Interactions (2025) 246:41
https://doi.org/10.1007/s10751-025-02267-y

CONFERENCE PROCEEDING

Cutting-edge cooling techniques for photovoltaic systems: a comprehensive review

Reji Kumar Rajamony[1,2] · K. Sridhar[3] · B. Kalidasan[4] · Richa Mishra[5] · Rizwan A. Farade[6] · A. Megalingam[3] · John Iruthaya Raj M[7] · Mohammad Nur-E-Alam[1,8,9] · Tarek Abedin[1]

Accepted: 4 February 2025

Abstract
The efficiency of photovoltaic (PV) systems is often limited due to surface temperature increases, which result from absorbed solar energy being converted into heat. This rise in temperature reduces power output, system performance, and panel lifespan. To address these challenges, combined photovoltaic thermal (PVT) systems have emerged, enabling the simultaneous generation of electricity and thermal energy. This review provides a detailed analysis of the factors affecting PV panel efficiency, explores various feasible cooling techniques including innovative methods to mitigate excessive heating, and highlights opportunities for future research in this field. The article focuses on the experimental and theoretical advancements in PV cooling over the past decade, offering valuable insights and practical guidelines for researchers aiming to improve PV module cooling strategies. Additionally, an economic assessment of PVT systems is conducted, evaluating their financial feasibility in terms of payback periods and costs. The review also presents a comparative analysis of PVT techniques, addressing their benefits, challenges, and potential applications. This work aims to serve as a comprehensive resource for researchers exploring the viability and industrial applications of PVT systems, paving the way for more efficient and sustainable solar energy solutions.

Keywords Photovoltaic thermal system · Electrical efficiency · Photovoltaic cooling · Energy

1 Introduction

Solar photovoltaic (PV) panels have the efficiency of converting just 15–20% of the incoming solar radiation to electrical energy. The rest of the incident solar radiation is transferred into heat, which initiates the temperature of the PV module to increase by up to 40 ℃ over the surrounding temperature [1]. The elevated temperature has both immediate and prolonged effects on photovoltaic modules. The PV efficiency experiences a reduction of approximately 0.4% per degree Celsius in the short term [2]. Over time, the repetitive heat stress can lead to structural harm to the PV module and decrease the lifespan of the

Extended author information available on the last page of the article

PV system by hastening the pace of aging [3]. According to Chauhan et al., the rate at which the PV module ages is multiplied by two for every 10 °C rise in the temperature at which the cells are operated [4]. A system that is capable of generating both electricity and thermal energy simultaneously is known as a photovoltaic thermal (PVT) system [5]. This innovative technology integrates traditional photovoltaic panels, which convert sunlight into electricity, with a thermal collector that captures the excess heat produced during the PV process. By efficiently utilizing the waste heat, a PVT system not only enhances the overall energy output but also provides thermal energy that can be used for a variety of applications, such as water heating, space heating, or industrial processes. This dual-purpose capability makes PVT systems particularly valuable for applications where both electrical and thermal energy are needed, offering a more efficient and sustainable solution compared to conventional PV systems [6]. This integrated approach helps lower the temperature of the PV cells, thereby boosting system efficiency while minimizing space requirements and costs Furthermore, the electric energy output for every unit area of PVT systems exceeds that of individual PV and solar thermal collectors. The concept of PVT collectors emerged in the 1970s with the purpose of cooling PV cells. The objective extended beyond mere efficiency enhancement; it aimed to maximize the utilization of expensive concentrated PV collectors, necessitating a cooling mechanism. PVT systems serve various purposes, including solar air systems, residential hot water production, and heating swimming pools [7]. Despite the recent global expansion of the PVT industry, the technology has yet to secure a significant market share compared to other solar technologies. This is primarily attributed to the complexity involved in the design of system and setting up [2].

Recently, a PVT module-based desiccant air-cooling system for buildings was analyzed using extended exergy analysis. The findings revealed significant differences between the results of extended exergy analysis and conventional exergy analysis, particularly in terms of exergy destruction and exergy efficiency. The maximum exergy efficiencies obtained were 0.84 and 0.18 for conventional and extended exergy analyses, respectively. Another notable difference was observed in the exergy destruction values, which increased from 5,085.50 kJ to 98,029.50 kJ for the conventional and extended analyses, respectively, highlighting the impact of the extended exergy approach on system performance evaluation [8]. Energy and exergy analyses of the air-based PVT system were conducted, along with temperature distribution on the panel surface and air velocity distribution in the cooling channel, using ANSYS Fluent. These results were compared to experimental data. The use of sparse and frequent fins, compared to the unmodified setup, increased the exergy efficiency of polycrystalline and monocrystalline panels by approximately 70% and 30%, respectively. Additionally, their thermal efficiency improved by around 55% for polycrystalline and 70% for monocrystalline panels [9]. Another study analyzed the performance of water-cooled PV panels, focusing on the efficiency improvements for residential applications. The results showed that at the lowest efficiency enhancement levels, the photovoltaic-thermal water (PVT-W) system achieved the highest values for energy gain, savings, and CO_2 reduction, with averages of 634.57 kWh, $272.86, and 368.05 kg, respectively [10]. Another researcher, Zhang et al. [11] reported that when operating the system in composite mode, the average electrical efficiency for the two phases was 16.79% and 18.33%, while the average collector efficiency reached 42.72% and 98.94%, respectively. Recently, Meon et al. [12] compared the performance of a conventional PV system with water-cooled and nanofluid-cooled PVT systems. The uncooled PVT system reached a maximum panel temperature of 68.4 °C at noon, with an average electrical efficiency of 12.98%. Water and nanofluid cooling reduced the panel temperature by 15 °C and 23.7 °C at noon, respectively. As a result, the average electrical efficiency of the water-cooled and nanofluid-cooled PVT systems increased by 12.32% and 35.67%, reaching 14.58% and 17.61%, respectively. The thermal efficiency of the nanofluid-cooled PVT system (71.17%) was significantly higher than that of the water-cooled system (58.77%), due to the enhanced heat absorption by nanoparticles.

Song et al. [13] reported that the proposed coaxial condensing heat pipe integrated PVT system (CCHP/PVT) shows a respective enhancement of 5.2% and 14.4% in electrical and thermal efficiencies compared to conventional heat pipes. Also, findings indicate that the morning period consistently exhibits the highest thermal efficiency throughout the seasons, remaining between 50% and 55%. In contrast to natural cooling and traditional heat pipe cooling approaches, the CCHP/PVT system showcased a notable decrease in PV panel temperatures, with reductions of approximately 30.3% and 16.3%, respectively. A detailed analysis was examined to assess the influence of various physical and environmental factors on PVT system performance. The outcome confirmed that, under favorable radiative cooling conditions, overnight cooling power escalated by up to 45.1 W/m^2. The model consistently underestimated the output temperature fluid by a maximum of 2°C, specifically during winter. However, it remains a convenient and efficient design tool, as it eliminates the need for intricate input data and extensive computing requirements was done by Almatham et al. [2]. Melaibari et al. [14] recently designed a novel PVT system with an elliptic cooling duct and nanofluid. It was reported that the increase in both electrical and thermal power with the increase in Hartmann number results in an improvement of around 80.81% and 15.1%, respectively, particularly with higher velocity. As the velocity increases, the cooling improves, and the electrical and thermal effectiveness increase by approximately 4.03% and 30.26%, respectively. Ensuring a consistent temperature distribution throughout the panel is essential for evaluating its performance. Another researcher performed the exergy analysis of PVT system cooling with desiccant air cooling for building applications. The findings indicate that extended exergy analysis yields distinct outcomes compared to traditional exergy analysis, specifically concerning exergy destruction and efficiency. The system achieves maximum exergy efficiencies of 0.84 and 0.18 when standard and extended exergy studies are considered, respectively [8]. Oclon et al. [15] analyzed the thermal performance of sun-tracked and cooled PVT systems for enhanced cooling performance of PV devices. The outcome revealed that the cooling and tracking system improved the electrical performance and harvested the heat energy from the system, the energy from heat can be utilized for medium-temperature applications. Reji Kumar et al. [16] recently performed the heat transport and energy evaluation of water-based PVT units. The study reported that by incorporating water cooling with a PVT system, the electrical power was enhanced by 3.1% compared to a conventional system, and the heat gain was found to be thermal power has found 329 W. In another study, Reji Kumar et al. [17] analyzed the thermal and electrical behavior of water-cooled and PCM integrated PVT device for domestic applications. It has been found that the electrical efficacy was improved to 6.34% and 34.9% for PCM integrated water-based PVT system than natural coolled PV system. In addition, the gained thermal efficiency was utilized for medium temperature applications. Recently, the water and nanofluid cool down PVT systems electrical performance improved by 12.3% and 35.7%, respectively, compared to PV system. This resulted in efficiencies of 14.58% and 17.61% for the water and nanofluid-cooled systems, correspondingly. The nanofluid-cooled PVT system exhibited a thermal efficiency of 71.17%, notably superior to the thermal efficiency of water cooling at 58.77%. This improvement can be attributed to the nanoparticles' ability to absorb a greater amount of heat, was analyzed by Menon et al. [12]. In another study, Zareie et al. [18] investigated a branch inspired channel in roll bond PVT system of enhancing the PVT performance. Based on the acquired findings, the optimal scenario system has the potential to enhance PV electricity efficiency by 20.4%. The electrical, thermal, and overall PVT efficiency of the ideal system is 17.7%, 61.9%, and 79.6%, respectively.

Reji Kumar et al. analyzed a detailed review of various types of cooling fluid in the PV system and their applications in various fields were analyzed extensively. Also, discussed the PCM-integrated PVT subsystem and their application and the challenges were discussed extensively [1]. Lazzarin [7] performed a comprehensive review of the insights of PVT systems in the future. The review to comprehend the progression from the initially intended solar-assisted heat pump designs to the current intricate systems, with a potential glimpse into the future. Dwivedi et al. [19] reviewed the various issues for increasing temperature and dust accumulation of the PV unit and the methods to lower the panel heat of the PV system, as well as the challenges faced during the cooling of the PV systems were extensively discussed. Chauhan et al. [4], comprehensively analyzed the latest tendencies and beneficial technologies for heat management in PVT collectors. The analysis is organized into categories: liquid-based, phase change material (PCM)-based, air-based, and heat pipe-based systems. The paper also explores the various applications of these technologies in areas such as buildings, PV systems, electronics, solar desalination, and textiles.

From the above literature, it was observed that considerable research and development efforts have been dedicated to PVT technology over the past decades, with activity levels gradually increasing. However, there has been a dearth of progress in terms of international involvement and the commercialization of PVT systems. The objective of this review article remains to provide a comprehensive sorting of PVT systems, examine both experimental and theoretical research conducted on various PVT systems in current years, and review the various causes for the utilization of cooling techniques in PVT applications. In addition to this, the experimental applications of hybrid PVT systems with and without PCM have been extensively reviewed, analyzed, and summarized for various industrial applications. This technology offers significant benefits by reducing electrical consumption, shifting peak cooling and heating loads to off-peak periods, minimizing temperature fluctuations, and enhancing thermal comfort and indoor stability. Furthermore, it entails a relative study of PVT methods based on their primary advantages, challenges, and prospects for future development. The structure of the paper is organized as follows: Section 2 provides a detailed overview of photovoltaic thermal (PV/T) systems, analyzing the impact of temperature on PV performance and factors affecting the PVT system, Section 3 provides the overview of PVT system, performance, advanced technologies for adaptive cooling frameworks, highlighting the latest innovations in the field and classifications. The economic impact of these systems is discussed in Section 4, followed by Section 5 concludes with a summary, and Section 6 future research recommendations.

2 Factors affecting pv module efficiency

The sum of electric power produced by PV systems constantly changes depending on the climatic conditions of the location. Electricity generated by the panels is impacted by variations in surface temperature, shadow effects, soiling, wind speed, and incident solar radiation [20]. Throughout the energy conversion process, the operating temperature of the photovoltaic panel is crucial. Typically, PV systems are optimized and function most effectively under standard test conditions (STP), which include a cell temperature of 25 °C, air mass of 1.5, and irradiation of 1000 W/m², aiming for peak efficiency [16]. Solar radiation and temperature are the key variables influencing PV system performance, while other factors also play a significant role in determining its effectiveness.

2.1 Effect of temperature

Direct solar radiation is effectively transformed into electrical power using photovoltaic panels, as they are efficient technology for harnessing solar energy. Solar PV panels contribute to about 60% of global renewable energy generation and are expected to increase significantly by 2026. Unfortunately, the majority of commercial PV technologies currently in use have energy conversion rates ranging from 5 to 20% [1]. However, continuous exposure to extremely high ambient temperatures causes this rate to drop, as the unavoidable rise in surface temperature negatively impacts efficiency. Overheating from excessive solar radiation and high ambient temperatures poses one of the biggest challenges for PV panel operation, particularly for crystalline silicon panels in Sunbelt countries. According to existing research, efficiency drops of PV panels range from 0.25 to 0.5% per °C rise in temperature, depending on the PV technology used [21]. Furthermore, overheating of PV panels in specific locations results in serious consequences for their lifespan, leading to economic loss [22].

PV panel overheating is caused by high ambient temperatures and excessive surface operating temperatures, lengthening the system's payback period and drastically reducing its lifespan and efficiency. In Middle Eastern and Asian countries, where ambient temperatures range from 40 to 45 ℃, this condition significantly reduces the overall performance of PV panels. To address this issue, various cooling techniques are employed to maintain the panel at its nominal working temperature [23]. However, Middle Eastern and Asian countries also face challenges due to a lack of water, which is commonly used as a thermic fluid for cooling PV panels. Conversely, European nations experience the predominant impact of the winter season on the working effectiveness of PV panels, as snow and mist accumulate on the panels, disrupting their operation and reducing incident solar power.

2.2 Effect of solar radiation

The level of the short-circuit current is influenced by the quantity of photons absorbed by the semiconductor material, thus directly connected to the level of light intensity [20]. Conversion efficiency typically remains relatively stable, meaning that the power output is often linked to irradiance. However, an increase in cell temperature diminishes efficiency. The open-circuit voltage exhibits minimal variation in response to changes in light intensity [24].

