Nasr Esfahany [65]	Not specified	Water + Al_2O_3	48% increase in heat transfer coefficient at 0.054 mass%; significant pressure loss observed
Sajadi and Kazemi [66]	Not specified	Water + TiO_2	22% increase in heat transfer coefficient at 0.25 mass% concentration; pressure drop increased
Akhavan-Behabadi et al. [67]	Not specified	Water + Nanofluids	Improved heat transfer rates in helical tubes compared to straight tubes
Kayhani et al. [68]	Not specified	Water + TiO_2	21% increase in average heat transfer coefficient; the single-phase model overestimated the coefficients
Ebrahimnia-Bajestan [69]	Not specified	DPD model for nanofluids	Deterioration in heat transfer at high nanoparticle volume fractions; slight enhancement at low fractions
Abu-Nada [70]	Not specified	W/EG + TiO_2 - SiO_2	35.32% enhancement at 70 °C; negligible friction factor increases
Hamid et al. [71]	Not specified	Propanol + CNTs	70% improvement in convective heat transfer coefficient at 0.3% concentration
Baskar et al. [72]	Not specified	Water + Al_2O_3 : SiO_2 hybrid	The 10:90 hybrid nanofluid showed the best thermal performance at Re 1000
Idris et al. [73]	30–100	Water + SiO_2	Enhanced thermal conductivity by 25% at 1 mass%; improved stability at higher temperatures
Gelis et al. [74]	Not specified	Deionised water + SiO_2	In a PVT system, SiO_2 /deionised water nanofluids at 0.1–0.3 vol% were used to evaluate the effects of radiation, flow rate, and concentration on electrical and thermal efficiencies; radiation, flow rate, and concentration were identified as the dominant performance parameters
Kazem et al. [75]	Not specified	Water–ethylene glycol + CuO	In a PVT system, using 2.0% CuO nanofluid improved electrical efficiency by 6.76% and thermal efficiency by 39.6% compared with the base fluid, owing to better cooling of the PV module
Chen et al. [76]	0.2–10 μm	Water-based 30 mass% paraffin emulsion + GO	In a PVT system, GO concentrations of 0.01–0.03 mass% were tested; the 0.02 mass% GO emulsion showed 0.505 $\text{W m}^{-1} \text{K}^{-1}$ thermal conductivity and improved thermal, electrical, and comprehensive efficiencies by 92.28%, 8.87%, and 45.75%, respectively, with 15.8% higher heat collection than water
Murtadha [77]	Not specified	Al_2O_3 / TiO_2 hybrid nanofluid	A 2 mass% Al_2O_3 / TiO_2 hybrid nanofluid was used for PV cooling. The cooled panel achieved a maximum output power of 46.6 W, compared with 45.1 W for water cooling and 41.9 W for the uncooled panel; output power increased by 11.2%, and the highest increase in electrical efficiency reached 17.6%

Table 4 (continued)

Author	Particles size (nm)	Fluids	Observations
Sharaby et al. [78]	Not specified	Hybrid MWCNT–ZnO nanofluid	In a PVT system, 0.2 mass% MWCNT–ZnO cooling reduced PV surface temperature by up to 16.6 °C and achieved a peak thermal efficiency of 55.1%; compared with water cooling, entropy generation decreased by 7.1% and exergy destruction by 4.9%, indicating improved thermo-electrical performance

nanofluids, thereby reducing the thermal losses. Al_2O_3 , CuO, and TiO_2 are some of the numerous nanoparticles that have been employed to formulate nanofluids, and the improvement of their performance in some solar collectors has been extensively investigated under different operating conditions. There are derived theoretical models that can be used to predict the behaviour of nanofluids in solar collectors based on the principles of heat transfer, thermodynamics, and fluid dynamics. Understanding how the mechanisms derived from these models impart the advantages of nanofluids on performance and optimised designs of the systems. Numerical simulations have also been conducted, including CFD modelling, to investigate the fluid flow and temperature distributions in solar collectors, further assisting researchers in understanding the improvement of collector performance when use is made of nanofluids. In addition, the synergy of nanofluid with porous materials like aluminium foam has been shown in some studies to further enhance thermal performance. Such a combination of materials not only offers better heat transfer but also maximises the overall performance of the solar collector heat system. The main emphasis and potential of the integration of nanofluids in solar collector systems lie in enhancing the efficiency and performance of solar energy harvesting technologies. Nanofluids are engineered fluids containing nanoparticles that enhance thermal conductivity and heat transfer rates, thus improving solar collector trending performance. Higher energy output is thereby expected, resulting in better performance under a variety of environmental conditions.

Flat-plate solar collector

Yousefi et al. [81] carried out an experiment to observe the effect of Al_2O_3 –water nanofluid as a running fluid on the performance of a flat-plate solar collector. They investigated how elements such as MFR, nanoparticle mass fraction, and the presence of surfactants stimulated the collector's efficiency. The nanoparticle concentrations were set at 2% and 4% by means of mass, with particle sizes of 15 nm. The mass flow costs of the nanofluids are numerous, between 0.017 and 0.051 kg s^{-1} . The power balance equation is used to decide the efficiency of the gadget. The outcomes confirmed

that the use of nanofluids in place of water as the absorption medium improved performance. Specifically, at a 2% mass fraction, the efficiency extended with the aid of 28.3%. Additionally, the presence of surfactants in addition to the warmness switch results in a maximum performance enhancement of 15.63%. Yousefi et al. [82] have done an experimental study to analyse the influence of MWCNT nanofluid as an absorption medium on the efficiency of a flat-plate solar collector. Four concentrations of carbon nanotubes (CNTs) were evaluated: 2 mass% and 4 mass%. The data were used to study the effect of the surfactant Triton X-100 on the nanofluid stabilisation. The experiments were conducted at different nanofluid MFRs (0.0167–0.05 kg s^{-1}), and the study revealed a 4 mass% improvement in the collector's performance. Efficiency was improved more by the use of Triton X-100. The GT dependence of efficiency increase observed for small temperature differences, efficiency was improved with flow rate, whereas at higher values, an opposite trend was noticed in efficiency, mainly for MWCNT nanofluid at 4 mass% peptone solutions without surfactant. An experimental setup was developed for solar energy collection using heat pipes. Nanofluids were investigated as the working fluid, and a solar-tracking system was analysed in terms of solar heat collector efficiency. In the experiment, three identical copper heat pipes with an outer diameter of 18 mm and a length of 620 mm are used. These included a pure water working fluid in one system and a nanofluid with pure water and carbon nanoparticles (10–12 nm in diameter) in the other [83]. The results of the study showed that both systems worked better at 50° than at the normal angle. When the sunrays were oblique, the performance of the solar collector was found to be better when a solar tracking system was added. Tiwari et al. [84] presented a detailed review of the thermal performance of a flat-plate solar collector for water heating with a few different types of fluids. The study also analysed CO_2 emissions (kg kWh^{-1}) from using nanofluids, emphasising their role in improving thermal characteristics. A study was conducted to enhance the collector temperature through the use of Al_2O_3 nanofluid as an absorption medium. Effects of MFR and ratio of particle size on efficiency of collector were examined. The findings demonstrated that the use of Al_2O_3 /water nanofluid improved

the thermal efficiency of the collector compared with water. The optimum performance was obtained at a 1.5% particle volume fraction of Al_2O_3 , which increased the collector efficiency by 31.64% relative to water. For instance, thermal efficiency of the collector represented a 31.64% increment in the case of using 0.4% mass and volumetric concentration of % Al_2O_3 nanofluid as the working fluid instead of water, along with an equivalent rise of CO_2 emissions of the collector system. In an experimental investigation by Vakili et al. [85] into the performance of a volumetric solar collector for home water heating applications, the solar collector used graphene nanofluid as collection media. The experimental temperature was controlled between 35 and 40 °C, using four different nanofluids, including one base fluid for comparison purposes. For the main part of the experiments, three mass ratios of the nanofluids (0.005, 0.01, and 0.1) were selected along with the MFRs of 0.075, 0.1, and 0.225 kg s^{-1} . From the results, performance increases with the increase in the solar collector's MFR from 0.075 kg s^{-1} to 0.1 kg s^{-1} ; however, any further increase in that MFR, namely up to 0.225 kg s^{-1} , results in a performance decrease owing to increased boundary losses taking place at higher MFRs. The optimum MFR for maximum collector efficiency is at 0.1 kg s^{-1} for both the nanofluids and the base fluid. These MFRs define the optimal operating conditions for the system. The study further revealed that the performance of the system increased with the increase in mass ratios of the nanofluids. When the mass ratio was further increased, however, the performance started decreasing as 'zero-loss' efficiency increased with the mass ratios. This implies that there exists an optimal range for any mass ratio that would maximise performance. Overall, this study provides useful insights concerning the extent to which graphene nanofluids can enhance the efficiency of solar collectors in the household water heating application. Gad et al. [86] investigated the impact of including nano- Al_2O_3 and TiO_2 in water as an operating medium on the efficiency of a flat-plate solar collector. The outcomes showed that by improving the thermal properties of the running fluid, the use of nanofluids could appreciably increase the performance of the collector. Outdoor experiments have been conducted according to ASHRAE 86–93, in which 25 nm nanoparticles were used to reduce agglomeration and boom dispersion. The nanofluids have been organised at an awareness of 2 mass%, with surfactants added to enhance balance. The tank outlet temperature was measured at extraordinary float costs of the nanofluids (2, 4, and 6 L min^{-1}). The maximum increase in the tank outlet temperature for Al_2O_3 and TiO_2 was located to be 5% and 7%, respectively, at a drift charge of 2 L min^{-1} . The nanofluids of Al_2O_3 and TiO_2 showed enhancements in collector performance of 30% and 32% at 2 L min^{-1} , respectively. TiO_2 confirmed an increase in collector performance in comparison with Al_2O_3 at all waft

quotes. The most enhancements in thermal conductivity of TiO_2 as compared to Al_2O_3 had been 1%, 2%, and 5% at flow rates of 2, 4, and 6 L min^{-1} . The growth in the friction coefficient of the nanofluids becomes less than 1% in all temperature ranges. Overall, the maximum collector performance increase for Al_2O_3 and TiO_2 became about 22% and 30%, respectively, as compared to the bottom fluid. Therefore, the use of Al_2O_3 and TiO_2 nanofluids is recommended to improve the performance of solar cells. Desisa [87] conducted research on the thermal properties of a flat solar collector using Al/water operating fluid in a parallel tube association. The studies specialise in the experimental investigation of the heat switch residences of a flat solar collector, wherein the collector performance is evaluated at one-of-a-kind mass flows of 0.1, 0.2, 0.3, and 0.4 kg min^{-1} with nanoparticles with an average diameter of 15–50 nm. A numerical thermodynamic model of the usage of ANSYS Fluent 17.1 software was changed to be implemented to numerically investigate the consistent and viscous flow in a flat solar collector, which includes experimentally uncoated nanofluids (CuO/water and TiO/water). They studied the warmness switch coefficient of various nanofluids in terms of Nusselt variety, comparing them to the collector used with water. The consequences confirmed that the boom in Nusselt quantity for 3 mass% CuO and AlO particles was the highest and the lowest improvement as compared to different nanofluids. The study also discovered that the pressure loss became slight in all instances.

