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TOPICAL REVIEW

A State-of-the-Art Review on Heat Extraction Methodologies of Photovoltaic/Thermal System

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ABSTRACT One of the critical emerging branches of solar technology is photovoltaic/thermal (PV/T) systems that amalgamate solar collectors and solar photovoltaic panels into a unit to produce heat and electricity from stochastic solar insolation. In sunny countries, the conversion efficiency (η) reduces due to the elevated temperature of solar cells because solar panels absorb a sizeable portion of solar insolation as heat. The critical function of PV/T is to minimize the temperature of photovoltaic modules and enhance their electricity production with yielded thermal energy used for other applications. Energy and exergy are two essential aspects of examining an energy system. The exergy analysis of such systems is of great concern because it works on the quality of energy. The energy and thermal and electrical efficiencies are enhanced by applying proper cooling media in the PV/T. This brief provides a comprehensive review of the air, fluids, and PCM-based cooling media of the PV/T systems. A thorough review of various recently published research in the heat extraction methodologies of PV/T systems has been incorporated into this study. Based on the rigorous review, future recommendations for the implementation of cooling medias are also included in this study. The vivid tabular analysis of heat extraction methodologies provides a proper guideline for the researchers. This review work will provide a deep insight into the investigated area for the industrialists and researchers working in the field of PV/T technology.

INDEX TERMS PV/T system, energy and exergy efficiency, cooling media, solar insolation.

I. INTRODUCTION

In the present era, the energy demand proliferates worldwide due to population spurt and industrialization [1], [2]. Depleting fossil fuels, emission of greenhouse gases, and damage to the ecosystem have paved a path toward using emission-free renewable energy sources [3], [4]. Exploration of eco-friendly energy resources is the need of the future and solar technologies play a critical role as a solution to eco-friendly energy exploration. The present solar technology is categorized into three parts: photovoltaic (PV), solar thermal collectors, and PV/T systems, as presented in Fig. 1 (a)-(c). PV is designed to convert solar energy into electrical energy, and the output electrical current is DC [5]. The transformation of solar energy to electrical energy is obtained via a photoelectric process when discharge electrons react with the photons present in sun energy [6]. Due to its higher flexibility, as it may be built-in mountains, plain areas, or deserts, PV is distinguished from the other applications of solar [7]. One of the significant setbacks of PV is its high installation cost with reduced η compared to fossil fuels [8], [9]. The reduction in η is due to an enhancement

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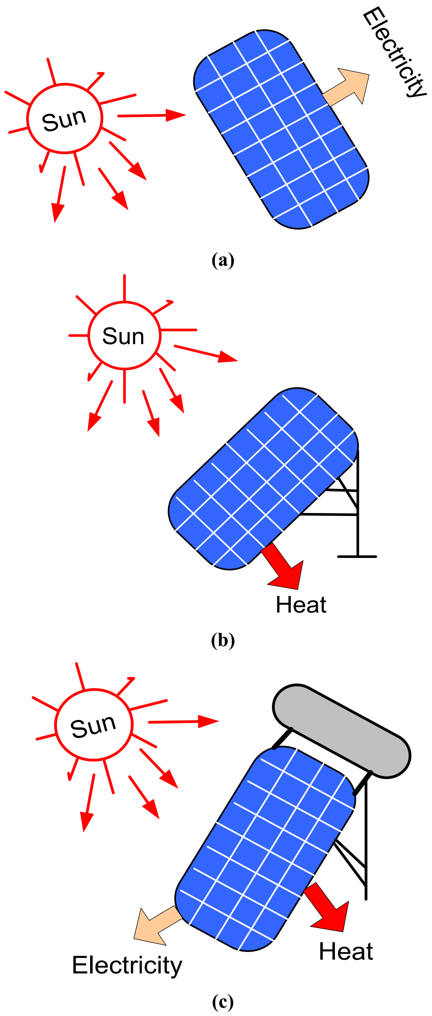

FIGURE 1. (a) PV (b) solar thermal collector (c) PV/T.

in the temperature of the solar PV surface while in operation [10]. This perception of reduced η is the motivation of the research in the field of PV/T that successfully evolved the different cooling techniques to enhance the overall performance of PV/T systems. The combination of thermal collector and PV technology is the basis of PV/T systems [11], [12]. The PV/T systems are categorized in various parts based on the heat extraction methods as air, liquid, and phase change material (PCM) based cooling media.

Martin Wolf was the first scientist who proposed and examine a hybrid PV/T system in 1976 [13]. Since then, much research has been done in the field of PV/T systems. As mentioned earlier, the PV/T system amalgamates thermal collectors and PV cells into a unit that simultaneously generates power and heat. Thermal collectors extract heat from the panel, which may be utilized in low or medium-temperature applications. In the simplest form, the η of the PV/T system is calculated as the summation of thermal and electrical η, i.e., $\eta_{total} = \eta_{the} + \eta_{ele}$. The main problem with this method is that thermal and electrical η is considered to have the same magnitude.

From the thermodynamic point of view, energy is in two forms, lower-grade, i.e., thermal energy and high-grade, i.e., electrical energy, based on how it is transferred into another form of energy. So, from the quality viewpoint, electrical η is evaluated by equivalent thermal η, which is obtained by the division of electrical η with the traditional power plant's average η. So, the total η of the PV/T system is as $\eta_{PES} = \eta_{the} + (\eta_{ele}/\eta_{power})$. The major goal of the fruitful critic is to improve thermal and electrical efficiencies. After the proper heat extraction (cooling media), the quality of electrical energy is enhanced, which is considered in this work. It is essential to mention that the criteria of η upliftment might be in terms of heat exchanging system, thermal collectors, cooling material, integration scheme, etc. Moreover, the following key points are necessary to be highlighted:

- ✓ If the PV cells are overheated, a reduction in their η has occurred, so it is necessary to cool them.
- ✓ According to heat transfer fluids (cooling media) and types of observers, PV/T systems are classified.
- ✓ Various cooling methods are available to maintain the temperature of PV cells. Moreover, varied materials have been used for cooling media, such as water, air, PCM, nanofluid, nanofluid/PCM etc.

Sopian et al. [14] investigated an experimental analysis where three PV/T water-cooled collectors were evaluated in thermal production. The three water collectors were direct, parallel, and split flow designs. After vivid investigation, it has been noticed that split flow design could provide a 51.40% enhanced ratio of thermal energy compared to similar and direct techniques. Kim and Kim [15] experimented with a water collector-based PV/T hybrid system. An observation has been made on wetted, sheet, and tube types of absorbers. The results demonstrated that the wetted absorber produced a combined PV/T performance of 65%, whereas 60.60% of combined performance was obtained with sheet and tube type design. Hosseini et al. [16] demonstrated the cooling effect of the PV/T system. A water film has been attached to the plan to reduce the adverse impact of temperature and enhance electric yield. A comparative experimental analysis of combined and traditional systems was performed, revealing that the panel temperature was minimized due to the combined structure. The electrical performance was also enhanced due to the integrated design.

Compared to traditional fluids, the optical and thermal performance is highly improved due to the development in the production and utilization of nanomaterials in nanofluids. Hence, various nanofluids have been used as a cooling media for PV/T systems and have significantly improved the overall performance. Lari and Sahin [17] briefed on the impact of nanomaterials with enhanced thermal properties on PV/T systems. The results revealed that electricity production improved by 13% via the proposed cooling media compared to an 8.5% enhancement via a water-driven cooling of the PV/T system. Moreover, the energy cost via nanomaterial-cooled PV/T system was reduced over the local cost of electricity by 82% in Saudi Arabia. In Reference [18], the authors have briefed the impact of three types of cooling media experimentally formed via nanoparticles (Al_2O_3, MWCNT, and C_uO) and water. Multiple fractions of the volume of all three types have mixed in water, and the resulting nanofluid properties were examined. Thermal conductivity, density and fluid viscosity were examined, and the impact of all these properties on thermal, electrical, and total efficiencies of the installed PV/T system. Compared to the water-cooling system, the proposed nanofluid cooling enhanced the energy efficiencies and generated electricity. Compared to the traditional PV system, the average electrical η was improved by 55%, 60% and 52% using nanofluids (Al_2O_3, MWCNT and C_uO with water).

Researchers observed that the system is independent of thermal energy demand and supply fluctuations by the latent heat; hence, materials having the capability of latent heat storage, known as PCMs, have come into consideration in recent years. Enhance the PV/T system's η and reduce construction cost and site area; authors [19] have considered paraffin wax a suitable PCM with nanofluid for cooling purposes. The study demonstrated mathematical modelling for the system. The thermal and electrical efficiencies for practical and simulation analysis are 72% and 71.3%, 13.7% and 13.2%. The optimal temperature noted in the glass was 41.2°C for paraffin 38.8°C, for PV cells 39.92°C and for nanofluid was 36.5°C. In [20], authors have briefed a practical and numerical study of graphene nanoparticle nanofluid-cooled PV/T systems in Saudi Arabia. The findings showed that the proposed setup improves the thermal behavior of nanoparticles mixed with the PCM layer located under the PV panel. The obtained results showed the superior performance of the nano-PCM nanofluid-based PV/T system compared to the standalone system. Authors have concluded that a significant decrement has been observed in the temperature of PV panels by increasing nanoparticle mass fraction in cooling fluid and PCM.

Moreover, much review work has been done on the PV/T system. Yazdanifard and Ameri [21] 2018 briefed on the exergetic advancement of the PV/T system, in which a detailed review was done on heat extraction of PV/T, and the reviewed articles are till 2018. A review of the PV/T system based on the application of fluids has been briefed in [22] with their life cycle assessment. A definitive study on concentrating PV/T collectors and techniques with their applications and checks has been done in [23], in this the articles reviewed till year 2018. Advancements and shortcomings in enhancing solar insolation for concentrating PV/T systems are performed in [24], and the literature surveyed till 2019. Development and applications of PV/T systems with their detailed tabular analysis are investigated in [25], and the article reviewed is till 2019. Das et al. [26] and Sathe and Dhoble [27] described a vivid review based on the latest published work till 2018 in the field of PV/T systems. Upgradation of PV/T in the last four decades is reviewed in [28]. A considerable time gap has appeared in which much work has been performed in the heat extraction of PV/T systems. So, it is required to make availability of a guidebook for the engineers, researchers, and manufacturers working in this field. Moreover, this review work offered a taxonomy based on the type of cooling material, number of cooling channels and coupled system. The novelties and key findings of the work are mentioned as follows:

1. A vivid review of the heat extraction methodologies of PV/T systems with the latest improvements and developments.
2. Focus on the novel progresses in the considered field with critical advancements such as nanofluid and nano-PCM cooled PV/T systems.
3. A vivid tabular analysis of the system, PV type, experimental/numerical analysis, cooling media, and critical notes are performed.
4. A vivid discussion with future recommendations is provided for the scientists working in this field.