2.3 Effect of dust

Soiling losses occur when the surface of a PV module is covered by snow, dirt, dust, or other particles. The dust accumulation on the PV module's surface consists of minuscule particles, typically smaller than 10 mm, but this may differ based on the location and environment of the PV panel installation. Various factors contribute to the formation of dust, such as airborne particles carried by wind, volcanic eruptions, and the movement of automobiles. Over time, the accumulation of dust exacerbates the process of soiling [24]. The quantity of dust accumulation on the PV unit's surface impacts its daily, monthly, seasonal, and yearly energy production. Despite advancements in energy efficiency, the operation of PV systems can still be inefficient due to environmental and natural factors such as soil, brine, bird droppings, snow, and debris that accumulate on the surfaces of PV modules. Hence, a comprehensive examination is necessary to evaluate the influence of solar panels on dust in order to attain peak efficiency and maximize energy production [25].

2.4 Effect of humidity

Air humidity denotes the quantity of water vapor contained within the atmosphere. Relative humidity is often used to measure atmospheric moisture, indicating the amount of moisture in the air. When assessing the impact of moisture, researchers commonly consider two conditions. The first effect is the influence of water vapor particles on the intensity of sunlight, while the second effect is the influence of humidity when entering enclosed PV modules. Relative humidity fluctuates in response to changing temperatures throughout the day, and humidity and temperature generally have an inverse correlation [22].

3 PVT principles and performances

The integrated PVT system stands as a notable advancement in solar technology. Multiple methods are employed to extract heat from the solar modules within these systems, with the extracted heat utilized in various thermal applications. The concept of PVT emerged in the 1970s, with numerous theoretical and experimental studies documented in the literature during that period. Initially, water and air were widely utilized to extract heat from PV devices. Technological advancements have significantly expanded during the past thirty years. In addition to harnessing the thermal energy from the PV modules, recent research has also focused on incorporating spectrum filters into PVT systems [26].

The theory of a PVT unit is approximately 50 years old. However, the methodology has not been widely marketed. Engaging in discussions about recent technological advancements is consistently advantageous as it allows for a comprehensive understanding of progress and provides guidance for future development.

3.1 PVT System

PV systems are utilized to capture electricity from solar radiation. When sunlight strikes a PV panel, around 15–20% of the irradiation is converted into electricity, while the rest of the energy may be transmitted, reflected, or converted into heat. The rise in panel temperature can lead to a decline in its electrical output. To address this issue, a system that generates both electricity and heat concurrently is termed a PVT system. Figure 1 illustrates the concept of the PVT system. PVT systems are hybrid technologies merging PV and thermal components to optimize solar energy utilization and enhance overall system outcome compared to conventional PV or solar thermal setups. These systems feature a series of parallel tubes attached to the rear side of the PV panel. A cooling fluid circulates through these tubes, extracting heat from the PV system. This process decreases the panel's temperature, improving its electrical performance, while raising the water temperature. Consequently, the panel's surface temperature decreases, its performance improves, and the hot fluid can be used for various medium-temperature applications. There are many types of PVT systems are used to cool the PV system as discussed in the next section,

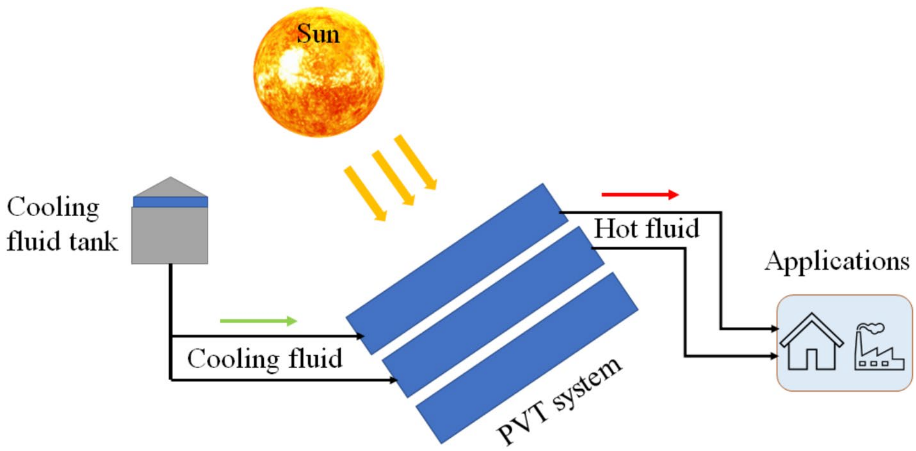

Fig. 1 Concept of PVT system

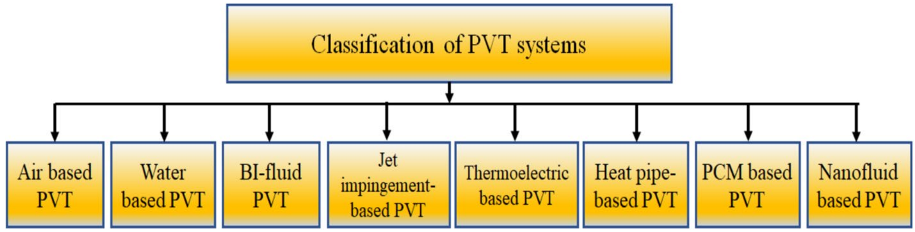

Fig. 2 Classification of the PVT system

3.2 Classification of PVT system

The PVT units are categorized based on the organization of the temperature extraction, working method, and end applications. In addition, PVT units can be categorized according to the arrangement of radiations, specifically based on whether they involve concentration or non-concentration. Figure 2 illustrates a comprehensive categorization of PVT systems. The following text discusses the significant research conducted on PVT systems in recent times.

3.2.1 Air-based PVT systems

In an air-assisted PVT system, air flows through the PV panels using either passive or active methods, taking use of natural or induced convection. Generally, forced convection mode involves the use of a blower or fan to achieve a higher airflow rate. This airflow facilitates the extraction of heat from the PV panel, consequently enhancing efficiency and extending the panel's lifespan [16]. The harvested heat energy can be applied to medium heating tasks. Numerous investigators have dedicated their endeavors to enhancing the effectiveness of air-based PVT units through both numerical simulations and practical experiments.

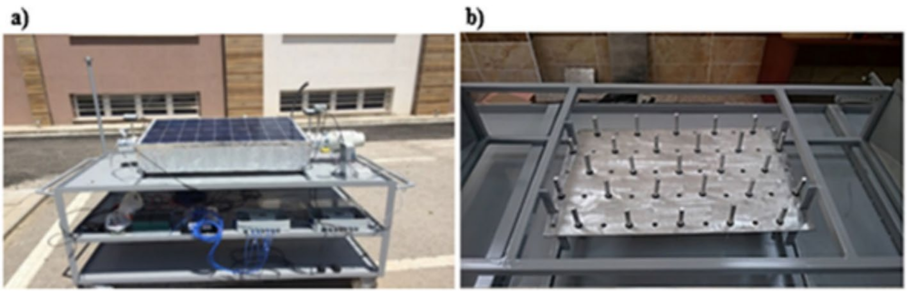

Fig. 3 Experimental setup **a**) Mobile PVT system **b**). Control volume at sparse configuration [9] [Reused with permission from publisher licence number-5950680663767]

The energy and exergy evaluation of air-based fin-type PVT devices was investigated by Ahmet Numan et al. [9]. They analyzed different fin configurations by using ANSYS Fluent software. The photographic view of air assisted fin type PVT system is demonstrated in Fig. 3. The exergy efficiency of polycrystalline and monocrystalline using sparse and frequent fin was increased by 70% and 30%, respectively than empty status and their thermal output improved by 55% and 70%. Correspondingly, the panel temperature was reduced between 10 and 15 °C for both PV panels.

Tiwari et al. [27] performed both theoretical and experimental work on mixed-mode greenhouse solar drier. The outcome was based on the quality of the dried product which increased and decolorization was minimized due to the gradual heating of the product. The theoretical and experimental work yielded overall thermal efficiencies of 1.9 kWh and 2 kWh, respectively. Also, the whole thermal exergy of theoretical and experimental work has been found 0.532 kWh and 0.535 kWh, respectively. The energy and exergy analysis of air-based PVT unit was done by Srimanickam et al. [28]. The important parameters considered were solar irradiation, voltage, current, ambient temperature, PV module temperature, air inlet, and outlet temperature. The result shows that the thermal, electrical, overall energy and overall exergy efficiency were 24.17%, 9.78%, 44.84% and 11.23%, respectively.

Singh et al. [29] analyzed the modeling and investigation of a dual-channel semitransparent photovoltaic thermal (DCSPVT) system proposed with different configurations of airflow, either one channel or two channels. Outcomes presented the improvement in thermal, electrical, overall and exergy efficiency of the DCSPVT system at 34.57%, 5.78%, 35.41% and 71.5%, respectively compared to SCSPVT. Also, the DCSPVT system temperature was reduced to 43.11 °C. Antonanzas et al. [30] focused on thermodynamic issues regarding improving the convective heat losses between the spacing in a covered panel by substituting air with different gas. The results suggested that the convective heat loss improved up to 50.4% and the overall heat loss coefficient improved 8.11% when use of xenon gas. However, environmental and economic considerations argon gas is a great opening for PVT systems.

Ooshaksaraei et al. [31] established four models: single path, double path parallel flow, double path counterflow, and double path returning flow. The results indicated that the bifacial PVT with double-path parallel flow exhibited higher overall efficiency than the other systems, surpassing the thermal efficiency of the other three models. However, a single-path flow system has higher electrical efficiency compared to the other three models. The air-based PVT unit with metallic fins with varied mass flow rates of 0.02 to 0.14 kg/s was done by Mojumder et al. [32]. It was viewed that the maximum thermal and electrical output of the PVT system with four fins was 56.19% and 13.75%, respectively at flow rate of 0.14 kg/s. Also, the experimental values were validated with the thermotical and statistical Analysis. Popovici et al. [33] performed numerical analysis on the temperature reduction in PV panels using air-cooled heat sinks with different configurations. It validates that the temperature is reduced in the PV panel with a heat sink at least 10 °C lower than the base one. The electrical energy enhanced 6.97–7.55% higher than the nominal one. Jha et al. [34] explored the energy and exergy of the PVT air system in Silchar northeast India with an airflow rate of 0.007 kg/s, to 0.0128 kg/s. This study considers parameters like panel temperature, outlet air temperature, energy and exergy gain, and mass flow rate for analysis. The result shows that the maximum flow rate of 0.0128 kg/s in December. Also, the energy and exergy gain in December was 152Whr and 7.88Whr respectively and in March 185 Whr and 17.82 Whr, respectively.

3.2.2 Water-based PVT system

In high-temperature applications, the effectiveness of air-cooled PVT units is hindered by their relatively low thermal properties. Conversely, water boasts superior thermal characteristics, including thermal conductivity and specific heat, when compared to air. In water-cooling PVT units, two distinct cooling approaches are employed: passive and active strategies [35]. The technique involves the attachment of water tubes to the back of the PV panel, through which water circulates. The water absorbs the heat emitted by the PV unit, resulting in a decline in the panel's temperature and a raise in its lifespan. The hot water from the outlet can be employed for different purposes. Only a limited number of research studies have specifically examined passive cooling PVT systems. In their study, Wu et al. [36] examined the use of rainwater for passive water-cooling of household photovoltaic (PV) panels. The gas expansion technique is employed to disperse the rail water to cool the PV module. The findings indicate a decrease in panel temperatures, accompanied by a gain in electrical efficiency of up to 8.3%. However, numerous researchers, including Kazemian et al. [37], Aste et al. [38], Herrando et al. [39], Rajoria et al. [40], Yazdanpanahi et al. [41], Shyam et al. [42] were performed the performance of cooling fluid-based PVT devise.

Chemisana et al. [43] examined the directly submerged PVT unit using several cooling fluids. The utilization of liquid-based spectrally selective filters in direct contact with the PVT unit offers numerous advantages. These liquid-based filters have the ability to selectively convert photons into electricity while preventing an increase in the temperature of the PV panel. The findings specified that the combination of deionized water and isopropyl alcohol solution yielded the most favorable electrical, thermal, and overall efficiency. Hamdoom et al. [44] analyzed the performance and created a numerical simulation of a PVT for solar domestic water heating (PVTSDHW). Figure 4 illustrates the cross-sectional perspective of the PVTSDHW system. It was concluded that the packing factor is crucial in PVTSDWH for meeting the process requirements. Moreover, an increase in the packing factor leads to a corresponding rise in electric generation. Ultimately, it was determined that PVTSDWH generated hot water ranging from 61.7 to 43.9% and power ranging from 24.5 to 43.9%, meeting the necessary requirements for a family's needs in different months.

Herrando et al. [39] studied a PVT system with 26 different absorber exchanger designs and compared it against a reference one. Figure 5 shows the cross-section of various cross-sections of the PVT system. It determined that the polycarbonate flat box design with

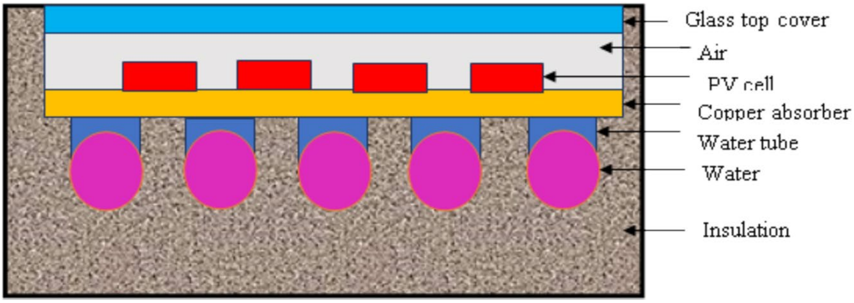

Fig. 4 Sectional view of PVTSDHW system [44] [Reused/reproduced with permission from publisher, licence number- 5950680917130]

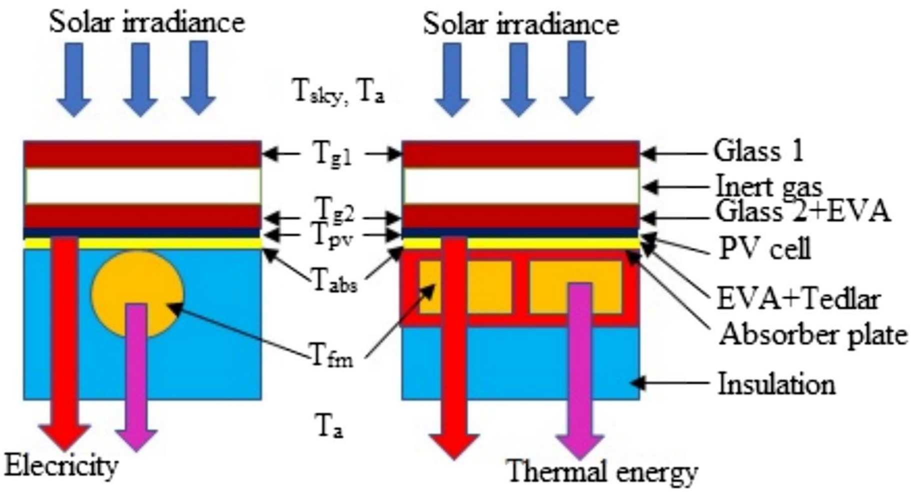

Fig. 5 Shell and Tube and box type configuration of PVT system [39] [Reused/reproduced with permission from the publisher, license number- 5950690440911]

3×2 mm rectangular channel PVT system is a more promising one than the commercial case. Also, thermal efficiency is 4% higher and weight 9% lower than the reference case.