Photovoltaic thermal collector

PV solar thermal integrates PV modules with a heat extraction mechanism, and it plays a dual-generation role, producing both electrical energy and thermal energy. This integrated system achieves a higher overall efficiency than when the solar cells and thermal collectors are treated as separate devices, as it can utilise both electrical and thermal gains. For further enhancements in the performance of such systems, it is required to improve the optical properties of the working fluid in these systems. More specifically, improving the fluid's responsivity to visible light and its ability to absorb infrared radiation enables a significant improvement in PVT efficiency. Zhao et al. [88] used the Lorenz-Drude model of a damped oscillator to study the optical properties of the working fluid based on a PVT system, guaranteeing that the Kramers–Kronig relations are satisfied. An inverse method based on a genetic algorithm was used to retrieve the refractive index from transmittance and absorptance values. It optimised the enhancement of solar transmittance for the 200–800 nm wavelength and the infrared light absorption for the 800–2000 nm wavelength. The resulting optimised fluid achieved 92% solar radiation absorption and 89% visible light transmittance, which dramatically

enhanced the overall effectiveness of the PVT system. In another study, Cui and Zhu [89] explored the performance of the PVT system with nanofluids, specifically, they used MgO–water nanofluid. Over silicon solar cells, the cooling medium was used, and considering the behaviour, the results showed that the power output of the solar cells decreased with an increase in the particle size ratio and film thickness of the nanofluid. A decline in the permeability of the nanofluid was responsible for this decrease, demonstrating the careful interplay between the characteristics of the nanofluid and the performance of the system. While nanofluids have been shown to improve thermal management, these results illustrate that excessive amounts and formulation of these liquids can have adverse effects on power generation. The effects of nanofluid size ratio and film thickness on the power output of solar cells were investigated. It was found that the electrical output of bare silicon cells is higher compared to PVT systems, while the efficiency of PVT systems is generally superior to that of conventional PV systems. Sardarabadi et al. [90] studied the effect of using nanofluids as a cooling medium on the thermal and electrical efficiencies of a PVT system. The cooling fluids used in the experiments were pure water and 1 mass% silica nanofluid (SiO_2)/water. When the electrical power output of the PVT system was converted into equivalent thermal power, the overall power efficiency with 1 mass% silica nanofluid was found to be increased by 3.6% compared to the case using pure water. The thermal efficiency of the heat collection of the PVT system with 1 mass% SiO_2 nanofluid was also increased by 7.6%. From the exciton point of view, it was observed that by adding a heat collector to the PV system, the total exciton of the cases using pure water and 1 mass% SiO_2 nanofluid increased by 19.36% and 22.61%, respectively. Overall, regardless of the economic aspects of nanofluid preparation, the SiO_2 nanofluid suspension significantly enhances the performance of the PVT system from both the energy and exciton points of view. Al-Shamani et al. [91] evaluated the effects of numerous nanofluids on the overall performance parameters of PVT creditors. They tested metrics together with the implied PV module temperature, outlet temperature, PVT electricity (such as electric, thermal, and mixed), and PVT performance. Among the one-of-a-kind nanofluids tested, silicon carbide (SiC) nanofluid was identified as the best. They have a look at located that the PV module and outlet temperatures stepped forward by way of 13.52% and reached 13.15 °C, respectively. Additionally, the PVT powers elevated significantly, with electrical energy rising to 100 and 50.7 W, thermal electricity to 697.9 W, and blended PVT strength to 813.6 W. In terms of efficiency, the electrical PVT efficiency was stronger at 13.52% at the same time as the thermal and blended PVT efficiencies stepped forward to 68.21% and 81.73%, respectively. The satisfactory basic energy coefficient (COE) of 0.93 is achieved at a

mass transfer rate of 0.170 kg s^{-1} and sun irradiance levels of 1000 W m^{-2} . Crisostomo et al. [92] studied the use of nanofluids in PVT structures. The results showed that using silica (SiO_2) nanofluids improves thermal efficiency by as much as 44% and electric efficiency by as much as 10%. Said et al. [93] showed that integrating solar cells and heat collectors into a PVT gadget within a single chamber appreciably enhances performance, because the device achieved electrical performance of up to 16.5% and thermal efficiency of up to 48%. In [94], this study demonstrated the effectiveness of using SiO_2 nanofluids in PVT structures, with improvements in electrical performance of 13.7% and thermal efficiency of 58%. In [95], the outcomes of this study confirmed that PVT technologies have significantly progressed the performance of solar cells, with electric efficiencies of as much as 16% and thermal efficiencies of up to 45% being recorded.

Ranjan et al. [96], in their discussion, provide insight into the performance assessment of a helix-type thermal energy collector, a specific kind of PVT collector as dealt with by Yang et al. [45]. This splendid invention consists of folded absorption tubing arranged under a PV panel, which also works to improve the cooling system's efficiency. The study underwent an application of a specific type of nanofluid consisting of 5% Al_2O_3 suspended in water for improving this thermal performance. For optimum heat collection, the configuration is also available in the form of an air channel, rectangularly placed beneath this panel. With extensive numerical computation-assisted simulations, the researchers performed the analysis of varying fluid flow rates and solar radiation intensities on the performance of this device. These results indicated that increasing the flow rates of the working fluid showed significant improvement in both thermal and electrical efficiencies. According to the report, efficiencies of up to 79% were achieved by the module when the nanofluid MFR was 0.0247 kg s^{-1} with an airflow rate of 0.034 kg s^{-1} . It further indicates that the relationship between fluid dynamics and energy conversion efficiency in the system is strong. On top of that, the research study has presented a comprehensive advancement summary that has been made in the performance of solar collectors, particularly in terms of their beneficial applications with nanofluids, as depicted in Fig. 7. This study shows how innovative designs and materials can influence the efficiency of solar energy systems.

Design and performance of absorbers

The design of absorbers and rear-side thermal management structures plays a central role in improving the thermal and electrical performance of PV systems, particularly when PCM is employed for passive cooling. In most PV/PCM configurations, absorber enhancement does not rely solely on the addition of PCM; rather, it also involves conductive

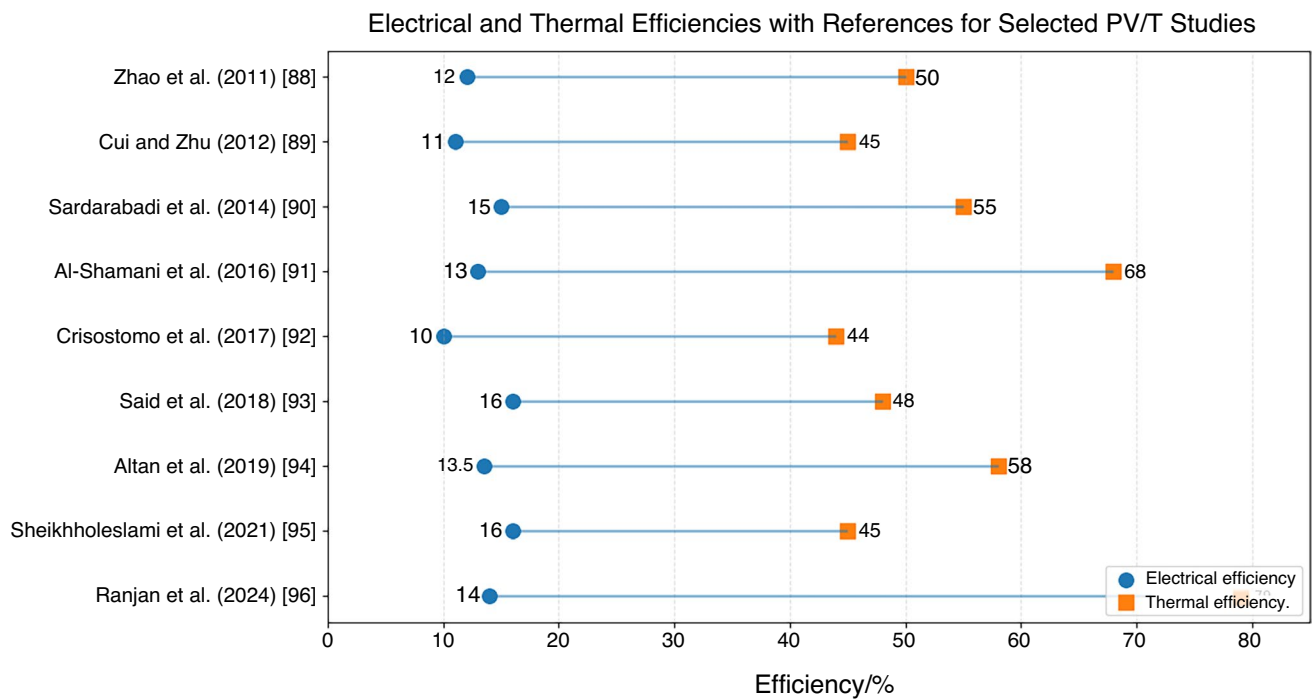


Fig. 7 Efficiency of the PVT system using nanofluid

and heat spreading elements such as fins, porous metallic media, and heat sinks that facilitate heat transfer from the rear surface of the PV module into the storage layer. Since the intrinsically low thermal conductivity of PCM restricts rapid heat diffusion, absorber designs that enlarge the contact area and promote more effective internal heat transfer are essential for maintaining the PV module within a favourable operating temperature range. Huang et al. [97] show that the thermal behaviour of a PV/PCM system is highly dependent on internal fin spacing. Their results indicate that finned arrangements improve heat transfer within RT27, strengthen natural convection inside the PCM, and shorten the melting period. The 4 mm spacing provides the most effective thermal control, highlighting the importance of optimising fin geometry in absorber-side PCM designs. Likewise, Hassan et al. [98] demonstrate that a PCM layer attached to the rear of a BIPV panel improves both temperature regulation and thermal energy storage potential under the climatic conditions of Al-Ain. The PCM-backed configuration maintains a distinctly lower operating temperature than the reference panel, with stronger cooling observed during periods of higher solar exposure. Similar behaviour is reported by Hasan et al. [99], who investigate a BIPV system incorporating RT42 within vertical fins mounted on the rear side of the module. Their study confirms that the combination of PCM and fins significantly suppresses the daytime PV temperature and improves electrical output, while the fin structure also alleviates the limitations