II. METHODOLOGY ADOPTED FOR REVIEW

In this study, four distinct phases are adopted: (1) selection of topic, (2) workflow for review, (3) conduction of the review, and (4) documentation, which is summarized as follows:

Key consideration: State of innovation in PV/T systems.

Sub-consideration 1: Critical achievements in the cooling media of PV/T systems.

Sub-consideration 2: Major achievements in nanomaterial applied to nanofluids and nano-PCMs.

Origin: Two scientific repositories, such as Google Scholar and ScienceDirect.

Index terms: PV/T systems; cooling media of solar thermal system; air-based PV/T design; water cooled PV/T system; nanofluid cooled PV/T; PCM cooled PV/T; multiple channel PV/T; single channel PV/T.

Inclusion strategy: Literature focusing on innovative PV/T systems, documents with cooling methods of PV/T systems, and research articles focusing primarily on PV/T systems.

Exclusion strategy: Replicated studies and documents that are out of scope lack inclusion criteria with general topics.

Filtration phase: Filtration via relevance of the title, abstract, and finally, by observing the complete document.

Categorization: Based on the type of thermal storage material and type of cooling media.

Evaluation: Technical, cooling behavior, energy, and exergy performance of PV/T systems.

Critical review and future recommendation: Point out shortcomings and the necessity for more research in the field of PV/T technology based on research trends and gaps.

III. AIR-COOLED PV/T SYSTEM

Allow forced or natural air to extract heat from the PV cells; an air-cooled PV/T system uses channels above or below the photovoltaic layer [29]. These systems are widely utilized in ventilation, space heating [30], and agricultural product drying due to their low operational cost and minimum utilization of materials. In Reference [31], the authors briefed a PV/T air collector with natural ventilation, in which a thin layer of the aluminium sheet has been attached to the air channel's middle portion to enhance heat extraction from PV. The authors have demonstrated optimal collector and channel lengths for optimizing the system's total energy. In [32], an experimental performance assessment of PV/T is performed via the first and second laws of thermodynamics. There is a vivid comparison of three configurations as an unglazed transpired collector (UTC), a single PV panel-based UTC, and two PV panel-based UTC, and a conclusion is made that the PV/UTC systems have enhanced η because of the production of electricity with heat. A numerical examination of the PV/T system with the air distribution system is performed in [33], as depicted in Fig. 2. They analyzed the η of the system based on the air flow rate per unit area of collector and variation of depth of air channel on the rate of thermal output energy and fan and PV powers while considering the fixed width and system length.

In [34], a PV module and three PV/T hybrid air collector-based accurate thermal and electrical model has been described, as depicted in Fig. 3. The results show that the two rows of air channels via placing the glass on the cell give higher η compared to a single row of air flow. Moreover, the PV module provides the highest electrical η at maximum air flow compared to the cooling rate. Because of glass coating, a positive impact has appeared on the system's total η. A conclusion has been made that multiple passes have higher η than single passes. In [35], the authors have examined the optimization of the energy output of an air-cooled PV/T system and concluded that the increase of air flow rate causes the enhancement of thermal and electrical η. The study also provided the idea of parameters design, such as heat transfer resistance to the flow of air inside the channel and ambient air, air mass flow rates, and size of the air channel. An air-cooled solar collector with a cost-effective design is briefed in [36]. In [37] examination of the improvements in the η of air-cooled PV/T systems with and without the glass, further, a conclusion has been made that installation of a blade on the back side of the channel or placing metal sheets in the middle portion of the pipeline could enhance the heat extraction capability. They observed that the thermal η is decreased due to the ambient temperature and introduced the optimized depth of the channel as a critical factor for system η.

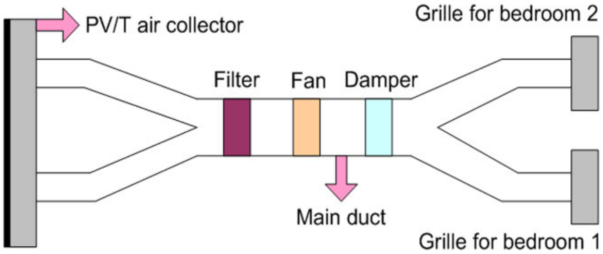

FIGURE 2. Air-cooled PV/T for building integration [25].

Dubey et al. [38] briefed the exergy and energy analysis of air-cooled PV/T collectors connected in a series manner and concluded that the demonstrated scheme provides enhanced electrical, exergy, and thermal energy results. The performance characteristics of diverse types of samples as air-based PV/T, glass-to-Tedlar, and glass-to-glass collectors with and without channels, were accessed. Higher electrical output is obtained via a glass-to-glass module and maintains a higher air temperature due to the closed area. The average η in modules without and without channels was 9.75% and 10.4%, respectively. Reference [39] detailed the forced convection-based PV/T system via a blown jet that absorbed 54% radiation energy and concluded that blow jets would enhance the system's productivity rate. A single-phase building-integrated air-cooled PV/T in an open loop is investigated in [40], and a conclusion has been made that the utilization of two air inlets enhances the thermal η by 5% compared to a single air inlet.

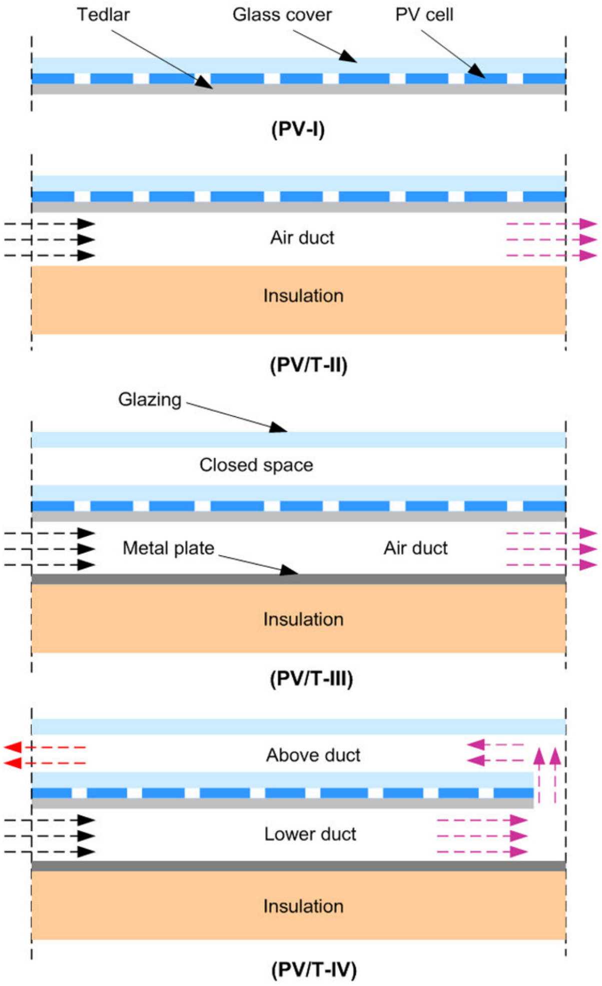

FIGURE 3. PV module (PV-I) and PV/Ts investigated in [34].

Moreover, due to the vertical glazed collector, thermal η is about 8%, and with the addition of wire mesh to the collector,

η enhancement is more than 10%. A PV/T system with added blades to the air-cooling channel is investigated by studying the velocity and temperature of air with ANSYS [41]. They obtained that using blades in the cooling medium enhances the thermal η by 55%-70%. Also, the exergy η is improved by 30%-70% via different material-based blades. The panel temperature is also reduced using blades compared to traditional PV/T systems. The positional impact of the channel in an air-cooled PV/T system is investigated in [42], while the performance of PV panels with geothermal-based air cooling is briefed in [43], and the key elements are presented in Table 1. The thermal regulation of PV panels integrated with thin-film solar cells is detailed in [44]. Gupta et al. [45] proposed a semi-transparent PV/T system for building integration, modeled the entire system based on energy balance equations, and validated it experimentally. In this, the authors have revealed the impact of air variation per hour on changing room temperature hourly, electrical power, PV cell temperature, thermal exergy, energy η, and overall system η. They showed that increment in air variations per hour reduces the temperature of the air in the room and the temperature of PV cells because the maximum heat is transmitted in the ambient. So, the PV power enhances, and thermal exergy reduces because of a reduction in the temperature of the PV cell with boosting air variations. Authors have also demonstrated that promoting air change from 0 to 4 in an hour gives a 1.15% enhancement in overall exergy daily.

TABLE 1. Experimental setup range, accuracy, and uncertainties [43].

Instrument	Range	Accuracy	Uncertainties
Anemometer	-	-	-
Temperature	$-20\ to\ 70°C$	0.5°C	0.28°C
Air velocity	Up to 50 m/s	0.015 m/s	8.61×10^{-3}m/s
Thermocouple	$0 - 200°C$	0.1°C	5.7×10^{-2}°C
Pyranometer	$0 - 2000\ W/m2$	$0.025\ W/m2$	14.41×10^{-3} W/m^2
Ammeter	-	±0.01 A	5.7×10^{-3}A
Voltmeter	-	$\pm 0.01\ V$	5.7×10^{-3}V

Singh et al. [46] briefed a dual-channel flat plate semi-transparent PV/T system in which two channels maintain air flow. One track is below PV, and the other is above PV, and they performed a comparative analysis with a semi-transparent one-channel-based PV/T system. They concluded that the dual-channel has 3.19%, 35.63%, and 30.49% higher overall exergy η, thermal gain, and electrical η, respectively, compared to one channel because of the additional heat dissipation from PV/T. Four novel designs of bifacial PV/T system, as depicted in Fig. 4, are revealed in [47], and authors have investigated exergy and energy experimentally. Model 1 was one path and single duct, models 2 and 3 were double paths and double ducts with parallel and counter flow of air, and model 4 was a dual path and single vent with returning flow. One of the critical features of bifacial PVs is that they can absorb radiations from the front and rare surfaces. They accessed each design with various packing factors as 0.22, 0.33, 0.50, and 0.67. Results demonstrated that optimum exergy and energy occurs at the optimal packing factor for all the proposed design. They also concluded that the optimized total energy η of 67% is obtained with model 2, while the highest total exergy η of 8.4% is obtained with model 1. An air-cooled naturally ventilated PV/T system for building integration is briefed in [48], and authors have investigated air velocity in PV and duct, outlet air, and inlet air temperatures experimentally. They utilized the obtained experimental results for calculating energy and exergy efficiencies.

