A detailed review on the performance of photovoltaic/thermal system using various cooling methods

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ABSTRACT

As an emerging technology, photovoltaic (PV) panels have made a vital energy source to meet increased energy consumption demand and to replace the associated scarcity of traditional energy resources. PV modules have electrical efficiency from 4 to 26%, depending on their materials. The PV panel transforms about 50–60% of total solar radiation into heat, leading to high temperatures during the operation of the PV panel. Due to high temperature, there is a decrease in electrical conversion efficiency and thermal stress in PV panels continue for a more extended period. In this context, a photovoltaic/thermal (PV/T) system is suggested to decrease the thermal stress of the PV panel by removal of heat and make it useful at high PV module temperature. This comprehensive literature review reports PV cooling techniques, research gaps and difficulties encountered by various researchers in this technology. To counter this drawback, active and passive methods of cooling have been studied, including jet impingement, airflow cooling, immersion cooling using liquids, thermoelectric based cooling, microchannel cooling, phase change materials (PCM) based cooling, water/liquid cooling and heat pipe cooling. This research study intends to present a modern, systematic review of PV/T cooling techniques and challenges associated with these methods. Furthermore, techno-economic analysis and the role of artificial intelligence in PV/T systems are also summarized.

Introduction

Energy is the most important for all human activities. It has become a crucial need for the global economy. Today, the development of any nation can be defined by its energy usage. As the world's population increases, energy consumption will further increase [1]. From the world's total energy demand, about 75% of energy needs were met from fossil fuels, contributing to a rise in CO_2 concentration in the atmosphere, causing global warming. Nowadays, renewable and clean energy is widely encouraged worldwide due to limited conventional energy resources, a better understanding of environmental issues, and abundant renewable energy sources [2,3]. Among all renewable energy sources, solar energy is most widely used due to its vast availability on this planet. On a typical sunny day, solar radiation received by the earth is more than 15,000 times the global consumption of overall energy and 100 times the world's combined reserves of coal, gas and oil [4,5].

Terrestrial solar radiation comprises 43% infrared, 48% visible light and 9% ultraviolet and has a wavelength range between 0.25 and 2.5 μm. Despite several benefits, the potential of solar energy is still untapped. Solar energy is used for both heat and electricity generation. Photovoltaic (PV) technologies are preferred sources for harnessing solar energy. Devices like PV cells help transform direct solar radiation into electricity with a commercial range of 9–20% depending upon the technology of solar cells [6,7]. The solar collector is a device where solar radiation is absorbed in the form of energy and converted to thermal energy. It is a vital part of the concentrated solar power (CSP) system [8,9]. All PV cells transform a limited portion of solar energy to

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Nomenclature

A	PV panel Area (m^2)
I	Current (Ampere)
V	Voltage (Volts)
I_{sc}	Short circuit current (A)
V_{oc}	Open circuit voltage (V)
β_c	Packaging factor
H	Convective heat transfer coefficient ($W/m^2.K$)
T_{cell}	Temperature of cell (°C/K)
ηe	Electrical efficiency
η_{th}	Thermal Efficiency
η_o	Overall efficiency
ΔP	Pressure drops in PVT
V_{max}	Maximum voltage (V)
I_{max}	Maximum current (A)
P_{max}	Maximum Power (W)
η_p	Pump efficiency
P	Density of fluid (kg/m^3)
Q_e	Electrical energy generated from PV
T_{pm}	Average mean temperature of absorber plate (°C/K)
$T\alpha$	Transmittance-absorption product due to glazing (°C/K)
U_L	Overall heat transfer coefficient
T_a	Ambient temperature (°C/K)
T_o	Outlet temperature (°C/K)
T_i K	Inlet temperature (°C/K)

Subscripts

C	Cell
E	Electrical
I	Inlet
O	Outlet
Oc	Open circuit
sc	Short circuit
$\dot{m}$	Mass flow rate (kg/s)
T	Time (sec)
L	Liter
hr.	Hour
mA	Milli-Ampere
mV	Millivolts

Abbreviations

CPV	Concentrated photovoltaic
MPP	Maximum power point
PV	Photovoltaic
PV/T	Photovoltaic/thermal
CSP	Concentrated solar power
CPV/T	Concentrated photovoltaic/thermal
NF	Nano-fluid
LPM	Liter per minute
TEG	Thermoelectric generator
TE	Thermoelectric
HTF	Heat transfer fluid
CR	Concentrating ratio
EVA	Ethylene-vinyl acetate
BIPV	Building integrated photovoltaic
BIPV/T	Building integrated photovoltaic/thermal
HP	Heat pipe
PCM	Phase change material
CFD	Computational fluid dynamics

electricity [10]. Only visible light radiations corresponding to the PV cell are used to generate electricity. Unused solar radiation will dissipate energy to the PV panel in the form of heat. To use this extra amount of heat, a new concept is introduced in solar energy technology, which is called photovoltaic/thermal (PV/T) system [11,12]. Therefore, cooling techniques are very crucial to maintain the rise in temperature and enhance the performance of PV panels.

The need for PV cooling

This section discusses the most important causes and consequences of non-uniformity on the solar cell to highlight the need for uniform cooling of PV panels. The concentrator geometry causes several losses in the solar cell, including optical losses, reflection losses, tracking losses, and non-uniform irradiation [13]. All these losses in the system raise the cell temperature and series resistance, which results in decreasing overall efficiency.

The Fig. 1 shows the hourly variation of cell temperature and efficiency on a particular sunny day. Due to geometric defects in concentrated systems, radiation flux and temperature are not uniformly distributed throughout the PV panel surface. Non-uniformity affects cell temperature, series resistance, and efficiency of PV systems [15,16]. So, it is evident that increased PV panel operating temperature results in lowered open-circuit voltage (V_{oc}), fill factor and power outputs by

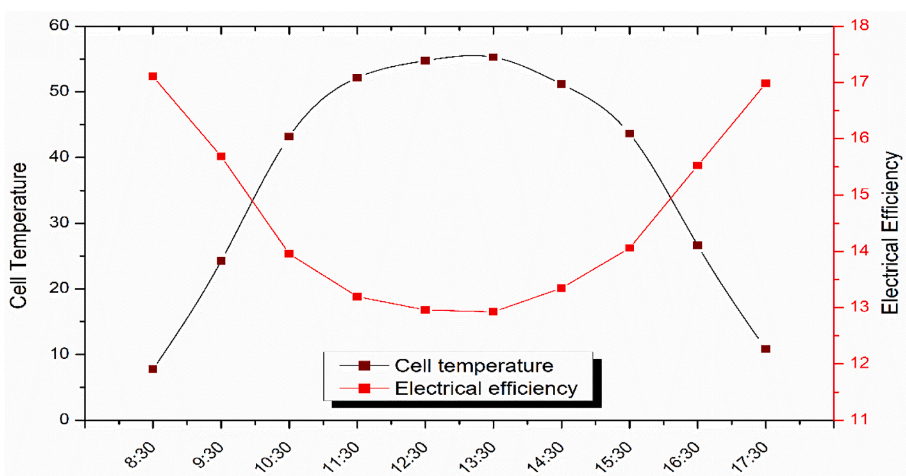

Fig. 1. Variation of temperature and electrical efficiency of module on hourly basis for a typical sunny day [14].

2–2.3 mV/°C, 0.1–0.2/°C and (0.4–0.5) %/°C, respectively, with an improvement of 0.06–0.1%/°C in short-circuit current (I_{sc}) for mono and polycrystalline photovoltaic panels. It will lead to the low conversion efficiency and degradation of the PV cell life due to high thermal stresses [17–19]. Therefore, to maintain the PV panel's temperature within the manufacturer's operating range, heat removal from the photovoltaic panels by uniform cooling methods is necessary. Various cooling methods are used for thermal management and performance improvement of PV/PVT panels, which are shown in Fig. 2.

From the literature, it is clear that various researchers use different uniform cooling methods to eliminate excess heat and increase the performance of photovoltaic modules. This study aims to discuss these stated gaps; to provide the state-of-the-art review involving a combination of electrical and thermal energy technologies in the form of a PV/T system that could be more useful than an individual PV panel. The market demand for different PV/T systems is explored with its utility applications. The implantation of the latest cooling techniques such as spectral filtering and nano-fluids in PV/T systems are discussed in summary as a future scope. The main aim of this systematic literature review is to helps the researchers and academicians to better understand the uniform cooling methods in the application of PV/T systems.

This study is organized in a way such as the introduction and need of PV cooling explained in section 1. The research methodology adopted for this systematic literature review is explained in section 2. Also, section 3 explained the concept of the PV/T system and its thermodynamic analysis. Section 4: briefly describe the overview of different uniform cooling methods, including the jet impingement cooling, airflow cooling, heat pipe cooling, liquid/water cooling, PCM cooling, thermoelectric cooling and microchannel cooling. In section 5 final summary of all cooling methods and their economic and environmental impacts. Section 6 and 7 explain the role of artificial intelligence, machine learning and techno-economic analysis in PV/T systems. In section 8 the key issues and challenges associated with PV cooling are addressed. Section 8 presents the conclusions of this study.

Methodology for systematic literature review

The literature review procedure is described in this section. The literature review is the methodological approach used to justify the review process. The literature review is also a study initiative that identifies, evaluates, discusses, arranges and reveals existing studies in many formulated questions. The main point is to clarify everything about current research, i.e. what is explored and what is not explored by increasing transparency, accuracy and validity [20]. This research aims to focus on different cooling methods, thermal and electrical performance of PV/T systems and factors influencing the performance output of such systems. This quick review is carried out because the use of PV/T technologies plays a vital role in renewable energy. Denyer and Tranfield had developed an important method to ensure that the literature review is transparent and reviewed efficiently [21]. There are following steps to complete this analysis: (1) Formulation of problems (2) Selecting and reviewing the articles i.e. formulate the inclusion and exclusion criterion of research articles (3) The assessment and synthesis carried out to analyze the results.

Framing of problems

This article reviews existing cooling methods for different PV/T systems that are studied around the globe. A set of research questions will be framed to be followed during this literature review to achieve the objectives. The information obtained from this review is summarized to develop some effective cooling methods.

- Why we need to introduce the PVT system?
- What are the different methods used for stabilizing the temperature of PV/T systems?
- What kind of investigations conducted on various cooling techniques to save and store the maximum amount of renewable energy through PV/T systems?
- What are the potential implications that could be used to improve PV/T systems performance?

Selecting and reviewing the research studies

The most applicable work was designed to refine the requirements for inclusion and exclusion of results. Criteria of inclusion and exclusion act as a division of distinctions between relevant and irrelevant research. Criteria selected for inclusion and exclusion of research articles are given as:

Exclusion criteria

- The articles are not related to the PV/T system cooling methods.
- Articles not in the English language.
- Articles published before the year 2005.
- Articles published as a short document.

Inclusion criteria

- An article was presenting the factors that influence the efficiency of PV/T systems.
- An article was providing a uniform cooling method for PV/T systems.

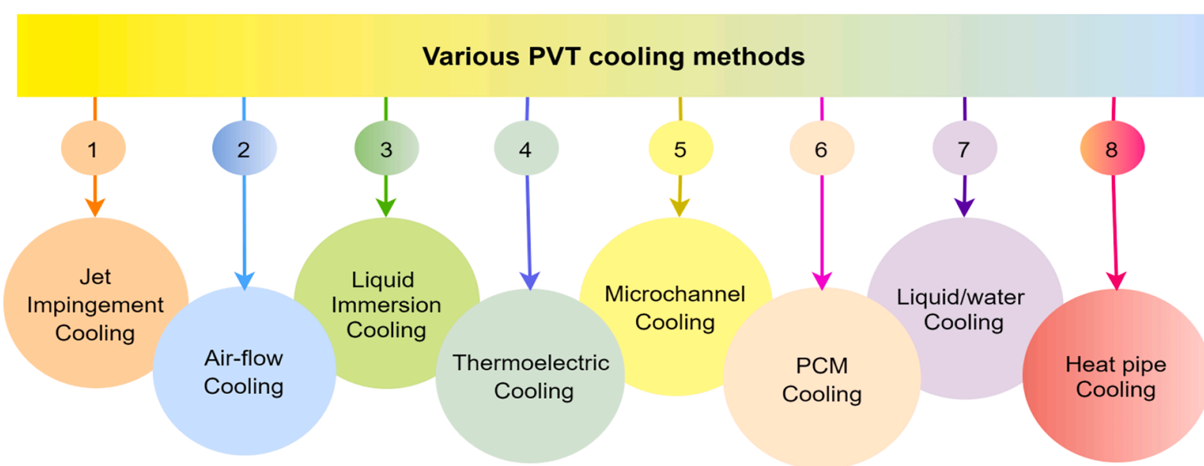

Fig. 2. Schematic diagram of uniform cooling methods.

- An article that providing (experimental and numerical) investigations performed on uniform cooling methods.
- An article that explores the future advanced cooling methods in PV/T systems

Assessment and synthesis process

After completion of the collection of the critical literature, the first goal is to divide each article into its components. In the first stage, the data extraction method was framed and the research papers were grouped according to their importance. The second step is to summarize the results. The method of synthesizing, arranging the findings of each article and creating a particular arrangement that is relevant to the fundamental point of the analysis, to give readers a comprehensive and distinctive perspective.

Concept of PV/T system

Three solid conclusions can be made about the driving factor behind photovoltaic-thermal (PV/T) system: (i) Mainly decreasing the working temperature of photovoltaic modules (ii) Increasing the system's total energy efficiency (iii) Reducing system area and cost. Although, PV/T systems are known to be promising technologies in utilization of solar energy. In these systems, heat from photovoltaic modules is collected using a variety of methods [22]. Fig. 3 describes the PV/T system schematic diagram.

In the past two decades, this PV/T technology has received considerable attention from researchers and academicians worldwide. Numerous system designs, theoretical and simulated models are evaluated under various operating conditions to decrease the working module temperature while still reaching the higher temperatures at the collector's outlet end efficiently and cost-effectively. In this study, several experimental, theoretical and numerical works on these systems have been presented in the literature [23]. In the beginning, air and water were used extensively to extract heat from photovoltaic modules. Recent research includes thermoelectric devices, organic and metal hydride PCM, heat pipe and spectral splitting techniques [24]. A PV/T system has various advantages and disadvantages, which are shown in Fig. 4.

The development of hybrid PV/T collectors has improved overall performance by varying design, operating conditions, specific applications, material quality etc. [25,26]. However, significant gaps in the existing literature indicate that hybrid photovoltaic/thermal systems are an ideal source of combined heat and power (CHP), with a strong emphasis on exergo-economic assessment and performance analysis of complex systems. Payback period for a typical PV/T system is determined to be between 1 and 4 years in terms of energy and greenhouse gas emissions. A brief overview of PV/T systems is shown in Fig. 5 with various applications [27].

Thermodynamic analysis of PV/T system

A PV/T system is essentially a combination of a flat plate solar thermal collector and a photovoltaic panel. The fill factor measures the I-V curve sharpness at the knee spot. When the temperature of the PV panel increases, the fill factor gets reduced. This reduction in fill factor drops the electric output and attracts an increase in cost [14]. The working principle and thermal performance of PV/T system is shown in Fig. 6. The performance parameters such as fill factor, the thermal and electrical efficiency along with overall efficiency of PV/T systems have been calculated using the following equations.

The overall efficiency of PV/T system

$$\eta_o = \eta_e + \eta_{th} \tag{1}$$

Thermal efficiency of PV/T system

Thermal efficiency of PV/T system is the ratio of useful heat gain (Q_u) to overall incident solar radiation on PV/T system area.

$$\eta_{th} = \frac{Q_u}{I \times A} \tag{2}$$

There are two ways to calculate the useful heat gain from the collector: (i) product of average mass flow rate of fluid, specific heat of fluid and temperature difference between in and out condition of fluid. (ii) the difference between the energy absorbed and energy losses with electrical energy produced from the system.

$$Q_u = \dot{m} \times C_p \times (T_{out} - T_{in}) \tag{3}$$

$$Q_u = A_c\left[I(\tau\alpha) - U_L\left(T_{pm} - T_a\right) - Q_e\right] \tag{4}$$

T_{pm} is difficult to get since it is a mixed function of system design, solar insolation, and working fluid characteristics, hence it is substituted by fluid inlet temperature T_i for simplicity of calculation. So, Eq. (4) may now be written as

$$Q_u = A_c.F_R[I(\tau\alpha) - U_L(T_i - T_a) - Q_e] \tag{5}$$

Here, F_R is called the heat removal factor and which is related to efficiency factor F', can be written as

$$\frac{F_R}{F'} = \left[1 - exp\left(-\frac{A_c U_L F'}{\dot{m} C_p}\right)\right] \tag{6}$$

In this equation the F' depends upon the working fluid. The F' for different fluid can be calculated as

$$F' = \frac{\frac{1}{U_L}}{D\left[\frac{1}{U_L}\left[D_o + (D - D_o)F\right] + \frac{1}{C_b} + \frac{1}{\pi D_i h_{wf}}\right]} \quad \text{for water} \tag{7}$$

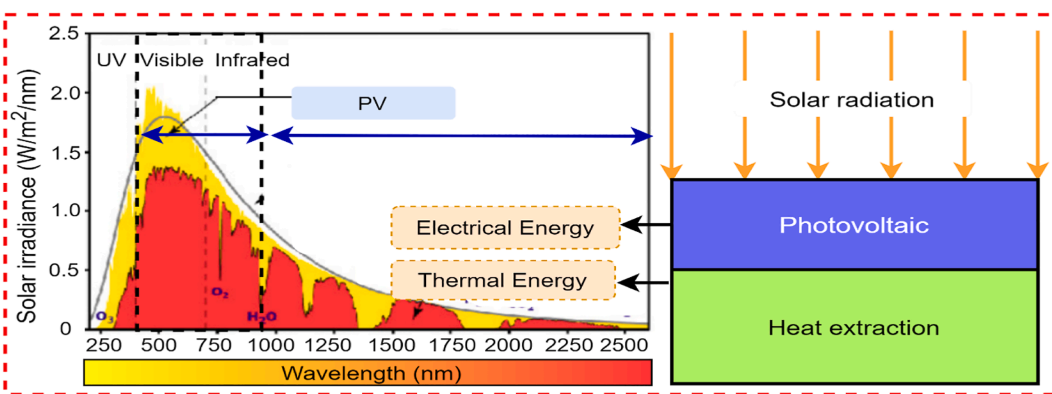

Fig. 3. A schematic diagram of photovoltaic/thermal system.