associated with the low thermal conductivity of PCM. Hasan et al. [100] further demonstrate that the effectiveness of absorber-integrated PCM cooling depends not only on the PCM itself but also on climatic conditions. By comparing fin-assisted PV-PCM systems in Dublin and Vehari, they show that both PCM1 and PCM2 contribute to thermal regulation, although PCM2 delivers superior cooling because of its more favourable thermophysical characteristics. Their findings also indicate that the electrical benefit of the PV-PCM system becomes more pronounced in warmer climates, emphasising that absorber design, PCM selection, and local weather conditions should be considered together. Tan et al. [101] reach a similar conclusion by testing PV modules coupled with RT27 and different fin numbers. They report that increasing the number of fins strengthens the thermal connection between the metallic surface and the PCM, accelerates melting, lowers the PV operating temperature, and improves conversion efficiency, with the 12-fin arrangement yielding the best performance. A more advanced passive cooling concept is presented by Kouravand et al. [102], who integrate finned PCM with nanofluid circulation in a CPV-T system. Their study shows that the CPV-T/NF/FPCM configuration achieves the highest cooling capacity among the tested cases, leading to improved electrical and thermal efficiencies, reduced average PV temperature, and higher output power. In addition to PCM-based concepts, absorber optimisation can also be achieved through passive metallic heat spreading structures. In this regard, Cuce et al. [103]

demonstrate that the attachment of an aluminium heat sink to the rear surface of a silicon PV cell markedly improves thermal dissipation and enhances energy, exergy, and power conversion performance. Their results confirm that properly designed passive heat sink geometries can function as efficient absorber-side cooling elements even without PCM, and they provide a useful basis for the development of more complex hybrid thermal management systems. This perspective is extended further by Cuce et al. [104], who propose a novel passive cooling configuration that combines a bio-inspired aluminium heat sink with nanoparticle-enhanced PCM. In that study, the coral-like branching geometry improves heat spreading across the rear surface, while the incorporation of nanoparticles into the PCM enhances thermal conductivity and latent heat utilisation. The hybrid configuration delivers a clear reduction in PV surface temperature fluctuations and a measurable improvement in conversion efficiency under real outdoor conditions, demonstrating the strong potential of combining absorber geometry optimisation with advanced PCM formulations. Beyond conventional fins and heat sinks, porous metallic structures also emerge as promising absorber enhancement tools. Hasan and Farhan [105] show that open-cell copper metal foam fins attached to the rear of a PV panel improve heat rejection by allowing air to circulate through the porous structure. As the number of longitudinal fins increases, the average PV temperature decreases, and the electrical output rises, indicating that porous extensions can serve as an effective alternative to solid fins. A related enhancement principle is observed by Mutar and Alaiwi [106] in a single-pass solar air collector equipped with high-porosity metal foams. Their results reveal that the 45-degree configuration provides the highest thermal efficiency, as the porous absorber structure intensifies turbulence, strengthens velocity gradients, and improves the mixing of hot and cold air streams. Taken together, these studies demonstrate that absorber design is evolving from simple flat rear surfaces towards finned, porous, bio-inspired, and hybrid heat transfer architectures, all of which aim to improve the thermal pathway between the solar device and the cooling or storage medium.

Summary of experimental and numerical studies

Several technologies have advanced PVT systems during the last decade by improving their efficiency for generating electricity and heat. The performance of such systems depends on the technology type, so it is essential to thoroughly analyse their benefits and drawbacks. The performance evaluation of leading PVT technologies includes air-based systems, nanofluids, and PCMs, with an investigation of their electrical and thermal efficiencies, cost factors, and key hurdles. Evaluating different PVT technologies reveals their key attributes and shortcomings, advancing sustainable solutions in the renewable energy field.

Table 5 presents a performance analysis of three PVT systems from 2015 to 2024, focusing on average electrical and thermal efficiencies and cost per watt, and identifying the technical hurdles of each technology. The electrical output of air-based PVT systems ranges from 8 to 12%, while their thermal performance averages 30–45%, Nassar et al. [107]. This technological choice provides economic benefits due to its price range between \$1.2 and \$1.8 per watt. The main limitation of these systems stems from their weak heat transfer capabilities; as air does not conduct, heat Al-Karboly et al. [108] efficiently. PVT systems that employ nanofluids deliver enhanced electrical efficiencies of 12–16% together with thermal efficiencies of 50–75% because of nanofluid efficiency in cooling PV cells. The high price points of these systems range from 2.0\$ to 3.5\$ per watt, although nanofluid instability issues during operation decrease cooling performance. PVT systems, which use PCMs, provide electrical efficiencies of 10–14% but achieve the highest thermal performance of all designs at 55–80%. These systems require a high investment due to their price range of 2.5–4.0 \$ per watt, yet suffer from material degradation over the system's lifespan, leading to increased operational expenses and maintenance requirements. This technical evaluation demonstrates that the air-based system has the lowest cost, although its heat transfer capabilities remain inadequate. Higher efficiency is a benefit of nanofluid systems, even though they face stability issues. The PCM-integrated system demonstrates top thermal performance but has the highest price point and requires sustainable material development to maintain ongoing operational effectiveness.

Table 5 Performance metrics of PVT systems (2015–2024)

Technology	Elec. efficiency/%	Thermal efficiency/%	Cost/\$ W ⁻¹	Key limitations
Air-based PVT	8–12	30–45	1.2–1.8	Low heat transfer rates
Nanofluid-PVT	12–16	50–75	2.0–3.5	Nanofluid instability
PCM-integrated PVT	10–14	55–80	2.5–4.0	PCM degradation

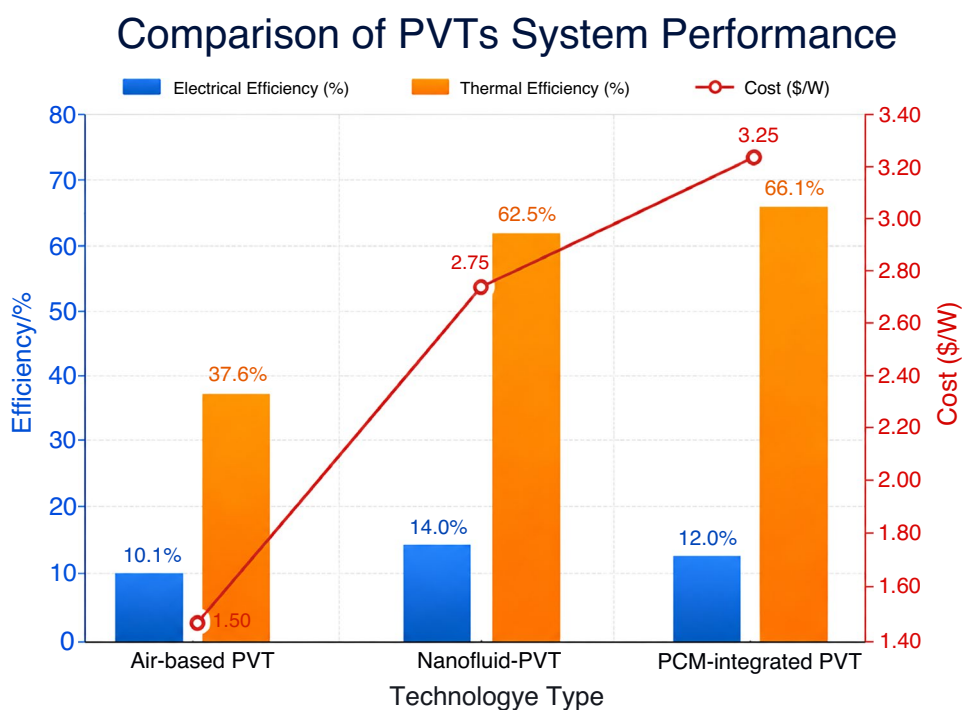
Performance needs and financial feasibility jointly determine which technology receives selection through this evaluation process, Imbayah et al. [109].

The performance enhancement statements made by the PVT systems with the use of nanofluid and PCM should be treated with some degree of caution and should be treated quantitatively and with some degree of conditionality. Based on the reviewed studies, the overall electrical efficiency of air-based PVT systems is generally in the range of 8–12%, and the overall thermal efficiency is in the range of 30–45%, which is largely due to the low heat transfer capacity of air, Elmnifi and Deyun [110]. Nanofluid-enhanced PVT systems have exhibited electrical efficiencies of 12%–16% and thermal efficiencies of 50%–75%, mainly due to the higher effective thermal conductivity of the working fluid and the better convective heat dissipation of the PV module. The efficiencies of the PCM-integrated systems range in electrical efficiency from 10 to 14%, and thermal efficiency from 55 to 80%, primarily because of latent heat storage and passive temperature stabilisation during the melting phase, El-Khozondar et al. [111]. The reported improvements, however, are not easily reproducible across studies due to experimental boundary conditions and system design. The experimental conditions used, such as the sun's intensity, ambient temperature, inlet temperature of the fluid, MFR, collector area, geometry of the absorber, type and concentration of the nanoparticles, PCM melting temperature, and testing duration, can cause significant differences in reported results. It is, therefore, important not to directly compare peak efficiencies without explicit specification of the operating conditions

and efficiency definitions. There are also trade-offs to consider for the use of nanofluids and PCM. Therefore, it is important for any nanofluid-based system to achieve high heat transfer coefficients while maintaining other desirable attributes, such as low viscosity, pressure drop, maintenance and pumping power needs, sedimentation, agglomeration, and clogging. The thermal regulation is improved in PCM-integrated systems, but there are disadvantages such as low thermal conductivity, incomplete melting and solidification, leakage risk, degradation of materials, increased mass, cost, and complexity of encapsulation. Hence, from the future point of view, it is suggested that the thermal and electrical efficiency should be reported, along with the pressure drop, pumping power, nanofluid stability, PCM cycling reliability, uncertainty ranges, and techno-economic indicators.