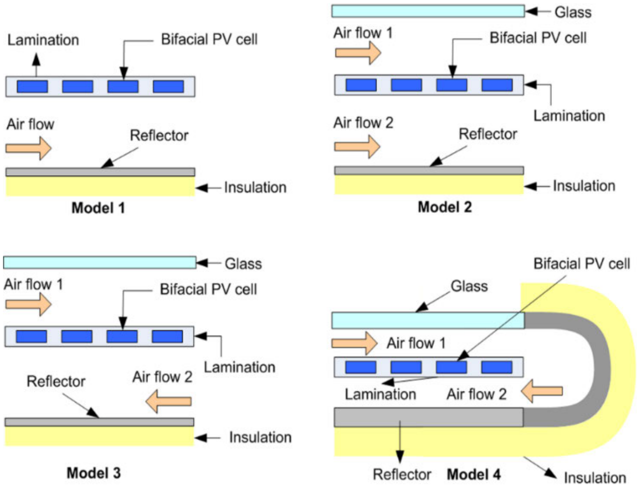

FIGURE 4. The bifacial PV/T system was investigated in [47].

The experimental analysis showed that boosting PV temperature increases the outlet air temperature and air velocity, and the numerical results revealed that input exergy is higher than output exergy due to irreversibility. Multi-objective based genetic algorithm is utilized to optimize air duct dimension and air mass flow rate [49]. The authors have considered unglazed and glazed situations and studied the hourly and annual system performance of unoptimized and optimized building-integrated PV/T systems. They revealed the annual exergy η of 10.75% and 10.81% and yearly energy η of 39.27% and 29.22% for glazed and unglazed optimized systems, respectively. An exergetic performance evaluation of an air-cooled PV/T system is proposed in [50]. A detailed tabular analysis of air-cooled PV/T systems is depicted in Table 2.

IV. LIQUID-COOLED PV/T SYSTEM

The performance of liquid-cooled PV/T systems is higher than air-cooled PV/T systems because the fluid's thermal capacity is higher. Liquid-cooled PV/T systems incorporate a channel behind the PV cell and a flat plate-type metal absorber to extract heat via fluid circulation [51]. Water is the most utilized fluid in liquid-cooled PV/T systems. Liquid-like water is a poor conductor of heat and, compared to solids, has reduced thermal conductivity because extraordinarily little space is present among the particles. They are excellent heat

TABLE 2. Air-cooled PV/T systems.

Ref.	PV type	System investigated	Experimental/numerical	Cooling media	Keynote
[31]	Polycrystalline silicon	Natural ventilated PV/T	Both	Air	Optimum collector length and channel depth to maximize total energy & exergy η
[32]	Polycrystalline silicon	PV/T solar collectors with transpired	Experimental assessment	Air	quantity of air mass flow rate influences the PV cooling; Exergy η is higher in PV/UTCs compared to UTCs
[33]	Crystalline silicon	Flat plate BIPV/T	Numerical assessment	Air	Radiation levels do not make concern if MPPT and fan are appropriately selected; PV location impact is a negligible and significant impact of PV coverage on system performance
[34]	Monocrystalline silicon	Hybrid air collector	Both	Air	A comparative analysis of four solar device configurations has been done; A double-pass glazed air-cooled PV/T system shows the enhanced annual energy output.
[35]	Monocrystalline silicon	Single pass, unglazed, open loop PV/T	Experimental assessment	Air	The experimental assessment depicts that the enhancement of air flow rate enhances the thermal and electrical η, the electrical η is between 10.6% to 12.2 %, and the thermal η is between 28% to 55%.
[37]	Polycrystalline silicon	Commercial PV module-based PV/T	Both	Air	The obtained results depict that the thermal performance enhances by enhancing the output area of the channel.
[38]	-	N hybrid air collector PV/T	Numerical assessment	Air	The difference between ambient and room temperature in winter and summer is 2.8°C and 6.5°C, respectively.
[39]	Monocrystalline silicon	Hybrid PV/T solar collector	Experimental assessment	Air	Modelling of the thermal mass of the collector has a lesser impact on the results; The time constant of the collector is 15 min.
[40]	Polycrystalline silicon	BIPV/T system	Both	Air	With the addition of wire mesh on the glazed collector, η enhances by around 10%; Simulation results indicate that the thermal η improves by 5% and electrical η enhances marginally via BIPV/T collector cooled with two inlets.
[41]	Monocrystalline silicon	Mobile PV/T system	Both	Air	The exergy η of monocrystal and polycrystal panels is enhanced by 30% and 70% via sparse and frequent fins; Thermal η is improved by 70% and 55%, respectively; Due to friction and viscous forces, air velocity near fine is slow.
[42]	Monocrystalline silicon	Air-cooled PV/T's heat transfer specifications	Numerical assessment	Air	Comparative analysis of two designs, (case 1) the placing of cooling channels above the PV panel and (case 2) below the PV panel are performed; At air inlet temperatures of 298.15K (case 1) and 295.65K (case 2), maximum total exergy η is obtained; Internal radiation in the channel of cooling affects system performance higher for case 1.
[43]	Monocrystalline silicon	Integrating earth air heat exchanger-based PV/T	Experimental assessment	Air	Experimental assessment of PV panel with a buried heat exchanger; The empirical analysis reveals that the proposed cooling media can reduce the operating temperature effectively and enhances the conversion η.
[44]	Monocrystalline silicon	BIPV/T system	Numerical assessment	Air	Thermal regulation of the PV façade via a passive air channel gives enhanced energy conversion η; It is observed that the optimal surface temperature extends to 49.1°C for the open channel and 57.1°C for the closed channel.
[45]	Monocrystalline silicon	Building an integrated semi-transparent PV/T system (BISPV/T)	Both	Air	By considering electrical and thermal, and daylight factors, energy analysis is performed; Via the enhancement of air changes per hour, the overall daily energy is enhanced.
[46]	-	Dual channel flat plate partially transparent PV/T system	Numerical assessment	Air	Better performance of the proposed system compared to single channel partial-transparent PV/T system.
[47]	Monocrystalline silicon	Air-cooled bifacial PV/T	Both	Air	Optimum energy η is achieved at the highest packing factor; Optimum exergy η is achieved with the single duct.
[48]	Monocrystalline silicon	Natural ventilation cooled the BIPV/T system	Both	Air	Total exergy and energy η are enhanced by enhancing outlet air temperature.
[49]	-	BIPV/T system	Numerical assessment	Air	Lower exergy η and higher energy η are achieved for the optimal system compared to the unoptimized system.
[50]	Monocrystalline silicon	Air-cooled flat plate PV/T system	Numerical assessment	Air	There are optimized air velocity and solar intensity at maximum exergy η.

convectors due to the higher molecular movement within liquids. In Reference [52], a linear triangular receiver and parabolic challenging concentrator-based novel CPV/T have been briefed via a finite-volume model. The authors have concluded that the exergy η is enhanced due to increasing receiver length because the temperature difference is highly reduced; hence, irreversibility reduces. Garcia-Heller et al. [53] demonstrated a concentrating CPV/T cogeneration plant's exergetic analysis via a point-focus dish concentrator in Algeria. They briefed the combination of adsorption chiller and CPV/T from exergy, energy, and economic viewpoints. A coolant temperature of 80°C, overall exergy η of 35.3%, and overall energy η of 87.5% are achieved in their study.

In [54], based on the exergy scheme, authors have optimized a water-based PV/T system, as revealed in Fig. 5 and investigated the effect of inlet water velocity, solar insolation, wind speed, and pipe diameter on exergy η while considering pressure drops in pipes. The outcomes of their analysis are tabulated in Table 3, and the overall exergy η evaluation is given by (1), as shown at the bottom of the page.

TABLE 3. **Important indices as demonstrated in [54].**

Parameter	Range of variation	Exergy η (%)
Inlet water velocity	$0.01-0.09\ m/s$ & $0.09-2\ m/s$	9 – 11.36 & 11.36 – 0
Solar insolation	$0-1000\ W/m2$	0 – 11.5
Wind velocity	$0-10\ m/s$	~11.36
Pipe diameter	$1-4.8\ mm$ & $4.8-10\ mm$	8.5 – 11.3 & 11.3 – 10.9

Reference [55] calculated the experimental η of an utterly wet absorbent with two non-glazed heat exchangers and revealed that the PV/T collector performs nicely with a damp absorbent to produce electricity and additional thermal energy. A conclusion has been made that the electrical η of a PV/T system with wet absorbent is higher than the simple photovoltaic system by 2%. Nualboonrueng et al. [56] have performed an experimental investigation on domestic PV heat collectors with a water-cooled PV/T system. The electrical η is higher with multi-crystal silicon panels compared to amorphous material, while thermal η is similar in both cases.

Their results also show that 0.45 per unit collector area is available for hot water. According to their study, the PV/T scheme is helpful for electricity and heat for tropical and domestic applications. In [57], the authors have briefed an optimal design of a water-cooled PV/T system via non-concentrated and concentrated radiations, which segregates the infrared and visible range of the solar spectrum and utilizes infrared for thermal and visual content for the solar module. Working fluid optical properties are also optimized in their study. In another work, Zhao et al. [58] demonstrated a CPV/T system [57]. Water is injected to cool the PV cells, and then a lesser amount of water flows via a thermal unit and absorbs infrared radiation. They concluded that 90% of visible light is transmitted through the thermal unit, and 33% of infrared radiation is absorbed. Evola and Marletta [59] benchmarked the water-cooled PV/T systems via 1^{st} and 2^{nd} Laws of thermodynamics. They concluded that low inlet water is preferred for energy η, while optimal inlet water flow is utilized for enhanced exergy η. In Reference [60], the authors have studied the exergy η of traditional water-cooled PV/T systems numerically and experimentally. They concluded that the maximum exergy η of 13.95% at an optimal mass flow rate of 0.002 kg/s. Atheaya et al. [61], [62] briefed a water-cooled semi-covered PV/T-CPC from an exergy and energy point of view. The authors have compared the proposed scheme with a fully covered PV/T-CPC water unit, a traditional CPC water collector, and a semi-covered PV/T system. By using a linear regression scheme, they develop an equation for thermal η for different cases:

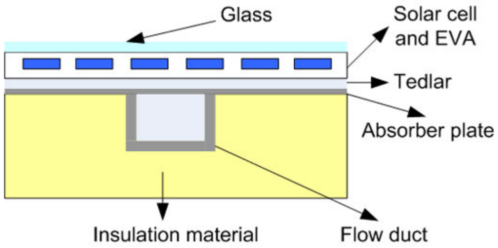

FIGURE 5. **Water-cooled PV/T system was briefed in [54].**

$$\eta_{th} = A - B\left[\frac{T_m - T_a}{I_b}\right] \tag{2}$$

A and B are the gain and loss factors, as shown in Table 4.