Herrando et al. [45] performed a techno-economic analysis of PVT with combined heating and cooling for building applications. Author suggested that PVT-based solar combined cooling heating and power (SCCHP) unit has a significant potential to decarbonate urban areas, where the space is at best since the electrical and thermal generating power from the same area. In addition, the author suggested that to enhance efficiency and minimize the investment make cost is cost-effective with other renewable energy systems like commercial PV systems. Micheal et al. [46] analyzed and fabricated a novel PVT module by laminating a thin copper sheet at the bottom of the panel instead of tedlar. It was observed that the primary energy-saving efficiency was 35.32% using a PVT system with a thin copper sheet, although 20.87% for conventional PVT unit. The authors confirmed that increasing flow rate of water can enhance thermal, electrical, and overall efficiency. Wei Pang et al. [47] analyzed the polycrystalline silicon PV and photovoltaic thermal systems were numerically and experimentally investigated based on roll bond aluminum collector.

In numerical simulation, temperature, pressure and velocity distribution the parameters considered as steady state conditions and the water flow rate and heat flux were 0.034 kg/s and 700 W/m^2, respectively. According to the findings, the system demonstrated daily electrical, thermal, and exergy efficiencies of 13.67%, 40.56%, and 15.56%, respectively, when compared to a standard PV system. Shehadeh et al. [48] investigated and developed a new model for different photovoltaic coverage with variable and constant flow rate. In this study, important parameters like solar irradiation, wind speed, flow rate of water, ambient temperature, water input and output temperature were recorded every minute of the year and PV coverage ratio are from 1 to 100% to calculate the max overall thermal output of PVT system. The author established a new model for calculating the PV ratio (Eq. 1) and maximum overall thermal efficiency (Eq. 2).

$$\text{Maximum OTE} = a * (\text{PV ratio})^2 + b * \text{PV ratio} + c \tag{1}$$

$$\text{PV ration} = a_0 + a_1 * \cos(xw) + b_1 * \sin(xw) + a_2 * \cos(2xw) + b_2 * \sin(2xw) + a_3 * \cos(3xw) + b_0 * \sin(3xw) + a_4 * \cos(4xw) + b_4 * \sin(4xw) + a_5 * \cos(5xw) + b_5 * \sin(5xw) \tag{2}$$

Where, a,b, c were model coefficients, x is month and w is frequency.

The author found that the PV coverage ratio which produces the maximum overall thermal efficiency with constant and variable flow rates are different. The result suggested that variable flow gives better results, especially for autumn and winter seasons. Also concluded that variable flow is most suitable for practical applications.

3.2.3 Bi-fluid based PVT systems

The utilization of both air and water in a single PVT system by researchers is referred to as a biofluid system. The majority of writers have focused their research on using water and air as biofluids to cool PV panels while simultaneously generating hot water, hot air, and improving the performance of electrical energy. This system surpasses the constraints of distinct air and water-based PVT units [49, 50].

Attia et al. [51] investigated the thermal performance of finned-type bi-fluid-based PVT systems. The obtained data demonstrated a direct correlation between the flow rate increase and the decrease in thermal efficiency. The thermal efficiency of modules 1 and 2, with a mass flow rate of 0.010 kg/s, is 50% and 60% correspondingly. Module 2 improved thermal efficiency by around 5.7% compared to module 1, at 0.010 kg/s. The addition of fins to the hybrid PVT system (module 2), which operates at a mass flow rate of 0.010 kg/s, has demonstrated significant effectiveness in preserving the system's thermal efficiency at its peak level.

Su et al. [53] explored a hybrid PVT system with a cooling mechanism that uses two different fluids. The authors developed a multi-channel PVT system that incorporates four distinct bi-fluid combinations flowing through the channels: water-air, water-water, air-water, and air-air. The findings validated that an increase in fluid mass flow rate directly correlates with an improvement in overall performance. The analysis demonstrates that the water-water bi-fluid exhibits superior electrical, thermal, and total efficiency, measuring 7.8%, 64.4%, and 84.2% when subjected to a flow rate of 0.15 kg/s. The performance of the bi-fluid system was assessed by Othman et al. [54]. Jarmi et al. [52] examined the theoretical and practical aspects of a PVT system that utilizes air and water as the working fluids. Figure 6 shows a cross-sectional view of air and water-based PVT system. The result

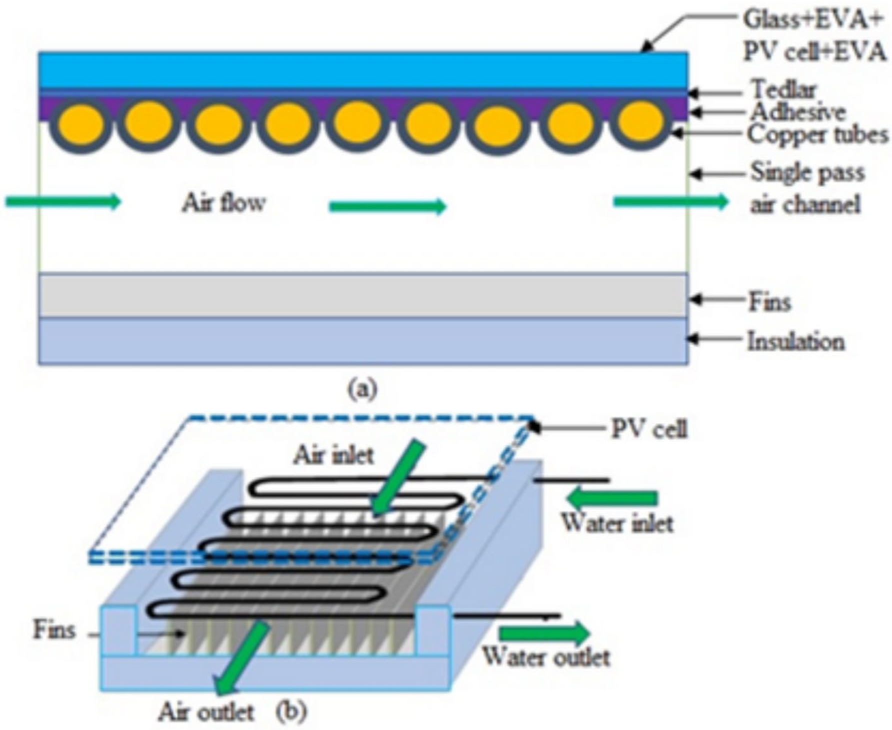

Fig. 6 **a**) side view of bi-fluid PVT system (**b**) 3D view of bi-fluid PVT system [52] [Reused/reproduced with permission from publisher licence number- 5950690793278]

shows that the energy-saving efficiency of bi-fluid system of air and water are 58.10% and 61.31%, respectively at optimum flow rate. The author confirmed that 2D developed model is novel, flexible and useful for three different modes of fluids can be simulated without any modification.

3.2.4 Jet impingement-based PVT system

Jet impingement is a highly effective technique for transferring heat between a PV panel and a fluid, such as water or air. This technology is highly effective in enhancing convective heat transfer and finds applications in several industries, such as food processing, electronic equipment cooling, turbine blade cooling, and boosting the electrical and thermal efficiency of PV panels [35]. Jaaz et al. [55] implemented PVT water jet impingement cooling along with a compound parabolic concentrator (CPC). The study's findings indicate that a higher mass flow rate of water leads to enhanced electrical productivity. The utilization of CPC with water jet impingement resulted in a notable 7% enhancement in the electrical efficiency of PV panels. Furthermore, the utilization of water jet impingement and CPC resulted in a significant enhancement of 36% in the power output of the PV unit. In their study, Belusko et al. [56] conducted an analysis of the experimental examination on the jet impingement of a solar collector. The findings indicated a 21% increase in thermal energy when employing jet impingement. The study performed by Abdulrasool et al.

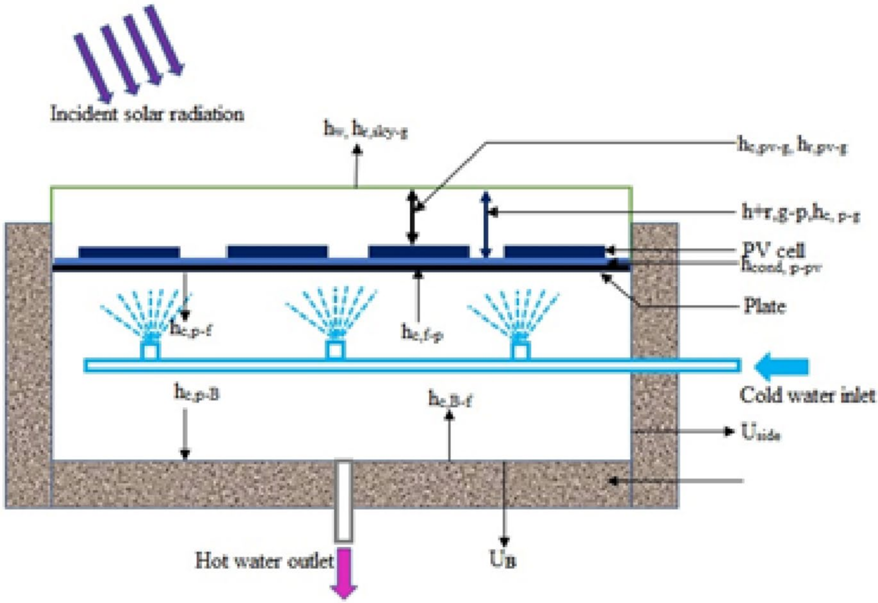

Fig. 7 Schematic illustration of jet collision system [57] [Reused/reproduced with permission from the publisher, license number- 5950691389075]

[55] explored the use of a water jet array nanofluid in a PVT system, utilizing different types of nanofluids. The findings indicate that the use of a nanofluid (SiC/water) jet array impingement results in improved efficiency.

Abdulrasool et al. [57] designed a PV collector with jet collision water system with varying rate of flow from 0.33 to 0.16 kg/s. The PVT solar collector with jet collision experimental setup is shown in Fig. 7. They observed a high heat transfer coefficient between the water and PV panel. The analysis indicates that the electrical efficiency was 11.35% and the thermal efficiency was 72%. In addition, a mathematical model was developed and correlated with the experimental findings, confirming an electrical accuracy of 95.8% and a thermal efficiency of 99.4%.

Experimental investigation and modeling of PV thermal management by using jet impingement was examined by Bahaidarah et al. [58] In this research, jet impingement system model was developed for the PV system to carry out the panel temperature, power output, and overall system performance. The result indicates that the panel temperature decreased from 69.7 °C to 36.6 °C when using the jet impingement system. Also, the power output and overall efficiency were improved 49.6% and 82.6%, respectively.

3.2.5 Thermoelectric-based PVT systems

The PVT cooling module operates by utilizing the Seebeck effect in thermoelectric materials. The thermoelectric effect is a phenomenon where a potential difference is generated among two different metals or semiconductors due to a temperature difference among them. Figure 8 depicts the sectional diagram of a thermoelectric generator. The backside of the PV module (source) is connected to one side of the junction, while cooling fluids such as air or water (sink), with a lower temperature than the source, are linked to the other side.

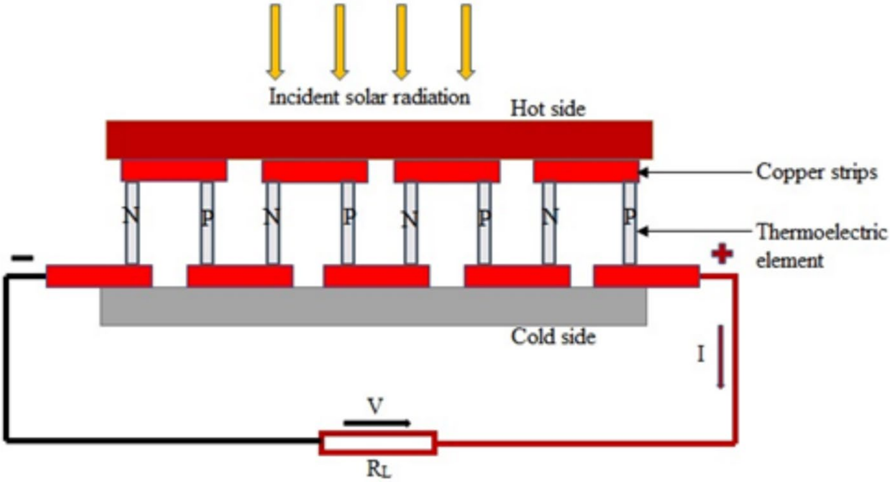

Fig. 8 Thermoelectric cooler [62]

The temperature differential between the two sides generates a potential difference across the metals. Thermoelectric cooling (TEC) is commonly employed for cooling electronic components, such as microprocessors [35]. Several writers have attempted to employ this strategy in PVT units. He et [59]. A thorough investigation of the theoretical and experimental aspects of thermoelectric heating and cooling within PVT systems was conducted. The findings revealed a coefficient of performance (COP) of 1.7 for the thermoelectric system. Furthermore, the thermoelectric-based PVT system displayed an electrical output efficiency of 16.7% and a thermal output efficiency of 23.5%. In their research, Makki et al. [60] outlined a theoretical analysis of a hybrid PVT system integrating a heat pipe-based TEC mechanism. The outcome indicated that the TEC system surpassed the standard PVT system in overall performance, effectively utilizing waste heat to enhance power output.