The electrical output of air-based PVT systems ranges from 8 to 12%, while their thermal performance averages 30%–45% (Fig. 8). This technological choice provides economic benefits due to its price range of \$1.2–\$1.8 per watt. The main limitation of these systems stems from their weak heat transfer capabilities, as air does not conduct heat efficiently. PVT systems that employ nanofluids deliver enhanced electrical efficiencies of 12–16% and thermal efficiencies of 50–75% due to nanofluid efficiency in cooling PV cells. The high price points of these systems range from \$2.0 to \$3.5 per watt, although nanofluid instability during periods of operation reduces cooling performance. PVT systems that use PCMs provide electric efficiencies between 10 and 14% but attain the highest thermal performance of all designs at 55–80%, Aqila et al. [112]. These

Fig. 8 Comparison of three types of PVT systems



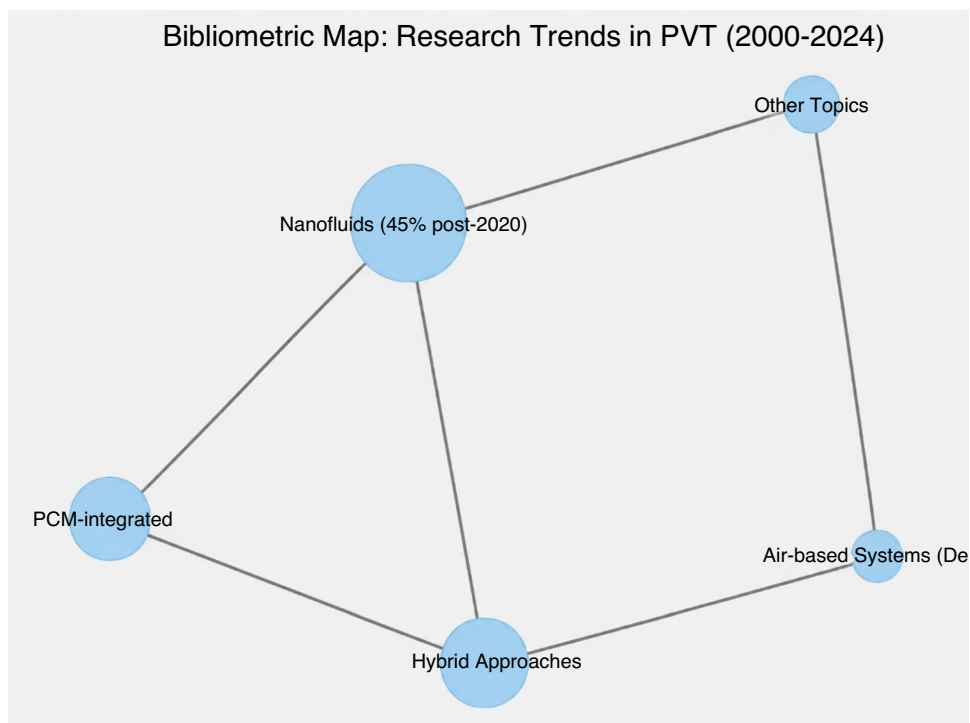
systems require a high investment due to their price range of \$2.5–4.0 per watt, yet suffer from material decline over the system's lifespan, which leads to increased operational expenses and maintenance requirements. This technical evaluation demonstrates that the air-based system has the lowest cost, although its heat transfer capabilities remain inadequate. Higher efficiency is a benefit of nanofluid systems, even though they face stability issues. The PCM-integrated system demonstrates top thermal performance but has the highest price point and requires sustainable material development to maintain ongoing operational effectiveness. Performance needs and financial feasibility jointly determine which technology receives selection through this evaluation process. The economic benefit of air-based PVT collector's needs to be understood relative to other PVT systems. Generally, air collector systems require less auxiliary equipment when compared with the nanofluid enhanced PVT and PCM-integrated PVT systems, as there are no nanofluid pumps, liquid flow circuits, heat exchanger, nanofluid preparation, corrosion control, and PCM containment systems required. This not only decreases capital cost, but the number of routine maintenance tasks, the risk of leakage, and the complexity of installation too. The air-based PVT systems have lower reported cost range as 1.2–1.8 \$/W, which is lower than that of the nanofluid-PVT system (2.0–3.5 \$/W) and PCM-integrated system (2.5–4.0 \$/W) in the reviewed studies, Abdulrazig et al. [113].

Air-based PVT systems, however, result in a clear trade-off of performance that is more cost effective. The efficiency

of the electrical conversion is typically 8–12%, and the efficiency of the thermal conversion is no more than 30–45%, primarily because of the low density, heat capacity, and convective heat transfer capacity of air. So air-based systems could be cost effective for low-cost applications such as space heating, drying, and water scarce areas, but not for those with high expectations for thermal recovery, if that is the case.

Contrastingly, PVT systems based on a nanofluid or PCM can achieve higher thermal and electrical performance, but the feasibility of these systems during their lifetime will rely on other factors of cost. Pumping power, filtration, periodic replacement of the fluid, monitoring and mitigating fluid stability, sedimentation, and clogging may be necessary for nanofluid systems. PCM-based systems could need to be encapsulated; leakage prevented, thermal conductivity increased, and be replaced or tested after multiple melting–solidification cycles. So, economic comparison should be based on capital cost along with maintenance complexity, auxiliary energy consumption, degradation rate, useful thermal demand, payback period, and lifecycle performance. Ideally, the reviewed studies should not only be interpreted in relation to the efficiency gains reported but should also be interpreted in relation to their other equally important features. Their practical usefulness also relies on the experimental boundary conditions, the complexity of the system, the flow rate, the pumping power, the stability of the material, its cost, and its reliability in outdoor application for long periods. Hence, the comparison of the field-based studies

Fig. 9 Research trends in PVT 2000–2024



with laboratory studies reporting high efficiencies should be done with caution as the field-based studies face extra losses due to dust deposition, the variation of the solar irradiation, the fluctuation of ambient temperature, water quality, instability of the nanofluids, degradation of PCM, and maintenance expenses.

Figure 9 demonstrates the evolution of PVT system research from 2000 to 2024 using a bibliometric map analysis of the most commonly used keywords in scientific publications. Research terms in this graphical representation are represented as nodes that adjust their size based on paper coverage counts and show inter-topic connections through connecting lines. Research interest in nanofluids increased substantially post-2020, when they accounted for 45% of studies in that period, driven by their effectiveness in cooling and heat transfer applications. The number of papers about air-based systems decreased relative to other research areas because scientists are pursuing advanced technologies to improve thermal and electrical system performance. The division between scientific fields arises as researchers seek new materials and innovations in frameworks to enhance the efficiency of future PVT systems. This figure demonstrates the evolution of PVT system research from 2000 to 2024 using a bibliometric map analysis of the most commonly used keywords in scientific publications. Research terms in this graphical representation manifest as nodes, which adjust their size according to paper coverage numbers and show inter-topic connections through connective lines. Research interest in nanofluids increased substantially post-2020, when they made up 45% of studies carried out in that period due to their effectiveness in cooling and heat transmission applications. The number of papers about air-based systems decreased relative to other research areas because scientists are pursuing advanced technologies to improve thermal and electrical system performance. The division between scientific fields emerges because researchers seek new materials and framework innovations for enhanced PVT system efficiency in the future.

Lessons learnt and research gaps in the three PVT systems

Regarding air-based systems, research has shown that these systems are an economical option due to their low cost, ease of design, and ease of maintenance. However, they suffer from poor heat transfer rates that negatively impact thermal performance, highlighting the need to improve cooling technologies and increase heat transfer efficiency through the use of innovative materials or methods. Nanofluid systems have been shown to enhance electrical and thermal efficiency compared to air systems, but their use at concentrations above 1.0 mass% can lead to system clogging and nanofluid deposition problems in the long term. Some studies indicate

that hybrid nanofluids (such as Al_2O_3 –graphene) may maintain stable performance up to 2.0 mass%, calling for further research on optimising nanofluid formulations to achieve a balance between performance and stability, as well as studying the effects of long-term use (more than 5 years) on their properties. Regarding PCM-integrated systems, their use has shown significant improvements in thermal output due to their ability to store and release heat when needed. However, this comes at the expense of electrical efficiency, as the optical properties of the materials used lead to losses of up to 5–8%, in addition to the degradation of these materials over time. This calls for the development of more sustainable and reliable PCM materials and integrated solutions that maintain a balance between thermal and electrical performance. In this regard, the main challenges lie in improving heat transfer in air-based systems, ensuring nanofluid stability over time, and developing PCM materials that meet the requirements for sustainable long-term performance.

Environmental and economic analysis of PVT systems

The economic assessment reviews system costs alongside payback duration and the cost of producing each unit of energy under LCOE measurement. Using PCM material systems proves less expensive because PCM products cost less than complex nanomaterials yet designing primed PCM systems creates moderate implementation costs through elements such as additional fins or enhanced heat-conducting elements. PV systems that implement PCM-based thermal management show a 3–5% increase in electrical output, according to research, providing budget-friendly projects with an attractive return on investment and extending PV panel lifespans through lower operating temperatures. A nanofluid-based system requires prototypical expenses to create stable nanofluid mixtures since it involves purchasing Al_2O_3 or TiO_2 nanoparticles and surfactants needed for stability maintenance. The thermal efficiency gains of 25–35% or higher through nanofluid utilisation become particularly beneficial in sunny regions because they accelerate return on investment even though initial expenses are higher; the enhanced heat transfer capability improves system efficiency, which compensates for the initial costs (Table 6). The initial capital expenditure for PCM with nanofluid systems peaks due to the need for sophisticated engineering and additional materials for PCM and nanofluids. The integration of PCM latent heat storage with the improved heat transfer capabilities of nanofluids provides an overall efficiency boost of 10–15%, making the initial investment more cost-effective during a medium-term payback period, particularly if implemented on a large scale.