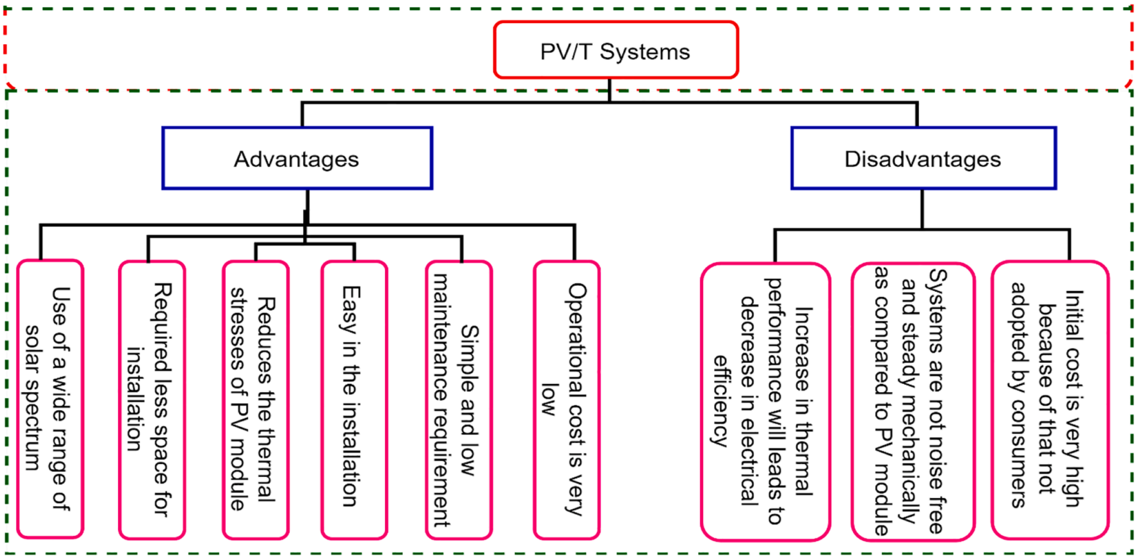

Fig. 4. Schematic diagram with advantages and disadvantages of PV/T system.

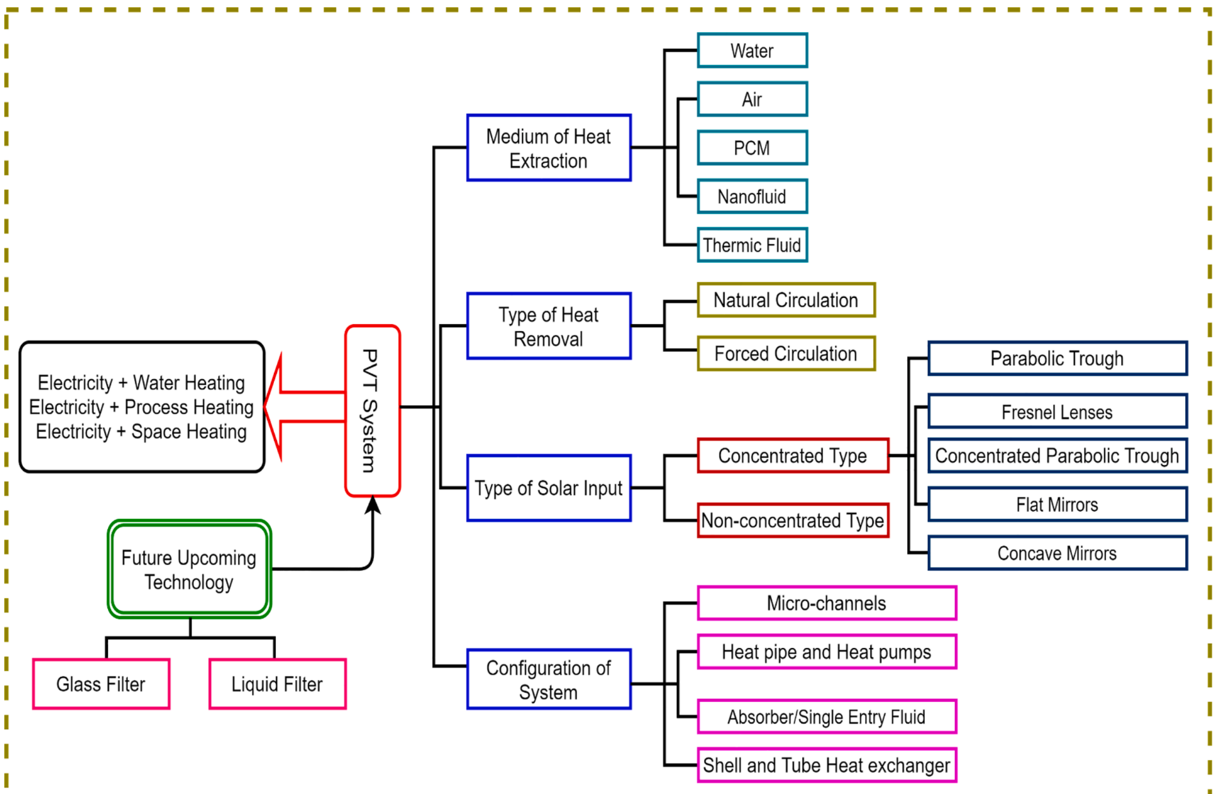

Fig. 5. Classification of various types of photovoltaic/thermal systems and their applications.

$$F' = \frac{1}{1 + \left[\frac{U_L}{h_{wf}}\frac{A}{A_c} + \left(\frac{1}{h_r} + \frac{1}{h_{wf}}\right)\right]} \text{ for air} \quad (8)$$

Here, F is called the fin efficiency and it can be written as

$$F = \frac{\tanh\left[\sqrt{\left(\frac{U_L}{k\delta}\right)}(D - D_o/2)\right]}{\sqrt{\left(\frac{U_L}{k\delta}\right)}(D - D_o/2)} \quad (9)$$

If the pump is used to circulate the fluid through collector, then power consumed by pump can be written as

$$E_p = \frac{\dot{m} \times \Delta P}{\rho \times \eta_p} \quad (10)$$

Electrical efficiency of PV/T system

Any PV-based system's electrical efficiency can be calculated by dividing its output power (P_{max}) by the incident solar radiation (I. A_c) received over a certain surface area. It can be written as

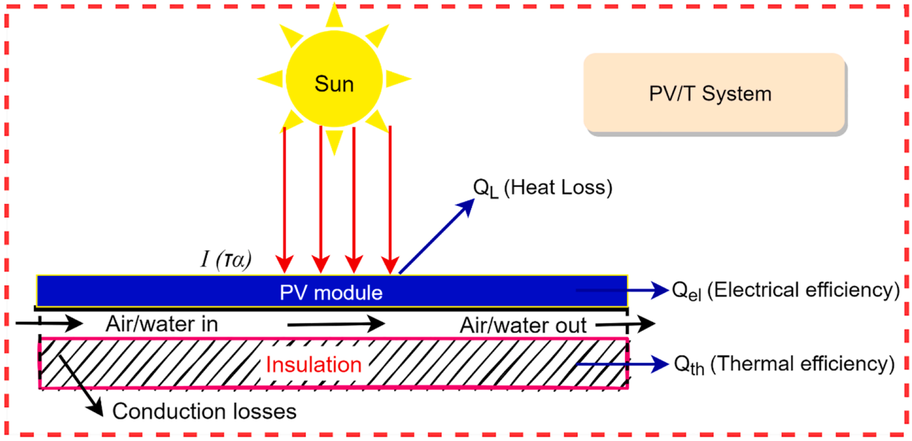

Fig. 6. Working principle and thermal analysis of PV/T system.

$$\eta_e = \frac{P_{max}}{I \times A_c} = \frac{V_{max} \times I_{max}}{I \times A_c} = \frac{V_{oc} \times I_{sc} \times FF}{I \times A_c} \tag{11}$$

$$FF = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}} \tag{12}$$

The electrical efficiency of the module degrades as the temperature of the cell rises, as shown by the equation

$$\eta_e = \eta_{rc}\left[1 - \beta_{pv}(T_{pv} - T_{rc})\right] \tag{13}$$

PV/T systems provide various environmental advantages such as energy-saving and reduced greenhouse gases. Study will provide information on PV/T from the economic and environmental perspectives [27,28]. Table 1 presents a summary of available review papers on uniform cooling methods. From the literature of these review articles, it is evident that no such research occurs in which heat pipe, nano-fluids mixed with water and other advanced cooling methods are explained thoroughly.

Detailed literature review of different cooling methods for PV/T systems

Proper cooling of PV/T systems is an essential factor in photovoltaic cell design and operation. A cooling technique is supposed to be a process that maintains the PV panel's temperature within the operating range and distributes uniformly. The idea of uniform cooling of the PV/T system is new, so there is limited literature in this field. However, it depends on high heat removal capability and heat transfer coefficient [44,45]. Various cooling techniques are shown in Fig. 7, recorded and reviewed in the literature for photovoltaic and electronic devices cooling.

In this section, various cooling methods, including jet impingement cooling, airflow cooling, Liquid immersion cooling, thermoelectric cooling, microchannel cooling, PCM-assisted cooling, water/liquid cooling and heat pipes based coolig are discussed in detail.

Jet impingement cooling

Jet impingement is an active cooling method that cools the heated body with excellent heat transfer rates. It occurs due to the atomization of fluid from nozzles. The technique was initially used in manufacturing applications during metal cutting, metal annealing, quenching, and cooling gas turbine blades.

Royne et al. [46] designed a cooling device for PV panel with jet impingement which is under high concentration. It contains a set of jets in which the cooling fluid is bypassed to the heated area of cells from sides in the normal direction. A model was proposed to calculate the pumping power and device configuration needed for a given heat transfer coefficient. The model is estimated to be maximum nozzles per unit area would be better than a few nozzles. The optimum nozzle diameter and number of nozzles are also estimated for a given area from this model.

Abdolzadeh et al. [47] experimented to explore efficiency and enhance the prospect of a photovoltaic water pumping system. The water is sprayed over the PV cells through a jet. The experimental result shows that the efficiency of cells is improved because of the photovoltaic cells being sprayed with water. However, it will lead to an increase in pumping power. After that, improved results are compared with the conventional PV system.

Masoud Rahimi et al. did experimental work on a jet impingement device to cools the PV cells. This system combines two renewable sources of energy, such as (solar and wind), to increase the total energy generated, as shown in Fig. 8. Also, CFD modelling was performed to validate the experimental results. It is observed from the results that a total increase in power due to PV cell and wind energy is 21%, then a primary cooling system [48].

Under the Middle East climate conditions of the Dhahran region, Bahaidarah [49] conducted experimentation for cooling of PV modules followed by numerical analysis using jet impingement. The PV module comprises eight cells. Each cell was supplied with a jet cooling device, which contributed to an equivalent average temperature and overcame the problems of erratic current and hotspots. The overall effectiveness of the PV panel was calculated with the help of optical, radiation, thermal, geometric and electrical models. Results indicate that at 1000 W/m^2 the heat transfer coefficient of PV panel performance is significantly improved. The maximum temperature for June has been decreased from 69.7 °C to 36.6 °C and 47.6 °C to 31.1 °C for December with a jet impingement cooling. The power output and electrical efficiency improved from 51.6% to 66.6% for June, while 49.6% and 82.6% for December.

Hasan et al. [50] with a nanoparticles (SiO_2, TiO_2 and SiC) combination with water as a base fluid tested the electrical efficiency of a PV/T device using a jet impingement. The PV/T system exposed to different levels of solar radiation. The performance of PV for various nano-fluids at 1% weight were examined. The effect of water mass flow rates of 0.050, 0.067 and 0.083 kg/s were duly tested. Fig. 9 showed the basic structure of the photovoltaic cooling device. High Power (P_{max}) and thermal efficiency obtained with PV/T-SiC nanofluid at a mass flow rate of 0.1666 kg/s. Zahhad et al. [51] had developed a three-dimensional model for a high CPV/T system. In this model, a triple-junction solar cell was made of GaInP/GaInAs/Gg sheets with an active area of 1 cm^2 and electrical efficiency of 40.3% under a high concentration of 1000× W/m^2. The results indicated that the electrical efficiency is increased by impinging coolant jet, but 1% of total generated power is consumed to

Table 1
Summary of available literature reviews for different cooling methods from 2015 to 2020.

Researcher	Ref.	Year	Technology	Content of the review paper
Bahaidarah et al.	[29]	2016	PV and CPV systems	This article aims to outline the need for uniform cooling of PV panels for low- and high-concentration systems.
Elbreki et al.	[30]	2016	PV/T systems	This research aims to provide an overview of active and passive cooling methods to regulate the PV panel's temperature.
Islam et al.	[31]	2016	PV/T system + PCM	PVT-PCM was presented as a separate study in this article. An effort has been made to review several PCM based PVT systems
Kane et al.	[32]	2016	PV modules + Thermoelectric modules	The present paper addresses the active heat sink by using thermoelectric modules from the PV system. The numerical model for the thermoelectric module is developed with proper temperature control material properties.
Sargunanathan et al.	[33]	2016	PV and CPV systems	The study describes passive cooling methods such as heat pipe, fins, and active cooling methods like spraying water at the front or back of the PV module.
Siecker et al.	[34]	2017	PV/T, PV/TE, STC and systems	The aim of this review is that the PV module's surfacing temperature can be minimized by considering the various technologies
Chandel and Agrawal	[35]	2017	PV + PCM systems	This study concentrates on the review of PV cooling previous research studies with PCM to find specific materials, research gaps and potential of future research scope in this field
Shukla et al.	[36]	2017	PV Modules	The current study focuses on a range of cooling technologies such as natural /forced air cooling, heat-tube cooling and phase-change material-based cooling.
Gilmore et al.	[37]	2018	CPV systems + microchannel	This study aims to address some identified gaps. Methods for non-microchannel cooling to provide a foundation for microchannel cooling are briefly explained.
Nizetic et al.	[38]	2018	PV systems	A systematic review and assessment of active cooling methods for photovoltaics was the key aim of the research.
Sajan Preet	[39]	2018	PV/T + PCM + water system	This study helps to identify new cooling technologies, various thermal absorber designs and various materials.
Waqas et al.	[40]	2018	PV + PCM system	This study aims to discuss PV-PCM technology's existing state, as well as its research limitations. A complete literature review discusses the development of current technology, performance analysis, PCM selection etc.
Sato et al.	[41]	2019	PV systems + Radiative cooling	The latest research outlines advanced photovoltaic (PV) refrigeration methods and explores the effectiveness of the radiative cooling mechanism.
Dwivedi et al.	[42]	2020	PV systems + cooling methods	This study provides an overview of cooling methods and their benefits used in PV panels.
Kandeal et al.	[43]	2021	PV + Nano enhanced cooling methods	This research evaluated and discussed the efforts made to enhance PV performance utilizing nano-based (nano-enhanced PCMs, nanofluid-based, and hybrid nano-based) cooling systems.
Present Study	–	–	PV/PVT systems + advance cooling methods	The present study discusses the various advanced cooling methods and smart technologies adopted for thermal management in PV/T systems. The PV/T system's techno-economic analysis and challenges associated with their developments are also covered in this study.

impinging the jet.

Airflow cooling

Air flow cooling is one of the simplest and easily available cooling methods. During this process, the air is used by natural/forced convection to remove heat from the PV/T system. However, forced air circulation is an active cooling method, which uses a considerable amount of fan work [52].

Baloch et al. [53] experimented on convergent channel cooling techniques at low and uniform PV module temperatures during June and December in the hot climate of Saudi Arabia (See Fig. 10). CFD results have shown that at an optimum tilt angle, the PV module's top surface temperature is uniform. The average cell temperature decreased to 45.1°C on typical hot days in June. The electrical conversion efficiency and power output have been increased.

Popovici et al. [54] developed a computational model to control PV device temperature using air-cooled sinks. The heat sinks mounted behind the PV panel have a width of 0.1 m for the canal of the double

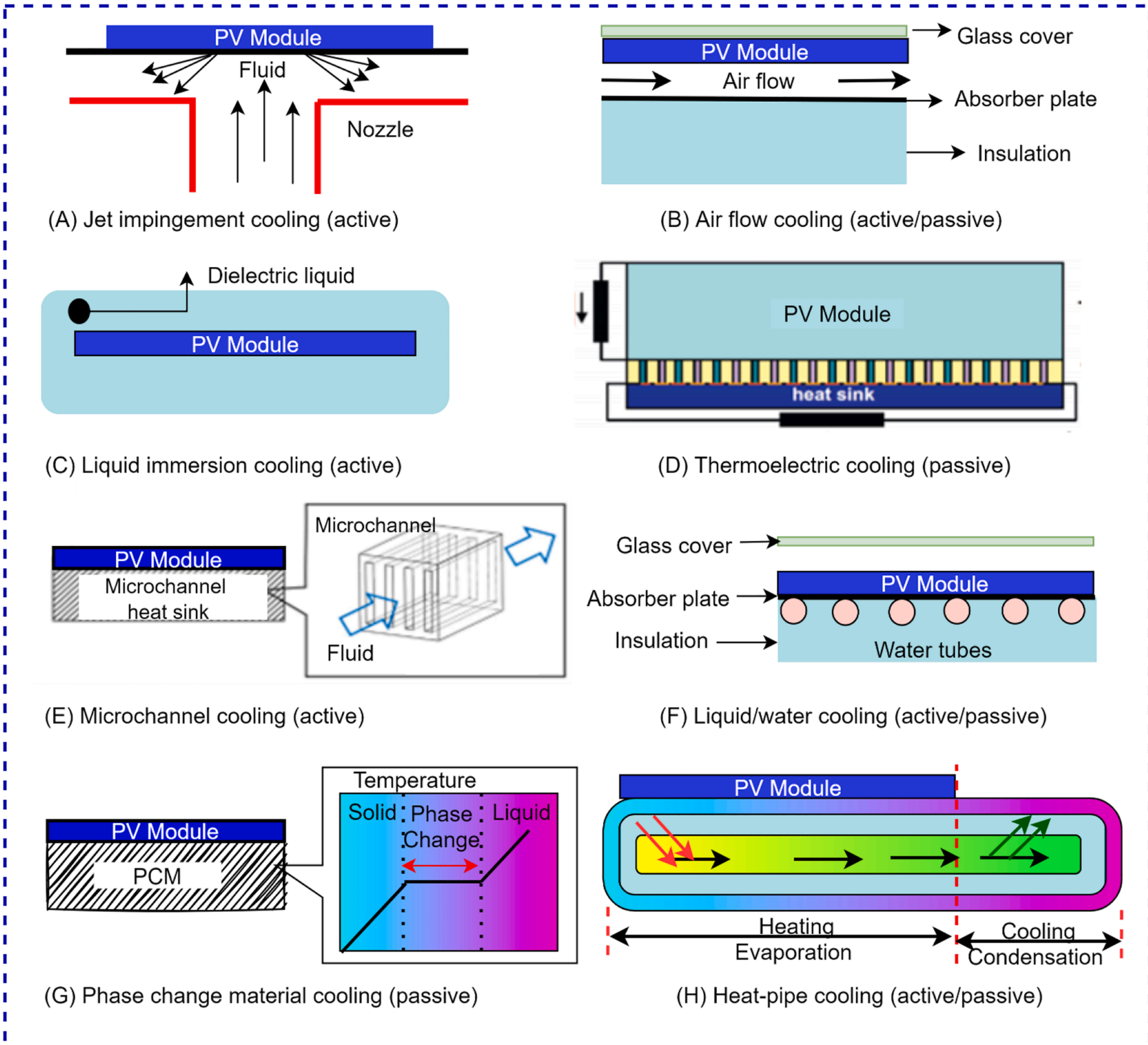

Fig. 7. Schematic diagram of uniform cooling methods for PV/T systems.