TABLE 4. **Gain factor and loss factor of (2) [61].**

Water collector	Gain factor	Loss factor
Traditional CPC	0.59	2.23
PV/T-CPC with partial covering	0.48	3.72
PV/T with partial covering	0.63	5.69
PV/T-CPC with full covering	0.30	6.59

In [63], the authors have investigated a tube and flat plate water-cooled PV/T system in turbulent and laminar flow regimes. The various parametric impacts on the system performance are glazing, solar insolation, collector length, packing factor, Reynolds number, number of pipes, and pipe diameter. Their observations showed that the total energy

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$$\varepsilon_{total} = \frac{\dot{m}c_p\left[T_{f,out} - T_{f,in} - T_a ln\left(\frac{T_{f,out}}{T_{f,in}}\right)\right] - \frac{\dot{m}\Delta P_f}{\rho} + \left(V_{mp}I_{mp} - P_{pump}\right)}{\left[1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4 - \frac{4T_a}{3T_{sun}}\right] IA} \tag{1}$$

TABLE 5. Percentage change in energy η as investigated in [63].

Parameters	Exergy η				Energy η			
	Turbulent		Laminar		Turbulent		Laminar	
	Glazing	Unglazing	Glazing	Unglazing	Glazing	Unglazing	Glazing	Unglazing
Solar insolation ($300-1000\ W/m^2$)	4.94	5.65	5.12	3.16	7.04	25.39	5.87	23.14
Packing factor (0.2-1)	462.01	462.70	252.11	291.53	0.47	1.46	1.31	3.67
Reynolds number (turbulent: 2300-6000, laminar: 100-2300)	-3.76	-2.73	∩	∩	1.73	3.88	751.26	519.17
Collector length (1-10 m)	6.27	4.14	20.98	8.00	-4.54	-8.11	-17.89	-34.64
Pipe diameter (3-10 mm)	45.38	51.27	0.29	0.28	4.87	5.06	0.25	0.52
Number of pipes (3-17)	∩	∩	∩	∩	32.91	73.29	49.55	94.10

Where ∩ is the increase or decrease trend.

η is higher with glazed PV/T compared to unglazed under both flow regimes due to the heat loss reduction from PV with a glazed structure. They also commented on the percentage variations of energy and exergy η, as noted in Table 5. According to Table 5, under both flow regimes, the packing factor is the critical element for exergy η, whereas the number of pipes and Reynolds number affect energy η in turbulent and laminar flow, respectively.

In [64], the authors have investigated the exergy and energy output of water-cooled PV/T theoretically with a PEM electrolyzer, as depicted in Fig. 6. This investigated system can generate electrical energy, heat energy, and hydrogen as fuel. The authors have obtained the average overall exergy and energy η of 14.11% and 29%, respectively. They concluded that the inculcation of the PV/T system with PEM water electrolysis is a more practical scheme for a larger unit of hydrogen production. In [65], authors have briefed the passive and active model-based exergy and energy performance of the PV/T system in the Tunisian climate conditions in two ways. First, they experimentally declared the PV/T to obtain immediate electrical and thermal η. Second, via TRNSYS software, they received the monthly/annual PV/T system's performance. Obtain the electrical and thermal η, and they utilized the following equations:

$$\eta_{ele} = \frac{U_m I_m - P_{pump}}{IA} \tag{3}$$

$$\eta_{th} = F'(\tau\alpha) K_\theta - a\frac{(T_{av} - T_a)}{I} - b\frac{(T_{av} - T_a)^2}{I} \tag{4}$$

where the incident angle modifier is K_θ, first and second-order η coefficients are a and b, respectively.

A bond graph modeling of a water-cooled PV/T system is briefed in [66]. In this technique, the PV/T collector amalgamates the solar thermal and PV modules to provide electricity and heat simultaneously. A novel configuration of water cooling is described in this work by the inculcation of parallel tubes and a tedlar layer. They developed a non-linear dynamic model that provides a practical and realistic system performance. Their results showed that the enhancement in wind speed could reduce thermal η from 70% to 40%. The nanosized particles (1-100 nm) are suspended in a standard working fluid to produce nanofluids, and they have enhanced heat transfer capabilities than traditional fluids like oil, ethylene glycol, and water. In recent years, numerous studies have been performed on utilizing nanofluids for cooling media in PV/T systems [67], [68], [69]. In [70], the authors have briefed the comprehensive review of works related to nanofluid-cooled PV/T systems. Authors have assessed the impact of nanofluid parameters like size, volume fraction, types (Al_2O_3 and TiO_2), and base fluid type on energy η under turbulent and laminar flow regimes. They concluded that heat transfer performance is more significant under nanofluid-cooled laminar flow than in turbulent flow. In [71], authors have investigated a unique structure of the PV/T system with two independent channels for cooling and spectral splitting of the PV/T system, as revealed in Fig. 7(a) and compared with dual pass cannel as presented in Fig. 7(b). They also investigated the impact of applying GaAs and silicon on the system's performance. Authors have concluded that the proposed structure with two different nanofluids, beam splitter and coolant, provides enhanced performance at a higher concentration ratio. Moreover, the increment of the volume of the nanofluid coolant enhances the overall exergy η for GaAs PV cells.

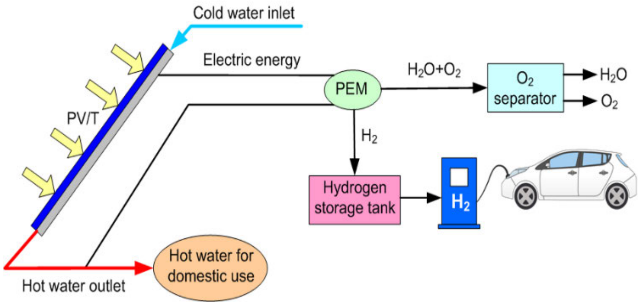
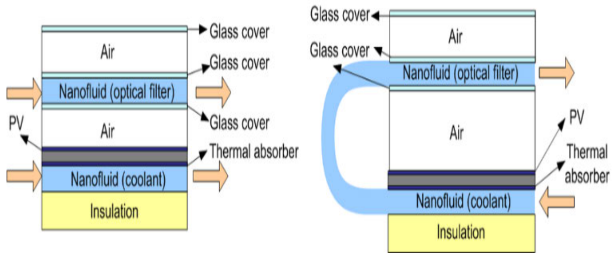


FIGURE 6. A water-cooled PV/T system with a PEM electrolyzer was investigated in [64].

Hassani et al. [72] revealed the comparative analysis of the life cycle exergy of traditional PV/T systems, PV panels, and two independent channel-based configurations. They analyzed various modes by working fluid variations (water, Ag/water, and CNTs/water nanofluids). The authors have



(a) (b)

FIGURE 7. Nanofluid cooled PV/T system (a) single and (b) double-pass channels briefed in [71].

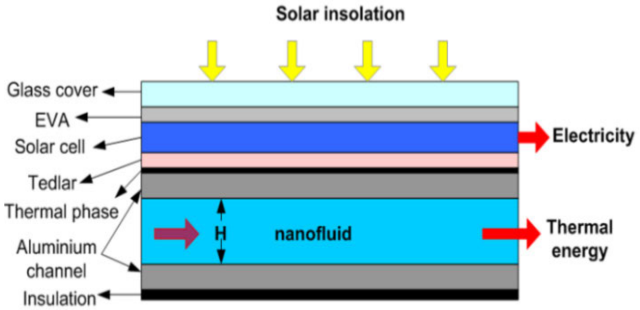


FIGURE 8. Hybrid PV/T with various layers [74].

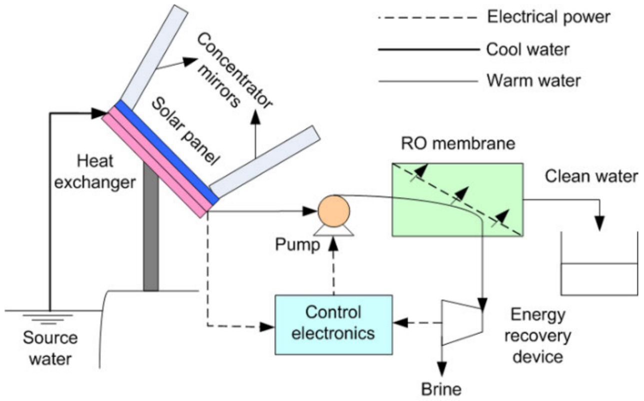


FIGURE 9. PV/T powered RO [78].

revealed that better exergetic performance is obtained by a PV/T system with a separate channel. In [73], numerical and experimental analysis of nanofluid cooled PV/T system is investigated. In this presented scheme, active cooling is maintained via a centrifugal pump, and a radiator is used to dissipate the heat of the nanofluid. A FEM-based COMSOL software is used for 3D numerical simulation, and hardware validation is performed by indoor experimental research with varying solar insolation levels. The η enhancement of the proposed nanofluid-cooled PV/T system is tabulated in Table 6. For the complete analysis, the fluid inlet temperature, the cooling fluid flow rate, and ambient temperature are constant at 32°C, 0.5 L/min, and 25°C. Cherif et al. [74] proposed a TiO_2-water-nanofluid-cooled hybrid PV/T system, as presented in Fig. 8. A comparative analysis of the proposed scheme is performed with a rectangular channel via the 1^{st} and 2^{nd} Laws of thermodynamics. In this, the water-TiO_2 nanofluid is placed under the PV module, and the reduction in temperature is 19.4°C for the PV/T system with $H = 3$cm if the daily surface temperature is 64.6°C. They also briefed the method for obtaining the optimized height H of the cooling reservoir under fully developed laminar flow and force convection heat transfer with a rectangular cross-section, and the analysis is shown in Tables 6 – 8. In [75], mono and hybrid nanofluid-cooled sheet and tube-based PV/T systems have been investigated. In this numerical assessment, CuO/water and CuO+Fe/water (50:50) and base fluid's different velocities (0.02-0.08 m/s) have been investigated via ANSYS Fluent 18.2 software. Examine the heat transfer capability, three-dimensional geometry such as absorber plate, serpentine channel, and solar cell are considered. A conclusion has been made that the enhancement in the velocity of inlet fluid positively impacts the thermal η but enhances the pressure drop.