Table 6 A comparison of PVT systems in terms of sustainability, economic, and environmental returns

Technology	Initial Cost	Payback Period	Efficiency Improvement/%	CO ₂ Reduction Impact	Material Sustainability
PCM	Low to moderate	Moderate with gradual performance gains	Approximately 3–5% increase in electrical output	Moderate reduction due to temperature stabilisation	Generally available materials that are easy to recycle
Nanofluids	Relatively high	Short to medium (especially in high irradiance regions)	25–35% (or higher) increase in thermal efficiency	Significant mitigation due to marked efficiency gains	Requires precise handling; environmental risks can be mitigated with proper protocols
PCM + Nanofluids	Highest	Medium cost compensated by high-performance improvements	Overall improvement of 10–15% or more	Maximum reduction due to dual enhancement effects	Complex system; sustainability depends on careful material management and recycling practices

The study evaluates environmental components that consist of CO₂ emission reduction strategies, together with assessment methods for investigating sustainable resource use. Thermal stabilisation by PCM materials helps improve electrical efficiency and decreases fossil fuel electricity usage, along with offering sustainability benefits through recyclability, combined with minimal environmental consequences. The implementation of nanofluid-based systems offers a 35% efficiency improvement, which directly affects the amount of energy produced by fossil fuels. Scientists must implement proper handling of synthesised nanoparticles and disposal methods to keep environmental safety in check, despite which appropriate procedures verify that benefits consistently outweigh environmental risks. When PCM features nanofluids and operates as a single system, it produces maximal energy boosts and helps reduce CO₂ emissions because this dual approach exceeds solo performance improvements for reducing fossil fuel consumption. The integrated system has complex substance requirements while using more environmental resources during production, yet it provides extended energy conservation together with reduced CO₂ emissions when recycling specific materials in a controlled manner. The lower installation costs of PCM-only systems produce economic benefits but result in moderate power efficiency improvements, whereas nanofluid-only systems present higher expenses for additional power efficiency that shortens payback time and reduces CO₂ emissions dramatically. A superior method exists when PCM combines with nanofluids through an advanced integrated system because these components yield optimum environmental results alongside enhanced efficiency, though it demands higher initial costs and specialised maintenance protocols. Detailed system explanations enable experts, along with decision-makers, to pick systems through financial and environmental assessments of projects, which take into account site-specific targets and project objectives.

Technical and economic feasibility and scalability of photovoltaic thermal systems enhanced with phase change materials and nanofluids

For advanced PVT systems, a techno-economic and scalability analysis is required since high solar–thermal efficiency or overall efficiency does not necessarily mean commercial viability. The usefulness of PCM- and nanofluid-assisted PVT systems relies on the possibility of obtaining the extra energy output for the different reasons, which include higher capital expenses, maintenance needs, operation complexity, and long-lasting risks. Hence, apart from electrical and thermal efficiencies, the cost of capital, operating costs, auxiliary energy consumption, maintenance frequency, replacement cost, useful heat demand, payback period, levelised cost of energy, and system lifetime should also be taken into account for economic evaluation. The techno-economic advantage of air-based PVT systems is that no pumps, circulating liquid, nanomaterials preparation, or PCM encapsulation are needed, which makes them the simplest and lowest cost to scale. But their comparatively low capability of heat transfer decreases the value of the recovered thermal energy. However, the nanofluid-based PVT systems offer higher thermal and electrical performance due to their superior heat transfer capability, but they demand extra investments in the preparation process, pumping units, filtration process, and monitoring system in addition to the investment in nanofluids and base fluids and their associated surfactants. These extra parts and components add to the initial cost and can add to operating expenses because of the pressure drop, pumping power requirement, need for replacement of the nanofluid, and maintenance requirements for blocked or fouled channels. The PCM-integrated PVT systems offer passive thermal management, thereby decreasing the need for active cooling systems and enhancing the reliability in remote or off-grid applications. However, the scalability depends on the cost of the PCM material, the encapsulation

method, enhancing the thermal conductivity, extra system mass, leakage prevention, fire safety, and degradation after repeated melting–solidification cycles. While these PCM-based systems may prove to be an economical alternative for low-cost and recyclable PCMs, they must be compatible with existing PV mounting structures, exhibit stable thermal cycling characteristics, and be durable enough to stand up to the rigours of manufacture and installation for wider implementation. Contributed by the hybrid PCM–nanofluid-PVT systems, which have the highest performance potential, they provide active heat removal and passive latent heat storage. However, they also offer the greatest capital costs and system complexity. Whether it is economically viable hinges on the efficiency increase they provide, versus the cost of using nanoparticles, holding them in a container, using a heat exchanger, a pump, a sensor, a control unit, and maintenance over the long term. For such systems, the net energy benefit should be determined by subtracting the auxiliary pumping power required and taking into account the actual value of the recovered heat. Even though high values of overall efficiency result, the economic benefit can be limited if the heat output is low-grade and there is no nearby thermal demand. Several pragmatic considerations need to be taken into account to enable scalability. On the module level, heat transfer efficiency, mass, leakage potential, and maintainability are prime concerns. For the building scale, the thermal energy recovered must be integrated into the domestic hot water system, space heating system, drying system, or industrial preheating system. When it comes to community or utility scale, the design of the collector, material procurement, maintenance procedures, environmental regulations, and qualified technical workforce are key. Other scale-up challenges could involve large-scale preparation of nanofluids, stability of the nanofluids, safe disposal, and environmental risk management. Some limitations, such as mass production, quality of encapsulation, loading of the PCM structures, and thermal stability of PCM, may be encountered in PCM systems. Thus, the following indicators should be considered in a realistic techno-economic analysis: initial cost of the system, cost per watt, annual useful energy produced, LCOE, simple payback period, NPV, IRR, operating and maintenance cost, replacement cost of the PCM or nanofluid, pumping-energy penalty, degradation rate, CO₂ reduction, and recyclability. Furthermore, the use of exergy is recommended for economic analysis because not all of the recovered thermal energy is of equal practical value. Low-temperature heat should be considered based on the purpose it is used for, and not as a substitute for electricity. In general, it is concluded that the PCM and the nanofluid-based PVT systems are technically viable, but the large-scale implementation requires a compromise between the performance enhancement, cost, reliability, and maintainability. The use of nanofluid-PVT systems might be

more appropriate in high irradiance areas and for systems that demand high heat removal capability, while maintaining stability and pumping penalty control. For passive thermal regulation and applications that recurrently require heat storage for 1 day, PCM-PVT systems might be more appropriate. Hybrid PCM-nanofluid systems are most suited to high-performance applications, which require the recovered heat to be of high value to warrant the extra complexity and cost. Economic monitoring over time, degradation-based economic modelling, pilot-scale demonstration, supply-chain evaluation, standardised life-cycle techno-economic analysis, and efficiency reporting should thus be complemented by future research.

Conclusions and future research priorities

In this review, recent advancements of PVT systems were critically reviewed with a particular focus on the development and performance of the various PVT system configurations, such as air, water, nanofluid, PCM-integrated, and hybrid PVT. The literature reviewed shows that PVT technology can be used to enhance the utilisation of solar energy by recovering a portion of the waste heat radiated at the back of the PV modules and simultaneously producing electrical power. It is also evident from the literature that the performance enhancement is also dependent on the operating condition, collector geometry, properties of the working fluids, choice of PCM, MFR, climatic conditions, and the definition of the efficiency used in various studies. One of the main findings of this review is that there is no one PVT configuration that is better in all situations. Although an air-based PVT system is technically straightforward, low-cost, and appropriate for dry or water-scarce areas, the low heat capacity and low heat transfer coefficient of air reduce the thermal performance of the system. Water-based PVT systems offer higher heat removal and better thermal control, but they necessitate the use of hydraulic elements, a power supply for a pump, corrosion control, and maintenance. Despite the superior heat transfer capability of nanofluid-based PVT systems due to better thermophysical properties, the various issues of instability, sedimentation, agglomeration, increase in viscosity, pressure drop, pumping power penalties, clogging, and environmental safety are the hurdles that limit its practical application. The essential features of PCM-integrated PVT systems for passive thermal stabilisation are the latent heat storage; however, the long-term reliability relies on the melting–solidification property, thermal conductivity, leakage, cycling stability, thermal degradation, and durability of the encapsulate. It is also noted from the review that very high reported thermal, thermodynamic, and overall efficiencies should be treated

with care. High-efficiency values were yielded in a few studies when the operating conditions were controlled in the laboratory or when the operating conditions were optimised, such as fixed irradiance, selected MFR, low inlet temperature, or specific absorber geometry. Thus, these values should not be regarded as universal ‘field performance’ values. The overall efficiency of PVT systems can consequently be very high, which can also be contributed to by the recovered thermal energy that can be low-grade. Therefore, energy efficiency should not be the only measure considered for future evaluation; other measures such as exergy efficiency, useful heat temperature, auxiliary energy consumption, pressure drop, uncertainty analysis, degradation rate, and techno-economic feasibility should also be considered. The most promising route to high-performance thermal management is hybrid PVT systems, using nanofluids, PCM, and incorporating advanced absorber geometries. However, the same goes for these systems; there is a lot of complexity, cost, maintenance, and risk in terms of reliability. Whether or not the extra energy gain can compensate for the greater capital cost, pumping power need, ageing of materials, environmental management requirements, and system maintenance burden, remains to be seen. Hence, future PVT studies must go beyond reporting peak efficiency and should instead consider whole system performance over realistic operating conditions. From the literature reviewed, the following research priorities are suggested:

Standardised testing and reporting procedures

Testing procedures to PVT systems with standardised irradiance, ambient temperature, wind speed, MFR, inlet temperature, collector area, and duration of operation should be applied in the future studies. In order to enable meaningful comparison between studies, the following information should be reported in a consistent manner: electrical efficiency, thermal efficiency, overall efficiency, exergy efficiency, uncertainty, and auxiliary energy consumption.

Long-term outdoor validation

The majority of the studies performed are of short duration, simulations, or conducted under controlled laboratory conditions. Seasonal performance, dust effect, water quality, fouling, corrosion, stability of nanofluids, degradation of PCM during cycling, the maintenance requirements,

and real energy savings on system life are of performance that require long-term outdoor testing to be evaluated.

Assessment based on the concepts of net energy and exergy

Future studies should determine the net useful gain, which is the useful gain minus pumping power, control system power, and maintenance losses. Energy analysis and exergy analysis should go hand in hand, as low-temperature, thermal energy recovered is not equal to electrical energy.

The stability and reliability of nanofluids

Long-term colloidal stability, sedimentation control, prevention of agglomeration, viscosity control, corrosion behaviour, pressure drop, pumping power requirement, and environmental protection are important areas of research in PVT system using nanofluid. The future studies should include the zeta potential, pH, particle size, sonication time, sedimentation time, viscosity, and stability following multiple thermal cycles.