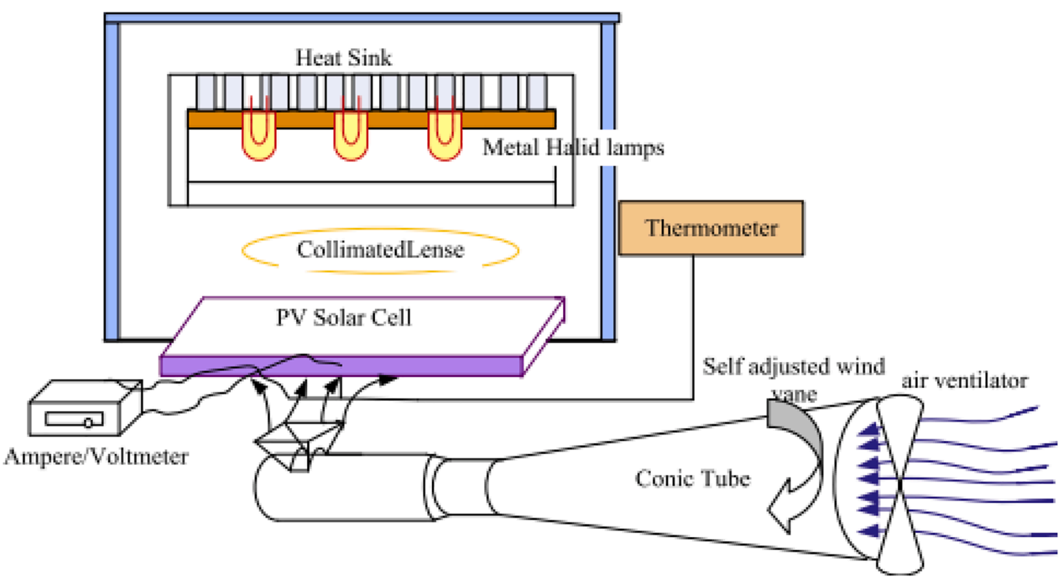

Fig. 8. A basic structure of the experimental setup [48].

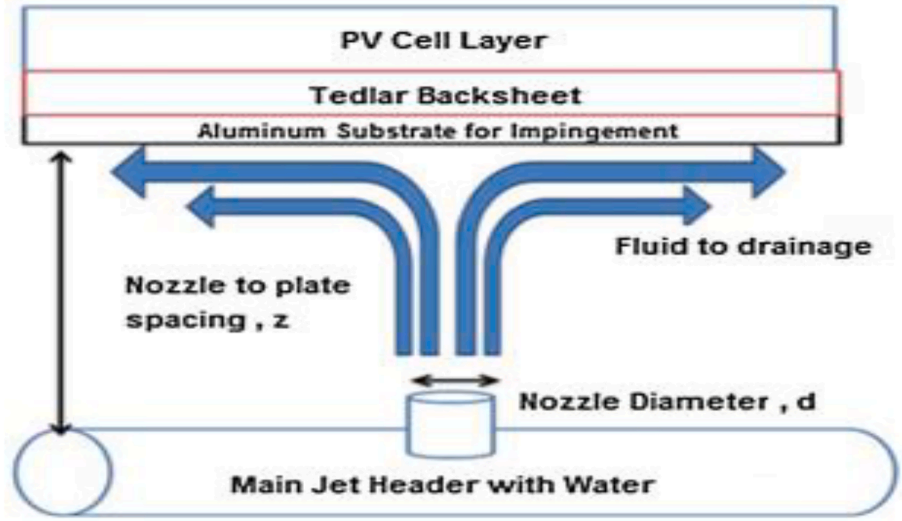

Fig. 9. Schematic diagram of jet impingement cooling for PV cell [49].

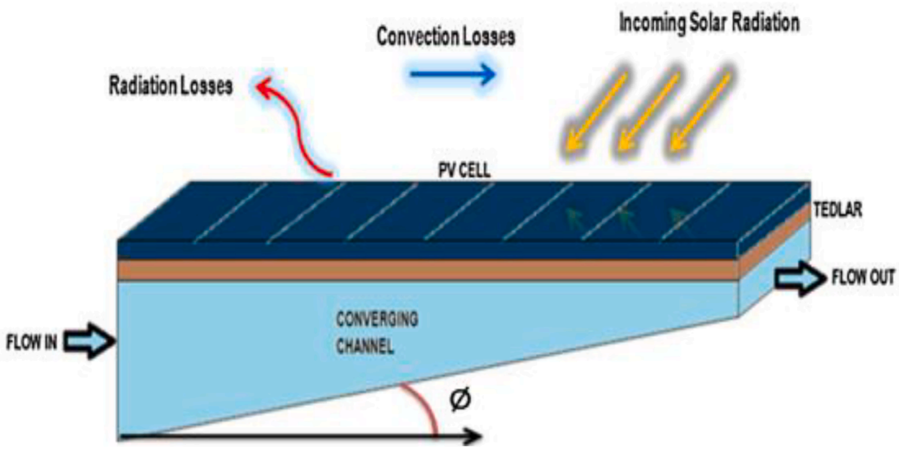

Fig. 10. Schematic diagram of converging heat exchanger [53].

façade. The holes help to improve airflow near the sink and remove heat from the PV module. Simulation results indicated that temperature drops by 10°C in comparison with the base case. Nizetic et al. [55] experimented on two conventional PV modules poly-Si and mono-Si, under Mediterranean climatic conditions. The focus was on examining the effect of air on the rear of the PV panel. A CFD model was developed

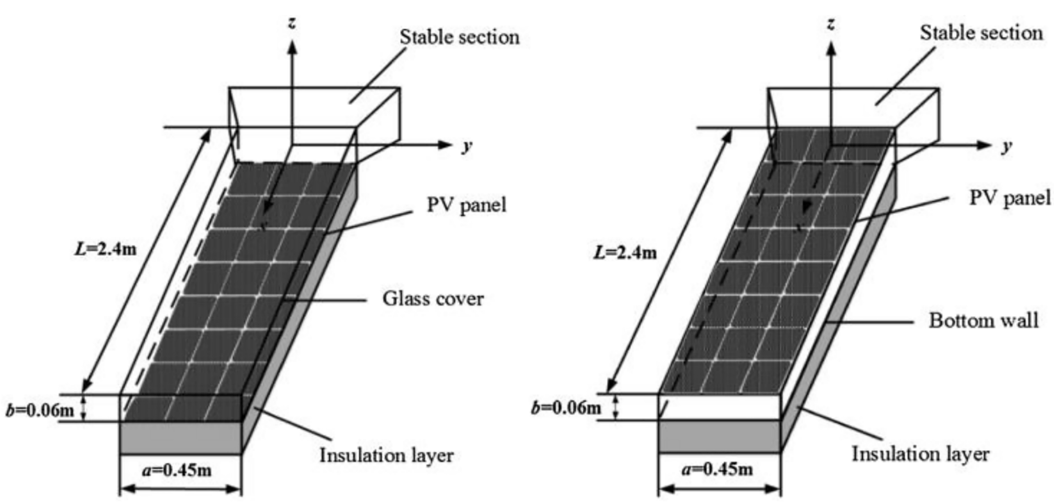

Fig. 11. Physical model structure of case (a) and case (b) [57].

to perform the sensitivity analysis. The CFD findings were found to be significantly higher than the experiment.

Boutina et al. [56] proposed a bi-dimensional simulation model of the turbulent natural convection for PV cooling by integrating a chimney tower with a hybrid PV/T solar collector. The heat transfer rate is improved by 78.13% compared with the base case (without an absorber and a chimney) with the help of the proposed hybrid system's geometrical parameters. Choubineh et al. [28] examined PCM disposition effects on the performance of the air-cooled PV/T system. In this experiment, two PV panels of dimensions (1053 × 554 mm) were used, and a steel plate was attached to the backside of these panels to extract the extra heat. PCM (salt hydrate PCM32/280 manufactured in PGSCRCO Company) is placed inside the absorber plate and an air channel is placed next to it. The temperature differences in the natural convection condition have been fluctuating behaviour, which reduces during the use of PCM. Wu et al. [57] investigate numerical research on cooling channel position in heat transfer properties on PV output. Two cases (shown in Fig. 11) are considered, such as case (a) the cooling channel above the PV system and case (b) the cooling channel below the PV system.

In the air-cooled PV/T system, electrical performance is regulated by solar intensity. The air intake temperature affects the thermal efficiency with some parameters irrespective of the position of the cooling channel. In parallel, overall and thermal efficiency trends are consistent, and trends in average electrical efficiency and overall exergy efficiency are similar. Kabeel and Abdelgaied [58] reported a hybrid system consisting of PV panels with reflectors and a cooling system is coupled solar still with air injection. They used a cooling system to decrease the PV panel temperature. On the other hand, reflectors are used to minimize the reflection losses and Increase the density of solar radiation absorbed by PV panels.

They examined the five different cases as shown in Fig. 12, which are known as case-1: (conventional PV panel), case-2: (PV + reflectors), case-3: (PV + reflectors + air cooling method), case-4: (PV + reflectors + water cooling technique) and case-5 (PV + reflectors + water + air cooling techniques) to optimize the best cooling results. Results indicate that there is an increase of 16.81%, 21.62%, 35.13% and 39.69% in electrical efficiency of case-2, 3, 4, and 5 in the PV panel compared with case-1. Elminshawy et al. [59] conducted a novel experiment in which a pre-cooled air is passing over the back of the PV panel under the climate condition of Port Said, Egypt. The temperature of a module is reduced by 8 °C, 10 °C, 11 °C and 13 °C at different discharges. Power output increased by 4.54% for 0.0228 m^3/s, 9.19% for 0.0248 m^3 /s, 13.99% for. 0. 0268 m^3/s and 18.90% for 0.0288 m^3/s compared to the reference module. Muneeshwaran et al. [60] had studied air cooling to maintain uniform PV module temperature. Study shows that the temperature of the cooling panel is 6–12 °C below the uncooled temperature. Temperature non-uniformity of 4–7 °C in the PV panel was observed, even with the cooling. Özakın and Kaya [61] Optimized PV/T electrical, thermal and exergy efficiencies using various materials and configurations fins. "ANOVA" was performed to identify the control parameters, which are also affecting both efficiencies. They conducted experiments in both monocrystalline and polycrystalline panels, under various and scarce configurations of fins made of copper, aluminum and brass. In both tests, fins material, air velocity and panel temperature were found to be the most important variables. Teo et al. [62] experimented with an air-cooled PV/T system under Singapore's climate conditions. The system consists of a polycrystalline PV panel, MPPT device, AC blower and a fin attached duct at the backside of the panel. Electrical performance was found to be maintained at about 12.5% under air cooling.

Liquid immersion cooling

Cooling based on liquid immersion removes excess heat from the PV module by immersing them in a fluid, which is dielectric to maintain the PV system's temperature. The water of this refractive index is selected to focus the solar insolation on the PV panel. This procedure will keep the temperature of the board at 30–45 °C.

Zhu et al. [63] experimented on water immersion cooling of high concentrating PV cells. They used a 250 times two-axis disk concentrator to construct a new CPV system (See in Fig. 13) and the use of de-ionized water for immersion cooling. Time-dependent temperature distributions of the high-powered PV module contact cells and I-V curves were measured. The liquid immersion approach's cooling capacity is exceptionally favorable. The module's temperature distribution is very uniform, but the cell module's electrical output degrades after pretty long immersion in de-ionized water.

Sun et al. [64] proposed that cooling of PV panels by a liquid-immersion technique using dimethyl silicon oil to remove heat from the CPV system. They designed a narrow rectangular channel to receive a heat flux of 9.2x (x-times) and also tested the long-term reliability of

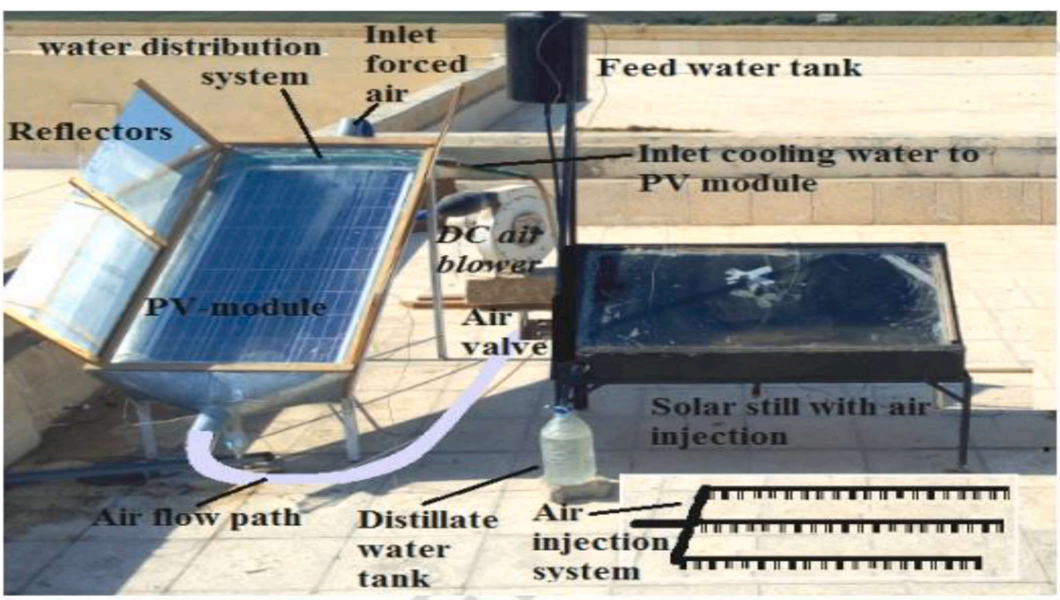

Fig. 12. A pictorial view of a hybrid system of PV panel + reflectors + cooling with still solar air injection [58].

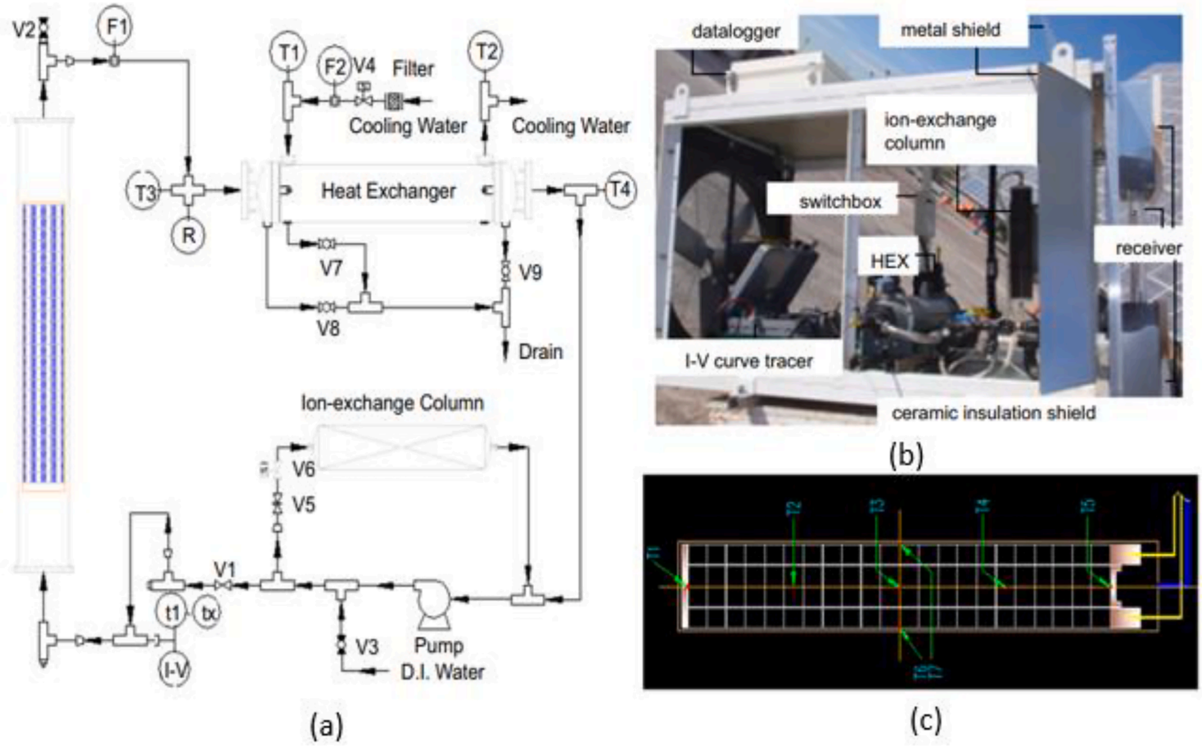

Fig. 13. (a) layout of liquid immersion cooling system and (b) Setup pic. (c) Location of thermocouples [63].