Dimri et al. [61] assessed a comparative evaluation of a water- and air-based PVT system combined with a thermoelectric cooler. The performance of three distinct PV modules, namely opaque, semitransparent, and aluminum, was compared. The findings indicate that the opaque PVT-TEC water system exhibits greater overall and thermal efficiency compared to the opaque PVT-TEC air system, with an increase of 1.9–2.8% and 20.8–21.8%, respectively.

The energy and economic analysis of PVT-TE was evaluated by Syakiah et al. [63] using the matrix inversion method. The author observed that PVT-TE systems can absorb energy and produce electrical energy at a minimum cost. The maximum electrical and thermal outputs were 12% and 84% at an optimum flow rate of 0.1 kg/s and 90 TE. Also, a cost-effective ratio (Annual cost (AC)/annual energy gain (AEG) is provided for various combinations of flow rate and number of TE to improve the user feasibility in choosing the optimal design features that parallel minimum AC/AEG.

Liu et al. [64] presents a modelling and simulation of PVT integrated with a thermoelectric ventilator (TEV) system. The author found that any increase in the fresh air volume flow rate improves the TEV system's electrical efficiency and heating performance. Syakiah et al. [65] evaluated the performance of an innovative PVT-TE air collector system by theoretically and experimentally. From the model electrical, thermal and exergy power ranges between 33.06 and 35.62, 0.56–1.43 and 72.92–75.29 W respectively at channel

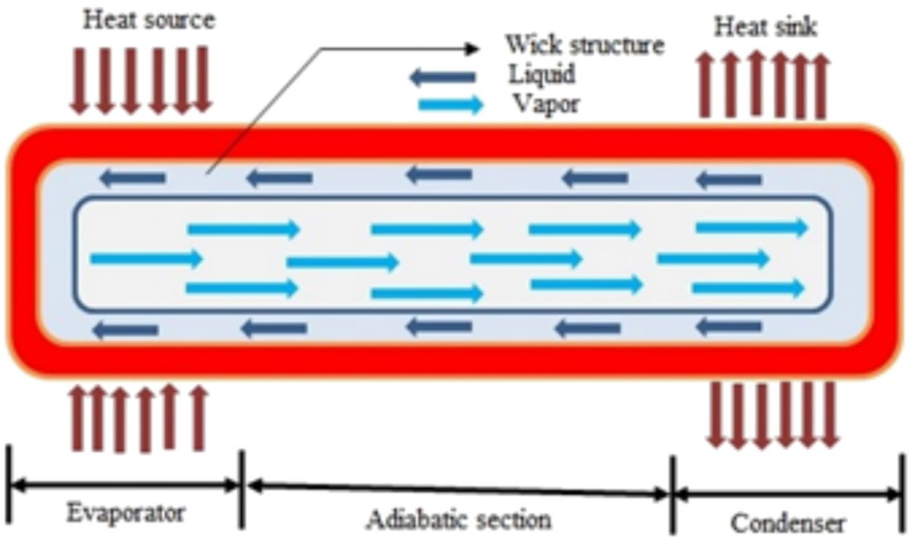

Fig. 9 Schematic diagram of heat pipe [69]

depth 0.09 m and the flow rate 0.001–0.15 kg/s. Also, thermal exergy decreases, and PV exergy increases with an increased mass flow rate. Finally concluded that temperature is the dominant factor affecting the conversion of energy in PVT-TE units.

Zhu et al. [66] designed thermo electric generator-based photovoltaic module (PV-TEG) and studied the energy analysis. Li et al. [67] compared the behavior of different types of photovoltaic panels like p-Si cells, Polymer cells and CIGS cells. The result highlighted that a hybrid Polymer-TE system's electrical output is 6.6% more than a Polymer system. Finally, the author concluded that the role of concentration ratio is very important to achieving electrical efficiency. When the concentration ratio is 200, the decrease in PV energy conversion energy is 4.0%, 3.5%, and 3.4%, and the increase in TE energy conversion is 2.4%, 6.0% and 4.8%, for the case of hybrid C-si-TE, hybrid P-Si-TE and hybrid CIGS-TE respectively. Moreover, the author concluded that the low-efficiency PV panel can be used in thermo-electric-based photovoltaic systems and maximum heat energy can be utilized in thermoelectric systems. The performance of a hybrid photovoltaic-thermo electric generator (PV-TEG) system using MATLAB/SIMULINK was analyzed by Babu et al. [68]. The result shows that the TEG system cools the PV panel and contributes the energy 1–3 of the PV rating. Also, the power developed from the hybrid PV-TEG system has increased to 8.3% with respect of 1000 W/m^2 solar irradiance.

3.2.6 Heat Pipe-based PVT systems

A heat pipe operates by leveraging the principles of evaporation and condensation to transfer heat efficiently between two solid surfaces, as illustrated in Fig. 9. In the evaporator section, a working medium facilitates the transfer of heat from the surroundings. This working fluid undergoes a phase change into vapor owing to pressure variations in the adiabatic section. The vapor phase then moves into the condenser unit, where it releases heat and undergoes a phase transition from vapor to liquid. Subsequently, it cycles back to the evaporator unit through the wick structure.

The PVT-HP technology utilizes heat pipes to passively cool the system. It is employed to dissipate the thermal energy from the PV unit. Several researchers have contributed to the development of PVT-HP systems. In their study, Shixiang et al. [70] administered an experimental investigation on a PVT-HP system using the vapor injection approach, also known as PVT VISHP. The analysis reveals that the system achieved an electrical efficiency of 7.51%, a thermal efficiency of 49.9%, and a power output of 7.24 kWh. The theoretical coefficient of performance (COPth) for the heat pipe was 3.27, whereas the coefficient of performance (COP_{PVT}) for the advanced PVT VISHP was 3.45. Zheng et al. [71] developed heat pipe without wick and heat pipe with wire mesh photovoltaic thermal systems and tested in 20° and 40° angles. The result shows that heat pipes without wick PVT have higher performance than heat pipes with wire mesh PVT devices. Also, observed that heat pipes with wire mesh PVT systems work efficiently at less than 20° inclined angle and wick less work efficiently at more than 20° angles. Yu, et al. [72] investigated a photovoltaic thermal-micro channel loop heat pipe (MC-CHP-PVT) system for producing electrical and thermal energy. The author suggested that by improving the solar thermal energy of MC-CHP-PVT, the inlet water temperature can be lowered, the flow rate can be increased, higher the ambient temperature and the larger distance between the evaporator and condenser. The result revealed that the most appropriate solar radiance is 561 W/m^2 and the thermal output and electrical output were 57.13% and 17.2%, respectively.

3.2.7 Nanofluid-based PVT system

The commonly recognized heat transfer fluids include water, ethylene glycol (EG), various oils, etc., all characterized by limited thermal conductivity and low heat transfer rates. The utilization of nanofluids [73] offers a viable solution to address this heat transmission issue. The concept of nanofluids was initially proposed in the 1990s. Nanofluids are composed of a base fluid, such as water or oil, and nanomaterials like TiO_2, Al_2O_3, CuO, CNTs, SiC, etc [50]. The combination of water and nanoparticles yields superior performance compared to traditional fluids, as the thermal properties of the nanomaterials significantly exceed those of the basic fluid. The addition of a small quantity of nanoparticles to a base fluid leads to a substantial improvement in heat conductivity. Improving the performance of photothermal research can be achieved by enhancing the efficiency of photovoltaic thermal systems through the utilization of nanofluids as a working medium [74–76].

Abdallah et al. [77] studied the performance of MWCNTs -water-based nanofluids as a base fluid on Egyptian climate conditions. Varying nanofluid volume concentrations of 0.05%, 0.075%, 0.1%, 0.2%, and 0.3% V were tested. Results optimized the rate of flow of 1.2 l per minute (LPM) under the test conditions as the best-used flow rate. Through evaluating the experimental findings, it is noticed that introducing nanoparticles to the water caused a momentous improvement in thermal properties, which improved electrical and thermal efficiencies. In addition, the use of MWCNT-water-based nanofluid achieved an total system efficiency of 83.26%, and a reduction in the temperature of 12 °C of the PV panel was achieved with the use of 0.075 volume concentration. Abdallah et al. [78] studied the performance of PVT unit using Al_2O_3-water-based nanofluid as a base fluid on Egyptian climate conditions. Varying nanofluid volume concentrations of 0.05%, 0.075%, 0.1%, 0.2%, and 0.3% V were tested. Results optimized the flow rate of 1.2 l/min under the test conditions as the best-used flow rate. In addition, the use of an Al_2O_3-water-based nanofluid achieved an overall system efficiency of 74% with 0.1% volume concentration. Al-Waeli et al. [79] examined the performance of the PVT system using SiC-water-based nanofluid as a base fluid on National University of Malaysia campus climate conditions.

They tested varying nanofluid concentrations 1, 1.5, 2, 3,4 wt% are tested. The electrical efficiency was increased by 24.1% and thermal efficiency was increased by 100.19 wt% compared to PV alone and the water cooling system, when use of 3.0 wt% SiC-nanofluid.

Experimental and numerical evaluation of the MWCNT-water-based PVT system was done by Nasrin et al. [80] with varying nanoparticle concentrations of 0.1 to 1 wt%. at a rate of 0.5 l per minute. The numerical and experimental work of thermal and electrical efficiencies were 81.48%, 79.2%, and 13.65%, 13.5%, respectively at 1.0 wt% nanoparticle concentration. The energy performance of the nanofluid-based photovoltaic system was analyzed by Aberoumand et al. [81] at 2 and 4wt% concentration. This experiment tested different flow regimes like laminar, turbulent, and transient flow. Also, to improve the stability of nanofluids, the authors implemented one new method: the electrical explosion of wire (EEW). In this method, the nanofluids are long-term stability recorded over the year. Also, the thermal and electrical efficiencies were 70% and 12.35%, respectively at 4wt% concentration. From the study, more authors reported that using nanofluids will improve thermal and electrical performance and also more reduction in PV panel temperature [82–85].

3.2.8 PCM based cooling

PCM are increasingly essential components in nearly all thermal energy management applications. They offer the possibility of maintaining a consistent temperature while adding or removing heat throughout the process of changing phases. Initially, a PCM is gradually heated until it reaches its saturated state, undergoing melting or solidification [86]. Then, it absorbs its latent heat at a steady temperature until completely melts. Afterwards, the PCM is gradually heated again, but this time in its melted condition. This process is referred to as the charging of PCM. During the discharging phase, the PCM releases both sensible heat and latent heat to the surrounding environment [87]. PCMs often utilize the latent heat of fusion or vaporization to effectively regulate temperature within a specific range [88]. The desired properties for using PCMs in thermal regulation include: (i) high heat of fusion and high specific heat [89, 90], (ii) a phase change temperature matching the application, (iii) low vapor pressure, (iv) chemical stability and low corrosiveness [5], and (v) minimal degree of supercooling [91]. Multiple studies have revealed that utilizing PCM for thermal regulation in PVT systems offers 33% greater potential for storing thermal energy compared to a conventional PVT water heating system. This results in a 75–100% increase in the duration of time during which the stored energy can be effectively utilized. The use of microencapsulated PCMs can lead to a substantial decrease in the operating temperature of PV systems. This, in turn, can result in improved power generation and enhanced thermal management. Consequently, the adoption of advanced techniques like PCM can further enhance the overall performance of the system [92].

Alsaqoor et al. [93] studied the impact of integrating PCM into the PVT system and their electrical and thermal performance. The findings indicate that PVT systems significantly reduce the temperature of solar cells and enhance electrical efficiency. The PVT system with PCM demonstrated a superior electrical efficiency of 14%, surpassing the 13.75% efficiency of the PVT system without PCM. Additionally, incorporating PCM into the PVT unit resulted in a peak electrical power output of 21 kW, compared to 18 kW for the PVT without PCM. Moreover, the research revealed that augmenting the coolant mass flow rate in the PVT unit with PCM reduced PV cell temperature and enhanced electrical efficiency. However, as solar incident radiation flux increased, the electrical efficiency of both PVT and PVT-PCM systems declined, leading to a significant rise in cell temperature. Recently, Reji Kumar et al. [16] informed that the addition of PCM into the PVT system significantly decreases the panel's temperature and improves the electrical power by 27.1% compared to a conventional PV system. In another study, Reji Kumar et al. [17] investigated the organic PCM-integrated PVT system to enhance thermal efficiency. The electrical efficiency of the PCM integrated water-based PVT system was improved by 34.9% compared to the conventional PV system.

3.2.9 Summary of PVT systems

This section elaborates on the fundamental concept of PVT systems, with significant emphasis placed on reviewing pertinent literature to foster robust research and development in this field. The overall performance of photovoltaic thermal systems and the commodities of nanofluids as energy transporters were discussed in depth for PVT systems. Also, the heat pipe and thermoelectric generator coupled with the PVT system were discussed briefly. Table 1 shows the summary of various thermal energy, electrical energy, and overall energy and their applications. It can be highlighted that most of the research are conducted on air-based PVT systems in low or medium-temperature climate areas, but very few works have been done in desert or high-temperature climate areas. It is expected that a greater number of PVT systems will be installed in those places in the future. In a water-cooled PVT system, the cooling water takes the heat from the PV, and the benefits from the heat and wasted heat need to be studied. In heat pipe photovoltaic thermal systems most of the studies water was a cooling fluid and limited heat pipe materials have been considered. In the future, applications of different heat pipe/material types can be tested to improve overall PVT performance. It was observed that very few types of nanomaterials only studied, and the base fluid used only water. Also, lack of compromise on acceptable optimum mass fraction of nanofluid. The utilization of PVT working fluids, including air, water, and nanofluids, has predominantly been noticed in water heating and space heating domains. However, in the future, enhancing the thermal efficiency of PVT systems is crucial for extending their use to high-temperature applications. One notable limitation of current PVT systems is the absence of TES facilities. These energy storage problems can be solved by integrating PCM with the PVT unit, PCM have the ability to absorb, store and release heat energy as well as cool the PV system. Need more research on PCM-integrated PVT system research and more focus on commercialized-based PVT systems.

4 Economic analaysis of PVT system

Equations (3)-(18) presents the key economic parameters essential for conducting the economic analysis of PVT systems. These parameters include the simple cost payback time (CPBT), life cycle cost (LCC), net present value (NPV), Levelized cost of energy (LCOE), cost of energy (COE), life cycle savings (LCS), payback time (PPT), and annual life cycle savings. Together, these metrics provide a comprehensive framework for evaluating the financial viability and long-term economic performance of the system.