TABLE 6. H enhancement by nanofluid [73].

Cooling fluids	H		
	Electrical	Thermal	Overall
Water	11.82%	72.02%	83.84%
Water/MWCNT	11.96%	75.69%	87.65%
H enhancement	0.14%	3.67%	3.81%

The optimum enhancement in thermal and electrical η for $\varphi = 2\%$ for hybrid nanofluid is 5.4% and 2.14% compared to a water-cooled system, wherewith nanofluid, these values are 3.33% and 1.32%, respectively. The investigated mono and hybrid nanofluid properties are shown in Table 9. Marcelo and Laura [76] have briefed nanofluid spectral filtering-based PV/T systems. They studied three solar power plants: hybrid Si-based, purely thermal parabolic trough, and hybrid GaAs-based. Their results showed that the Levelized energy cost is minimum for a purely thermal parabolic trough of $17.83 \not\subset /kWh$ for a solar multiple of 2.5, and for a solar multiple of 3, it is $14.50 \not\subset /kWh$.

Sardarabadi et al. [77] briefed on the impact of silica/water nanofluid on hourly varying exergy and energy η. The authors have benchmarked the effect of 1% and 3% weighted nanofluids and performed a comparative analysis with PV panels and water-cooled PV/T systems. They concluded that the maximum exergy η is obtained via a 3 wt% silica/water nanofluid. In [78], water-cooled PV/T system-based reverse osmosis (RO) desalination system for off-grid, minor and remote communities are proposed and depicted in Fig. 9. In this, a higher amount of power is produced at lower cell temperature, and RO has more freshwater at higher water temperature. The PV/T system is cooled by RO feed water, which warms the water. Simulation, as well as experimental analysis, is performed to validate the proposed scheme. Sardarabadi et al. [79] proposed a liquid/PCM cooled PV/T system that simultaneously uses PCM and fluid for the cooling, as revealed in Fig. 10. They perform a comparative analysis of the proposed system experimentally with traditional

TABLE 7. Average daily results of 1st law [74].

G_T and $H = 3 - cm$								
T_{cell}(°C)	T_{outlet}(°C)	η_{pv}(%)	η_{ther}(%)	η_{pvt}(%)	$E^{"}_{elc}\,(W/m^2)$	$E^{"}_{ther}\,(W/m^2)$	$E^{"}_{pvt}\,(W/m^2)$	$G_T\,(W/m^2)$
44.9	41.94	13.8	30.38	44.18	126.52	278.63	405.15	918.3
G_{reff} and $H = 3 - cm$								
44.9	41.94	13.8	37.51	51.31	102.46	278.63	381.09	743.82

TABLE 8. Average daily results of 2nd law [74].

G_T and $H = 3 - cm$										
ε_{pv} (%)	ε_{ther} (%)	ε_{pvt} (%)	$E^{"}_{x\,elec}\,(W/m^2)$	$E^{"}_{x\,ther}\,(W/m^2)$	$E^{"}_{x\,pvt}\,(W/m^2)$	$E^{"}_{x\,sun}\,(W/m^2)$	$E^{"}_{x\,elec}Q\,(W/m^2)$	$E^{"}_{x\,loss}\,fric\,(W/m^2)$	$E^{"}_{x\,loss}\,pvt\,(W/m^2)$	$S_{gen\,tot}\,(W/K.m^2)$
14.57	0.88	15.46	126.52	7.8	134.32	869.51	699.6	2.72×10^{-9}	699.6	2.28
G_{reff} and $H = 3 - cm$										
11.8	0.88	12.68	102.48	7.8	110.28	704.3	723.64	2.72×10^{-9}	723.64	2.36

TABLE 9. Mono and hybrid nanofluid's properties [75].

Velocity	$f = \frac{64}{Re}$		$Re = \frac{\rho.V.D}{\mu}$		$a_t = \frac{k}{\rho.c_p} \times 10^{-7}$	
	mono	hybrid	mono	hybrid	mono	hybrid
0.02	0.30	0.39	211.30	163.65	1.55	1.69
0.03	0.20	0.26	316.95	245.47		
0.04	0.15	0.20	422.60	327.29		
0.05	0.12	0.16	528.25	409.12		
0.06	0.10	0.13	633.90	490.94		
0.07	0.08	0.11	739.55	572.77		
0.08	0.08	0.10	845.20	654.59		

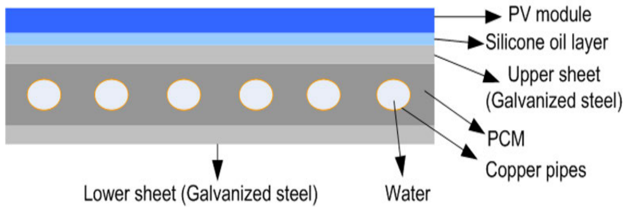


FIGURE 10. Nanofluid/water/PCM cooled PV/T system [79].

PV modules and PV/T systems. They used working fluids such as water, ZnO/water nanofluids, and PCM as organic paraffin wax. They noted that traditional PV/T systems, PV modules, and nanofluid/PCM-cooled PV/T systems had optimized thermal-electrical output energy. The exergetic performance evaluations of these systems were compared and tabulated in Table 10, concluding that the PCM/nanofluid cooled PV/T system provides optimal exergy performance.

Like [79], Hosseinzadeh et al. [80] studied a PCM/nanofluid-cooled PV/T system via experimentation and investigated the entropy generation of the system with energy and exergy analysis. The authors have concluded that the highest overall exergy (13.61%) and energy (65.71%) are obtained with the proposed cooling compared to the nanofluid-cooled PV/T system. Furthermore, they also concluded that via the proposed cooling media, the entropy generation is reduced by 3.19% compared to standard PV modules and by 1.62% compared to the nanofluid-cooled PV/T system. In [81], the authors briefed the nanofluid-cooled CPV/T system and investigated the impact of pipe diameter and length, glazing in both turbulent and laminar flow regimes. They detailed that by the concentration ratio enhancement, in laminar flow, total energy η enhances, and there is an optimized concentration ratio in the turbulent flow where total exergy η maximizes. They noted that installing a glass cover negatively affects overall η under both flow regimes. Aberoumand et al. [82] briefed the impact of the Ag/water nanofluid-cooled PV/T system experimentally by considering various flow regimes as turbulent, transient, and laminar. Authors have made the cooling media with the concentration of 2 wt% and 4 wt% via the electrical explosion of the wiring scheme. They demonstrated that enhancing the engagement of nanofluid and moving toward a turbulent flow regime enhances η. In [83], the authors have briefed Al_2O_3/methanol nanofluid cooled PV/T system experimentally. The optimized nanofluid filling ratio and concentration by considering thermal and electrical output. A conclusion has been made that 12.8%

TABLE 10. Exergy performance in [79].

Exergy of the system (W/m²)	PV	Liquid/PCM cooled PV/T		Liquid-cooled PV/T	
		Nanofluid	Deionized water	Nanofluid	Deionized water
Thermal exergy output	0	9.11	7.37	4.35	4.21
Input exergy (Sun)	845.42	845.42	845.42	845.42	845.42
Electrical exergy output	92.16	104.4	103.99	99.63	99.23
Total exergy output	92.16	113.51	111.36	103.98	103.44
Overall exergy η (%)	10.9	13.42	13.17	12.29	12.23

TABLE 11. **Fluid-cooled PV/T systems.**

Ref.	PV type	System investigated	Experimental/numerical	Cooling media	Keynote
[52]	Triple-junction cells	Linear triangular receiver with tough parabolic concentrator	Numerical assessment	Water	Enhancement of fluid mass flow and receive length enhances exergy η.
[53]	Triple-junction cells	High-concentrating PV/T cogeneration plant	Numerical assessment	Water	Authors have concluded that to optimize the proposed plant for a specific location, a 10 MW PV/T power plant is investigated from an exergetic point of view.
[54]	Polycrystalline silicon	Flat plate PV/T	Numerical assessment	Water	Optimization is performed based on the exergy phenomenon; the exergy η of the proposed work is compared to the previous work.
[57]	Silicon cells	PV/T and CPV/T	Numerical assessment	-	System optimization via non-concentrated and concentrated radiations; By optimum working fluid, the PV module accepts 84% of visible light and 89% of infrared radiation is absorbed by the thermal unit.
[58]	Crystalline silicon	Beam split CPV/T system	Numerical assessment	Water	Conversion of visible light and infrared radiation separately into electricity and heat Stabilized and high thermal and electrical energy η at various solar insolations; Enhancing total exergy η via enhancing radiation intensity.
[59]	Polycrystalline PV cells	Flat plate PV/T	Numerical assessment	Water	An optimal inlet temperature optimizes exergy η; Finding optimal inlet water temperature.
[60]	Monocrystalline silicon	Flat plate PV/T	Both	Water	Investigation of exergy η of the considered system At the mass flow rate of 0.002 kg/s, optimum exergy η of the proposed system occurs.
[62]	Semi-transparent PV module	PV/T-CPC	Numerical assessment	Water	Evaluation of exergy of PV/T-CPC for continuous temperature; By the enhancement of constant collection temperature, overall exergy η enhances.
[63]	Polycrystalline silicon	Flat plate PV/T	Numerical assessment	Water	Optimal mass flow rate and several pipes that optimize exergy η: Positive impact of packing factor, solar insolation, and collector length on exergy η.
[70]	Polycrystalline silicon	Flat plate PV/T	Numerical assessment	TiO_2/water, Al_2O_3/water, Al_2O_3/EG-water	Under the laminar flow, utilization of nanofluids is more impactful compared to turbulent flow; Total exergy η enhances under laminar flow, while no meaningful change occurs under turbulent flow.
[71]	Silicon and GaAs cells	CPV/T system	Numerical assessment	Ag/water	Compared to double pass channels, a separate channel configuration has enhanced performance; Overall, η of Si and GaAs cells is enhanced due to enhancing volume fraction.
[72]	Single – crystalline silicon	CPV/T system	Numerical assessment	Ag/water , CNTs/water	Nanofluid-cooled PV/T system gives higher performance than a water-cooled PV/T system; CO_2 emission is reduced due to nanofluid cooling.
[73]	Polycrystalline silicon	CPV/T system	Both	Water/MWCNT	Implementation of cooling media via the development of a novel heat exchanger design Assessment of proposed cooling-based PV/T in terms of output power, thermal energy and overall η.
[74]	Monocrystalline silicon	Flat plate PV/T	Numerical assessment	TiO_2/water	The proposed coolant is circulated via a rectangular channel; A novel methodology is proposed to obtain the height of the heat exchanger with a rectangular cross-section.
[75]	Monocrystalline silicon	Sheet and tube-based PV/T	Numerical assessment	CuO+Fe/water, CuO/water	Investigation of hybrid and mono nanofluid cooled PV/T system Using hybrid nanofluid as cooling media, the overall performance specifications of the PV/T system are enhanced.