PV cells when these are immersed in dimethyl silicon oil with a viscosity of 2 mm^2/s. The outcomes revealed that the cooling capacity of liquid immersion is desirable in the designed receiver. Mehrotra et al. [65] conducted an experiment where the PV module is immersed in water to maintain its temperature under real working conditions. They conducted the tests in MANIT, Bhopal, with different depths of water for six days in April 2014. The findings show that surface temperature decreases as depth increases and electrical production rise to a limit. The maximum increase in efficiency is 17.8%, which shows progress in the panel output and encourages water immersion cooling technology in CPV systems. Wang et al. [66] depicted a unique cooling method for the CPV systems of direct liquid film contact in which water as a working fluid is used. An electrical heating panel conceived the high concentrated PV cells. The PV cell average temperature remained beneath 80 °C. The mean temperature variation between the various temperature measurement points was less than 10 °C, suggesting a consistent temperature distribution.

Thermoelectric cooling

Thermoelectric modules are solid-state devices that transform electricity (Peltier effect) into a temperature difference and a temperature difference into electricity (See-Beck effect). These devices can control the temperature highly sensitive and accurate. Thermo-electric modules were used for cooling PV cells and producing electricity from their predominant temperature differences [67,68].

Lamba and Kaushik [69] developed a model of the concentrated photovoltaic-thermoelectric hybrid system (See Fig. 14). They derived

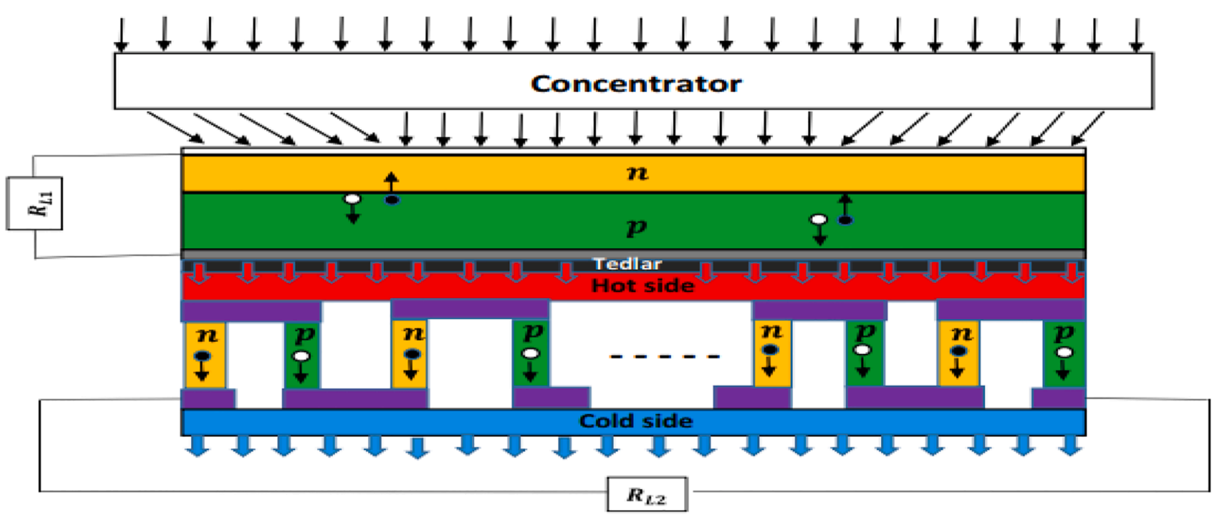

Fig. 14. Schematic of CPV-TEG hybrid system [69].

analytical expressions to calculate module temperature, hot and cold sides of the thermoelectric module. The optimal concentration ratio relating to the hybrid system's maximum performance was determined by considering the Thomson effect. The increase in performance (efficiency and power output) of the hybrid PV/TEG system as compared to the PV system alone is 13.37% and 13.26% for C = 3 and n = 127.

Zhang and Xuan [70] designed a new PV-TEG hybrid device to control the temperature fluctuation and also compared it to the system in which phase change materials are positioned between the PV and the TE module. The part of the thermoelectric module mounted on the black side of the copper plate is to utilize the heat obtained in the PV panel by the Seebeck effect. The results show that the current PV-TE hybrid device will achieve a minor temperature fluctuation and improved power output than the conventional hybrid system.

Wu et al. [71] derived a mathematical model for performance analysis of a glazed/unglazed hybrid type of PV-T system. Nano-fluid is used to improve the heat removal rate. They examined some critical parameters like wind velocity and flow rate of nano-fluid. Their experimentation revealed that the PV-TE system's performance is always higher for $Z = 0.0021\ K^{-1}$ than the unglazed one. The usage of the glass cover with high transmissivity was seen to improve the value of efficiency. Soltani et al. [72] experimented on the PV/TE system (Shown in Fig. 15) to lower the PV module temperature by extracting the amount of heat and simultaneously using it in the TE module to get power output. Researchers compared a nano-fluid based cooling system with TE module cooling. SiO_2 and water-based nanofluid cooling achieves the maximum power and efficiency. Fe_3O_4/water based cooling demonstrated 52.40% and 3.13% greater power output and performance compared to standard TE cooling.

Dimri et al. [73] evaluate PV modules of three different classifications such as opaque, semi-transparent and aluminium base using thermal modelling and artificial neural network technique. Fig. 16 provides a cross-sectional view of the PVT-TEC system. It was observed that the opaque PV/T-TEC water collector had thermal and electrical efficiency higher than the opaque air collector. Highest overall electrical efficiency and daily gain in η_{th} achieved by aluminium base PV/T-TEC water collector system.

The photovoltaic, thermoelectric, and high-grade power cogeneration device was proposed by Yin et al. [74] and they also developed a CPV-TE system that was used to overcome the flaws of the existing system (See Fig. 17). The current device is designed by analyzing the hybrid output effects of controlled temperature and thermoelectric structure to increase solar energy usage. The cost prediction and economic analysis were made to overcome the cost of this system. The latest system offers more energy than the current ones, as it produces high-grade thermal and electrical output. The exergy efficiency of the current device is estimated at 31.43% on a sunny day.

Haiping et al. [75] experimented on a low (LCPV/T-TEG) system. They did the test on a sunny day in Beijing (China) at actual climate conditions. The results reveal that the average daily thermal efficiency is 45%, the average daily electrical efficiency of PV is 11.8% and the average daily efficiency of TEG is 0.23%. Rodrigo et al. [76] proposed an economic model of the passive cooling technique for concentrating the photovoltaic-thermoelectric system. The average output of 39.2% for the hybrid device can be achieved by utilizing low thermal resistance heat sinks with advanced thermal materials at a cell temperature of 100 °C. Salari et al. [77] investigated a numerical analysis of a PV/T-TE system by developing a three-dimensional numerical model. They measured the outputs of PV/T and PVT/TE systems and compared them based on operational factors like coolant mass flow rate, ambient temperature, and solar radiation. The results show that the PVT/TE device's efficiency, when exposed to 600 and 1000 W/m^2, is 6.23% and which 10.41% higher than the conventional system. Furthermore, the PV/T and PVT/TE electric efficiency is decreased by 2.58% and 4.56% respectively by raising the fluid inlet temperature from 26 °C to 34 °C.

Microchannel cooling

Micro-channels are small thermal sinks usually described by channel size: 10–200 μm, but cases of 1–3 mm channel size have also been reported. The improved areas of heat exchange increase are responsible for enhanced rates of heat transfer. Small-scale stress drops are, however, also increased. Multi-layer structures can improve the efficiency of a traditional single-layer microchannel.

Barrau et al. [78] pioneered a new hybrid jet microchannel cooling system for high concentration PV cells, as shown in Fig. 18. When pressure drops lower than the microchannel device, the hybrid cooling system has a minimum coefficient of thermal resistance of 2.18×10^{-5}

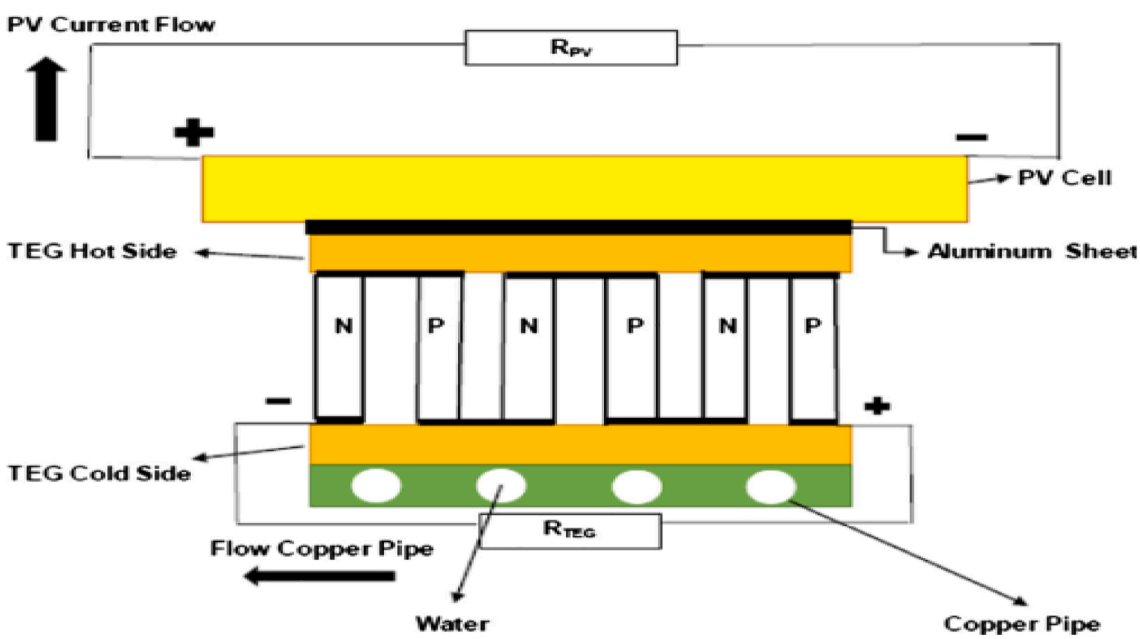

Fig. 15. A hybrid PV-TE system with (water + Nanofluid) cooling [72].

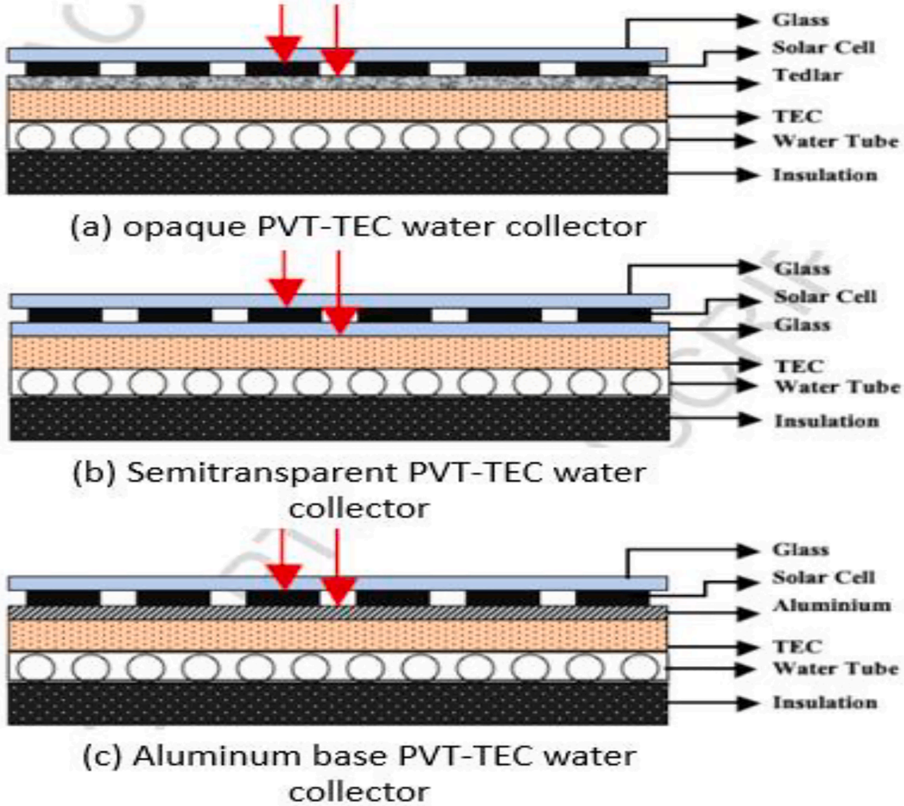

Fig. 16. A cross-section description of PV/T-TEC for case(a), case(b) and case(c) [73].

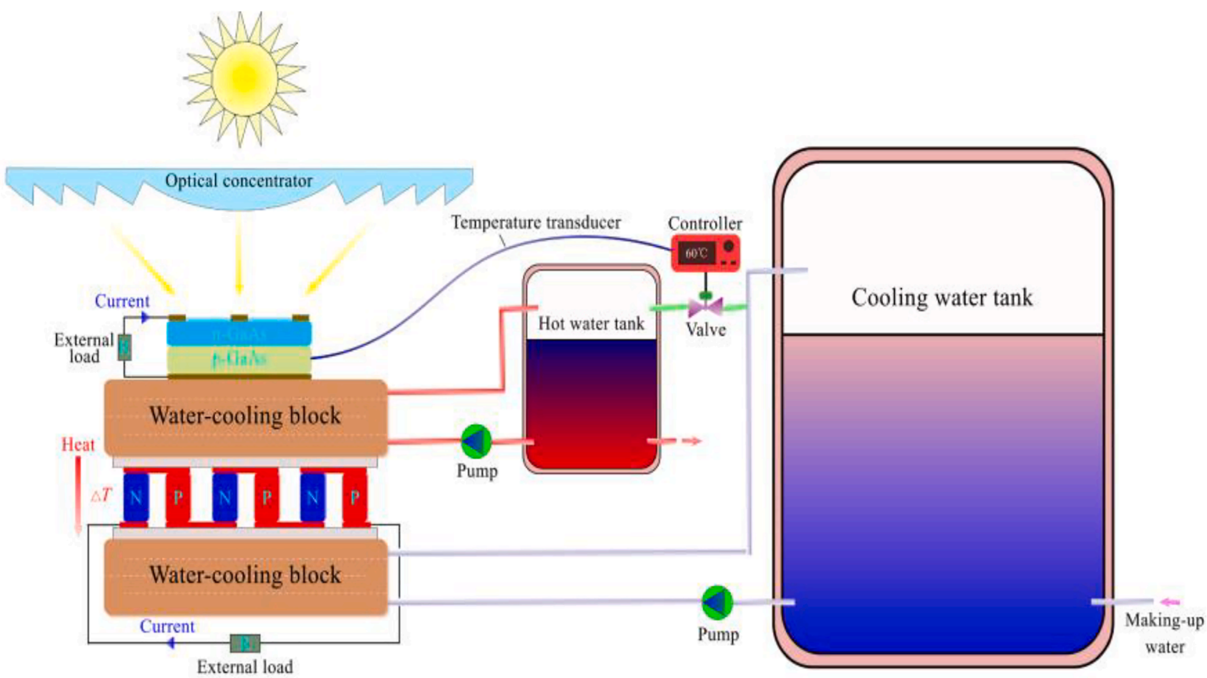

Fig. 17. A schematic diagram of the CPV-TE-T system [74].

K.m^2/W. Due to this, PV cell net performance is better by using hybrid system cooling than microchannel cooling.

Reddy et al. [79] did a numerical investigation into the successful cooling of concentrated solar cells based on micro-channels. The numerical model was developed using ANSYS Fluent, a commercial CFD software. The simulation results reveal that a 0.5 mm width and aspect ratio of 8 is the optimum configuration of a microchannel. The temperature rises across the microchannel is 10 K in the 120 × 120 mm^2 CPV module and a pressure drop of 8 kPa in one channel with six channels at a flow rate of 0.105 L/s. It results in a lower pressure drop at a fast heat transfer between hot spots and parallel flux channels. Ali et al. [80] did both experimental and simulation work on micro-channel

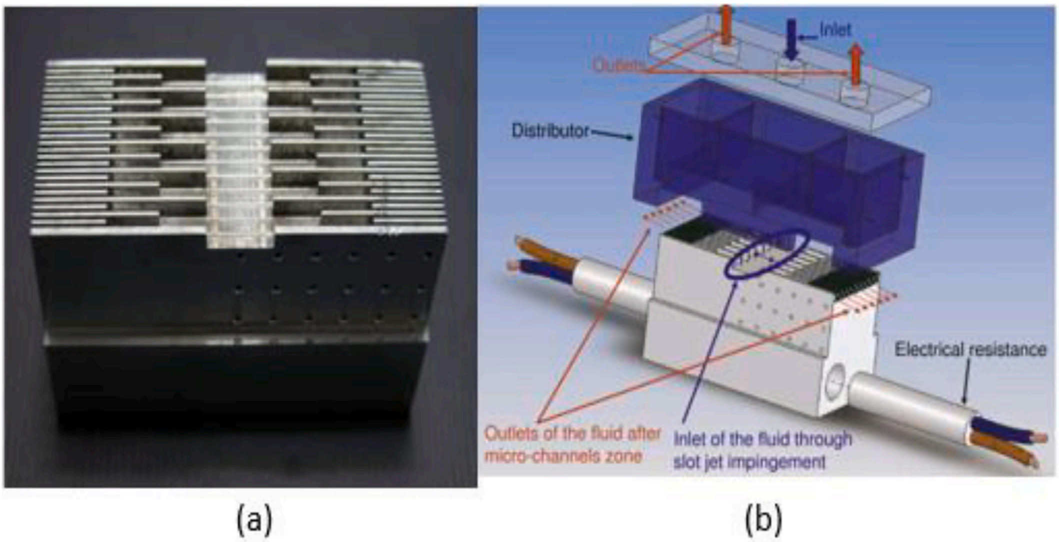

Fig. 18. (a) Experimental device (b) 3-D view of the experimental setup [78].

cooling of PV cells under the hot climate condition of Taxila (Pakistan), where peak temperature reached up to 80 °C. Experiments were done on two 35 W PV panels. The outcomes indicate that the surface temperature of PV cells decreases 15 °C at an average of 3 LPM water flow rate with a power rise of about 14%. Furthermore, the CFD and experimental results also have a good agreement, the researchers say.