The potential of using various materials in TES systems was evaluated, with zeolite demonstrating the highest average overall efficiency at 40%. Additionally, the zeolite-integrated PVT system showed a relatively shorter payback period of 8 years compared to other systems [115]. The economic analysis of the proposed system was conducted using the Net Present Value (NPV) method, which is widely regarded as a reliable approach for

Table 1 Summary of PVT systems

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Air-based PVT system				
Srimanickam et al. [28]	9.78%	24.17%	44.84%	The forced circulation air flows through the photovoltaic thermal system. The temperature of PV panel reduced at noon time is 6.5 °C
Singh et al. [29]	34.5% enhancement compared to single-channel	5.78% enhancement compared to a single-channel	35.41% enhancement compared to single-channel	Dual-channel semitransparent photovoltaic thermal (DCSPVT) system was proposed and analyzed. DCSPVT has higher performance compared to SCSPVT system.
Antonanzas et al. [30]	NA	NA	3.5% improvement	thermodynamic issue regarding improving the convective heat losses between the spacing in a covered panel by substituting air with different (xenon and argon) gas. Environmental and economic considerations argon gas is best gas in photovoltaic thermal systems.
Tsai et al. [94]	63% enhanced	> 52% enhanced	> 63% enhanced	PVT air system with finned heat sink was used for the improvement of heat transfer. Thermal and electrical efficiency enhanced up to 52% and 63%, respectively.
Agarwal et al. [95]	12.4%	35.7%	NA	Case 1 has higher electrical performance than case 2 Case 2 has higher thermal energy than case 1.
Mojumder et al. [32]	13.75%	56.19%	NA	PVT system with fin has higher electrical and thermal output than without fin system.

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Ahn et al. [96]	15%	23%	38%	The HRV system coupled with a photovoltaic thermal system has a maximum electrical output than the conventional one.
Li et al. [97]	10.6	50%	NA	Numerical and experimental study with static miniature solar concentrators was analyzed.
Good et al. [98]	12%	71.5%	NA	To get zero energy balance simulation study was conducted.
Agarwal et al. [99]	14.7%	10.8%	20.28%	The result proves that MCPVT has higher efficiency than SCPVT.
Khalil et al. [100]	20% increased use of glazed one	40% increased use of glazed one	90.48%	The highest value of daily combined efficiency was 90.48% and 62.16% use of glazed cover and un glazed cover.
Water-based PVT system				
Boumaaraf et al. [101]	6.26%	57.72%	74.2%	Compare the overall energy output of the PVT system at varied flow rate.
Fudholi et al. [102]	13.8%	54.6%	64.8%	The author designed and fabricated three different configurations of absorbers as web flow, direct flow, and spiral flow type. The Spiral type has maximum efficiency at 0.041 kg/s.

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Micheal et al. [46]	7.72%	16.72%	NA	Fabricated novel PVT system with laminating a thin copper sheet at the bottom of the panel instead of tedlar. The thermal, electrical, and overall efficiency can improve by increasing the mass flow rate.
Kazem et al. [103]	6% improved	NA	NA	The peak power and voltage are 67 W and 18.9 V. Produce more power during the examination period.
Kazemian et al. [37]	14.13%	66.27%	NA	PVT system with and without glazing system and different cooling fluids (water, EG, water + EG) for cold climate conditions. Water + EG has good performance for cold climate conditions.
Pang et al. [47]	13.67%	40.56%	NA	Polycrystalline silicon photovoltaic and photovoltaic thermal systems were numerically and experimentally investigated.
Bi-fluid PVT systems				
Su et al. [53]	7.8%	64.4%	84.2%	Performance investigation of bi-fluid PVT system with multi fluids. Water-water has higher efficiency at 0.15 kg/s.
Othman et al. [54]	17%	76%	NA	Hottel-Whillier-Bliss equation was used to find the numerical output.

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Jarimi et al. [52]	NA	26.6% improved	NA	The energy-saving efficiency of air and water-based PVT systems were 58.10% and 61.31%. The developed novel model is flexible simple and useful for three different modes of fluids can use.
Abu Bakar et al. [104]	10.0–10.7%	76%	NA	Newly developed a mathematical model of bi-fluid PVT system with single pass air chamber and serpentine shaped coper tube system. 2D steady-state balance equation was developed, validated, and forecast the performance of the bi-fluid system.
Jet impingement-based PVT system				
Hameed Jazz et al. [55]	7% improved	NA	NA	The short circuit and open circuit currents were improved by 28.5% and 11% using jet impingement and CPC, respectively.
Abdulrasool et al. [57]	11.35%	72%	NA	A PVT solar collector with a jet collision water system with a 0.33 to 0.16 kg/s flow rate was designed and tested. Mathematical model results were validated with experimental values.
Sebastien et al. [105]	NA	NA	NA	A prediction model was developed for the PVT-jet impingement system. It examined the influence of time setup and thermal mass on model accuracy.

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Belusko et al. [56]	NA	21%	NA	Investigation of jet impingement of solar collector. The efficiency was improved by increasing hole spacing of the tubes.
Bahaidarah et al. [58]	Increased from 12.7 W to 19 W	NA	Improved 82.6%	The power output and the conversion efficiency were improved 49.6% and 82.6%, respectively.
Thermoelectric-based PVT system				
Dimri et al. [61]	15.2–16.6%	33.4–34.9%	NA	Compared the performance of three different PV modules as opaque, semitransparent and aluminum. Aluminum PVT-TEC water system has higher efficiency compared to other configurations.
Syakiah et al. [63]	12%	84%	NA	Matrix inversion method is used to find the energy and economics of PVT-TE system. The study shows that 0.1 kg/s and 90 numbers of TE were optimum values. To improve the user feasibility in choosing the optimal design features that parallel to minimum AC/AEG
Dimri et al. [106]	NA	PVT-TEG is 7.266% higher than PV	NA	Thermal modeling and evaluation of semitransparent PV and semi-transparent thermo electric based photovoltaic thermal (PVT-TEG) collector. PVT-TEG has higher thermal efficiency than PV.

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Zhu et al. [66]	PV-TG system has 25% higher than PV	NA	NA	The authors focused on energy analysis of combined photovoltaic thermoelectric have been examined.
Heat pipe-based PVT systems				
Wang et al. [107]	7.8%	61.8%	68.9%	Heat pipe-based PVT system with composite metal wire and PCM filled the space between the finned wire and insulation
Sweidan et al. [108]	Optimum was found in January month 12.23%	Optimum was found in August month 35.3%	Optimum was found in August month 64.14%	Development of PCM integrated heat pipe-based PVT system. It was noted that 13.7 years of payback time for cost-effective and energy-saving.
Hu et al. [71]	NA	51.5% with wire mesh and 52.8% wickless at a 40° angle.	NA	Compared the performance of two configurations; heat pipe without wick and heat pipe with wire mesh PVT system.
Hou et al. [109]	13%	40%	NA	The thermal efficiency of the collector fluctuates between 20% and 40%.
Deng et al. [110]	Between 12.4% and 15.1%	Between 25.6% and 36.8%	Between 37.9% and 47.3%	PVT- micro heat pipe array and utilize the waste heat in four different seasons.
Zhang et al. [111]	15.69%	34.3%	NA	Investigation of heat pipe-based PVT system with varied of tank volume. The tank volume and inclination were optimized.

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Yu et al. [72]	17.20%	57.13	NA	The use of an evaporator and condenser improves the thermal energy of the system.
Nanofluid based PVT system				
Abdallah et al. [77]	33.9% improved	NA	83.26%	The maximum temperature reduction was observed 12 °C at the concentration of 0.075% MWCNT. The increase of weight fraction of nanoparticles increases of thermal efficiency.
Nasrin et al. [80]	13.5% experiment, 13.65% Numerical	79.2% experiment, 81.48% Numerical	87.65% experiment, 89.2% Numerical	The maximum efficiencies were observed at 1wt% of MWCNT at 0.5 LPM flow rate.
Aberoumand et al. [81]	12.35%	70%	NA	For long-term stability of nanofluid EEW- Electrical explosion of wire method was implemented.
Munzer et al. [112]	14.38%	NA	NA	Compare the performance of two different nanofluids in PVT system. $Al2O_3$ has higher electrical efficiency and TiO_2 has better thermal performance.
Lari et al. [113]	8.5% improved	18% improved	NA	The energy analysis of nanofluid PVT system for residential applications was developed. The projected system is 82% lesser price than the domestic electricity of Saudi Arabia

Table 1 (continued)

Author	Electrical efficiency/ Energy	Thermal efficiency/ energy	Overall efficiency/Energy	Observations
Ghadiri et al. [114]	7.23%	72%	76%	The effect of ferrofluids in PVT system was analyzed at 1 wt% and 3wt%. 3wt% ferrofluid has higher performance.

assessing financial performance. This method not only provides insights into the repayment period but also evaluates the cash flow over the system's lifecycle. The following Eq. 1 estimates NPV;

$$NPV = \sum_{i}^{n} (B - C) i a_i \tag{3}$$

$$a = \frac{1}{(1 + i)^p} \tag{4}$$

Where, B is the income, C is the cost, p is the period, i is the discount ratio, and a (Eq. 2) is the NPV factor.

The economic analysis of a novel PVT system with nanofluid [113] was done with three key indicators, Cost Pay Back Time (CPBT), Internal Rate of Return (IRR) and Cost of Energy (COE). The cost payback time is estimated using the Eq. 3, and it is estimated to be two years.

$$CPBT = \frac{IC}{EC_{sav\ per\ year} * COE_i} \tag{5}$$

IC corresponds to investment cost, COE_i corresponds to the cost of input energy (Eq. 5)

$$ALCC = LCC * CRF \tag{6}$$

$$COE = \frac{ALCC}{EC_L} \tag{7}$$

ALCC denotes annualized life cycle cost of the system (Eq. 4), LCC denotes life cycle cost, CRF represents capital recovery factor, EC_L denotes electrical energy savings by the PVT system.

From the estimated calculation, the cost of energy generated by PVT is 0.002367per kW/h which is 82% less than the domestic electric price. Moreover, the payback time for a PVT-PCM water system installed at Kottayam, India [116] is six years which 11.26% faster in comparison with a conventional PV panel.

Crystalline Silicon Heterojunction PVT was designed, and the payback estimations were done for the system. The cost of these systems was found to be lesser in comparison with conventional PV systems. The Investment Pay Back Time (IPBT) is calculated using Eq. 6.

$$IPBT = \frac{Y_{input}}{Y_{output}} \tag{8}$$

Y_{input} refers to the cost inputs during PV installation and Y_{output} corresponds to annual revenue generated by the sale of electricity. The payback time of the proposed system was estimated to be less than three years which is lesser in comparison with PV systems [117]. The Annualised Life-Cycle savings($ALCS$) of a PVT-SAH installed is estimated by the following Eq. 7.

$$ALCS = \frac{LCS}{PWF(N_L 0, D)} \tag{9}$$

LCS is the life cycle cost savings for operating the PVT- solar air heater system, $PWF(N_L 0, D)$ is the present worth factor.

The payback time (PBT) is defined as the ratio of time required for cumulative fuel cost savings in the present worth to the capital investment cost of the PVT-SAH system are as per Eqs. 8 and 9. The system was able to deliver a competitive payback period between 5.7 and 16.8 years and an annualized energy savings ranging between 925 and 4606 AUD [118]

$$PBT = \frac{\ln\left[\frac{C_{ca}(e-d)}{s_{fuel,1}} + 1\right]}{\ln\frac{(1+e)}{(1+d)}} \tag{10}$$

$$LCS = \sum_{j=0}^{j=N} P^{W\_S_{Total,j}} \tag{11}$$

The PBT of a combined solar cooling, heating, and power system (S-CCHP) is estimated by the following Eq. 10 and is found to be around 16.7 years.

$$PBT = \frac{\ln\left[\frac{C_0(i_F-d)}{CS_{S-CCHP}} + 1\right]}{\ln\left[\frac{1+i_F}{1+d}\right]} \tag{12}$$

d is the discount rate i_F is the fuel inflation rate CS_{S-CCHP} is the annual cost savings and was computed by the following Eq. 11. The payback period is higher (2.7 times) when compared with an equivalent PV system (6.1years) [119].

$$CS_{S-CCHP} = E_{COV}.c_e + \frac{Q_{COV}}{\eta_{boiler}}.c_{ng} + E_{grid}.FIT - C_{O\&M} \tag{13}$$

The performance analysis of four solar trigeneration systems for sub-tropical climates was done by simple payback method (SPB) and internal rate of return (IRR) (coupling glazed & unglazed PVT collector with single and half effect absorption chillers) according to Eq. 12.

$$SPB = \frac{CI}{ECS - MC} \tag{14}$$

CI denotes the capital investment, ECS was determined by electricity savings, MC denotes the maintenance cost.

The payback period falls shortest for PVugl ABCHHE layout and is approximately 12.7 years. However, when considering a 50% rise in electricity prices or a 35% reduction in PVT collector prices, PVTgl ABCHHElayout's payback shortens from 14.7 years to 10 years [120].

A comprehensive 3E analysis was performed on PVT systems as well as conventional solar systems. The economic analysis of the proposed system is shown by Eq. 13.

$$LCS = \frac{C_S}{d - i_F}\left[1 - \left(\frac{1 + i_F}{1 + d}\right)^n\right] - C_0 \tag{15}$$

D denotes the discount rate, C_S corresponds to the inflation rate for yearly fuel savings associated with investment cost (Eq. 14)

$$C_S = E_{COV}.c_{el} + E_{exc}.S_{el} + \frac{Q_{COV}}{\eta_{boil}} C_{ng} - C_{O\&M} \quad (16)$$

The LCS of the PVT S-CHP system was reported to be 0.77 M€, and that of the PV system is 0. 76 M€. The LCS is highest for combined PV-ETC (75%) S-CHP (25%) with 0.80 M€ for a life cycle of 25 years. The payback time of the PVT S-CHP system was estimated to be 13.7 years. The PBT of the ICE-CHP system is 6.2 years which is primarily due to the low investment cost associated with the system. Among solar-based systems, the PBT of PV systems was 9.4 years [121]. A 15% reduction in investment cost and 30% reduction in roof space occupied was noted with the novel PVT collector system compared to PV systems having equivalent capacity [122].