TABLE 11. ***(Continued.)*** **Fluid-cooled PV/T systems.**

[77]	Monocrystalline silicon	Flat plate PV/T	Experimental assessment	SiO$_2$/water	Effect of nanofluid cooling on the investigation of system performance Using proposed nanofluid cooling, a higher overall η is achieved.
[78]	-	PV-powered reverse osmosis (PV/RO)	Both	RO feed water	Cooling PV panels by RO feed water can enhance water production by RO; Cooling PV panels and warming RO feed water enhance the electrical output and water flow rate.
[79]	Monocrystalline silicon	Nanofluid/PCM-PV/T	Experimental assessment	ZnO/water	Fabrication, designing and investigation of PCM/nanofluid-cooled PV/T; Proposed cooling gives the enhanced overall η compared to traditional PV and PV/T systems.
[81]	Polycrystalline silicon	CPV/T with parabolic trough	Numerical assessment	TiO$_2$/water	Under both flow regimes, parametric variations impact the performance of CPV/T; an optimal concentration ratio enhances overall η; the Adverse impact of glazing on total exergy η.
[82]	Monocrystalline silicon	Flat plate PV/T	Experimental assessment	Ag/water	Investigation of exergy and energy η of proposed nanofluid cooled PV/T system; Exergy η enhanced by increasing nanofluid concentration and moving toward the turbulent regime.
[83]	Single – crystalline silicon	PV/T with wickless heat pipes	Experimental assessment	Al$_2$O$_3$/methanol	Impact analysis is performed on the PV/T system for nanofluid cooling; Via the proposed cooling media, overall η is improved compared to methanol cooled PV/T system.
[84]	GaAs and crystalline silicon	CPV/T system	Numerical assessment	Au/Duratherm S, ITO/Duratherm S	Parametric investigation of spectral splitting of CPV/T system With GaAs system gives enhanced exergy η compared to a system with Si cell.

average exergy η and 40% average energy η at the optimum condition are enhanced compared to traditional PV/T systems. A nanofluid-cooled PV/T system's 2D model via a nanofluid spectral filter is demonstrated in [84]. A comparative analysis has been performed of two decoupled and coupled CPV/T systems. They obtained 36% exergy η for the decoupled system and 19.3% for the coupled system. A vivid discussion of fluid-cooled PV/T systems is tabulated in Table 11.

V. PCM-COOLED PV/T SYSTEM

In various phases and materials, thermal energy can be reserved. Thermal energy is stored as a changing phase of materials as a solid → liquid, or liquid →, gas. Liquid to gas is the state in which PCMs store energy [85]. Enhancing the η of the solar system via PCMs is briefed in [27]. The PCM source's critical task is removing additional heat from the PV panel and maintaining the constant optimized temperature of the panel. In the initial stage, the transmitted heat from the board to the PCM makes the PCM temperature rise. PCM absorbers the latent heat at the melting temperature, not changing the temperature during the phase variation, and only acquires energy. The period of phase variation and the temperature at which it takes place depends on the thermal conductivity, mass, and characteristics of every element used to enhance PCM heat transfer. In [86], nanofluid and nano-PCM cooled PV/T system is investigated via artificial neural network as depicted in Fig. 11. In Reference [87], the authors have briefed the optimization of electrical and thermal η of PV/T system via PCMs and thermos-conductive filters. Novel PCMs such as BWCO with paraffin (PBWCO) are introduced. Upgrade the thermal conductivity; terephthalic acid powder (TPA) is mixed with PBWCO. Thermal and electrical η at optimal conditions is depicted in Table 12. Different models of PV/T collectors with PCM are investigated in [88]. Four prototypes such as back side insulation (PVT-1), PVT-1 with PCM (PVT-1 + PCM), back side insulation with frontal cover (PVT-2), and PVT-2 with PCM (PVT-2 + PCM), are investigated in this. The results did not show an excellent thermal enhancement, but nice dissemination of heat was produced.

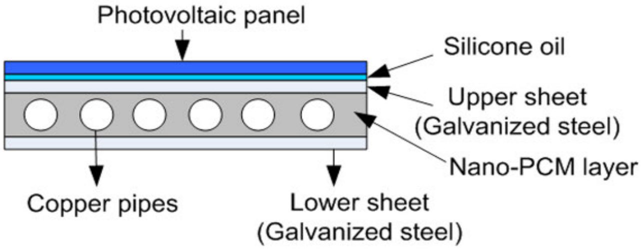


FIGURE 11. **Nanofluid, nano-PCM cooled PV/T [86].**

Reference [89] passive thermal management of PV modules via multiple PCMs is investigated. The study demonstrates the utilization of various PCMs with different

TABLE 12. **Thermal and electrical η at optimal condition [87].**

Specifications	Lower bound	Upper bound	Destination	Optimal value
Fractional weight of TPA in TPA/PBWCO	3	9	In range	8.489%
Fractional weight of BW in BWCO	25	75	In range	40.022%
Fractional weight of BWCO in PBWCO	12.5	37.5	In range	36.903%
PCM weight (kg)	2.6	3.6	In range	3.253
Thermal η	35.2	89.54	Maximum	
Electrical η	9.86	14.71	Maximum	14.884

TABLE 13. **Effect of multiple PCMs [89].**

Arrangement	% Charge time (↑)	Charge time (min)	% Energy charge capacity (↑)	Energy charge capacity (kJ)
1-PCM layer	00.0	93	0.0	226.3
2-PCM layer	14.0	106	2.3	231.5
3-PCM layer	18.3	110	3.4	233.8

melting temperatures that give higher thermal management in PVs. The arrangement of PCMs is such that their melting points are reducing in nature along the direction of heat flow. The numerical analysis shows that the PCM melting time is enhanced by up to 18%, and PV thermal management increases by up to 33%. The effect of multiple PCMs on energy charge rate and charging time is depicted in Table 13. Performance assessment and the thermal regulation of hybrid PV/T systems via nano-enhanced PCMs are briefed in [90]. Various combinations of nanomaterials and different PCMs are employed to overcome the increased temperature of the PV/T system. When paraffin wax is utilized as PCM, the temperature of PV panels reduces from 41% to 12%. Infiltrated PCM in PS-CNT foam-cooled PV/T system is investigated in [91]. Solar insolation variations for experimental performance are considered 800-1700 W/m^2. The best PV/T system studied in this work is the PV-PCM hybrid system, with energy η in active cooling falling under 66.8-82.6%.

Thermal and electrical performance assessment of PCM cooled PV/T system is investigated in [92]. In this investigation, primary, electrical, and thermal efficacies decreased. During the pump, the period from 30.4% to 16.8%, 4.8% to 3%, and 19.6% to 5%, their average values are 17.6%, 4%, and 7.1%, respectively. The optimal primary energy η of the proposed system is 10.7% and 7.9% higher than PT-CPC and separate PV-CPC, respectively. The experimental investigation of PV systems with PCM as the cooling media is demonstrated in [93]. A comparative analysis of three methods has been performed: traditional PV panel, double absorber plate with water-cooled, and water-based PV/T with PCM. In the double absorber plate, the PV panel is linked to the top of the absorber plate, and the other absorber plate is connected with a copper pipe. For cooling, paraffin wax RT-30 PCM is utilized, whose property is depicted in Table 14. It is concluded that the electrical η of water-based PV/T PCM is more significant compared to traditional PV. The average enhancement in electrical η is 300% in PV/T PCM and 230% in water-cooled PV/T compared to conventional PV panels at 0.031 kg/sec mass flow rate of water. They also noted that the PV module's temperature without the application of cooling media was more remarkable than the ambient temperature, with an optimum temperature of 85°C throughout the day. Two sides serpentine flow-based PCM cooled PV/T system has been briefed with exergy, energy, and economic assessment in [94]. In this, a large amount of heat is stored in a PCM-cooled PV/T collector. Lauric acid is used as PCM with the leak-proof aluminium packet and kept around the channel. 250 W, 60 cell-polycrystalline solar panels are selected for the analysis with different flow rates between 0.5 – 4 liters per minute. The optimal power output is 160.3 W at a mass flow rate of 4 LPM, which is 14 % greater than the reference value. They also concluded that the proposed scheme benefits the household family by using a solar water heater.

An experimental evaluation of nanofluid and nano PCM-cooled PV/T systems has been investigated in [95]. In this study, nano-SiC is mixed with a tank filled with paraffin wax to enhance thermal conductivity; the water and nano-SiC mixture pass in a copper tube. A comparative analysis of the proposed scheme has been done with a PV plate, and the water tank is cooled via water; also, the wax tank is cooled via water. The obtained results demonstrated that the proposed scheme reduces the PV cell's temperature more than another scheme during peak time. The reduction in temperature was 17°C during the peak time (12:00 PM – 2:30 PM). The proposed method gives enhanced thermal energy (37.84% more than a water tank cooled with water) that may be utilized in many other applications. They concluded that their proposed scheme has higher thermal and electrical η than any PV/T system investigated. A unique PVT loop heat pipe (PVT-LHP) via a novel PCM heat storage exchanger has been briefed in [96]. A parametric assessment has been done to investigate the performance of various parameters such as air temperature, solar insolation, wind speed, micro-channel heat pipes, packing factor of PV cell, glazing cover, and water mass flow rate. It was concluded that enhancement of ambient temperature, solar insolation, micro-channel heat pipe number, cover number, and packing factor was good for the system, and increment in wind speed and mass flow rate of cold water were unfavorable for the system performance. Operating conditional impact on the performance assessment of PV/T – PCM has been demonstrated in [97]. In this, a 3D numerical benchmarking is performed via COMSOL multi-physics software and is assessed at various volume flow rates of 0.5 LPM – 3 LPM at ambient temperature and inlet water temperature at 27°C with 1000 W/m^2 solar insolation.