Radwan and Ahmed [81] developed a 3-D model of the CPV/T system with various configurations of micro-channel. The experiments performed a box microchannel, a single layer microchannel and a parallel double layer and opposite flow microchannel in five separate ways. After completing the simulation, experimental data was utilized for validating the results. They observed that the highest efficiency of the CPV/T device is obtained by a parallel single layer microchannel heat sink.

Cabo et al. [82] suggested the passive cooling approach consists of aluminum fines on the back of the epoxy-conductive glue panel. The tests were conducted on a 50 W poly-Si panel. In this experiment, fins are placed in two positions, first (L-shaped) profile, and second is randomly placed perforated (L-shaped) fins. The findings are significant because they provide direct insight into the heat transfer phenomenon, i.e. the overall impact and disadvantages of a passive cooling strategy with wind gusts. The cooling technology studied demonstrated promise. This could also be tested on a photovoltaic device that had a longer measurement duration to obtain more reliable performance, given lengthy time spans with typical seasonal weather, which may have a beneficial impact on the PV module's life cycle.

Table 2 presents a detailed summary of microchannel cooling methods for PV/T systems to maintain solar cell temperature. Microchannel cooling's biggest downside is pressure drop. Besides, we will explore potential microchannel cooling solutions.

Phase change materials (PCMs) cooling

PCMs are compounds that, during phase transition, release/absorb energy. The phased transitions are most frequently utilized for heating, cooling, and other applications [184]. Paraffin (PCM) is a kind of C_nH_{2n+2}, i.e. hydrocarbons of saturated and direct chain with a melting temperature between 23 and 67 °C. PCM is used to retain the PV panel at a relatively constant temperature owing to its high latent heat capacity. The collected energy can then be used for different applications like heating of space, water and other applications. However, the initial investment in this equipment is very high [93]. During phase changes, PCM can absorb/release large amounts of energy. The PCM's temperature regulation capability depends on its property, methods of heat transfer and device configuration [94–97]. The change in melting enthalpy as a function of melting temperature is shown in Fig. 19 for several popular PCMs. Table 3 shows the thermophysical characteristics of different PCMs used for PVT systems in thermal storage and other industrial applications.

Wei et al. [101] designed a PCM cooling based system for the 60 W monocrystalline PV module. They used tealights candle as PCM material for cooling of PV panel. Analysis indicates that the solar panel produces a power output of 44.4 W and the efficiency of the panel was 15%, respectively. The efficiency improvement of the solar panel in the study by tealights as a PCM cooling is not efficient. Biwole et al. [102] developed the models of CFD simulation in a system composed of a PCM placed at the back of a solar panel. In this study, a change in the enthalpy method enables the simulation of the material properties in thermal physics. The thermal boundary conditions for the model are heat flux E $= 1000$ W/m^2, external air temperature $T_e = 20$ °C, heat transfer coefficient $h_e = 10$ W/m^{2}K. Similarly, a convection heat flux of $T_i = T_e = 20$ to 30 °C, and $h_i = 5$ W/m^2 K is added on the correct aluminum block. Simulated results maintained the panel temperature less than 40 °C in constant radiation exposure of 1000 W/m^2. Atkin and Farid [103] did the experiment and MATLAB modelling for PV thermal regulatory system of phase change material (PCM) enriched graphite with an external finned heat sink with four different cases. Two 500 W halogen lamps are used with peak insolation of 920 W/m^2. Case D is the most efficient for growing the overall performance of the PV plate. Kant et al. [104] performed a thermodynamic analysis of the PV panel coupled with PCM using the finite element method. They validate the simulation results with previous experimental studies. In this study, for the realistic simulation of the PCM-connected heat and mass transfer studies: melted PCM, wind velocity, angles of inclination and convection effect. PCM-convection effects must be taken into account. The results indicate that the maximum operating temperature is 54.9 °C and 58.5 °C for conduction and convection. When convection mode is not considered in melted PCM (only convection mode), they found a reduction in the PV panels' operating temperatures for higher wind velocity and tilt angle. S. Stritih [105] experimented on a PV panel coupled with a PCM. They also simulated heat removal from the PV panel through the software TRNSYS. The PV-PCM are encapsulated, consisting of seven layers: tempered glass, EVA, Si-solar, EVA, PCM and clear acrylic glass. The average energy output improvement of the PV-PCM panel was 1.1% and a maximum of 2.8% for a given set of conditions. The simulation result shows a 4.3–8.7% improvement of the produced electricity output and a

Table 2
Summary of available research studies for microchannel cooling methods.

Author	Technology	Nature of work	Description	Findings
Siyabi et al. [83]	CPV+Microchannel cooling	Experimental and Numerical	• The experimental rig comprised of the heat sink testing module, heat transfer fluid diffusion bath with a built-in pump and flow meter. • The aluminium plate was used to construct a microchannel having a width of 32 mm and a length of 30 mm.	• The amount of heat flows through layers was 5 to 30 W/cm^2 and 1 to 4, respectively. • Due to an increase in the layers from 1 to 2, thermal efficiency declined by 17%. • As the number of layers increased from 1 to 3, thermal efficiency improved by 20%
Sheyda et al. [84]	PV+Microchannel cooling	Experimental	• A PV panel with an active area of 15 × 77 mm as well as a non-circular microchannel with hydraulic diameters of 0.667 mm was used. • The experimental system has been designed to control temperature-, air and water flow at the inlet of the test area. The air and Water entered into the cell through separate tubes.	• Studies have shown that the amount of airflow in the microchannel reduces the power production of the PV cell by more than 4.20 L/m. It increases the production capacity of PV cells in relation to single-phase flow. • The PV cell average capacity rise was about 38%. • The principle of gas–liquid slug flow has introduced a modern approach in the cooling of PV cells.
Rahimi et al. [85]	PV+Microchannel cooling	Experimental	• The cooling performances were compared between two separate microchannel designs. • Two types of the microchannel, one header and one single header were used. Air has been used as a cooling agent. • The experiments were performed under indoor climate conditions.	• Results revealed that the heat removed by a multi-header was approximately 19% higher than a single header • A percentage increase in the power produced by the PV cell was 28%. • The experimental results confirmed the significant influence on the cooling performance of the flow distribution pattern of a coolant.
Yang et al. [86]	CPV+Microchannel cooling	Experimental	• There are three layers in the built testing unit, the microchannel, the CPV cells and the complete chamber with the duct. • In this experiment the working fluid passes into a circulatory inlet into a chamber of 8.5 mm in diameter, 98 mm in length and 1 mm wall thickness. It was welded to the side plate of this entrance tube.	• The multi-layer design of the multi-channel increases the contact region between the micro-channels and the cell surface, resulting in a higher heat transfer coefficient and lower cell surface temperature. • The maximum heat transfer coefficient is attributed to the simultaneous usage of several inlet/outlet and absolute chambers.
Radwan et al. [87]	CPV+(Microchannel+Nano-fluid)cooling	Numerical	• Nano-fluids are used as cooling media of different volume fractions. The efficiency of the LCPV/T by cooling mass flow rate and volume fraction of various nanoparticles are examined. • A two-phase flow thermal fluid model was developed for the micro heat sink.	• The solar cell temperature is reduced considerably to 38 °C with the use of nano-fluid compared to water. • The usage of SiC-water lowers the cell temperature comparatively less than the use of Al_2O_3–water. Volume increments in SiC-water and Al_2O_3–water Nano-fluids reduce the cell temperature considerably.
Tan et al. [88]	HCPV+Water+Microchannel cooling	CFD simulation	• Mainly three main components of the Ultra High Concentrated Photovoltaics system used in this simulation work. • Fin heights, average velocities of water, and heat sink speed have been used to analyze microchannel heat sink performance.	• The total solar input provided by CPV cells, DBCs and heat sink was obtained as 12,772 W, 1612 W and 1895 W respectively, from the optical performance results. • For all heat sink configurations, the heat sink with the 1 mm thickness & height 20 mm fin (1–20) configuration was found to be the most effective.
Soliman et al. [89]	PV+Heat spreader+Microchannel cooling	Numerical and simulation	• 3-D steady-state physical model has been developed and numerically solved for PV cell. • The structure of the coolant water in the microchannel is measured in varying ratios of solar radiation and separate Reynolds numbers.	• At lower CR, the heat spreader cooling device's cell effectiveness and net efficiency improve by about 8% and 13%. • At higher CR, cell efficiency and net power output increase as 50 % and 2.8%, with Re equal to 5 and 50% and 2.8 % with Re equal 65 respectively.
Radwan et al. [90]	CPV+(Microchannel+Nano-fluid)cooling	Numerical and simulation	• The efficiency under intense radiation with CR of 20 is examined in this analysis of polycrystalline PV cells. Two separate water-based Nano-fluids are used as a coolant. • A comprehensive 3D model has been developed that incorporates the two-phased model (Eulerian-Eulerian) for the micro-channel flow of nano-fluids.	• The usage of SiC-water Nano-fluid has a better cooling impact compared with Al_2O_3-water. • The rise in the volume fraction of nanoparticles decreases the coolant's heat transfer significantly. • The drop in the average local solar cell temperature is very large with the usage of nano-fluids relative to water.
Soliman et al. [91]	PV+(Microchannel+Nano-fluid)cooling	Numerical	• The spreader is mounted between the microchannel and PV with varying area ratios between them. • A 3D mathematical model is built and solved using ANSYS to validate the results.	• Results indicate a lower PV temperature, better flexibility, and higher parallel coolant flow output strength inside the micro-channels. • Increasing area ratios improve the performance of the PV, production strength and uniformity in temperatures.
Widyolar et al. [92]	PV/T+Microchannel cooling	Experimental and numerical	• PV/T collector is composed of a glass tank, mini-channel absorber, half-circle reflector, and solar cells. The semicircle reflector offers optical visibility for solar cells. • A prototype of 1.2 m^2 aperture area made from silicon solar cells was used.	• At stagnation temperature around 80 °C, 57.4% thermal efficiency and 12.3% electrical effectiveness were demonstrated. • PVT collector generates 226 kWh of power and 603 kWh of heat per square meter per year for solar energy of 5.5 kWh/m^2/day

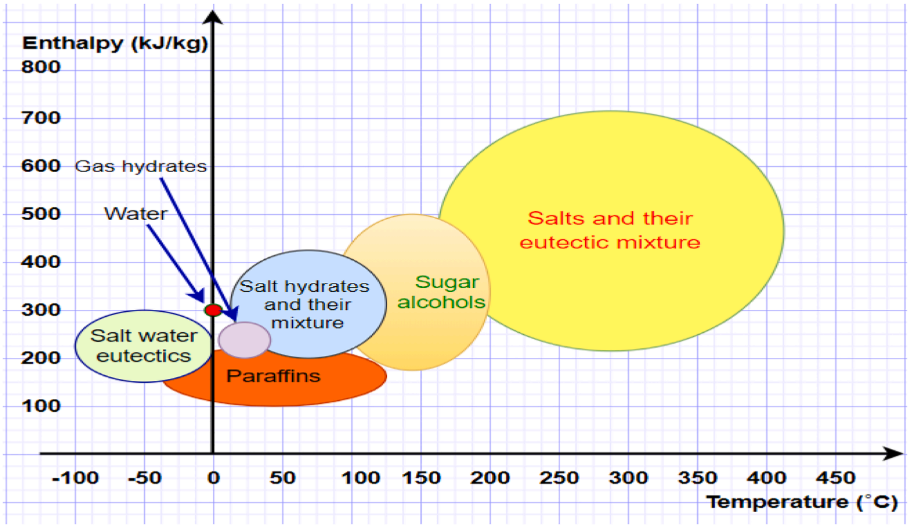

Fig. 19. Melting enthalpy versus operating temperature for a range of PCMs [98].

Table 3
Various PCMs used in PVT systems with their thermophysical properties [99,100,187].

S. No.	Name of PCM	Melting point (°C)	Latent heat of fusion (kJ/kg)	Thermal conductivity (W/m.K)
Category: Organic PCMs (Including paraffin and fatty acids)				
1.	Paraffin wax (C13-C18)	32	251	0.214
2.	Palmitic acid	57.5	185.4	0.162
3.	Lauric acid	44.2	187	0.16
4.	Myristic acid	54.4	155.5	0.22
5.	Steric acid	69.3	199	0.173
6.	Capric acid	32	152.7	0.153
7.	Acetamide	81	241	0.43
8.	Eladic acid	47	218	–
9.	Tristearin	56	191	–
10.	Pentadecanoic acid	52.5	178	–
11.	Polyglycol E600	22	127.2	0.189
12.	$KNO_3/NaNO_3$	220	100.7	0.56
13.	$LiNO_3/KNO_3/NaNO_3$	121	310	0.52

0.5–1% rise in energy efficiency than conventional PV modules. Hachem et al. [106] fabricated three prototypes designed and tested. Prototype 1 consists of a frame, PV plate, and electric circuit as a reference case with a specified load. Prototypes 2 and 3 are planned to produce pure PCM (white petroleum jelly) and combined PCM (graphite, copper, and white petroleum jelly) on the backside of each PV module to maintain thermal regulation and electrical performance. The system's thermal actions and correlation with the electrical outputs often presents a transient energy balance. The PCM panels also increased electrical performance by 3% with PCM, and an average of 5.8% with mixed PCM applications. The PV-PCM design has been studied numerically by Nižetić et al. [107] to analyze electrical output and thermal behavior parameters of passive cooled photovoltaic panels. They used pork fat and conventional organic PCM. They used pork fat and conventional organic PCM. When comparing PV-PCM systems, the difference in the annual simulated generation of energy was negligible. The previous findings were significant because they demonstrated that pork fat has success potential. Emam et al. [108] investigate the heat transfer performance of a (CPV-PCM) system. The impact of angle inclination in the range of-45° to 90° at 45° intervals was examined. In contrast, the concentration ratio and PCM thickness was varied from 5 to 20 and 50 to 200 mm respectively. The model developed was simulated numerically to determine the production and transient distribution of temperatures inside the CPV-PCM device. Lower average temperature is reported at a 90°angle of tilt. Fig. 20 depicts CPV-PCM system and its main components. Experimental analysis by Sardarabadi et al. [109] has been presented in order to understand the results of the combined usage of ZnO/water nanofluid and PCM as coolant media inside the photovoltaic fluid-nanofluid (PV) device collector. The thermal and electrical performance and surface temperatures were compared to conventional systems, and the results of the nanofluid-based system were compared to the results of the pure deionized water working fluid as a reference system. PVT device coolant can include fluid (deionized water or nanofluid). This would decrease the cell temperature by a maximum of 10 °C. The PVT fluid/nano-fluid coolant system's reduction in cell temperature by PCM medium is over 16 °C relative to the reference device in the same situation. Hasan et al. [110] experimented on a PV-PCM system in the very heat climate of the UAE to determine energy output during the year. At the bottom of the PV panel, they mounted a paraffin-based PCM with a melting range from 38 to 43 °C and is controlled for cooling. The model is used for forecasting fractions of melting and solidification in each month of the year. In the hot climatic conditions, the PV-PCM system increased the PV annual power output by 5.9%. Khanna et al. [111] worked upon analyzing the PV-PCM system performance. They explore the inclined arrangements with an angle of β inclination. PV is built with 5 separate coverings in all configurations. PCM box length and depth are respectively L and d. In addition to the booster power for the simulation of PCM, a volumetric force is developed. With a wind angle ranging from 0 to 75°, electrical output increases to 8.6 h from 7.0 h for PCM panel which is 5 cm deep. Yet from 17.6 W/m^2 to 13.6 W/ m^2 the rise in capacity is limited. Hasan et al. tested outdoors with the use of Nano-fluid (graph/water) and phase change (RT-35HC) simultaneously at lower PV temperature in Taxila [112]. The efficiency of this hybrid PVT device was compared to the PVT/PCM system integrated with the flow of water through the tubes within the PCM, PV/PCM system. Best result of 40 lpm flow rate and 0.1% concentration was obtained. Table 4 presents a detailed summary of PCM cooling methods applied to PV/T to maintain the temperature of PV.

Liquid/water cooling

Liquid cooling methods can be assumed to be those methods that actively use energy to maintain a lower temperature of the PV panel. As water is mainly used for cooling; therefore, a pump is needed to maintain liquid flow (see Fig. 21). Active cooling processes produce more

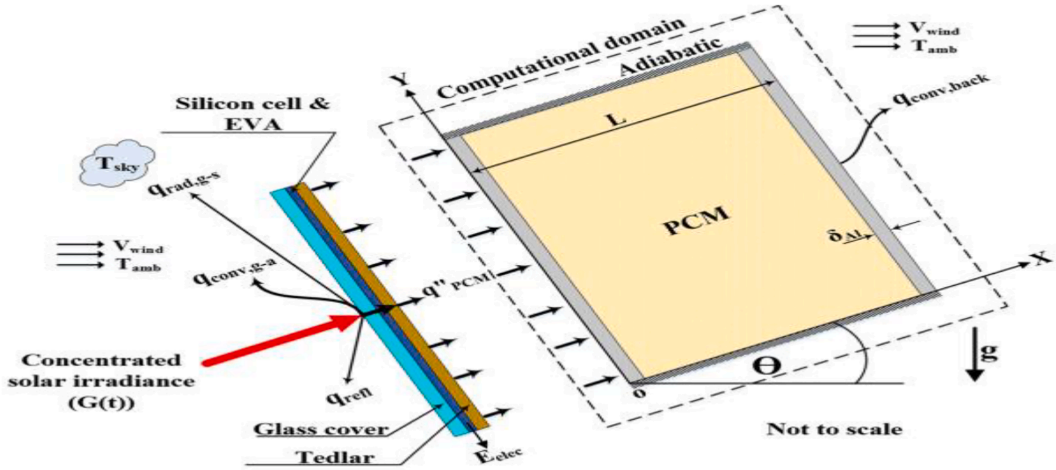

Fig. 20. Primary components of CPV-PCM system [108].

electricity and thermal energy, but cost is an obstacle when considering energy consumption [186].