The following Eq. 15 is used to estimate the life cycle cost of the novel proposed PVT system with nanofluids.

$$LCC = C_{capital} + \sum_1^n C_{O\&M}.R_{PW} + \sum_1^n C_{replacement}.R_{PW} - C_{salvage}.R_{PW} \quad (17)$$

$C_{capital}$ is the total capital, $C_{O\&M}$ annual operating& maintenance cost and R_{PW} denotes the current value of each factor and was computed using

$$R_{PW} = \frac{F}{(1+i)^n} \quad (18)$$

F denotes the future sum of money, n denotes the interest rates.

The recovery period of the proposed system was estimated to be 4.4–5.3 years, the LCC of the system was 1288.37 USD, and the energy cost was found to be 0.112 USD/kWh [123].

Recent research has explored the integration of MWCNT-enhanced PCMs into PVT systems to improve both electrical and thermal performance. The study revealed that the energy payback periods for PVT systems using MWCNT-enhanced PCMs, PCM-integrated PVT, and standard PVT systems were 4.7, 4.8, and 5.6 years, respectively. Furthermore, the thermal efficiency of the PVT-PCM and PVT-NePCM systems showed a significant improvement compared to water-based PVT systems. This enhancement is primarily attributed to the ability of the thermal energy storage material to effectively store and utilize thermal energy, thereby optimizing the overall system performance [124]. This study investigates the thermophysical properties, cooling efficiency, and economic viability of copper oxide–palm oil nanolubricants for tribological applications in PVT systems. The cooling capacities of the nanolubricants were assessed through an economic analysis using the price-performance index. The findings indicate that while elevated temperatures can negatively impact economic efficiency, higher concentrations of nanolubricants significantly enhance cooling performance, demonstrating their potential for effective thermal management in PVT systems [125].

5 Conclusions

Renewable energy sources are becoming increasingly prominent due to several factors, including the rapid depletion of fossil fuels, the fluctuating increase in gasoline prices, and the environmental degradation they cause. Solar photovoltaic technologies are highly promising among all the renewable energy sources. Consequently, extensive research is being conducted on this subject, resulting in substantial improvements in its performance.

In conclusion, this study has thoroughly examined the key factors influencing the efficiency of PV panels, identifying dust accumulation, humidity, and elevated temperatures as the most significant contributors to performance degradation. A detailed analysis of various cooling techniques revealed that PV/T systems using air as a heat transfer medium are particularly well-suited for space heating applications in cold regions, often being integrated into building structures. Among the cooling methods, active water cooling emerged as the simplest and most efficient approach. However, its practical implementation poses challenges, such as the need for a consistent supply of cool water and the requirement for sufficiently large systems to justify the energy consumption. Bi-fluid systems demonstrated superior performance by utilizing both air and liquid as heat transfer mediums, significantly enhancing cooling efficiency and system performance. Additionally, nanofluids outperformed conventional water-based PV/T systems due to their high thermal conductivity, which allows for greater heat extraction, resulting in improved cooling and electrical output. Furthermore, the integration of PCMs into PVT systems proved to be highly effective, as they not only provide cooling but also store thermal energy for use during periods when energy supply is unavailable. These findings underscore the potential of advanced cooling technologies to enhance the efficiency and versatility of PVT systems, paving the way for more sustainable and efficient energy solutions.

6 Future recommendations

The future direction of technological advancement should prioritize the development of hybrid cooling techniques, with the primary objective of consistently and effectively maintaining low surface temperatures and enhancing electrical output. Future research should give priority to investigating the hybrid cooling system with the incorporation of thermal energy storage material cooling techniques. Also, it is recommended to use highly conductive PCM with a cooling medium, heat pipes, vacuum, and innovative gases to further enhance the performance of PVT system.

Further an comprehensive analyses of PVT systems should encompass energy, exergy, economic, and environmental (4E) aspects. Various geometrical designs and surface textures for passive cooling can be explored by utilizing commercially available ribs or obstacles. Further advanced experimental studies are necessary to assess the practicality and effectiveness of organic and hybrid PCMs for PV cooling applications. Further assessments and optimizations of efficient cooling techniques for large-scale grid-connected systems are essential. Concentrate on examining the long-term resilience and efficacy of cooling technologies throughout various environmental conditions. Truly sustainable "zero-energy" hybrid PVT systems should be designed with practical applications in mind, such as solar desalination, HVAC systems, and more. The role of nanotechnology in PV cooling could also be expanded, for instance, through the use of advanced nano-coatings.

It is highly beneficial to explore scenarios where hot water is required for additional purposes. In such cases, experiments should be conducted using standard PV panels and PV panels integrated with either pure or nano-enhanced PCMs and water in various configurations. These experiments should include different PCMs with varying melting points and thicknesses to enable precise comparisons between these techniques. Such a comprehensive study would not only identify the most effective combinations and configurations for optimizing both electrical and thermal energy output from PV systems but also emphasize the potential for dual-purpose solar energy applications. Addressing these aspects would significantly advance photovoltaic cooling technologies and contribute to the development of more efficient and sustainable energy solutions.

Acknowledgements The authors would like to express their sincere gratitude to the Institute of Sustainable Energy, Universiti Tenaga Nasional (UNITEN) for providing the necessary support and facilities to carry out this research work.

Author contributions R.R.K: Writing Original Draft, Conceptualization, Methodology, Project administrationS.K: Writing Original Draft, Formal analysisK.B: Writing Original Draft, Formal analysisM.R: Project administration, Writing Original DraftF.R: Conceptualization, Writing Review & EditingM.A: Investigation, Formal analysisI.R.J. M: Writing Review & EditingNM: Writing Review & EditingA.T; Data Curation, Resources, Writing Review & Editing.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Reji Kumar, R., Samykano, M., Pandey, A.K., Kadirgama, K., Tyagi, V.V.: Phase change materials and nano-enhanced phase change materials for thermal energy storage in photovoltaic thermal systems: A futuristic approach and its technical challenges. Renew. Sustain. Energy Rev. **133**, 110341 (2020). https://doi.org/10.1016/j.rser.2020.110341
2. Almoatham, S., Chiasson, A., Mulford, R., Moreno-Pena, M.: Development of experimentally-validated models for nocturnal cooling of thermal systems with photovoltaic thermal (PVT) modules. Sol. Energy **268**(April 2023), 112279 (2024). https://doi.org/10.1016/j.solener.2023.112279
3. Chow, T.T.: A review on photovoltaic/thermal hybrid solar technology. Appl. Energy. **87**(2), 365–379 (2010). https://doi.org/10.1016/j.apenergy.2009.06.037
4. Chauhan, A., Tyagi, V.V., Anand, S.: Futuristic approach for thermal management in solar PV/thermal systems with possible applications. Energy Convers. Manag. **163**(January) 314–354 (2018). https://doi.org/10.1016/j.enconman.2018.02.008
5. Fikri, M.A., et al.: Recent progresses and challenges in cooling techniques of concentrated photovoltaic thermal system: A review with special treatment on phase change materials (PCMs) based cooling. Sol Energy Mater. Sol Cells. **241**(5), 111739 (2022). https://doi.org/10.1016/j.solmat.2022.111739
6. Hamada, A., Emam, M., Refaey, H.A., Moawed, M., Abdelrahman, M.A.: Investigating the performance of a water-based PVT system using encapsulated PCM balls: An experimental study. Energy. **284**, 128574 (2023). no. July10.1016/j.energy.2023.128574
7. Lazzarin, R.: Heat pumps and solar energy: A review with some insights in the future. Int. J. Refrig. **116**, 146–160 (2020). https://doi.org/10.1016/j.ijrefrig.2020.03.031
8. Açıkkalp, E., Caliskan, H., Hong, H., Piao, H., Seung, D.: Extended exergy analysis of a photovoltaic-thermal (PVT) module based desiccant air cooling system for buildings. Appl. Energy. **323**, 119581 (2022). https://doi.org/10.1016/j.apenergy.2022.119581
9. Özakin, A.N., Kaya, F.: Effect on the exergy of the PVT system of fins added to an air-cooled channel: A study on temperature and air velocity with ANSYS Fluent. Sol. Energy **184**(February) 561–569 (2019). https://doi.org/10.1016/j.solener.2019.03.100

10. T. Ibrahim, J. Faraj, H. El Hage, K. Chahine, M. Mortazavi, and M. Khaled, "Theoretical parametric study of photovoltaic cooling by water—Energy enhancement and environmental-economic insights. *Int. J. Thermofluids* **24**(November), 100988 (2024). https://doi.org/10.1016/j.ijft.2024.100988
11. Zhang, L., et al.: Experimental study of dual-source heat pump coupled with water-cooled photovoltaic/thermal system. Appl. Therm. Eng. **258**(PC), 124758, (2025). https://doi.org/10.1016/j.applthermaleng.2024.124758
12. Menon, G.S., Murali, S., Elias, J., Aniesrani Delfiya, D.S., Alfiya, P.V., Samuel, M.P.: Experimental investigations on unglazed photovoltaic-thermal (PVT) system using water and nanofluid cooling medium. Renew. Energy. **188**, 986–996 (2022). https://doi.org/10.1016/j.renene.2022.02.080
13. Song, Y.J., Li, B., Zhang, C.Y., Wang, W.W., Zhao, F.Y., Guo, J.H.: Solar photo-voltaic and thermal (PVT) system facilitated with novel coaxial condensing heat pipe (CCHP): Thermo hydrodynamic modelling and parametric optimization for overall operation performance. Sol Energy **264**(June), 112019 (2023). https://doi.org/10.1016/j.solener.2023.112019
14. Melaibari, A.A., Abu-Hamdeh, N.H., Alorfi, A.S., AL-bonsrulah, H.A.Z., Elsiddieg, A.M.A.: New design for PVT system with elliptic cooling duct involving nanofluid in existence of MHD and utilizing TEG. Case Stud. Therm. Eng. **53**(October 2023), 103815 (2024). https://doi.org/10.1016/j.csite.2023.103815
15. Ocłoń, P., et al.: Modeling and experimental validation and thermal performance assessment of a sun-tracked and cooled PVT system under low solar irradiation. Energy Convers. Manag. **222**(August), (2020). https://doi.org/10.1016/j.enconman.2020.113289
16. Kumar, R., et al.: Heat transfer and energy performance analysis of photovoltaic thermal system using functionalized carbon nanotubes enhanced phase change material. Appl. Therm. Eng. **243**(January), 122544 (2024). https://doi.org/10.1016/j.applthermaleng.2024.122544
17. Rajamony, R.K., et al.: Energizing the thermophysical properties of phase change material using carbon-based nano additives for sustainable thermal energy storage application in photovoltaic thermal systems. Mater. Today Sustain. **25**(5), 100658 (2024). https://doi.org/10.1016/j.mtsust.2023.100658
18. Zareie, Z., Ahmadi, R., Asadi, M.: A comprehensive numerical investigation of a branch-inspired channel in roll-bond type PVT system using design of experiments approach. Energy **286**(June 2023), 129452 (2024). https://doi.org/10.1016/j.energy.2023.129452
19. Dwivedi, P., Sudhakar, K., Soni, A., Solomin, E., Kirpichnikova, I.: Advanced cooling techniques of P.V. modules: A state of art. Case Stud. Therm. Eng. **21**(December 2019), 100674 (2020). https://doi.org/10.1016/j.csite.2020.100674
20. Luo, W., et al.: Potential-induced degradation in photovoltaic modules: A critical review. Energy Environ. Sci. **10**(1), 43–68 (2017). https://doi.org/10.1039/c6ee02271e
21. Chow, T.T., Pei, G., Fong, K.F., Lin, Z., Chan, A.L.S., Ji, J.: Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover. Appl. Energy. **86**(3), 310–316 (2009). https://doi.org/10.1016/j.apenergy.2008.04.016
22. Kaldellis, J.K., Kapsali, M., Kavadias, K.A.: Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. Renew. Energy. **66**, 612–624 (2014). https://doi.org/10.1016/j.renene.2013.12.041
23. Singh, P., Ravindra, N.M.: Temperature dependence of solar cell performance - an analysis. Sol Energy Mater. Sol Cells. **101**, 36–45 (2012). https://doi.org/10.1016/j.solmat.2012.02.019
24. Michael, J.J., S, I., Goic, R.: Flat plate solar photovoltaic-thermal (PV/T) systems: A reference guide. Renew. Sustain. Energy Rev. **51**, 62–88 (2015). https://doi.org/10.1016/j.rser.2015.06.022
25. Conceição, R., et al.: Saharan dust transport to Europe and its impact on photovoltaic performance: A case study of soiling in Portugal. Sol Energy. **160**, 94–102 (2018). https://doi.org/10.1016/j.solener.2017.11.059
26. Sandnes, B., Rekstad, J.: A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. Sol Energy. **72**(1), 63–73 (2002). https://doi.org/10.1016/S0038-092X(01)00091-3
27. Tiwari, S., Tiwari, G.N., Al-Helal, I.M.: Performance analysis of photovoltaic-thermal (PVT) mixed mode greenhouse solar dryer. Sol Energy. **133**, 421–428 (2016). https://doi.org/10.1016/j.solener.2016.04.033
28. Srimanickam, B., Vijayalakshmi, M.M., Natarajan, E.: Experimental study of Exergy Analysis on flat plate solar photovoltaic thermal (PV/T) hybrid system. Appl. Mech. Mater. **787**, 82–87 (2015). https://doi.org/10.4028/www.scientific.net/amm.787.82
29. Singh, S., Agrawal, S., Avasthi, D.V.: Design, modeling and performance analysis of dual channel semitransparent photovoltaic thermal hybrid module in the cold environment. Energy Convers. Manag. **114**, 241–250 (2016). https://doi.org/10.1016/j.enconman.2016.02.023