The experimental analysis is performed in indoor weather conditions and with passive cooling of the PV module. The maximum power of the PV module is 305 W, and the open-circuit voltage and current at the optimum power point are 30.6 V and 8.17 A, respectively. A paraffin group

TABLE 14. **Paraffin wax RT-30 properties [93].**

Properties of paraffin wax RT-30	
Melting point (°C)	28
Thermal conductivity ($Wm^{-1}K^{-1}$)	0.2
Heat of fusion ($kJkg^{-1}$)	222
Density ($kg\ m^{-3}$)	1.8 ($liquid$)
	0.87 ($solid$)
	0.76 ($liquid$)
Specific heat capacity ($kJkg^{-1}K^{-1}$)	2.4 ($solid$)

material, A44-PCM, is utilized for the investigation. The optimal cell temperatures are 82.9°C and 82.4°C; 74.59°C and 71.05°C; 69.13°C and 67°C for PV, PV/T, and PCM cooled PV/T systems experimentally and numerically, respectively. The highest overall η for PV/T – PCM and PV/T is obtained as 83.59% and 89.6%, respectively.

Real-time benchmarking with a numerical assessment of PCM cooled PV/T system is proposed in [98]. A 3D FEM-numerical analysis via COMSOL Multiphysics under solar insolation 200 W/m^2 – 1000 W/m^2 with a fixed mass flow rate of 0.5LPM and 32°C temperature of inlet water is utilized for the analysis. The experimental setup with the cross-sectional view of the PV/T system is diagrammatically represented in Figs 12 (a) and (b). Output temperatures for PV/T – PCM is 38.14°C at 200 W/m^2 and 59.76°C at 1000 W/m^2 for numerical analysis and 38°C at 200 W/m^2 and 58.1°C at 1000 W/m^2 for the experimental research. Enhancing the performance of PV panels via PCM is briefed in [99]; in this study, computational fluid dynamics modelling is performed. The buoyancy term in the momentum conversation equation of Navier-Stokes is changed via an additional term when PCM is solid. For the validation, velocity fields and isotherms are computed and compared with the experimental setup. The authors have concluded that adding PCM on the backside of PV could maintain the temperature of less than 40°C for constant solar insolation of 1000 W/m^2. One of the significant limitations of this study is that the impact of sky temperature is not considered for the numerical analysis due to difficulty in experimentation. The enhancement of PV performance via yellow petroleum jelly as PCM contained in a rectangular aluminium tube and connected to the backside of the PV panel has been briefed in [100]. The lower PV temperature manages higher power production. The average η and power for PV on-stand and PV on-roof are 6%, 7.3%, 21.2%, and 22.6%, respectively. A conclusion has been made that the proposed cooling is more suitable for the BIPV system.

PCM-cooled building-integrated concentrated PV has been demonstrated in [101]. Paraffin wax-based RT42 as PCM is utilized for the cooling media. A highly collimated light source at 1000 W/m^2 is considered for indoor experimentation. The effectiveness of PCM increases as the insolation increase by $1.15\%\ at\ 500\ W/m^2, 4.20\%\ at\ 750\ W/m^2$ And $6.80\%\ at\ 1200\ W/m^2$. The experimental analysis demonstrates that the PCM can contribute to the effective thermal management of the BICPV system. Enhancement of electrical η via PCM as cooling media is investigated in [102]. The work focuses on experimental evaluation and simulation analysis via TRNSYS software. A comparative study has been done with and without PCM on the PV cell temperature. The optimal and average enhancement of electrical η was calculated via TRNSYS software. A case study on BIPV with thermal storage has been performed in [103]. Parametric analysis and numerical assessment of PCM cooled PV system are briefed in [104]. The considered parameters in this study are thermal conductivity, enthalpy of fusion, melting temperature, solar insolation, and mass flow rate. The range of parameters is chosen based on properties of PCM that are commonly available in the market. A 3D model of PV/T – PCM was simulated via the CFD method, and a transient solver was used to solve the numerical equations. The authors have concluded that the enhancement of coolant mass flow rate 30 kg/h – 70 kg/h reduces the percentage of melted PCM by 48.9% - 43.1%, while the enhancement of solar insolation as 600 W/m^2 – 1000 W/m^2 increases the share of melted PCM as 0% - 64.9%. Water-saturated microencapsulated PCM (MEPCM) as colling media of the BIPV system is investigated in [105]. A CFD numerical simulation is used to access the impact analysis of the MEPCM layer's thickness and PCM's melting points on the performance of PV/T. The results demonstrated that MEPCM cooled BIPV system significantly enhanced electrical and thermal performance criteria compared to the untreated PV module.

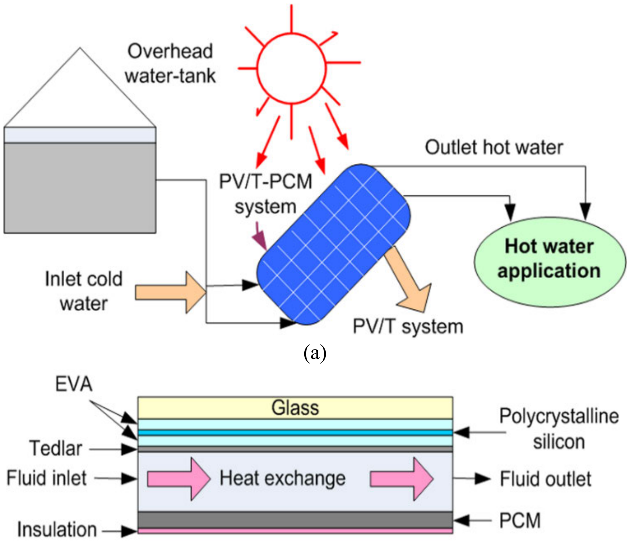


FIGURE 12. **(a) Experimental setup (b) cross-sectional view of PV/T system [98].**

A double water-saturated MEPCM-cooled water surface floating PV/T system is investigated in [106]. The results showed that the proposed cooling enhances the thermal and electrical η of the PV system. Compared to untreated PV modules, 3-cm thick lower MEPCM and 3-cm thick top MEPCM with melting points 26°C and 30°C, respectively, enhance the power generation by 1.48%. A thermoelectric generator (TEG) may be used to soak the additional heat

TABLE 15. PCM-cooled PV/T systems.

Ref.	PV type	System investigated	Experimental/numerical	Cooling media	Keynote
[86]	-	Nano-PV/T PCM system	Both	Nanofluid and nano-PCM	To validate the experimentation, three artificial neural networks, MLV, SVM, and SOFM, are implemented; Compared to traditional PV, nanofluid and nano-PCM improve the electrical current from 3.69A to 4.04A and η 8.07% to 13.32% To.
[87]	Monocrystalline silicon	CPV/T system	Experimental assessment	PBWCO and TPA with PCM	The mixture of TPA remarkably enhances the cooling system to PBWCO; The obtained thermal and electrical η at an optimum point is 90.76% and 14.88%.
[88]	Polycrystalline silicon	Photovoltaic thermal panels	Experimental assessment	PCM	Experimental analysis of different PVT collectors with energy performance is done; In between glazing and unglazing structures, electrical generation change is minimal, but a huge difference in thermal performance.
[89]	Polycrystalline silicon	Multi PCM cooled PV/T system	Numerical assessment	PCM	In a comparative analysis of multiple PCMs and single PCM cooled PV/T systems Via multiple PCMs, melting time was enhanced by up to 18%, and energy charge capacity increased by up to 3.4% compared to single PCM.
[90]	-	Hybrid PV/T system	Numerical assessment	Nano-enhanced PCM	Four types of nanoparticles and four kinds of PCMs are utilized; the Thermal regulation of the PV panel is enhanced by inserting a PCM layer between the PV panel and the cooling channel.
[91]	Polycrystalline silicon	-	Experimental assessment	Paraffin PCM	To enhance the thermal conductivity of PCM, infiltration is performed via a particular type of heat conductive foam (PS-CNT foam); Proposed cooling can minimize the PV temperature to 6.8% and enhances electrical η up to 14%.
[92]	Monocrystalline silicon	Compound parabolic concentrator PV/T	Experimental assessment	PCM	Simultaneous improvement of thermal and electrical η via PCMs and Compound parabolic concentrator; At the time of melting, the non-uniform distribution is improved via PCM application.
[93]	Monocrystalline silicon	Outdoor PV/T	Experimental assessment	Water with paraffin wax RT-30 as PCM	The experimental assessment was performed with mass flow rates of 0.013 kg/sec, 0.023 kg/sec., and 0.031 kg/sec. With thermal and electrical η evaluations.
[94]	Polycrystalline silicon	Outdoor PV/T	Numerical assessment	Lauric acid as PCM	Different volume flow rates of 0.5 – 4 LPM are used to obtain the optimal system performance; the Optimal thermal η of 87.72% is obtained at 2 LPM, and the optimal electrical η is obtained at 4 LPM with 11.08%.
[95]	Polycrystalline silicon	Outdoor PV/T	Experimental assessment	Nanofluid and paraffin wax PCM	The maximum energy gained by the proposed scheme was 72% greater than the PV/T cooled with PCM-water; The fluid flow rate was 0.17 kg/s, electrical η was 7.1% - 13.7%, and the thermal η reached 72%.
[96]	Polycrystalline silicon	-	Numerical assessment	PCM	The proposed scheme's thermal, electrical, and overall η is 55.6%, 12.2% and 67.8%, and may obtain 28% greater overall energy and 2.2 times greater performance than a traditional system.
[97]	Polycrystalline silicon	Indoor PV/T	Both	PCM	Optimal electrical η of PV/T system is achieved as 12.28% and 12.4% experimentally and numerically, respectively, the same for PV/T – PCM is 12.59% and 12.75%, respectively; Electrical performance enhancement is 12.75% and 12.91% experimentally and numerically.
[98]	Polycrystalline silicon	Outdoor PV/T	Both	Paraffin wax A44 PCM	Reduction in PV cell temperature of 12.6℃ and 10.3℃ is obtained from PV module via proposed cooling media; Optimal electrical η as 13.56% and 13.72% for PV and 13.74% and 13.85% for PV/T experimentally and numerically; For PV/T – PCM electrical η is obtained as 13.87% and 13.98% experimentally and numerically.