Optimisation of PCM systems from a thermodynamic point of view

The melting–solidification cycles, incomplete melting, delayed solidification, supercooling, phase segregation, volume expansion, leakage, and degradation of PCM-based PVT systems after repeated cycles need to be explored. Future studies might involve field-scale reliability validation, encapsulation durability, leakage tests, accelerated cycling tests, and DSC.

Techno-economic and scalability analysis

The life-cycle cost, payback period, levelised cost of energy, net present value, maintenance cost, material replacement cost, and supply-chain feasibility should be considered for advanced PVT systems that include PCM and nanofluids. Scalability should be considered at the module, building, and community level, especially in high sun resource areas and developing countries.

Provide a machine learning approach for monitoring and control

AI and machine learning can be used to aid in real-time flow-rate control, performance prediction, fault detection, and predictive maintenance. Future ML studies should, however, rely on well-prepared datasets, transparent pre-processing techniques, independent validation, uncertainty

analysis, and various accuracy metrics including R^2 , RMSE, MAE, MAPE, and residual analysis.

Development of environmentally safe materials

The new research should be directed for the development of low cost, nontoxic, non-polluting, recyclable nanofluids, and PCMs, which are thermally stable. These should be a part of the design process and not an afterthought: environmental risk analysis, safe disposal, recycling, leak management, etc.

PVT technology has great potential in enhancing the utilisation of solar energy in general, particularly in conjunction with advanced cooling and thermal storage approaches. The shift from the laboratory level performance improvement to commercialisation, however, calls for standardisation of testing, long-term reliability test, exergy analysis, techno-economic validation, and scalable material design. These priorities are critical to the successful development of advanced PVT systems from prototype demonstration projects to robust, sustainable, and economically viable energy technologies.

Author contribution Monaem Elmnifi helped in conceptualisation, methodology, data curation, and writing—original draft. Hasan A. Al-Asadi worked in investigation, validation, resources, and writing—review and editing. Karrar A. Hammoodi helped in formal analysis, visualisation, and writing—review and editing. Erdem Cuce helped in conceptualisation, supervision, project administration, validation, and writing—review and editing. Duyun Tatyana Aleksandrovna helped in literature review, resources, validation, and writing—review and editing. Hala J. El-Khozondar helped in formal analysis, validation, visualisation, and writing—review and editing. Yasser F. Nassar helped in methodology, resources, and writing—review and editing. Shahad A. Salih helped in investigation, writing—original draft, and writing—review and editing. All authors contributed to the article, critically revised the manuscript, and approved the final version of the manuscript.

Funding The authors declare that no funding was received from any agency.

Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

- Hammoodi KA, Dhahad HA, Alawee WH, Omara ZM, Yusaf T. Pyramid solar distillers: a comprehensive review of recent techniques. *Results in Engineering*. 2023;18:101157.
- Abdirahman AA, Asif M, Cuce E, Ahmed I, Alqahtani M, Khalid M. Optimizing PV systems in high-temperature environments: A SWOT-based analysis of cooling technologies. *Energy Strat Rev*. 2025;61:101828.
- Elmnifi M, Duyun TA. Experiment and simulation to improve the efficiency of PVT panels using aluminum foam fins, to improve energy consumption in oil facilities. *SOCAR Proceedings*. 2025;4:139–50.
- Cuce PM, Alvur E, Cuce E, Soudagar MEM, Bouabidi A, Guo S, et al. Solar thermal systems and AI: Past, present, and future. *J Therm Anal Calorim*. 2026;151:3–60.
- Al-Aasam AB, Ibrahim A, Syafiq U, Sopian K, Abdulsahib BM, Dayer M. Enhancing the performance of water-based PVT collectors with nano-PCM and twisted absorber tubes. *International Journal of Renewable Energy Development*. 2023;12(5):891–901.
- Rajamony RK, Pandey AK, Sofiah AGN, Wadaan MA, Paw JKS, Suraparaju SK, et al. Energy, exergy, economic and environmental (4E) analysis of serpentine tube absorber photovoltaic thermal system using nano enhanced phase change material. *Energy*. 2025;319:135032.
- Majdi HS, Younis A, Abdullah AR, Elmnifi M, Habeeb LJ. A comparative analysis of the efficiency of monocrystalline and polycrystalline photovoltaic modules: CTI-80 and YHM-205-27P. *International Journal of Design & Nature and Ecodynamics*. 2023;18(4):775–82.
- Diwania S, Agrawal S, Siddiqui AS, Singh S. Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement. *Int J Energy Environ Eng*. 2020;11(1):33–54.
- Saxena A, Kumar R, Sagade AA, Singh DB, Tyagi VV, Cuce E, et al. A state-of-art review on photovoltaic systems: Design, performance, and progress. *Process Saf Environ Prot*. 2024;190:1324–54.
- Herez A, El Hage H, Lemenand T, Ramadan M, Khaled M. Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems. *Sol Energy*. 2020;207:1321–47.
- Sheik MA, Aravindan MK, Cuce E, Dasore A, Rajak U, Shaik S, et al. A comprehensive review on recent advancements in cooling of solar photovoltaic systems using phase change materials. *International Journal of Low-Carbon Technologies*. 2022;17:768–83.
- Elmnifi M, Aleksandrovna DT. Economic and Technical Feasibility of a Hybrid Renewable Energy (PV/Wind) Grid-Connected System in Libya for Various Locations. In *Renewable Energy Resources Assessment and Development in MENA/Mediterranean Regions, 2026*, 223–236, Cham: Springer Nature Switzerland.]
- Nassar YF, Amer KA, El-Khozondar HJ, Ahmed AA, Alsharif A, Khaleel MM, Elnaggar M, El-Khozondar R, Salem A. Thermoelectrical analysis of a new hybrid PV-thermal flat plate solar collector. *8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES) 2023*; 1–5.
- Elmnifi M, Mansur AN, Hassan AK, Abdullah AR, Ayed SK, Majdi HS, et al. Experimental and Simulation Study for Improving the Solar Cell Efficiency by Using Aluminum Heat Sinks. *Proceedings on Engineering*. 2024;6(1):161–70.
- Hammoodi KA, Abdulghafor IA, Kadhim SA, Elsheikh A, Nayyaf DR, Alsayah AM, et al. Effect of air layer on PCMs melting process inside a spherical container: A numerical investigation. *Results in Engineering*. 2024;24:103088.
- Elmnifi M, Aleksandrovna DT, Al-Asadi HA, Hammoodi KA, Kadhim SA, Nassar YF, et al. Design and manufacture of a photovoltaic thermal solar collector equipped with aluminum foam fins for enhanced electrical, thermal, and