It focuses on cooling PV panels using water/liquid without consuming any pumping power known as a passive cooling system. PV cooling is ensured when there is better thermal interaction between the PV and the collector device is provided. Therefore, the excess heat contained in the water/liquid must be drained continuously [185].

Odeh and Behnia [121] performed experimental work and modelling of a proposed water pumping system. Test findings found that the device performance is increased by about 15% under high radiation conditions. Long-term efficiency will be measured using site radiation and ambient temperature data. Bahaidarah et al. [122] experimented on a monocrystalline PV module (230 Watt), which is combined with a solar thermal collector under the climate condition of Saudi Arabia. They have also developed a numerical model using energy equation solver (EES) tools. The hybrid device produced 750 W production with almost 900 W/m^2 irradiation.

Alami [123]studied the use of a passive cooling system to regulate the temperature of PV panels, which gets raised due to the absorption of solar radiance. A porous clay coating at the PV panel's rear allows a thin water film to evaporate. The application of clay is successful, inexpensive, quiet and eco-friendly. The analytical expressions were developed by Gaur and Tiwari [124] to calculate the electrical output of the a-Si thin-film PV modules based on the temperature and the effect of the mass flow rate of water. The results of this analysis were validated with an experimental one. The daily average PV-Module electrical output with and without liquid cooling was 7.36% and 6.85%. The water flow exergy and the total thermal quality were 7.33% and 22.1% respectively. The performance module and coefficient of convective heat transfer were found at 7% for a low mass flow rate (0.001 kg/s). Nizetic et al. [125]. conducted a water spray cooling analysis on the PV panel. For simultaneous cooling on all sides, the number of nozzles are installed at the front and back of the frame. The average temperature of the panel was lowered to 24 °C. Hossain et al. [126] developed a novel serpentine pipe flow PV/T system and tested for the climate conditions of Malaysia. Due to their improved thermal conductivity, copper pipes are used in this test. The results showed that the PV/T system's overall power output was 149.72 W, with a mass flow rate of 0.5 LPM. The overall electrical performance of 4 LPM is 10.46% and the maximum thermal performance 74.62%.

Schiro et al. [127] experimented on a PV panel set up to validate the model results, cooled from the front using water. They also developed a steady-state dynamic model to predict the time response results at different conditions. The economic analysis was also performed to improve the overall long-term performance of the PV system. Bhattacharjee et al. [128] introduced three types of designs for back surface cooling of PV panels: semi-oval serpentines, circular spirals, and circular sprint semi flattened. The overall power output was increased from 22.60 to 26.39 W, while the FF improved from 0.6295 to 0.7542. The absorber (circular spiral-shaped semi-flattened copper pipe) is the best-suited design. Fakouriyan et al. [129] experimented on a water-cooled (spraying from the backside of PV module) monocrystalline PV panel in July in Tehran. The findings indicate that electrical, thermal and overall efficiencies have been improved by 12.3%, 49.4% and 61.7%, respectively. The proposed device has a better performance than the conventional photovoltaic panel. The payback time is calculated to be 1.7 years with cooling. Ebaid et al. [130] performed a study on the cooling of the PV module by using two nano-fluids (Al_2O_3 and TiO_2) with water at different concentrations at the outdoor conditions of Jordan. Nano-fluid cooled PV panel caused a higher decrease in average cell temperature. Al_2O_3 demonstrated better performance than TiO_2 for all volume flow rates. Haider et al. [131] analyzed the impact of evaporative cooling in the outdoor conditions of Riyadh city on the efficiency of the PV module. The findings indicate a large decrease in the temperature of the PV panel 20 °C. The performance of the PV panel improved from 10% to 14% compared with the reference panel. Sopian et al. [132] proposed two cooling methods (nano-fluids and nano-PCM) for grid-connected PV systems and tested these PV/T systems in the outdoor conditions of Malaysia. The results indicate that nanofluid and nanofluid with nano-PCM were the two highest electrical exergies of 73 and 74.52% were achieved. These systems were more efficient than conventional PV/T systems. Al-Shamani et al. [133] performed a mathematical and experimental study on a PV/T system (See Fig. 22). They used water and nano-fluids (CuO, SiO_2 and ZnO) to absorb the excess amount of heat from the PV panel. Nano-fluid SiO_2 has a higher impact as compared to other nano-fluids and water. The PV/T-nanofluid (SiO_2) grid-connected system is economically viable. Pang et al. [134] developed an experimental setup consisting of a mono-PV panel and hybrid copper–aluminum collector. They experimented on a high mass flow rate (0.25 kg/s) to analyze the thermal and electrical performance of the PV/T system.

It can be seen from the results that the improvement in electrical and thermal efficiency was 11% and 57% respectively for PV/T system. The highest performance was observed at a mass flow rate of 0.15 kg/s for the PV/T collector with a sheet-tube structure installed at a 25° angle. Hissouf et al. [135] fabricated a hybrid PV/T system to reduce the cell temperature using liquid (a combination of nano-fluids such as CuO and Al_2O_3 with water) cooling. By using energy balance equations, they established a mathematical model, and its findings were confirmed with experimental results. The findings indicate that the usage of Cu-water nanofluid improves device efficiency. Table 5 presents a detailed summary of water/liquid cooling methods applied to PV/T systems to

Table 4
Summary of available research studies for phase change materials cooling methods.

Author	Technology	Nature of work	Description	Findings
Maiti et al. [113]	PV + PCM cooling	Experimental	• The PV module used at 2300 W/m^2 standard light, which is produced from the lamp. • The paraffin wax's 56–58 °C melting range was used as PCM and placed behind the PV module to absorb any excess heat. • Two types of tests have been carried out indoor (0.06 m bed of PCM) and outdoor (PCM in V-trough form) .	• With packed metal turning, wax remained in the solid form, the issue of low thermal conductivity was solved. • The temperature of the module could be sustained over 3 h at 65–68 °C for indoor test conditions with PCM. • The module temperature could be reduced in the V-trough from 78 °C to 62 °C and activity could be sustained through the day.
Preet et al. [114]	PV/T + Water + PCM cooling	Experimental	• Three specific mass flow rates were used for the analysis of three different systems. Conventional PV, Water-based PV/T with double absorber plate and RT-30 PCM were tested.	• The decrease in PV/T and PV/T-PCM (water-based) devices was 47% and 53% relative to traditional modules at 0.031 kg/ sec. • Electrical efficiency was improved by 10.66% for PV/T-water and 12.6% for PV/T-water-PCM at 0.031 kg/sec
Karthick et al. [115]	BIPV + PCM cooling	Experimental	• The testing was performed in fixed directions with BIPV modules with novel inorganic galuber salt (PCM)	• The results indicate that the electrical performance of the BIPV-PCM is improved by 10%.
Radziemska et al. [93]	PV/T + PCM cooling	Experimental	• The experiment was performed on a PV system with a PCM (42–44 paraffin) fitted in a steel tank up to 2 cm deep attached on the rear side with water cooling.	• It can be seen from the results that lower temperature was maintained for more than 5 h during the experiment.
Waqas and Ji [116]	PV + PCM cooling	Numerical	• The rear of the tedlar is attached with rotatable shutters loaded with PCM. The shutters loaded with PCM are used as heat sink in daylight hours for the PV panel.	• The PV module temperature without using PCM is 64 °C; it is reduced to 42 °C by using PCM filled shutters. The performance for the PV panel in hot humid environment conditions is increased up to 9% during the peak season.
Mousavi et al. [117]	PV/T + PCM cooling	Numerical	• A foam metal was used as a porous medium and five separate PCMs such as organic and inorganic were tested for their output. • In addition, various primary parameters, such as mass flow rate, solar radiance, water inlet temperature and inclination, have been tested for the same system.	• It can be seen that the porous matrix enhanced the distribution of temperatures and increased thermal efficiency was obtained by the porosity of 0.8. • Finally, an exergy analysis was used for the device and the outcomes indicated that system's exergy output with PCM-filled metal foam is 16.7%
Manikandan et al. [69]	CPV + PCM cooling	Numerical and Simulation	• In COMSOL multi-physics finite element applications, a CPV integrated with a heat sink and PCM at the backside has been developed. • The low CPV output was achieved with different fill volumes of PCM and the solar concentration ratio (CR)	• This analysis indicates that solar radiation, by reducing the temp cell temperatures, can be used efficiently to generate electrical energy. In fact, this development would increase the generation of power from the CPV cells.
Wongwuttanasatian et al. [118]	PV + PCM cooling	Experimental	• Tests were carried out with three conditions: a rainbow box (4158.8 cm^2 surface area), a tubing box (4346.8 cm^2 surface area) and a finned box (5,402 cm^2 surface area). These three boxes were 3000 cm^3 in volume. • Palm wax is mainly used as PCM	• The finned PCM box that decreases the PV surface temperature from 57.9 °C to 51.8 °C has produced improved power and efficiency by reducing current. • The finned PCM container will increase module efficiency from 9.33% without PCM to 9.82% with PCM.
Xu et al. [119]	PV/T + PCM cooling	Experimental	• This research was done on a PV/T system in the district of Yangpu, Shanghai, China (longitude 121.52°E, latitude 31.27° N). • The fatty acid is used as PCM with a phase transition temperature of 37 °C at back side of PV/T system	• Results revealed that using PCM in the solar collector will considerably improve the PV performance and control the temperature fluctuation of the panel. • It was noticed that through a rational thermal control approach, the overall energy production ratio of the PV/T-PCM device can be improved
Shastry et al. [120]	PVT + PCM (Matrix form) cooling	Experimental	• Three experimental set-up PV/T and PV/T conventional + PCM + Metal matrix PV/T were tested. • There was a new form in the framework of PV/T of aluminum metal matrix with a soapbox structure for this research. • Since the matrix is porous, the diffusion rate is greater than a massive metal plate.	• The average temperature falls from 33.8% to 40 % of PV/T in comparison to PV. • Ultimately, the improvement in output is negligible. So, the selection of PCM and PV device at a greater scale could be made. • With the cooling, both V_{oc} and I_{sc} boost the WM layout with a higher value of 4% and 10.8% relative to PV.

maintain the temperature of the solar cell.

Heat pipe cooling

A heat pipe is a device mainly used for cooling of electronics cooling. It consists of a hollow metal pipe with a porous wick in the inner surface as shown in Fig. 23. In a heat-pipe, the working liquid fills inside of the tube, which transfers heat through a continuous cycle produced by evaporation in the section of heating and condensation in the section of cooling. PV cells are connected to the heating portion and the heat generated is used to evaporate latent heat [145–147]. The heat pipe assisted PV/T systems are mainly used in a cold region like Europe.

Wu et al. [148] proposed a heat pipe-based PV/T system. The wick heat pipe is used to isothermally collect excess heat from PV cells. The hybrid PV/T device has a thermal, electrical and energy performance of 63.60%, 8.45% and 10.26%, respectively. The PV/T hybrid heat pipe design is feasible and has a capacity and profitability compared to other regular BIPV/T systems.

Gang et al. and Zhao et al. [149,150] designed a heat pipe PV/T system simulation model (See in Fig. 24) and examined the yearly thermal and electrical performance of heat pipe PV/T system using this model under three climate conditions of namely Hong Kong, Lhasa and

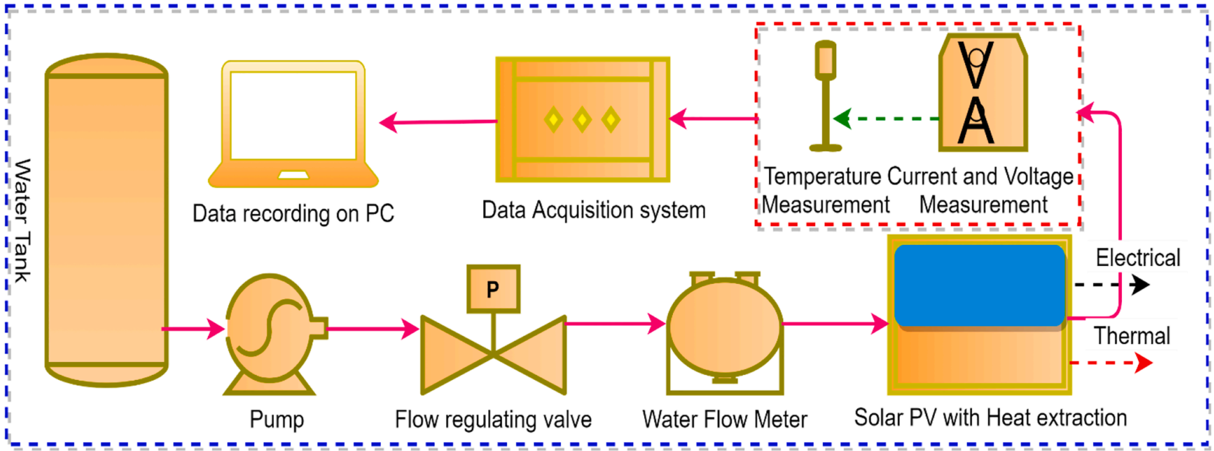

Fig. 21. Component's diagram of the active liquid cooling system.

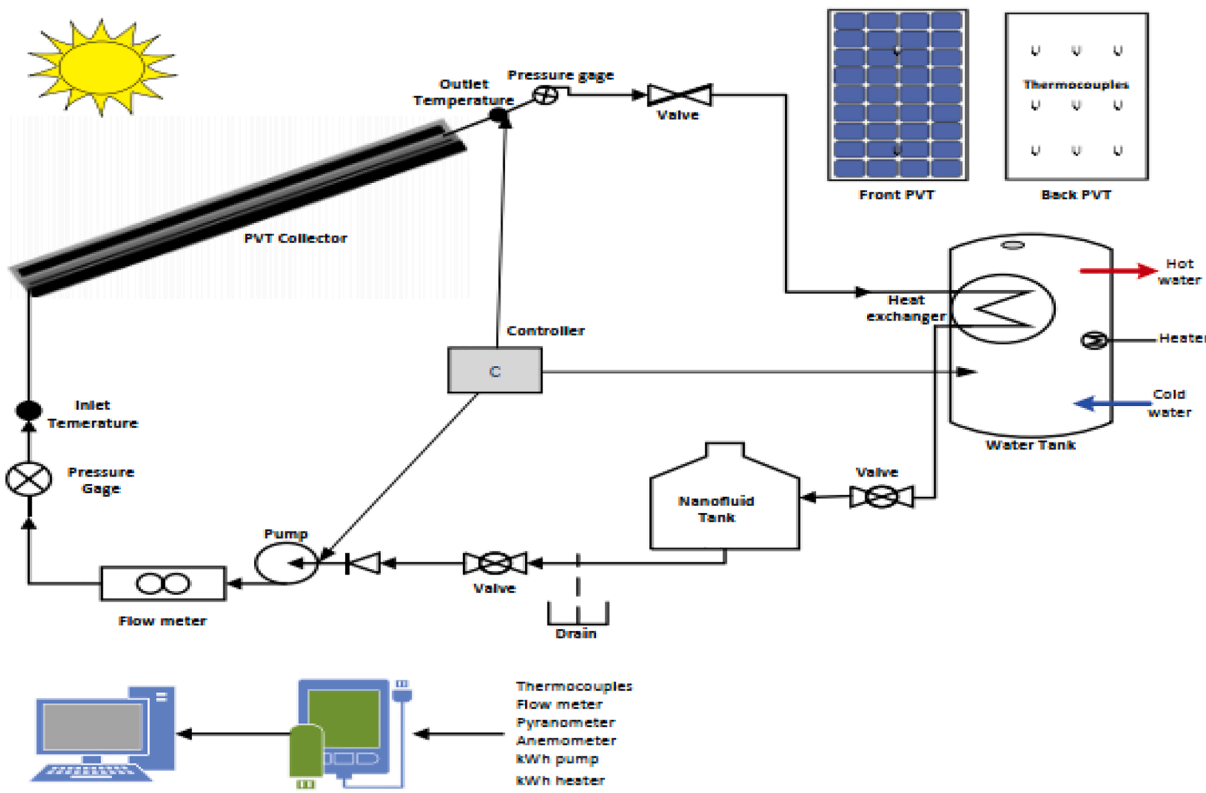

Fig. 22. Schematic diagram of the PV/T system [133].

Beijing. The yearly thermal energy was obtained as 1665.25–1872.22 MJ/m^2, 2939.67–33328.25 MJ/m^2, 2111.07–2352.95 MJ/m^2, and yearly electrical energy of 261–264.98 MJ/m^2. Fu et al. tested the PV-SAHP/HP system under three different modes [151]. The exergy and energy analysis was used to predict the instantaneous daily performance for with and without solar-assisted heat pumps. The results showed that the PV-SAHP/HP system will produce 61–82% of electricity in the solar-assisted heat pump mode. The average daily coefficient of performance of the heat pump was 4.01 during intense solar radiation. Moradgholi et al. [152] experimented in both spring and summer on the PV/T system assisted with a novel thermosiphon heat pipe to absorb the excess amount of heat from the solar cells.

The test set up was mounted at 30° in the spring and methanol was used as working fluid of heat pipe. The PV/T device produced 5.67% higher electrical efficiency than the average photovoltaic output. The system's thermal performance was 16.35% greater than average. Hou et al. [153] suggested a modern PV/T supported micro heat pipe device, and developed a heat dissipation process-based mathematical model. The collector's average output varies from 30% to 50% across the entire year. The calculated annual thermal output and thermal loss coefficient are 0.30 and 0.105, respectively. Wang et al. [154] developed a BIPV/T heat pipe system with a metal wires network special system arrangement residing between the finned heat pipes and insulation. The average thermal output with the simulated solar radiations of 300 W/m^2 and 200 L/h mass flow rate of water was estimated at 44.04% and average electrical efficiency of 7.9%. Chen et al. [155] designed a heat pipe solar PV/T heat pump system to simultaneously analyze the electrical and thermal performance. The models are composed of an heat pipe system

Table 5
Summary of different liquid/water cooling methods for thermal management of PV/T systems.