30. Antonanzas, J., del Amo, A., Martinez-Gracia, A., Bayod-Rujula, A.A., Antonanzas-Torres, F.: Towards the optimization of convective losses in photovoltaic-thermal panels. Sol Energy. **116**, 323–336 (2015). https://doi.org/10.1016/j.solener.2015.04.013
31. Ooshaksaraei, P., Aghili, K., Sopian, K., Zulkifli, R., Zaidi, S.H.: Steady state characterization of bifacial solar cells at different configurations of air-based photovoltaic thermal solar panels. J. Renew. Sustain. Energy. **6**(3) (2014). https://doi.org/10.1063/1.4885117
32. Mojumder, J.C., Chong, W.T., Ong, H.C., Leong, K.Y., Abdullah-Al-Mamoon: An experimental investigation on performance analysis of air type photovoltaic thermal collector system integrated with cooling fins design. Energy Build. **130**, 272–285 (2016). https://doi.org/10.1016/j.enbuild.2016.08.040
33. Popovici, C.G., Hudişteanu, S.V., Mateescu, T.D., Cherecheş, N.C.: Efficiency improvement of photovoltaic panels by using air cooled heat sinks. Energy Procedia **85**(November 2015), 425–432 (2016). https://doi.org/10.1016/j.egypro.2015.12.223
34. Jha, P., Das, B., Gupta, R.: Energy and exergy analysis of photovoltaic thermal air collector under climatic condition of North Eastern India. Energy Procedia. **158**, 1161–1167 (2019). https://doi.org/10.1016/j.egypro.2019.01.299
35. Islam, M.M., Pandey, A.K., Hasanuzzaman, M., Rahim, N.A.: Recent progresses and achievements in photovoltaic-phase change material technology: A review with special treatment on photovoltaic thermal-phase change material systems. Energy Convers. Manag. **126**, 177–204 (2016). https://doi.org/10.1016/j.enconman.2016.07.075
36. Wu, S.Y., Wang, T., Xiao, L., Shen, Z.G.: Effect of cooling channel position on heat transfer characteristics and thermoelectric performance of air-cooled PV/T system. Sol. Energy **180**(December 2018), 489–500, 2019, (2018). https://doi.org/10.1016/j.solener.2019.01.043
37. Kazemian, A., Hosseinzadeh, M., Sardarabadi, M., Passandideh-Fard, M.: Effect of glass cover and working fluid on the performance of photovoltaic thermal (PVT) system: An experimental study. Sol. Energy **173**(July), 1002–1010, (2018). https://doi.org/10.1016/j.solener.2018.07.051
38. Aste, N., Leonforte, F., Pero, C.D.: Design, modeling and performance monitoring of a photovoltaic-thermal (PVT) water collector. Sol Energy. **112**, 85–99 (2015). https://doi.org/10.1016/j.solener.2014.11.025
39. Herrando, M., Ramos, A., Zabalza, I., Markides, C.N.: A comprehensive assessment of alternative absorber-exchanger designs for hybrid PVT-water collectors. Appl. Energy **235**(November 2018), 1583–1602, 2019, (2018). https://doi.org/10.1016/j.apenergy.2018.11.024
40. Rajoria, C.S., Agrawal, S., Tiwari, G.N., Chaursia, G.S.: Exergetic and enviroeconomic analysis of semitransparent PVT array based on optimum air flow configuration and its comparative study. Sol Energy. **122**, 1138–1145 (2015). https://doi.org/10.1016/j.solener.2015.10.020
41. Yazdanpanahi, J., Sarhaddi, F., Mahdavi Adeli, M.: Experimental investigation of exergy efficiency of a solar photovoltaic thermal (PVT) water collector based on exergy losses. Sol Energy. **118**, 197–208 (2015). https://doi.org/10.1016/j.solener.2015.04.038
42. Shyam, G.N., Tiwari, O., Fischer, R.K., Mishra, Al-Helal, I.M.: Performance evaluation of N-photovoltaic thermal (PVT) water collectors partially covered by photovoltaic module connected in series: An experimental study. Sol Energy. **134**, 302–313 (2016). https://doi.org/10.1016/j.solener.2016.05.013
43. Chemisana, D., Fernandez, E.F., Riverola, A., Moreno, A.: Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications. Renew. Energy. **123**, 263–272 (2018). https://doi.org/10.1016/j.renene.2018.02.018
44. Hamdoon, O.M., Alomar, O.R., Salim, B.M.: Performance analysis of Hybrid Photovoltaic Thermal Solar System in Iraq Climate Condition. Therm. Sci. Eng. Prog. **100359** (2019). https://doi.org/10.1016/j.tsep.2019.100359
45. Herrando, M., Ramos, A., Freeman, J., Zabalza, I., Markides, C.N.: Technoeconomic modelling and optimisation of solar combined heat and power systems based on flat-box PVT collectors for domestic applications. Energy Convers. Manag. **175**(September), 67–85 (2018). https://doi.org/10.1016/j.enconman.2018.07.045
46. Michael, J.J., Selvarasan, I., Goic, R.: Fabrication, experimental study and testing of a novel photovoltaic module for photovoltaic thermal applications. Renew. Energy. **90**, 95–104 (2016). https://doi.org/10.1016/j.renene.2015.12.064
47. Pang, W., et al.: Numerical simulation and experimental validation of a photovoltaic/thermal system based on a roll-bond aluminum collector. Energy. **187**, 115990 (2019). https://doi.org/10.1016/j.energy.2019.115990

48. Shehadeh, S.H., Aly, H.H., El-Hawary, M.E.: Investigation of photovoltaic coverage ratio for maximum overall thermal energy of photovoltaic thermal system. Renew. Energy. **134**, 757–768 (2019). https://doi.org/10.1016/j.renene.2018.11.080
49. Al-Waeli, A.H.A., Sopian, K., Kazem, H.A., Chaichan, M.T.: Photovoltaic/Thermal (PV/T) systems: Status and future prospects. Renew. Sustain. Energy Rev. **77**(March), 109–130, (2017). https://doi.org/10.1016/j.rser.2017.03.126
50. Sathe, T.M., Dhoble, A.S.: A review on recent advancements in photovoltaic thermal techniques. Renew. Sustain. Energy Rev. **76**(March), 645–672, (2017). https://doi.org/10.1016/j.rser.2017.03.075
51. Hadi Attia, M.E., Khelifa, A., Abdulmajeed, O.M., Arıcı, M.: Thermal analysis on the performance of a finned hybrid bi-fluid PVT system. Therm. Sci. Eng. Prog. 102135 (2023). https://doi.org/10.1016/j.tsep.2023.102135
52. Jarimi, H., Abu Bakar, M.N., Othman, M., Din, M.H.: Bi-fluid photovoltaic/thermal (PV/T) solar collector: Experimental validation of a 2-D theoretical model. Renew. Energy. **85**, 1052–1067 (2016). https://doi.org/10.1016/j.renene.2015.07.014
53. Su, D., Jia, Y., Huang, X., Alva, G., Tang, Y., Fang, G.: Dynamic performance analysis of photovoltaic-thermal solar collector with dual channels for different fluids. Energy Convers. Manag. **120**, 13–24 (2016). https://doi.org/10.1016/j.enconman.2016.04.095
54. Othman, M.Y., Hamid, S.A., Tabook, M.A.S., Sopian, K., Roslan, M.H., Ibarahim, Z.: Performance analysis of PV/T combi with water and air heating system: An experimental study. Renew. Energy. **86**, 716–722 (2016). https://doi.org/10.1016/j.renene.2015.08.061
55. Hameed Jaaz, A., Hasan, H.A., Sopian, K., Kadhum, A.A.H., Gaaz, T.S., Al-Amiery, A.A.: Outdoor performance analysis of a photovoltaic thermal (PVT) collector with jet impingement and compound parabolic concentrator (CPC). Mater. (Basel). **10**(8) (2017). https://doi.org/10.3390/ma10080888
56. Belusko, M., Saman, W., Bruno, F.: Performance of jet impingement in unglazed air collectors. Sol Energy. **82**(5), 389–398 (2008). https://doi.org/10.1016/j.solener.2007.10.005
57. Hasan, H.A., Sopian, K., Fudholi, A.: Photovoltaic thermal solar water collector designed with a jet collision system. Energy. **161**, 412–424 (2018). https://doi.org/10.1016/j.energy.2018.07.141
58. Bahaidarah, H.M.S.: Experimental performance evaluation and modeling of jet impingement cooling for thermal management of photovoltaics. Sol Energy. **135**, 605–617 (2016). https://doi.org/10.1016/j.solener.2016.06.015
59. He, W., Zhou, J., Chen, C., Ji, J.: Experimental study and performance analysis of a thermoelectric cooling and heating system driven by a photovoltaic/thermal system in summer and winter operation modes. Energy Convers. Manag. **84**, 41–49 (2014). https://doi.org/10.1016/j.enconman.2014.04.019
60. Makki, A., Omer, S., Su, Y., Sabir, H.: Numerical investigation of heat pipe-based photovoltaic-thermoelectric generator (HP-PV/TEG) hybrid system. Energy Convers. Manag. **112**, 274–287 (2016). https://doi.org/10.1016/j.enconman.2015.12.069
61. Dimri, N., Tiwari, A., Tiwari, G.N.: Comparative study of photovoltaic thermal (PVT) integrated thermoelectric cooler (TEC) fluid collectors. Renew. Energy. **134**, 343–356 (2019). https://doi.org/10.1016/j.renene.2018.10.105
62. Shilpa, M.K., Raheman, M.A., Aabid, A., Baig, M., Veeresha, R.K., Kudva, N.: A systematic review of Thermoelectric Peltier devices: Applications and limitations. Fluid Dyn. Mater. Process. **19**(1), 187–206 (2022). https://doi.org/10.32604/fdmp.2022.020351
63. Nazri, N.S., et al.: Energy economic analysis of photovoltaic-thermal-thermoelectric (PVT-TE) air collectors. Renew. Sustain. Energy Rev. **92**, 187–197 (2018). https://doi.org/10.1016/j.rser.2018.04.061
64. Liu, Z., et al.: Modeling and simulation of a photovoltaic thermal-compound thermoelectric ventilator system. Appl. Energy **228**(April), 1887–1900, (2018). https://doi.org/10.1016/j.apenergy.2018.07.006
65. Nazri, N.S., et al.: Exergy and improvement potential of hybrid photovoltaic thermal/thermoelectric (PVT/TE) air collector. Renew. Sustain. Energy Rev. 111(March), 132–144, (2019). https://doi.org/10.1016/j.rser.2019.03.024
66. Zhu, W., Deng, Y., Wang, Y., Shen, S., Gulfam, R.: High-performance photovoltaic-thermoelectric hybrid power generation system with optimized thermal management. Energy. **100**, 91–101 (2016). https://doi.org/10.1016/j.energy.2016.01.055
67. Li, D., Xuan, Y., Li, Q., Hong, H.: Exergy and energy analysis of photovoltaic-thermoelectric hybrid systems. Energy. **126**, 343–351 (2017). https://doi.org/10.1016/j.energy.2017.03.042
68. Babu, C., Ponnambalam, P.: The theoretical performance evaluation of hybrid PV-TEG system. Energy Convers. Manag. **173**(July), 450–460, (2018). https://doi.org/10.1016/j.enconman.2018.07.104

69. Abramushkina, E., Zhaksylyk, A., Geury, T., Baghdadi, M.E., Hegazy, O.: A thorough review of cooling concepts and thermal management techniques for automotive wbg inverters: Topology, technology and integration level. Energies. **14**(16) (2021). https://doi.org/10.3390/en14164981
70. Lu, S., Liang, R., Zhang, J., Zhou, C.: Performance improvement of solar photovoltaic/thermal heat pump system in winter by employing vapor injection cycle. Appl. Therm. Eng. **155**(September 2018), 135–146 (2019). https://doi.org/10.1016/j.applthermaleng.2019.03.038
71. Hu, M., Zheng, R., Pei, G., Wang, Y., Li, J., Ji, J.: Experimental study of the effect of inclination angle on the thermal performance of heat pipe photovoltaic/thermal (PV/T) systems with wickless heat pipe and wire-meshed heat pipe. Appl. Therm. Eng. **106**, 651–660 (2016). https://doi.org/10.1016/j.applthermaleng.2016.06.003
72. Yu, M., et al.: Experimental investigation of a Novel Solar Micro-channel Loop-Heat-Pipe Photovoltaic/Thermal (MC-LHP-PV/T) system for heat and power generation. Appl. Energy. **256**(September), 113929 (2019). https://doi.org/10.1016/j.apenergy.2019.113929
73. Al-Shamani, A.N., et al.: Nanofluids for improved efficiency in cooling solar collectors - a review. Renew. Sustain. Energy Rev. **38**, 348–367 (2014). https://doi.org/10.1016/j.rser.2014.05.041
74. Bozorgan, N., Shafahi, M.: Performance evaluation of nanofluids in solar energy: A review of the recent literature. Micro Nano Syst. Lett. **3**(1), 1–15 (2015). https://doi.org/10.1186/s40486-015-0014-2
75. Verma, S.K., Tiwari, A.K.: Progress of nanofluid application in solar collectors: A review. Energy Convers. Manag. **100**, 324–346 (2015). https://doi.org/10.1016/j.enconman.2015.04.071
76. Mahian, O., Kianifar, A., Kalogirou, S.A., Pop, I., Wongwises, S.: A review of the applications of nanofluids in solar energy. Int. J. Heat. Mass. Transf. **57**(2), 582–594 (2013). https://doi.org/10.1016/j.ijheatmasstransfer.2012.10.037
77. Abdallah, S.R., Saidani-Scott, H., Abdellatif, O.E.: Performance analysis for hybrid PV/T system using low concentration MWCNT (water-based) nanofluid. Sol. Energy **181**(October 2018), 108–115 (2019). https://doi.org/10.1016/j.solener.2019.01.088
78. Abdallah, S.R., Elsemary, I.M.M., Altohamy, A.A., Abdelrahman, M.A., Attia, A.A.A., Abdellatif, O.E.: Experimental investigation on the effect of using nano fluid (Al2O3-Water) on the performance of PV/T system. Therm. Sci. Eng. Prog. **7**, 1–7 (2018). https://doi.org/10.1016/j.tsep.2018.04.016
79. Al-Waeli, A.H.A., Sopian, K., Chaichan, M.T., Kazem, H.A., Hasan, H.A., Al-Shamani, A.N.: An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system. Energy Convers. Manag. **142**, 547–558 (2017). https://doi.org/10.1016/j.enconman.2017.03.076
80. Nasrin, R., Rahim, N.A., Fayaz, H., Hasanuzzaman, M.: Water/MWCNT nanofluid based cooling system of PVT: Experimental and numerical research. Renew. Energy. **121**, 286–300 (2018). https://doi.org/10.1016/j.renene.2018.01.014
81. Aberoumand, S., Ghamari, S., Shabani, B.: Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study. Sol. Energy **165**(March), 167–177, (2018). https://doi.org/10.1016/j.solener.2018.03.028
82. Al-Waeli, A.H.A., Chaichan, M.T., Kazem, H.A., Sopian, K.: Comparative study to use nano-(Al2O3, CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors. Energy Convers. Manag. **148**, 963–973 (2017). https://doi.org/10.1016/j.enconman.2017.06.072
83. Al-Waeli, A.H.A., Chaichan, M.T., Kazem, H.A., Sopian, K., Safaei, J.: Numerical study on the effect of operating nanofluids of photovoltaic thermal system (PV/T) on the convective heat transfer. Case Stud. Therm. Eng. **12**, 405–413 (2018). https://doi.org/10.1016/j.csite.2018.05.011
84. Imtiaz Hussain, M., Kim, J.H., Kim, J.T.: Nanofluid-powered dual-fluid photovoltaic/thermal (PV/T) system: Comparative numerical study. Energies. **12**(5) (2019). https://doi.org/10.3390/en12050775
85. Harikrishnan, S., Imran Hussain, S., Devaraju, A., Sivasamy, P., Kalaiselvam, S.: Improved performance of a newly prepared nano-enhanced phase change material for solar energy storage. J. Mech. Sci. Technol. **31**(10), 4903–4910 (2017). https://doi.org/10.1007/s12206-017-0938-y
86. Fikri, M.A., et al.: Enhanced Thermal properties of Phase Change materials through surfactant-functionalized Graphene Nanoplatelets for Sustainable Energy Storage. Energies. **16**(22) (2023). https://doi.org/10.3390/en16227668
87. Goel, V., et al.: PCM-assisted energy storage systems for solar-thermal applications: Review of the associated problems and their mitigation strategies. J. Energy Storage **69**(May), 107912 (2023). https://doi.org/10.1016/j.est.2023.107912
88. Rajamony, R.K., et al.: Energizing the thermal conductivity and optical performance of salt hydrate phase change material using copper (II) oxide nano additives for sustainable thermal Energy storage. E3S Web Conf. **488** (2024). https://doi.org/10.1051/e3sconf/202448801009
89. Said, Z., et al.: Nanotechnology-integrated phase change material and nanofluids for solar applications as a potential approach for clean energy strategies: Progress, challenges, and opportunities. J. Clean. Prod. **416**, 137736 (2023). https://doi.org/10.1016/j.jclepro.2023.137736