- integrated performance. *Int Commun Heat Mass Transfer*. 2026;173:110844.
17. Zondag HA, de Vries DD, Van Helden WGJ, Van Zolingen RC, Van Steenhoven AA. The thermal and electrical yield of a PV-thermal collector. *Sol Energy*. 2002;72(2):113–28.
 18. Wolf M. Performance analyses of combined heating and photovoltaic power systems for residences. *Energy Conversion*. 1976;16(1–2):79–90.
 19. Bergene T, Løvvik OM. Model calculations on a flat-plate solar heat collector with integrated solar cells. *Sol Energy*. 1995;55(6):453–62.
 20. Huang BJ, Lin TH, Hung WC, Sun FS. Performance evaluation of solar photovoltaic/thermal systems. *Sol Energy*. 2001;70(5):443–8.
 21. Omar I, Alrudhan A, Hammoodi KA, Mohammed AA. Experimental and theoretical comparison between metallic and mirror reflectors with different receiver tank. *Journal of Mechanical Engineering Research and Developments*. 2020;43(7):51–61.
 22. Dubey S, Tay AA. Testing of two different types of photovoltaic–thermal (PVT) modules with heat flow pattern under tropical climatic conditions. *Energy Sustain Dev*. 2013;17(1):1–12.
 23. Sultan SM, Fadhel MI, Alkaff SA. Performance analysis of the photovoltaic/thermal collector (PV/T) system for different Malaysian climatic conditions. *Appl Mech Mater*. 2014;467:522–7.
 24. Baloch AA, Bahaidarah HM, Gandhidasan P, Al-Sulaiman FA. Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling. *Energy Convers Manage*. 2015;103:14–27.
 25. Kazem HA. Evaluation and analysis of water-based photovoltaic/thermal (PV/T) system. *Case Studies in Thermal Engineering*. 2019;13:100401.
 26. Senthilraja S, Gangadevi R, Marimuthu R, Baskaran MJJOHE. Performance evaluation of water and air based PVT solar collector for hydrogen production application. *International Journal of Hydrogen Energy* 2020; 45(13): 7498–7507.
 27. Menon GS, Murali S, Elias J, Delfiya DA, Alfiya PV, Samuel MP. Experimental investigations on unglazed photovoltaic-thermal (PVT) system using water and nanofluid cooling medium. *Renewable Energy*. 2022;188:986–96.
 28. Tiwari AK, Chatterjee K, Agrawal S, Singh GK. A comprehensive review of photovoltaic-thermal (PVT) technology: Performance evaluation and contemporary development. *Energy Rep*. 2023;10:2655–79.
 29. Rao VT, Sekhar YR, Arıcı M, Pochont NR, Prasad DR. Experimental investigations on bi-symmetrical web flow water based photovoltaic-thermal (PVT) system: energy, exergy, and entropy (3-E) analysis. *Sol Energy*. 2024;271:112445.
 30. Yildirim MA, Cebula A. A numerical and experimental analysis of a novel highly-efficient water-based PV/T system. *Energy*. 2024;289:129875.
 31. Gharaee H, Erfanimatin M, Bahman AM. Machine learning development to predict the electrical efficiency of photovoltaic-thermal (PVT) collector systems. *Energy Convers Manage*. 2024;315:118808.
 32. Harby K, Attia MEH, Khelifa A, Amin M, Cuce E, Abdelgaied M. Performance characteristics of optimized bi-fluid photovoltaic-thermal solar system: A comparative study of innovative cooling system made of different materials. *Appl Therm Eng*. 2025;278:127283.
 33. Zheng L, Cao J, Peng J, Lu Z, Hong X, Cuce E, et al. Optimization on the structure and filling ratio of a flexible separate heat pipe applied for tracking-type photovoltaic/thermal systems. *Renewable Energy*. 2025;239:122046.
 34. Rejab O, Dhaou H, Jemni A. Parameters effect analysis of a photovoltaic thermal collector: Case study for climatic conditions of Monastir. *Tunisia Energy Conversion and Management*. 2015;89:409–19.
 35. Rosli MAM, Ping YJ, Misha S, Akop MZ, Sopian K, Mat S, et al. Simulation study of computational fluid dynamics on photovoltaic thermal water collector with different designs of absorber tube. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*. 2018;52(1):12–22.
 36. Rao VT, Sekhar YR, Pandey AK, Said Z, Prasad DR, Hossain MS, et al. Thermal analysis of hybrid photovoltaic-thermal water collector modified with latent heat thermal energy storage and two side serpentine absorber design. *Journal of Energy Storage*. 2022;56:105968.
 37. Al-Aasam AB, Ibrahim A, Sopian K, Abdulsahib B, Dayer M. Nanofluid-based photovoltaic thermal solar collector with nanoparticle-enhanced phase change material (Nano-PCM) and twisted absorber tubes. *Case Studies in Thermal Engineering*. 2023;49:103299.
 38. El Alami Y, Lamkaddem A, Bendaoud R, Talbi S, Baghaz E. Numerical study of a water-based photovoltaic-thermal (PVT) hybrid solar collector with a new heat exchanger. *E-Prime-Advances in Electrical Engineering, Electronics and Energy*. 2024;9:100693.
 39. Zondag HA, De Vries DW, Van Helden WGJ, Van Zolingen RJC, Van Steenhoven AA. The yield of different combined PV-thermal collector designs. *Sol Energy*. 2003;74(3):253–69.
 40. Fan J, Shah LJ, Furbo S. Flow distribution in a solar collector panel with horizontally inclined absorber strips. *Sol Energy*. 2007;81(12):1501–11.
 41. Ibrahim A, Othman MY, Ruslan MH, Mat S, Sopian K. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. *Renew Sustain Energy Rev*. 2011;15(1):352–65.
 42. Sardarabadi M, Passandideh-Fard M. Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT). *Sol Energy Mater Sol Cells*. 2016;157:533–42.
 43. Zhou C, Liang R, Riaz A, Zhang J, Chen J. Experimental investigation on the tri-generation performance of roll-bond photovoltaic thermal heat pump system during summer. *Energy Convers Manage*. 2019;184:91–106.
 44. Palaskar VN, Deshmukh SP. Performance analysis of especially flow design heat exchanger used in hybrid solar system. *International Journal of Renewable Energy Research*. 2015;5(2):476–82.
 45. Yang X, Zhou J, Yuan Y. Energy performance of an encapsulated phase change material PV/T System. *Energies* 22019; 12(20): 3929.
 46. Choi SU. Enhancing thermal conductivity of fluids with nanoparticles. In *ASME International Mechanical Engineering Congress and Exposition*. 1995;17421:99–105.
 47. Zennifer MA, Manikandan S, Suganthi KS, Vinodhan VL, Rajan KS. Development of CuO–ethylene glycol nanofluids for efficient energy management: Assessment of potential for energy recovery. *Energy Convers Manage*. 2015;105:685–96.
 48. Murshed SMS, Leong KC, Yang C. Enhanced thermal conductivity of TiO₂–water based nanofluids. *Int J Therm Sci*. 2005;44(4):367–73.
 49. Baheta AT, Woldeyohannes AD. Effect of particle size on effective thermal conductivity of nanofluids. *Asian Journal of Scientific Research*. 2013;6(2):339–45.
 50. Hwang YJ, Ahn YC, Shin HS, Lee CG, Kim GT, Park HS, et al. Investigation on characteristics of thermal conductivity enhancement of nanofluids. *Curr Appl Phys*. 2006;6(6):1068–71.
 51. Yu W, Xie H, Wang X, Wang X. Significant thermal conductivity enhancement for nanofluids containing graphene nanosheets. *Phys Lett A*. 2011;375(10):1323–8.
 52. Eastman JA, Choi SUS, Li S, Yu W, Thompson LJ. Anomalous increased effective thermal conductivities of ethylene

- glycol-based nanofluids containing copper nanoparticles. *Appl Phys Lett*. 2001;78(6):718–20.
53. Milyani AH, Al-Ebrahim MA, Attar ET, Abu-Hamdeh NH, Mostafa ME, Nusier OK, et al. Artificial intelligence optimization and experimental procedure for the effect of silicon dioxide particle size in silicon dioxide/deionized water nanofluid: preparation, stability measurement and estimate the thermal conductivity of produced mixture. *J Mater Res Technol*. 2023;26:2575–86.
 54. Urmi W, Rahman MM, Hamzah WAW. An experimental investigation on the thermophysical properties of 40% ethylene glycol based TiO₂-Al₂O₃ hybrid nanofluids. *Int Commun Heat Mass Transfer*. 2020;116:104663.
 55. Madas SR, Narayanan R, Gudimetla P. Numerical investigation on the optimum performance output of photovoltaic thermal (PVT) systems using nano-copper oxide (CuO) coolant. *Sol Energy*. 2023;255:222–35.
 56. Sangeetha M, Manigandan S, Chaichan MT, Kumar V. Progress of MWCNT, Al₂O₃, and CuO with water in enhancing the photovoltaic thermal system. *Int J Energy Res*. 2020;44(2):821–32.
 57. Kanti P, Sharma KV, Khedkar RS, Rehman TU. Synthesis, characterization, stability, and thermal properties of graphene oxide based hybrid nanofluids for thermal applications: experimental approach. *Diam Relat Mater*. 2022;128:109265.
 58. Fotukian SM, Esfahany MN. Experimental investigation of turbulent convective heat transfer of dilute γ -Al₂O₃/water nanofluid inside a circular tube. *Int J Heat Fluid Flow*. 2010;31(4):606–12.
 59. Wang G, Zhao K, Shi J, Chen W, Zhang H, Yang X, et al. An iterative approach for modeling photovoltaic modules without implicit equations. *Appl Energy*. 2017;202:189–98.
 60. Sharaby MR, Younes M, Baz F, Abou-Taleb F. State-of-the-Art review: nanofluids for photovoltaic thermal systems. *Journal of Contemporary Technology and Applied Engineering*. 2024;3(1):11–24.
 61. Kandeal AW, El-Naggar AA, Sharaby MR, Sharshir SW, Swidan A, Abdelaziz GB, et al. Augmentation of the tubular distiller performance via hot air injection from a parabolic trough collector, nanocoating, and nanofluid. *Sol Energy*. 2024;277:112743.
 62. Sharaby MR, Sharshir SW, ElBahloul AA, Kandeal AW, Rashad M. Performance evaluation of fixed and sun-tracking photovoltaic systems integrated with spray cooling. *Sol Energy*. 2025;288:113310.
 63. Sharshir SW, Sharaby MR, El-Naggar AA, Lotfy LA, Ismail M, Al Bahir A, et al. Utilizing a novel metal-organic framework for clean water production: synergistic evaporation boost in double slope distiller. *Case Studies in Thermal Engineering*. 2025;68:105876.
 64. Sharshir SW, El-Naggar AA, Ismail HA, Sami MM, Lotfy LA, Sharaby MR, et al. Degradation mechanisms and stability challenges in perovskite solar cells: a comprehensive review. *Sol Energy*. 2025;299:113707.
 65. Fotukian SM, Esfahany MN. Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube. *Int Commun Heat Mass Transfer*. 2010;37(2):214–9.
 66. Sajadi AR, Kazemi MH. Investigation of turbulent convective heat transfer and pressure drop of TiO₂/water nanofluid in circular tube. *Int Commun Heat Mass Transfer*. 2011;38(10):1474–8.
 67. Akhavan-Behabadi MA, Pakdaman MF, Ghazvini M. Experimental investigation on the convective heat transfer of nanofluid flow inside vertical helically coiled tubes under uniform wall temperature condition. *Int Commun Heat Mass Transfer*. 2012;39(4):556–64.
 68. Kayhani MH, Soltanzadeh H, Heyhat MM, Nazari M, Kowsary F. Experimental study of convective heat transfer and pressure drop of TiO₂/water nanofluid. *Int Commun Heat Mass Transfer*. 2012;39(3):456–62.
 69. Ebrahimnia-Bajestan E, Moghadam MC, Niazmand H, Daungthongsuk W, Wongwises S. Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers. *Int J Heat Mass Transf*. 2016;92:1041–52.
 70. Abu-Nada E. Simulation of heat transfer enhancement in nanofluids using dissipative particle dynamics. *Int Commun Heat Mass Transfer*. 2017;85:1–11.
 71. Hamid KA, Azmi WH, Nabil MF, Mamat R. Experimental investigation of nanoparticle mixture ratios on TiO₂-SiO₂ nanofluids heat transfer performance under turbulent flow. *Int J Heat Mass Transf*. 2018;118:617–27.
 72. Baskar S, Chandrasekaran M, Vinod Kumar T, Vivek P, Ramasubramanian S. Experimental studies on flow and heat transfer characteristics of secondary refrigerant-based CNT nanofluids for cooling applications. *Int J Ambient Energy*. 2020;41(3):285–8.
 73. Idris MS, Zakaria IA, Hamzah WAW, Mohamed WANW. The characteristics of hybrid Al₂O₃: SiO₂ nanofluids in cooling plate of PEMFC. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*. 2021;88(3):96–109.
 74. Gelis K, Celik AN, Ozbek K, Ozyurt O. Experimental investigation into efficiency of SiO₂/water-based nanofluids in photovoltaic thermal systems using response surface methodology. *Sol Energy*. 2022;235:229–41.
 75. Kazem HA, Chaichan MT, Al-Waeli AH. Effect of CuO-water-ethylene glycol nanofluids on the performance of photovoltaic/thermal energy system: an experimental study. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 2022;44(2):3673–91.
 76. Chen H, Gao X, Wang C, Jia L, Zhao R, Sun J, et al. Experimental study on the performance enhancement of PV/T by adding graphene oxide in paraffin phase change material emulsions. *Sol Energy Mater Sol Cells*. 2024;266:112682.
 77. Murtadha TK. Effect of using Al₂O₃/TiO₂ hybrid nanofluids on improving the photovoltaic performance. *Case Studies in Thermal Engineering*. 2023;47:103112.
 78. Sharaby MR, Sharaby MR, Younes MM, Taleb FSA, Baz FB. The impact of hybrid nanofluid cooling on photovoltaic/thermal system performance: a 3E analysis approach. *J Therm Anal Calorim*. 2025;150(23):19575–89.
 79. Sangeetha M, Manigandan S, Ashok B, Brindhadevi K, Pugazhendhi A. Experimental investigation of nanofluid based photovoltaic thermal (PV/T) system for superior electrical efficiency and hydrogen production. *Fuel*. 2021;286:119422.
 80. Hasan DJ, Farhan AA. The Effect of Staggered porous fins on the performance of Photovoltaic panel in Baghdad. *Journal of Engineering*. 2020;26(8):1–13.
 81. Yousefi T, Shojaeizadeh E, Veysi F, Zinadini S. An experimental investigation on the effect of pH variation of MWCNT-H₂O nanofluid on the efficiency of a flat-plate solar collector. *Sol Energy*. 2012;86(2):771–9.
 82. Yousefi T, Veysi F, Shojaeizadeh E, Zinadini S. An experimental investigation on the effect of Al₂O₃-H₂O nanofluid on the efficiency of flat-plate solar collectors. *Renewable Energy*. 2012;39(1):293–8.
 83. Chougule SS, Pise AT, Madane PA. Performance of nanofluid-charged solar water heater by solar tracking system. *International Conference on Advances in Engineering, Science and Management* 2012; 247–253.
 84. Tiwari AK, Ghosh P, Sarkar J. Solar water heating using nanofluids—a comprehensive overview and environmental impact analysis. *International Journal of Emerging Technology and Advanced Engineering*. 2013;3(3):221–4.
 85. Vakili M, Hosseinalipour SM, Delfani S, Khosrojerdi S, Karami M. Experimental investigation of graphene nanoplatelets nanofluid-based volumetric solar collector for domestic hot water systems. *Sol Energy*. 2016;131:119–30.