Author	Technology	Nature of work	Description	Findings
Ebrahimi et al. [136]	PV+Natural vapour cooling	Experimental	• The experimental setup consists of a PV module, 400 W halide lamp, a vapour simulator, and a generator. • The tests were performed under steady-state conditions of 1000 W/m^2 and 0–5 gms/min vapour flow rate.	• The results showed that the distribution of natural vapour flowing at 0–5 gms/min in the backside of PV cell improving the rate of heat transfer and performance. • This result can be concluded that both vapour and velocity distributions have an important effect on the cooling performance
Spertino et al. [137]	PV+water cooling	Numerical modelling	• A theoretical model was developed to set up. The experiments were performed under the test conditions such as $G_{stc} = 1000$ W/m^2 @ 1.5 AM and $T_{cell} = 298$ K	• The tests were conducted to characterize the standard test conditions (STC) of PV module. • It can be seen that in clear sky conditions, the STC can be repeated in the field due to the proper cooling.
Al-waeli et al. [138]	PV+Nano-fluid (SiC) cooling	Experimental	• Experimented with a PV/T module with nano-fluid (water with SiC nanoparticles) cooling. • The nanofluid stability was examined in 3-month intervals.	• Thermal conductivity was reduced to 0.003 W/m.K after six months. This confirmed the stability and usability for longer use. • The average output in the PV/T nanofluid system was roughly 88.9%
Bashir et al. [139]	PV+water cooling	Experimental	• A back surface water cooled PV/T system has been studied at Mirpur University (Pakistan, 33.2°N, 73.7°E) • Four PV panels (2-mono and 2-poly) were used in this study. • A duct on the back has been made with its external surface insulation for cooling of the PV module.	• The decrease in module temperature by 13.6% results in improve of $\eta_e = 13\%$ and with a decrease of 7% in temperature, of a poly-PV cell, $\eta_e = 6.2\%$ was improved. • The module temperature is the linear function of solar irradiance. The performance ratio for mono and poly is 15.3% and 9.7% higher than the conventional PV system.
Wu et al. [140]	PV/T+water cooling	Numerical modelling	• In order to study the effects of mass flow rates and other duct parameters a 3D model of water-cooled PV/T device was developed. • Nusset no was calculated for the top and bottom surfaces of the channel.	• The heat transfer coefficient of the lower side was determined to be higher than the top surface in all situations. • With a mass flow rate of 0.003 kg/s and a channel height of 5 mm the overall exergy performance of the device is optimum
Ahmed et al. [141]	PV/T+water cooling	Experimental	• The tests were conducted on a back surface cooled PV panel placed at 26.5°N and 31.7°S in the climate conditions of Egypt.	• The results showed that the module's T_{cell} decreased from 44.8 °C to 30.3 °C from the backside and 46.6 °C to 36.9 °C from the front side after cooling.
Zanlorenzi et al. [142]	Hybrid PV/T+Water cooling	Numerical modelling	• In this study, an automated water-cooled hybrid prototype of the PV/T system was proposed and analyzed under three phases (a) Technologies background (b) Conceptual model (c) Detailed design and prototype.	• T_{cell} average reduction was 11.42% and the increase in ηe was 1.25%. The performance coefficient is 8.22% greater than the first element. • The average efficiency of the hybrid solar system was 33.28%.
Alous et al. [143]	PVT+Water-based nano-fluids cooling	Experimental	• The experiment was performed using MWCNT and graphene nano-platelets on a PV/T device, dispersed in water with a 0.5% weight percentage. • Energy and exergy analysis was carried out for the tested PV/T system.	• The findings revealed that MWCNT-water nano-fluids perform better than nano-platelets-water graphene and nanofluid distillation • The overall energy output of all three cases was 11.2%, 12.1% and 20.6%, respectively.
Abdallah et al. [144]	PVT+Water-based nano-fluids cooling	Experimental	• The experiment was conducted on a PV/T system using multiwall carbon nanotubes (MWCNT) and water with a volume concentration from 0 to 0.3 wt%.	• The best results obtained for the MWCNT-water combination at 0.075 wt%, such as a decrease in T_{cell} is 12 °C and $\eta_o = 83.26\%$. • A significant 10.3 °C drop in temperature was also observed in the daytime with $\eta_o = 61.23\%$

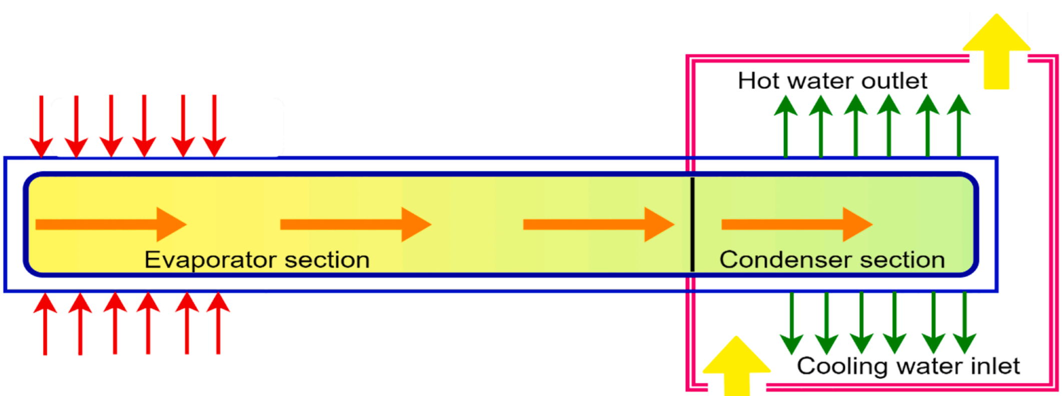

Fig. 23. Schematic diagram of the thermosiphon heat pipe.

PV/T collection device continuously dispersed parameter model and a quasi-steady state parametric model of the heat pump. It was found that increased solar radiation and packaging factors will raise the advanced thermal and electrical efficiency coefficient.

Du and Modjinou et al. [156,157] studied the nano-coated heat pipe plate (See Fig. 25) and microchannel heat pipe (MHP) for thermal

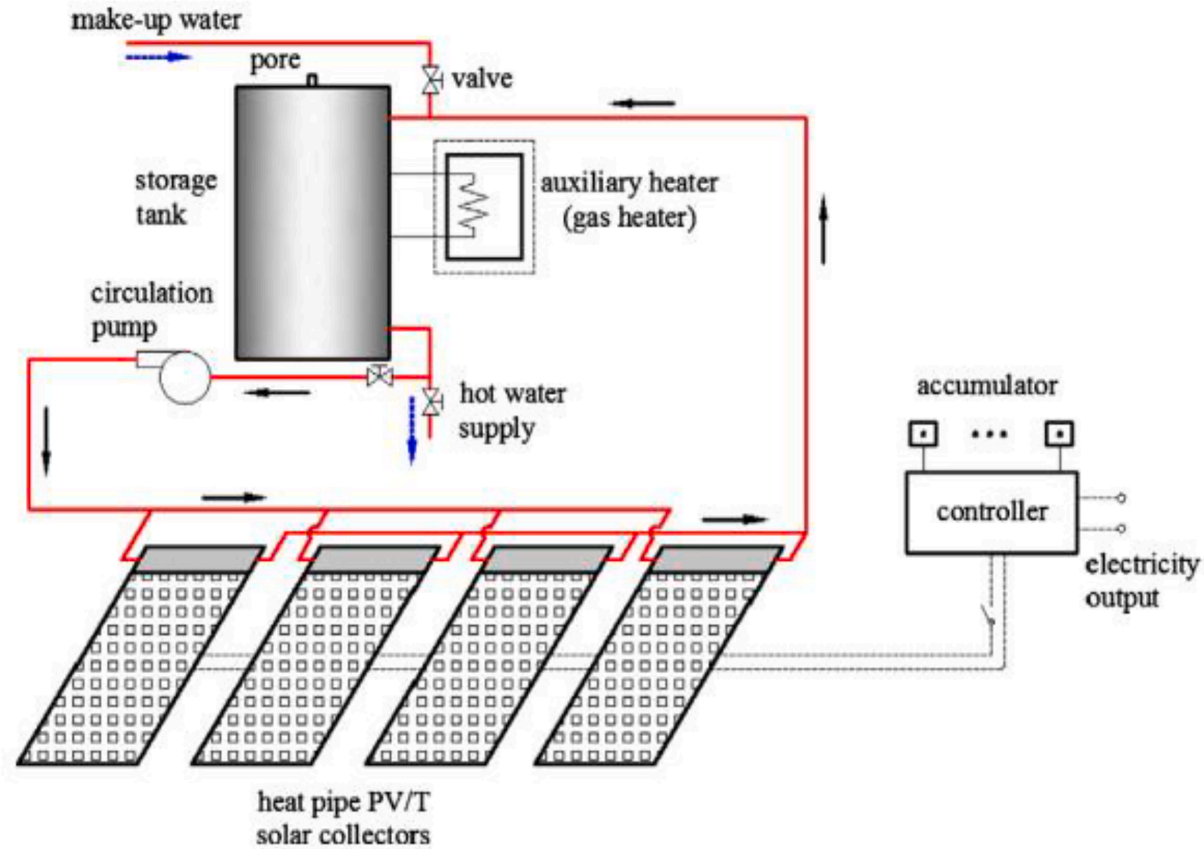

Fig. 24. Schematic diagram of the heat pipe PV/T system [150].

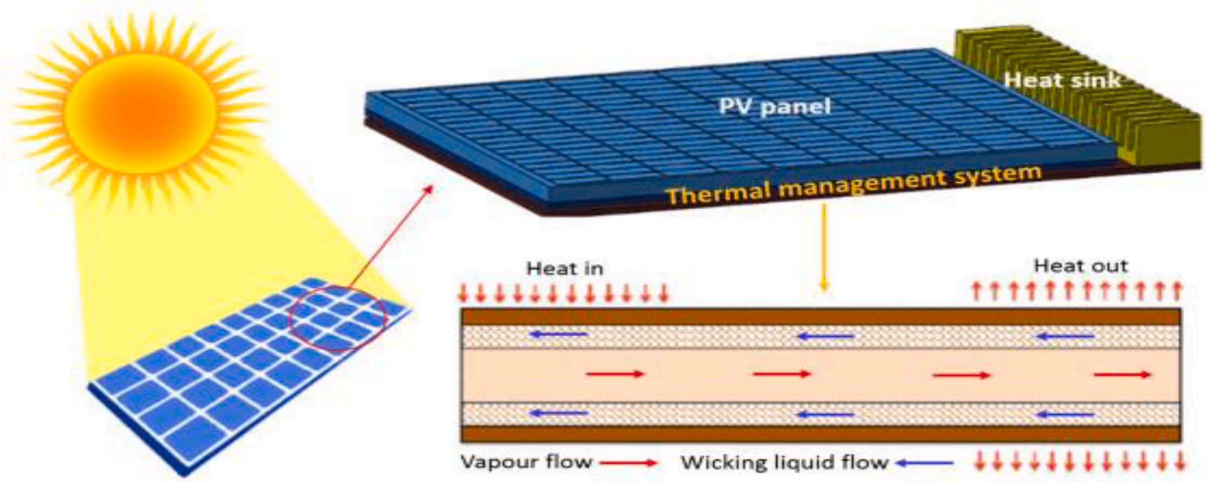

Fig. 25. A schematic diagram of the hybrid PV/TM setup [156].

regulation of PV cells. They used a plate heat pipe to ensure enough reduction in the temperature of PV cells. The heat removal flux from the condenser was 390 W/m^2. The MHP is exhibiting a more rapid thermal response to heat when temperature ranges between 48.7 and 49.2 °C and thermal response reduced due to a fall in thermal diffusivity

Alizadeh et al. [158] performed a numerical simulation on PV cooling assisted with single tern pulsating heat pipe (PHP). A copper fin of the same length as PHP was used to cool the PV panel compare the PHP output with solid metal such as copper. It can be observed that PHP cooling decreased the PV's surface temperature up to 16.1 K, whereas the PV panel temperature was lowered by just 4.9 K using a copper fin arrangement. Habeeb et al. [159] performed a theoretical and experimental study to investigate the effects of the thermosyphon heat pipe on the performance of the PV module. The studies were conducted in Baghdad in July 2017 with three standard tests set up of different configurations. The experimental findings show that module I electrical performance was (11–14) % improved and module II (4–8) %. Chen et al. [160] experimented on a PV/T system assisted with a heat pipe. The PV/T systems contain two tests set up (A and B), which used water and 30% alkyl hydrocarbon PCS as a working fluid. 55.2 L hot water could be generated at 45 °C/unit area of the heat pipe PV/T system. The results observed significant improvement in thermal performance and electrical efficiency improvement. Siddiqui et al. [161] developed a modern heat exchanger using a CFD model to cool PV modules uniformly. Since 14 designs were evaluated for the consequences of different configuration parameters for the heat exchanger (such as the channel numbers, multiple lengths, direction of input/output ports, tapering channels). As a result, a modern V-shaped heat exchanger system for integrated photovoltaic cooling is the optimal design. Almahmoud and Jouhara [162] performed an experimental and analytical study on a radiative flat heat pipe (FHP), a heat exchanger. The FHP consists of 14 steel tubes attached to the bottom collector and the top header at the shell and tube condenser. Four cases were tested; the results showed a significant improvement in heat recovery. In the next section, Table 6 showed a summary of the different heat-pipe assisted PV/T systems.

Role of artificial intelligence in PVT systems

Artificial intelligence (AI) and machine learning (ML) has recently been used in several study fields to solve complicated engineering problems, including interrelationships between input and output data. Renewable energy researchers are presently using this amazing technology to forecast and quantify PVT system performance. Artificial Neural Network (ANN), Support Vector Machine (SVM), Multilayer Perceptron (MLP), Genetic Algorithm (GA), and others are used to forecast solar PV performance and make intelligent decisions from it [172]. The use of artificial intelligence in renewable energy relies on past experimental, numerical, and theoretical data. Depending on the application scenario, input and output parameters must be defined. The predicator/independent variable is the input, while the outcome is reliant on the input parameters. Modeling in ANN is a two-step process. The first phase is to train the network using a collection of data, and the second step is to test the network using data that is distinct from the training set. The training set contains the input data, and the training output contains the output data [173]. Few recent studies of machine learning have been included in this section. Agbulut et al. [174] used machine learning techniques to forecast power production from a V-trough PV system. The system's power production was projected using four machine learning algorithms: kernel and closest neighbour, SVM, ANN, and deep learning. Compared to previous techniques, the SVM accurately predicted the system power output. The emergence of artificial intelligence simplifies the collection of system performance data and avoids resource waste if the system fails in service. The forecast and

Table 6
Summary of different heat-pipe assisted PV/T systems for the thermal management of PV from 2011 to 2020.

Author	Technology	Nature of work	Description	Findings
Gang et al. [163,164]	PV/T system+Heat pipe cooling	Experimental and simulation	• A heat pipe PV/T system was fabricated, and its results were compared with a water-based system. • A dynamic thermal model was also developed, and its numerical results were validated with experimental.	• The thermal and electricity production increases were 41.9% and 9.4%, respectively. The η_{IIlaw} was 6.8% with solar radiation of 661 W/m^2. • The simulation results are consistent with the test values with a relative error of ± 5 %.
Sweidan et al. [165]	PV/T system+PCM and heat pipe cooling	Mathematical modelling	• The (HP-PV/T) system with a PCM-integrated heat storage tank to produce electricity and hot water • A statistical model for the HP-PV/T with PCM developed to predict the performance.	• Results revealed that in low annual auxiliary heating expense for heating hot water demand • The use of the PV/T device with a pay-back duration of 13.7 years was considered to be energy-saving and cost-effective.
Koundinya et al. [166]	PV+Finned heat pipe cooling	Experimental and Computational	• Experiments were performed on a prototype and compared with simulation results. • The monocrystalline PV module of 36 cells was used in this study.	• The test results show that with finned heat pipes, the temperature drop and solar panels performance was improved. • The findings of the experiments are compatible with the computational results
Moradgholi et al. [167]	PV/T system+AL_2O_3/methanol nanofluid with thermosiphon heat pipe cooling	Experimental	• A novel two-phase thermosiphon heat pipe assisted PV/T system was fabricated. The heat pipe is filled with methanol and Al_2O_3/methanol. • The effect on thermal and power output of the PV/T system was tested for filling ratio (30,40,50 and 60%) as well as for concentrations (1, 1.5 and 2 wt%) of Al_2O_3 nanoparticles in the working fluid	• It was revealed from the results that the optimum value of filling ratio and nanofluid concentration was 50% and 1.5 wt% respectively. • The average decrement in temperature was 14.52 °C and an increase in 1.42 W more electrical efficiency. • The overall rise in electrical and thermal performance was 1.1% and 27.3% respectively.
Li and Sun [168]	PV+Loop heat pipe/solar assisted heat pump cooling	Numerical	• A novel PV loop heat pipe/solar assisted heat pump system was developed. • The tests were conducted at different structural parameters, operation strategy analysis	• The results of the simulation showed the optimum volume of a water tank and PV coverage to be 150L and 0.668 respectively. • The total energy usage of the optimized system will be reduced by 55.7 % with this operating strategy
Rejeb et al. [169]	PV/T system+Heat pipe cooling	Numerical case study	• The efficiency of the PV/T heat pipe system was simulated and modelled. • The numerical findings were confirmed using the current experimental literature evidence.	• The findings indicate that using the PV/T collector, heat pipe integration yields stronger electricity than the traditional solar photovoltaic array. • The electrical performance was 116 kWh and 102 kWh respectively in the PV/T heat pipe and the classic PV module.
Modjinou et al.[170]	PV/T system+Microchannel heat pipe cooling	Experimental	• The research examined and compared current encapsulate PCM-PV/T, micro-channel heat pipe PV/T and standard PV/T. • A theoretical model was developed and analyzed.	• The overall efficiency η_o was achieved by 36.71%, 36.53% and 31.78% for encapsulated PCM, microchannel heat pipe and conventional PV/T systems. • Daily PV/T freezes have been avoided to an extent.
Kianifard et al.[171]	PV/T system+Half heat pipe cooling	Numerical	• A water PV/T collector has been tested for this analysis with a half- serpentine pipe. • A detailed mathematical model with experimental data from a lab-scale system is generated and validated.	• This new design has 70 % thermal output and 11.5% electrical performance. The thermal performance of the new models is between 10 and 13% better and the electrical output is between 0.4 and 0.6% higher than traditional models.

quantification results would assist the designer in making a logical choice. Each day, new machine learning algorithms are created and applied to various engineering issues to select the optimal method for a given application. Theocharides et al. [175] evaluated and compared the effectiveness of machine learning models for forecasting the output power of photovoltaic (PV) systems using artificial neural networks (ANN), support vector regression (SVR), and regression trees (RT). The ANN model outperformed other models by 0.76% and 0.6%, respectively, in normalized root mean square error (nRMSE) and mean absolute percentage error (MAPE).