90. R, R.K., et al.: Phase change materials integrated solar desalination system: An innovative approach for sustainable and clean water production and storage. Renew. Sustain. Energy Rev. **165**(5), 112611 (2022). https://doi.org/10.1016/j.rser.2022.112611
91. R, R.K., et al.: Investigation of thermal performance and chemical stability of graphene enhanced phase change material for thermal energy storage. Phys. Chem. Earth **128**(September), 103250 (2022). https://doi.org/10.1016/j.pce.2022.103250
92. Rajamony, R.K., et al.: Investigation on thermophysical properties of multi-walled carbon nanotubes enhanced salt hydrate phase change material. Int. J. Automot. Mech. Eng. **20**(3), 10595–10605 (2023). https://doi.org/10.15282/ijame.20.3.2023.03.0817
93. Alsaqoor, S., Alqatamin, A., Alahmer, A., Nan, Z., Al-Husban, Y., Jouhara, H.: The impact of phase change material on photovoltaic thermal (PVT) systems: A numerical stud. Int. J. Thermofluids **18**(April), 100365 (2023). https://doi.org/10.1016/j.ijft.2023.100365
94. Tsai, H.L. , Hsu, C.Y., Chen, Y.C.: Efficiency enhancement of novel photovoltaic-thermal (PVT) air collector. *Appl. Mech. Mater.* **494–495**, 1845–1848 (2014). https://doi.org/10.4028/www.scientific.net/AMM.494-495.1845
95. Agrawal, S., Tiwari, G.N., Pandey, H.D.: Indoor experimental analysis of glazed hybrid photovoltaic thermal tiles air collector connected in series. Energy Build. **53**, 145–151 (2012). https://doi.org/10.1016/j.enbuild.2012.06.009
96. Ahn, J.G., Kim, J.H., Kim, J.T.: A study on experimental performance of air-type PV/T collector with HRV. Energy Procedia. **78**, 3007–3012 (2015). https://doi.org/10.1016/j.egypro.2015.11.705
97. Li, G., Pei, G., Ji, J., Yang, M., Su, Y., Xu, N.: Numerical and experimental study on a PV/T system with static miniature solar concentrator. Sol Energy. **120**, 565–574 (2015). https://doi.org/10.1016/j.solener.2015.07.046
98. Good, C., Andresen, I., Hestnes, A.G.: Solar energy for net zero energy buildings - A comparison between solar thermal, PV and photovoltaic-thermal (PV/T) systems. Sol. Energy **122**(2015), 986–996 (2015). https://doi.org/10.1016/j.solener.2015.10.013
99. Agrawal, S., Tiwari, G.N.: Enviroeconomic analysis and energy matrices of glazed hybrid photovoltaic thermal module air collector. Sol Energy. **92**, 139–146 (2013). https://doi.org/10.1016/j.solener.2013.02.019
100. Omer, K.A., Zala, A.M.: Experimental investigation of PV/thermal collector with theoretical analysis. Renew. Energy Focus. **27**(00), 67–77 (2018). https://doi.org/10.1016/j.ref.2018.09.004
101. Boumaaraf, B., Touafek, K., Ait-cheikh, M.S., Slimani, M.E.A.: Comparison of electrical and thermal performance evaluation of a classical PV generator and a water glazed hybrid photovoltaic–thermal collector. Math. Comput. Simul. **167**, 176–193 (2020). https://doi.org/10.1016/j.matcom.2018.09.003
102. Fudholi, A., Sopian, K., Yazdi, M.H., Ruslan, M.H., Ibrahim, A., Kazem, H.A.: Performance analysis of photovoltaic thermal (PVT) water collectors. Energy Convers. Manag. **78**, 641–651 (2014). https://doi.org/10.1016/j.enconman.2013.11.017
103. Kazem, H.A.: Evaluation and analysis of water-based photovoltaic/thermal (PV/T) system. Case Stud. Therm. Eng. **13**(December 2018), 100401 (2019). https://doi.org/10.1016/j.csite.2019.100401
104. Abu Bakar, M.N., Othman, M., Hj Din, M., Manaf, N.A., Jarimi, H.: Design concept and mathematical model of a bi-fluid photovoltaic/thermal (PV/T) solar collector. Renew. Energy. **67**, 153–164 (2014). https://doi.org/10.1016/j.renene.2013.11.052
105. Brideau, S.A., Collins, M.R.: Development and validation of a hybrid PV/Thermal air based collector model with impinging jets. Sol Energy. **102**, 234–246 (2014). https://doi.org/10.1016/j.solener.2014.01.022
106. Dimri, N., Tiwari, A., Tiwari, G.N.: Thermal modelling of semitransparent photovoltaic thermal (PVT) with thermoelectric cooler (TEC) collector. Energy Convers. Manag. **146**, 68–77 (2017). https://doi.org/10.1016/j.enconman.2017.05.017
107. Wang, Z., Zhang, J., Wang, Z., Yang, W., Zhao, X.: Experimental investigation of the performance of the novel HP-BIPV/T system for use in residential buildings. Energy Build. **130**, 295–308 (2016). https://doi.org/10.1016/j.enbuild.2016.08.060
108. Sweidan, A., Ghaddar, N., Ghali, K.: Optimized design and operation of heat-pipe photovoltaic thermal system with phase change material for thermal storage. J. Renew. Sustain. Energy. **8**(2) (2016). https://doi.org/10.1063/1.4943091
109. Hou, L., Quan, Z., Zhao, Y., Wang, L., Wang, G.: An experimental and simulative study on a novel photovoltaic-thermal collector with micro heat pipe array (MHPA-PV/T). Energy Build. **124**, 60–69 (2016). https://doi.org/10.1016/j.enbuild.2016.03.056
110. Deng, Y., Quan, Z., Zhao, Y., Wang, L., Liu, Z.: Experimental research on the performance of household-type photovoltaic-thermal system based on micro-heat-pipe array in Beijing. Energy Convers. Manag. **106**, 1039–1047 (2015). https://doi.org/10.1016/j.enconman.2015.09.067

111. Zhang, B., Lv, J., Yang, H., Li, T., Ren, S.: Performance analysis of a heat pipe PV/T system with different circulation tank capacities. Appl. Therm. Eng. **87**, 89–97 (2015). https://doi.org/10.1016/j.applthermaleng.2015.04.074
112. Ebaid, M.S.Y., Ghrair, A.M., Al-Busoul, M.: Experimental investigation of cooling photovoltaic (PV) panels using (TiO2) nanofluid in water -polyethylene glycol mixture and (Al2O3) nanofluid in water-cetyltrimethylammonium bromide mixture. Energy Convers. Manag. 155(October 2017), 324–343 (2018). https://doi.org/10.1016/j.enconman.2017.10.074
113. Lari, M.O., Sahin, A.Z.: Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications. Energy Convers. Manag. 149(July), 467–484 (2017). https://doi.org/10.1016/j.enconman.2017.07.045
114. Ghadiri, M., Sardarabadi, M., Pasandideh-Fard, M., Moghadam, A.J.: Experimental investigation of a PVT system performance using nano ferrofluids. Energy Convers. Manag. **103**, 468–476 (2015). https://doi.org/10.1016/j.enconman.2015.06.077
115. Al-Nimr, M.A., Al-Ammari, W.A.: A novel PVT/PTC/ORC solar power system with PV totally immersed in transparent organic fluid. Int. J. Energy Res. **43**(9), 4766–4782 (2019). https://doi.org/10.1002/er.4615
116. Maatallah, T., Zachariah, R., Al-Amri, F.G.: Exergo-economic analysis of a serpentine flow type water based photovoltaic thermal system with phase change material (PVT-PCM/water). Sol. Energy 193(September), 195–204 (2019). https://doi.org/10.1016/j.solener.2019.09.063
117. Pang, W., et al.: Comparative investigation of performances for HIT-PV and PVT systems. Sol. Energy **179**(August 2018), 37–47 (2019). https://doi.org/10.1016/j.solener.2018.12.056
118. Fan, W., Kokogiannakis, G., Ma, Z.: Optimisation of life cycle performance of a double-pass photovoltaic thermal-solar air heater with heat pipes. Renew. Energy. **138**, 90–105 (2019). https://doi.org/10.1016/j.renene.2019.01.078
119. Herrando, M., Pantaleo, A.M., Wang, K., Markides, C.N.: Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. Renew. Energy. **143**, 637–647 (2019). https://doi.org/10.1016/j.renene.2019.05.004
120. Chen, H., Li, Z., Xu, Y.: Evaluation and comparison of solar trigeneration systems based on photovoltaic thermal collectors for subtropical climates. Energy Convers. Manag. **199**(May), 111959 (2019). https://doi.org/10.1016/j.enconman.2019.111959
121. Wang, K., Herrando, M., Pantaleo, A.M., Markides, C.N.: Technoeconomic assessments of hybrid photovoltaic-thermal vs. conventional solar-energy systems: Case studies in heat and power provision to sports centres. *Appl. Energy* 254(January), 113657 (2019). https://doi.org/10.1016/j.apenergy.2019.113657
122. Widyolar, B., et al.: Experimental performance of an ultra-low-cost solar photovoltaic-thermal (PVT) collector using aluminum minichannels and nonimaging optics. Appl. Energy **268**(October 2019), 114894 (2020). https://doi.org/10.1016/j.apenergy.2020.114894
123. Al-Waeli, A.H.A., Kazem, H.A., Chaichan, M.T., Sopian, K.: Experimental investigation of using nano-PCM/nanofluid on a photovoltaic thermal system (PVT): Technical and economic study. Therm. Sci. Eng. Prog. **11**, 213–230 (2019). https://doi.org/10.1016/j.tsep.2019.04.002
124. Kumar, R., et al.: Materials today sustainability evaluating the energy and economic performance of hybrid photovoltaic thermal system integrated with multiwalled carbon nanotubes enhanced phase change material. Mater. Today Sustain. **28**(October), 101035 (2024). https://doi.org/10.1016/j.mtsust.2024.101035
125. Sofiah, A.G.N., Pasupuleti, J., Samykano, M., Rajamony, R.K., Pandey, A.K., Sulaiman, N.F.: Thermo-economic performance analysis and multi-objective optimization of viscosity ratio and thermal conductivity ratio of copper oxide-palm oil nanolubricants. Phys. Fluids. **36**(11) (2024). https://doi.org/10.1063/5.0233392

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

Authors and Affiliations

Reji Kumar Rajamony[1,2] · K. Sridhar[3] · B. Kalidasan[4] · Richa Mishra[5] · Rizwan A. Farade[6] · A. Megalingam[3] · John Iruthaya Raj M[7] · Mohammad Nur-E-Alam[1,8,9] · Tarek Abedin[1]

✉ Reji Kumar Rajamony
rejikumar.r2006@gmail.com

1 Institute of Sustainable Energy, Universiti Tenaga Nasional (The Energy University), Jalan Ikram-Uniten, Kajang 43000, Selangor, Malaysia

2 Faculty of Engineering and Technology, Parul University, Waghodiya Road, Vadodara 391760, Gujarat, India

3 Faculty of Mechanical & Automotive Engineering Technology, University Malaysia Pahang Al-Sultan Abdullah, Pekan 26600, Pahang, Malaysia

4 Research Centre for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No. 5, Jalan Universiti, Bandar Sunway, Petaling Jaya 47500, Selangor Darul Ehsan, Malaysia

5 Department of Computer Engineering, Parul institute of engineering and technology (PIET), Parul University, Ta. Waghodia, Vadodara 391760, Gujarat, India

6 Advanced Lightning, Power and Energy Research (ALPER), Department of Electrical and Electronics Engineering, Faculty of Engineering, University Putra Malaysia, Serdang 43400, Malaysia

7 Department of Mechanical Engineering, Mar Ephraem College of Engineering and Technology, Malankara Hills, Elavuvilai 629171, Tamil Nadu, India

8 School of Science, Edith Cowan University, Joondalup 6027, WA, Australia

9 School of Engineering and Technology, Central Queensland University Australia, Melbourne, VIC 3000, Australia