86. Gad MS, Said M, Hassan AY. Effect of different nanofluids on performance analysis of flat plate solar collector. *J Dispersion Sci Technol*. 2021;42(12):1867–78.
87. Desisa TR. Experimental and numerical investigation of heat transfer characteristics in solar flat plate collector using nanofluids. *International Journal of Thermofluids*. 2023;18:100325.
88. Zhao J, Song Y, Lam WH, Liu W, Liu Y, Zhang Y, et al. Solar radiation transfer and performance analysis of an optimum photovoltaic/thermal system. *Energy Convers Manage*. 2011;52(2):1343–53.
89. Cui Y, Zhu Q. Study of photovoltaic/thermal systems with MgO-water nanofluids flowing over silicon solar cells. *Asia-Pacific Power and Energy Engineering Conference* 2012; 1–4.
90. Sardarabadi M, Passandideh-Fard M, Heris SZ. Experimental investigation of the effects of silica/water nanofluid on PV/T (photovoltaic thermal units). *Energy*. 2014;66:264–72.
91. Al-Shamani AN, Sopian K, Mat S, Hasan HA, Abed AM, Ruslan MH. Experimental studies of rectangular tube absorber photovoltaic thermal collector with various types of nanofluids under the tropical climate conditions. *Energy Convers Manage*. 2016;124:528–42.
92. Crisostomo F, Hjerrild N, Mesgari S, Li Q, Taylor RA. A hybrid PV/T collector using spectrally selective absorbing nanofluids. *Appl Energy*. 2017;193:1–14.
93. Said Z, Arora S, Bellos E. A review on performance and environmental effects of conventional and nanofluid-based thermal photovoltaics. *Renew Sustain Energy Rev*. 2018;94:302–16.
94. Altan H, Alshikh Z, Belpoliti V, Kim YK, Said Z, Al-Chaderchi M. An experimental study of the impact of cool roof on solar PV electricity generations on building rooftops in Sharjah. *UAE International Journal of Low-Carbon Technologies*. 2019;14(2):267–76.
95. Sheikholeslami M, Farshad SA, Ebrahimpour Z, Said Z. Recent progress on flat plate solar collectors and photovoltaic systems in the presence of nanofluid: a review. *J Clean Prod*. 2021;293:126119.
96. Ranjan A, Podder B, Das B, Biswas A. Computational investigation of an innovative solar photovoltaic thermal collector with spiral shaped absorber using bifluid coolant. *Int J Environ Sci Technol*. 2024;21(3):2827–42.
97. Huang MJ, Eames PC, Norton B, Hewitt NJ. Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics. *Sol Energy Mater Sol Cells*. 2011;95(7):1598–603.
98. Hassan A, Nouman H, Assi A, Norton B. Temperature regulation and thermal energy storage potential of phase change materials layer contained at the back of a building integrated photovoltaic panel. *30th International on Passive and Low Energy Architecture Conference-Sustainable Habitat for Developing Societies: Choosing the Way Forward, PLEA 2014*; 139–145.
99. Hasan A, Alnoman H, Rashid Y. Impact of integrated photovoltaic-phase change material system on building energy efficiency in hot climate. *Energy and Buildings*. 2016;130:495–505.
100. Hasan A, McCormack SJ, Huang MJ, Sarwar J, Norton B. Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates. *Sol Energy*. 2015;115:264–76.
101. Tan L, Date A, Fernandes G, Singh B, Ganguly S. Efficiency gains of photovoltaic system using latent heat thermal energy storage. *Energy Procedia*. 2017;110:83–8.
102. Kouravand A, Kasaeian A, Pourfayaz F, Rad MAV. Evaluation of a nanofluid-based concentrating photovoltaic thermal system integrated with finned PCM heatsink: an experimental study. *Renewable Energy*. 2022;201:1010–25.
103. Cuce E, Bali T, Sekucoglu SA. Effects of passive cooling on performance of silicon photovoltaic cells. *International Journal of Low-Carbon Technologies*. 2011;6(4):299–308.
104. Cuce E, Cuce PM, Guclu T. A novel passive cooling configuration for photovoltaic panels based on bio-inspired heat-sinks and nanoparticle-enhanced PCM. *Appl Therm Eng*. 2026;292:130312.
105. Hasan DJ, Farhan AA. Enhancing the efficiency of photovoltaic panel using open-cell copper metal foam fins. *International Journal of Renewable Energy Research*. 2019;9(4):1849–55.
106. Mutar WM, Alaiwi Y. Experimental investigation of thermal performance of single pass solar collector using high porosity metal foams. *Case Studies in Thermal Engineering*. 2023;45:102879.
107. Nassar YF, Alsadi SY, Ali KA, Yousef AH, Fakher MA. Numerical analysis and optimization of area contribution of the PV cells in the PV/T flat-plate solar air heating collector. *Journal of Solar Energy Research Updates*. 2019;6:43–50.
108. Al-Karboly AM, Ibrahim A, Fazlizan A, Sopian K, Al-Aasam AB, Ishak MAAB, et al. Experimental evaluation of a photovoltaic thermal collector using twisted tape absorber with nano-enhanced phase change material for thermal storage. *Journal of Energy Storage*. 2025;109:115122.
109. Imbayah I, Nassar Y, Khaleel M, El-Khozondar H, Elmnifi M, Mohammed M. Modeling A 600 MW Floating Photovoltaic System in Al-Khums city, Libya: Performance Analysis and Implementation Using PVSyst. *Wadi Alshatti University Journal of Pure and Applied Sciences*. 2026;4(1):223–37.
110. Elmnifi M, Duyun TA. Performance Studies of Photovoltaic Air Collector with Aluminum Foam Fins. *Engineering Technologies and Systems*. 2025;35(3):389–404.
111. El-Khozondar H, El-Khozondar R, Nassar Y, Asfour A, Albardawil M, El-Zesty M, et al. Economic and environmental implications of solar energy street lighting in urban regions: a case study. *Wadi Alshatti University Journal of Pure and Applied Sciences*. 2025;3(1):142–51.
112. Aqila AH, Abubaker A, Nassar Y. Design of a hybrid renewable energy system to meet housing thermal loads: performance evaluation under real conditions of a house in Samno region, Libya. *Wadi Alshatti University Journal of Pure and Applied Sciences*. 2025;3(2):179–91.
113. Abdulrazig OD, Al-Zuhairy RC, Nadhim AA, Elmnifi M, Aleksandrova DT, Elbreki AM, et al. Enhancing Solar Cell Efficiency via Nanotechnology: A CFD-Driven Comparison with Conventional Models. *Mathematical Modelling of Engineering Problems*. 2025;12(6):2177.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Monaem Elmnifi¹ · Hasan A. Al-Asadi² · Karrar A. Hammoodi³ · Erdem Cuce^{4,5,6}  · Duyun Tatyana Aleksandrovna¹ · Hala J. El-Khozondar^{7,8} · Yasser F. Nassar⁹ · Shahad A. Salih¹⁰

✉ Erdem Cuce
erdem.cuce@erdogan.edu.tr

Monaem Elmnifi
Monm.hamad@yahoo.co.uk

Hasan A. Al-Asadi
Monm.hamad@yahoo.co.uk

Karrar A. Hammoodi
karrar1989@uoa.edu.iq

Duyun Tatyana Aleksandrovna
tanduun@mail.ru

Hala J. El-Khozondar
hkozondar@iugaza.edu.pa

Yasser F. Nassar
y.nassar@wau.edu.ly

Shahad A. Salih
shahad.ahmed@uoa.edu.iq

¹ Department of Mechanical Engineering Technology,
Belgorod State Technological University Named After V.G.
Shukhov, Belgorod, Russia

² Center for Research On Environment and Renewable Energy,
University of Karbala, Karbala, Iraq

³ College of Engineering, University of Al Maarif, Ramadi,
Al Anbar, Iraq

⁴ Department of Mechanical Engineering, Faculty
of Engineering and Architecture, Recep Tayyip Erdogan
University, Zihni Derin Campus, 53100 Rize, Türkiye

⁵ Center for Research Impact & Outcome, Chitkara University,
Rajpura, Punjab 140401, India

⁶ University Centre for Research and Development,
Chandigarh University, Mohali, Punjab 140413, India

⁷ Electrical Engineering and Smart Systems Department,
Islamic University of Gaza, Gaza, Palestine

⁸ Department of Materials and London Centre
for Nanotechnology, Imperial College, London SW7 2AZ,
UK

⁹ Mechanical and Renewable Energy Engineering Department,
Engg, Faculty, Wadi Alshatti University, Brack, Libya

¹⁰ Department of Medical Instruments Engineering Techniques,
College of Engineering, University of Al Maarif, Al Anbar,
Ramadi 31001, Iraq