Techno-economic aspect of PVT systems

The four factors discussed in this section can be used to analyse the PV system's technical and economic viability. Technical parameters such as yield factor (Y_F) and capacity factor (C_F) are used to assess the productivity of the PVT system [176]. Economic parameters such as the cost of energy (CoE) and payback time (PBP) are used to determine the practicality of a PV system. The yearly capacity factor is computed as "the ratio of the actual annual energy production to the amount of energy the PV array would produce if it operated at full rated power (P_r) for 24 h per day for a year [177].

$$C_F = \frac{Y_F}{8760} = E_{pvannual}/P_r \times 8760 \tag{14}$$

Meanwhile, the yield factor is calculated as per the following equation

$$Y_F = E_{pv}(kWh/year)/PV_{wp}(kWp) \tag{15}$$

Payback time and energy costs are also taken into consideration while evaluating the system economically. Expenses for system design, installation labour, preparation of the site, operation and maintenance costs may also be included in the life cycle cost (LCC) of a PV system [178]. It is calculated as

$$LCC = C_{capital} + \sum_{I}^{n} C_{O\&M}.R_{pw} + \sum_{I}^{n} C_{replacement}.R_{pw} - C_{salvage}.R_{pw} \tag{16}$$

Capital cost ($C_{capital}$) replacement cost ($C_{replacement}$), maintenance cost ($C_{O\&M}$) and salvage value ($C_{salvage}$) are used in calculation of LCC. R_{PW} denotes each factor's present value, which is determined using a future amount of money (F_m) in a specified year (N) and a specified discount rate (I)

$$R_{pw} = F_m/(1+I)^N \tag{17}$$

The cost of energy (CoE) is calculated after getting the LCC

$$COE = LCC/\sum_{I}^{n} E_{pvannual} \tag{18}$$

where $E_{PVannual}$ is representing annual energy output of the solar photovoltaic system and n denotes the system's life expectancy in years. Finally, the payback period is calculated as

$$PBP = C_{capital}(USD)/\left[E_{pv}(kWh/year) \times CoE(USD/kWH) \times R_{pw}\right] \tag{19}$$

Various studies have been conducted on economic analysis of various cooling methods applied on PVT systems. Life cycle analysis of 3 kWp PV/T systems indicated that they are more cost effective and environmentally benign than ordinary PV panels [179]. Sima Pro was used to assess the energy and environmental consequences, as well as the benefits of heat recovery. The study revealed that both glazed and unglazed PVT systems provide for more environmental savings than effects, reducing payback times by 58.6% (unglazed PVT) and 62.15% (glazed PVT) (glazed PVT). Ghadikolaei [180] assess the environmental effect of photovoltaic cooling on CO_2 emissions. Then, the impact of PV cell cooling on the environmental cost of CO_2 emission decrease in the atmosphere was evaluated using various PV cell cooling approaches. The results show that increasing water pressure improves cell performance when using water cooling. Also, the enviro-economic study demonstrates that using hybrid nano-PCM, hybrid PCM, and hybrid PCM-water is more effective than using each technology alone in reducing CO_2 emissions. Some research examines the economics of improving the efficiency of photovoltaic cells, as seen in Table 7.

Summary of uniform cooling methods and statistics of the research review

The effect and impact of the elevated working temperature on the performance of the PV panel and the different cooling methods are defined briefly. A detailed report is given on the methodology used by different researchers to improve the efficiency of PV/T systems with various cooling methods. Other authors have conducted numerous researches on experimental, computational and theoretical framework. For assessing the performance of PV/T jet impingement-based air-based, thermoelectric based, microchannel based, PCM-based, water-based and heat pipe-based methods utilizing specific parameters. The literature showed that the Jet impingement could be used for the thermal control of PV cells as a cooling technique [46,47,50,84]. Air cooling is also a promising strategy for preserving the temperature of the PV module and can be used as both active and passive cooling methods reported by different researchers [52–54]. Some investigators have documented that water immersion cooling technique may be used to overcome solar cell surface heating [63,64]. Many researchers focus on thermoelectric cooling in PV/T systems because it is a good choice to use the excess energy from the PV panel and convert it into electricity [68,70,72–75]. The microchannel cooling-based PV/T systems have satisfied concentrate photovoltaic's rising heat flux demand.

The microchannel cooling developed in a single phase meets the short-term heat flow requirements [78–80,83–86]. The manifold microchannels provide higher performance than single micro-channels, but they are difficult to manufacture. Many studies for PV/T systems attached with PCM are reported in the literature [101–103]. PV-PCM provides several benefits over other photovoltaic panel heat control systems without power storage. PCM heat can be used for a long time, and PCM power for room heating applications can be used. Water-based systems have a better cooling ability because of forced water flow's high heat transfer coefficient [167–169]. Therefore, the excess heat in the

Table7
Techno-economic studies of modified PVT systems.

Researcher	Ref.	Technologies adopted to improve efficiency of PV/T system	Results of economic analysis
Baloch et al.	[53]	PV panel with liquid/water cooling technology	The cost per kWh generated by a photovoltaic panel was 1.95 (€ /kWh) in the absence of cooling technology and 1.57 (€ /kWh) in the presence of cooling technology, respectively.
Kabeel et al.	[181]	PV system with reflectors for three types of cooling: forced air, water, and forced air and water combined.	For PV without cooling, air cooling, water cooling and air and water combined, the prices of kWh were 0.062, 0.072, 0.061, and 0.0722 $/kWh, respectively.
Al-Waeli et al.	[182]	PV/T system with nanofluid	The cost of kWh is 0.196 USD/kWh, and the payback time is 7–8 years.
Al-Waeli et al.	[183]	PV/T system with nanofluid and PCM	The cost of kWh is 0.125 $/kWh, and the payback time is 5–6 years, respectively.

water/liquid should be constantly drained out or used somewhere else in domestic hot water applications. Different research on the heat pipe has been discussed about the cooling of PV/T systems [159–163]. The excess heat absorbed by the working fluid of the heat pipe from the rear end of the PV panel is utilized as thermal energy. Table 8 presented a detailed summary of different cooling methods.

In this segment, we aim to mention the research contributions in respective cooling methodologies based on the published journal articles. The Fig. 26 indicates that reputed journals have given fair value to the works being carried out all around for thermal management of PV panels. It can be seen that most of the research has been disseminated through ample research articles in Solar Energy seconded by publications in Energy Conservation and Management (ECM).

Similarly, Fig. 27 helps the reader visualize the breakdown of the technologies addressed in the present study. It can be seen that researchers prefer hybrid cooling (a combination of any two cooling phenomenon like water-PCM cooling) followed by water/liquid and heat pipe based cooling for the achievement of their goals. It can be realized from Fig. 28 that the past five years have attracted tremendous research towards PV/T cooling and a considerable rise in the trend is expected to be seen in upcoming years. Research on PV/T cooling is profoundly undertaken worldwide as it offers a clean, green and sustainable source of energy. Countries, both developed and developing, have been investing heavily to explore the opportunities for efficiency improvement. India was able to find a decent place in this sector.

It has been concluded that the literature demonstrates different solar PV panel-based uniform cooling techniques. Immersion cooling, heat pipes, microchannels, impingements jet, phase change material cooling, heat sinks, and better heat exchanger designs were found to provide consistent temperature in most PV systems. These are made up of active and passive cooling systems depending on the PV system's shape and concentration. Heat pipe cooling with high heat flux dissipation was found to be best suitable for PV cooling with fins. One such passive cooling method described is the use of heat sinks and heat spreaders. But the passive method is not economically viable because to the high amount of material fins/planes [188,189]. Phase transition materials passive cooling improved thermal management for PV systems. PCM's main benefit is its capacity to modulate temperature utilizing latent

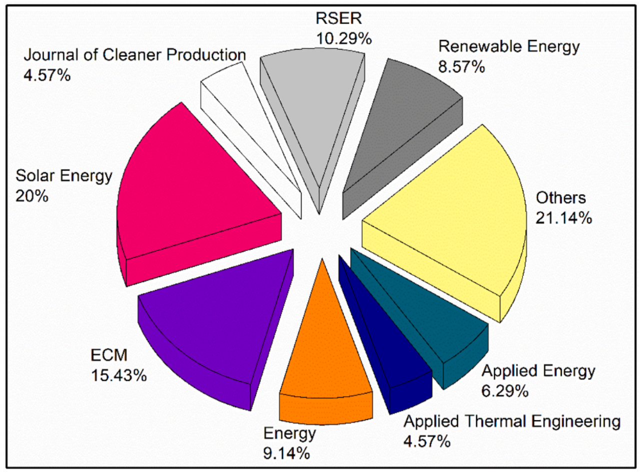

Fig. 26. Pictorial presentation of published articles based on journals.

Table 8
A detailed summary of different uniform cooling methods of photovoltaic/thermal systems.

Technology	Highlights	Advantages	Disadvantages
PV/T with jet impingement cooling	• Electrical efficiency improved • Better heat transfer features • A considerable amount of water is wasted	• Solar radiation conversion into electricity rate improved • Better thermal conductivity and low thermal resistance	• PV panel surface region is partly cooled and the amount of heat is wasted • Maintenance/pumping cost is high
PV/T system with air cooling	• Forced circulation of air is more effective. • More efficient in cold weather • Variation in design is possible	• Modest technology, low risk of corrosion and air readily available • The electrical and thermal efficiency improved	• Performance lower than soothing water • Forced air circulation external power (blowers) needed
PV/T with Liquid immersion cooling	• Reduced temperature and enhanced performance • Needs leak-proof design	• Highly effective and environment-friendly • Remove heat from front and back surfaces	• Depth of submersion affects performance • Increased cost and intricate system design
PV/T system with Thermoelectric cooling	• Excess heat to improve electrical energy production • The heat sink reduces the temperature on the surface	• Clean energy supply • Rate of electrical conversion efficiency improved • Increased PV modules life	• Low performance of the TE device • Conduction loss through thermo-electric device • Higher energy conversion prices
PV/T system with Microchannel cooling	• The effective rate of heat transfer • Low heat resistance between substrate and heat sink • Keeps cell under isothermal conditions	• Removes maximum heat through a smaller region • Less power consumption • Reduced inventory of fluid required, low thermal strength	• Limitations in pressure drop and corrosion problem • Manufacturing cost is high • Unwanted distribution of temperature along the line
PV/T system with PCM Cooling	• The PV panel heat is stored during phase change • Material absorption capability degrades over time • Well-suited requires less maintenance and fast cooling	• Absorb a large amount of heat with low-temperature shift • The system can be operational during the night • Heat can be used in buildings for heating	• Low thermal conductivity of solid PCM and active volume for heat storage reduces due to segregation • Most PCMs are poisonous and are prone to fire • Disposal issues after usage
PVT system with liquid/ water cooling	• Increases electric performance efficiently and is less active at the bottom than at the top. • Temperature regulation by variation of mass flow rate	• Overall efficiency is improved • Higher electrical conversion rate • Availability of domestic hot water • Minimal requirement of space	• The initial cost is high • Possible freezing in cold weather • Power required for water pumping • Prone to and corrosion, leakage and fouling
PV/T system with Heat pipe cooling	• The design of system is complex • High thermal performance • Corrosion problems affect the choice of material for heat pipe	• Higher values of heat flux • Heat transfer is passive • Transfer of heat over long-distance • Easy to incorporate	• The initial cost is high • Manufacturing challenges • Non-condensable gas evolvement • Leakage of substance
PV/T and Nano-fluids (PV/T-NFs)	• Enhanced thermal output • Improved heat transfer rate • Nanoparticle's deposition can be a concern	• Accessibility of nano-fluids • Greater thermal efficiency • Nano-particles high cost	• Incipient technology • Undetermined factors (base fluids interactions and characteristics)

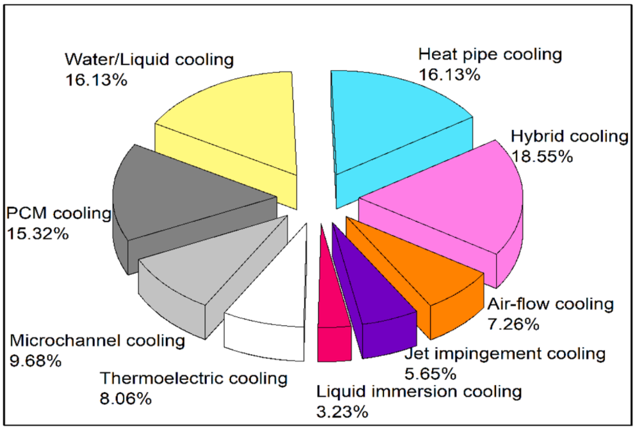

Fig. 27. Contribution of published articles based on cooling methods.

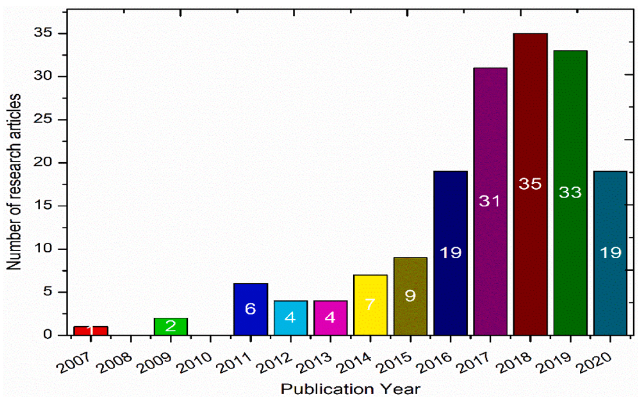

Fig. 28. Representation of published articles per year.

heat, resulting in consistent temperature cooling. However, this method is still in its development and is seldom employed for concentrated systems. Various PCM materials were used to regulate cell temperature between 28 and 65 °C.

Key issues and challenges associated with PV cooling

Thermal management of PV modules is an attractive research area that aims to improve electrical and thermal efficiencies and leads towards sustainable energy development [42,190]. It will lead us towards the PV/T system concept that can generate electrical and thermal energy simultaneously. Such systems attract additional costs and some technical glitches.

1. The parameters such as the temperature of the module, the scope of cooling systems and its possible effects need to be considered. System design should depend on numerous aspects like module positioning, geographical location, and cooling system components.
2. The area to be cooled will often be higher than the low power output per panel, which contributes to more comprehensive cooling requirements.
3. Hotspot development leads to degradation of module life, making it difficult to maintain even temperature all over the module surface area.
4. Higher initials costs are imperative for better performance and should be balanced accordingly. So, an efficient heat removal system must be highly cost-effective as it does not substantially increase the system costs.
5. When a PV/T system is constructed without considering impacts on the environment, the cost of repairs may dominate over the advantages of improved power production.
6. Several parameters and variables evaluate PV output using different cooling systems, but the standards used for testing are not up to the mark.

It can be summarized that economical cooling; photovoltaic modules face several challenging issues that demand continuous exploration through research. The review of the various PV cooling techniques listed in the study contains all recent improvements to the key issues (See section 9).

Conclusions

This paper offers a review of the experimental and empirical research on solar photovoltaic cell efficiency enhancement through efficient cooling methods. It can experimentally and numerically be seen that the active and passive cooling techniques will reduce the operating cell temperature, which is increased with time at constant radiation intensity. The role and future scope of artificial intelligence was also summarized in this research article. The techno-economic analysis of PVT systems was also discussed in this study. Furthermore, future study should concentrate on the techno-economic impacts of cooling methods for the development of feasible sustainable PVT systems. This paper's review can be very helpful for researchers and academicians who are working in this field regarding future study. Each cooling system has its own uses, and the cooling performance varies. The following conclusions have been drawn from this study:

- Jet Impingement cooling is a better option to maintain the uniform temperature of the PV module, but impinging the jet is an active technique and suffers an extra cost to the end-user.
- PV/T systems based on airflow cooling are modest in design as compared to liquid-based systems. Hot air uses are minimal and not viable for the hot environment.
- The reflection losses decreased with liquid immersion cooling. It improves power output and allows the operating temperature to remain constant.
- A thermoelectric cooling system uses excess heat efficiently to increase performance. A PV/T-TE solar hybrid array, cooled by a heat sink, would considerably decrease the PV panel's surface temperature. Excess heat can also be used to improve electrical efficiency.
- Microchannel cooling-based studies seem to be focusing on electronics cooling as compared to CPV cooling. In most cases, boiling microchannel flows are used to cool CPVs. However, changes in current electronics and CPV systems, the cooling require dedicated research to establish the functioning of a better microchannel cooling based PV/T system.
- The PCM operated cooling method will be economically viable with substantially reduced costs of PCM. The passive and active cooling methods are not economically feasible because of their increased volume per unit energy density. PCM cooling is the most efficient method.
- The findings have shown that active cooling based on liquid/water is the simplest and most efficient form of cooling. Rapid cooling of the water is also not feasible. The PV/T system, cooled by spraying water, shows an improvement in its efficiency.
- The heat pipe conducts heat rapidly and operates without any external influence. Studies show that the heat pipe-focused PV/T system is typically integrated with a heat pump. Heat pipe behavior typically depends on its process parameters like gas operation and evaporator and condenser direction, tilting angle etc. it can be used in high-power PV/T systems.
- The PV/T system using nano-fluids has promising results, but experimental research is quite typical. Combining an optical filter

with nanofluid in a single device will intensely improve the system's efficiency during cooling.
- The incorporation of artificial intelligence and machine learning in advanced cooling techniques will increase the performance of PV/T systems. Also, the LCC and PBP results prove that PV/T cooling systems are economically and environmentally feasible.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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