TABLE 15. ***(Continued.)*** **PCM-cooled PV/T systems.**

[99]	-	-	Both	PCM	A parametric study has been done on the PV panel's temperature presented by a flat aluminum plate.
[100]	Monocrystalline silicon	BIPV system	Experimental assessment	Yellow petroleum jelly as PCM	Experimental comparative analysis was performed via 2 monocrystalline panels, as one panel utilizes PCM, and the other does not operate PCM; the Average power and energy enhancement for on-roof PV are 22.6% and 21.2%.
[101]	Polycrystalline silicon	Building integrated concentrated PV	Experimental assessment	Paraffin wax RT42 as PCM	With PCM, relative electrical η enhances by 7.7%; the Average reduction in PV module temperature is 3.8°C; the Effectiveness of the proposed scheme varies with varying solar insolation.
[102]	Monocrystalline silicon	Outdoor PV/T system	Both	PCM	The PV surface temperature difference with and without PCM is 35.6°C; Electricity production via the proposed scheme is 7.3% higher in a year.
[104]	Monocrystalline silicon	-	Numerical assessment	PCM	Enhancement in PCM's melting temperature from 40°C to 65°C and surface temperature enhancement from 51.53°C to 58.78°C also minimizes the melted PCM temperature from 82.7% to 9.6%; Thermal conductivity enhances the thermal and electrical η.
[105]	-	BIPV system	Numerical assessment	Microencapsulated PCM	In winter, the maximum PV surface temperature was 26.7°C and the minimum electrical η of 19.846% for untreated PV cells. In summer, the highest surface temperature was 38.5°C, and the lowest electrical η was 18.784%.
[106]	Polycrystalline silicon	-	Numerical assessment	Microencapsulated PCM	The untreated PV has an optimum surface temperature of 32.6°C and electrical η of 19.46%; In winter, the proposed cooling media enhances the lowest temperature of PV.
[107]	Polycrystalline silicon	Outdoor PV/T system	Experimental assessment	Cobalt oxide nanofluid and PCM	The novel system with six cooling media as 0.25%, 0.5% and 1% nanofluid flow, 1% nanofluid flow with PCM and finally, PCM with Al_2O_3 powder was assessed via experimentation.

generated on the surface of the PV module. The process of heat soaking is performed via the capitalization of the temperature difference between the two sides. The concept of PV-TEG is schematically represented in Fig. 13 [22]. An experimental investigation of cobalt nanofluid and PCM-cooled PV/TEG system has been briefed in [107]. The authors have utilized six TEG components connected to the aluminium sheet at the backside of the PV module. The CO_2O_4/water nanofluids are prepared with various volumes to obtain the optimal condition, while PCM is enhanced via Al_2O_3. The authors have concluded that the exergy η is improved by 11.6% while using the proposed cooling media. Using CO_2O_4/water nanofluids enhances the produced electrical power compared to water. The overall electrical η is improved by 4.52% via PCM and 1% nanofluid. A vivid literature review of the all-discussed PCM-based cooling media of the PV/T system is summarized and tabulated in Table 15.

VI. DISCUSSION AND RECOMMENDATIONS

Based on the rigorous review, this section deals with the vivid discussion and future directions for the heat extraction methodologies of PV/T systems. The PV/T systems have not been widely and commercially spread, yet they have proven successful in enhancing electricity production from PV modules and have provided excess heat that can be utilized for other applications. To date, selecting a specific type of PV/T system is a very tough task for researchers. In this presented review paper, various references have been vividly reviewed, which worked assiduously to minimize the temperature of the PV panel, enhance electrical production, and take advantage of its additional heat for other applications. Table 16 shows the comparative analysis of the reviewed cooling media of PV/T systems. However, after this rigorous review, authors have concluded that nanofluid as cooling media provide better results than air or water as cooling media.

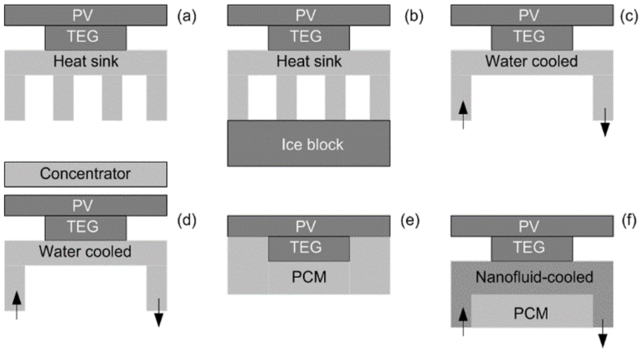


FIGURE 13. **PV-TEG (a) heat sink (b) heat sink with ice block (c) water-cooled heat sink (d) concentrator with water cooling (e) PCM cooled (f) Nanofluid with PCM cooled [22].**

Moreover, the inculcation of PCM into the PV/T system enhances heat storage and transfer stability. This enhancement can be further improved by adding nanoparticles with

TABLE 16. Comparative analysis of various cooling media.

System	Critical benefits	Critical shortcomings	Future scope	Applications
Air-cooled PV/T	✓ Reduced bulkiness. ✓ Suitable for BIPVT system. ✓ Well developed technology. ✓ Working medium (air) abundantly and freely available. ✓ No corrosion risk.	✓ Low heat capacity of air. ✓ For air circulation, fans/blowers are required. ✓ Not suitable for many applications.	✓ Adequate airflow duct design (multi-inlet type. ✓ Selective glazing. ✓ Improvement of heat transfer coefficient of air side. ✓ Uni laminated system. ✓ To avoid fans or blowers, utilization of natural ventilation system. ✓ For BIPV systems. ✓ Large scale installation. ✓ Assessment for long duration in sunlight.	✓ Space heating. ✓ Solar dryers. ✓ Industrial process heating.
Water-cooled PV/T	✓ Easy to operate. ✓ Nice and developed technology. ✓ Other liquids for cooling can be used. ✓ Suitable for various end usages.	✓ Availability of cooling media (water). ✓ Rusting of absorber/tedlar due to continuous use. ✓ Power loss in auxiliary pumps. ✓ In cold climatic conditions, freezing of water occurs. ✓ Difficulty in water channel cooling. ✓ Higher weight/surface area. ✓ Lesser system life. ✓ Risk of corrosion and leakages.	✓ Effective design of absorbers. ✓ Utilization of different thermic liquids. ✓ Large-scale system design. ✓ Assessment of flow dynamics for enhanced cooling. ✓ Assessment for long duration in sunlight. ✓ Uni laminated system. ✓ A cooling tower is used in tropical and hot regions to cool the inlet water.	✓ Space heating. ✓ Domestic water heating. ✓ Laundries ✓ Pool heating. ✓ Sanitation in industries, hotels, hospitals etc. ✓ Feed water preheater for power plants. ✓ Desalination.
PCM-cooled PV/T	✓ Enhanced system performance. ✓ Various PCM is available commercially. ✓ The system may work in off-sunshine hours.	✓ PCM adds cost to the system. ✓ Start-up stage for technology.	✓ Enhancement in thermal conductivity of PCM. ✓ PCM-based PV/T system for a longer time in sunlight. ✓ Development of novel PCM and its containers.	✓ Like water cooled PV/T system. ✓ Thermal storage for various applications.
Nanofluid-cooled PV/T	✓ Enhanced nanofluid technology with various nanoparticles. ✓ The improved thermal output of the system.	✓ Technology is in its initial stage. ✓ Sedimentation of nanoparticles.	✓ Impact of sizes, types, and shapes of nanoparticles. ✓ Enhancement of novel combinations of base fluids and nanomaterials.	✓ Like water cooled PV/T system.
Thermoelectric generator	✓ No direct contact of PV with coolant. ✓ Enhanced thermal storage. ✓ Higher heat gain.	✓ Technology is in its initial stage. ✓ Expensive PV materials. ✓ All solar cell materials are not suitable. ✓ Higher operating temperature. ✓ Immature technology. ✓ Filter glasses are expensive. ✓ Risk of structural damage.		✓ Use of transparent plastic glazing. ✓ Improvement in receiver design. ✓ Reduction of weight of the system. ✓ Development of novel solar cell suitable for elevated temperature.

higher thermal conductivity. Some critical observations and recommendations are listed as follows:

- ➢ The η of a traditional PV system is exceptionally low and falls in the 7% - 19% [108], [109], [110]. By inculcation of the cooling media in traditional PV panels, the electrical η is enhanced and reaches the range of 50% - 80%.
- ➢ Much research has been performed via a nanofluid-cooled PV/T system. However, it is necessary to point out that nanofluid is utilized to extract heat to enhance the η without using the collected thermal energy.
- ➢ To assess the optimal PV/T efficiency, thermal and electrical efficiencies must be added if they appear simultaneously. But it is observed that some researchers add the optimal thermal and electrical efficiencies even though they are not obtained simultaneously. It is suggested to calculate the optimal η at a particular time for both thermal and electrical for proper comparison and evaluation.
- ➢ It is required to analyze exergy for thermal and electrical aspects, which various conducted research miss.
- ➢ The utilization of nanoparticles in nanofluid is costly, yet the addition of these surface-active agents for stability is required. Moreover, the y to change the nanofluid frequently enhances the overall cost. Few conducted research missed the cost assessment. It is recommended to provide a cost assessment for PV/T systems.
- ➢ To date, researchers have not agreed to choose a specific type of material to form nanofluid as cooling media for PV/T systems.
- ➢ The larger diameter of nanoparticles corresponds to higher exergy and energy flow in the turbulent state, while the situation is reversed in the laminar flow state.
- ➢ In the back portion of the PV panel, adding a thin film of PCM provides good heat extraction, but to date, no specific type of PCM has been chosen for all PV/T applications.
- ➢ Most theoretical and practical analyses have concluded that nanofluids and nano-PCM cooled PV/T systems provide optimal η and performance. However, not all researchers have agreed to select a specific type of PCM, nor have they agreed on establishing nanofluids for PV/T applications.
- ➢ Using nanofluid in PCM enhances the power output and produces voltage difference and thermal η twice.
- ➢ In all the reviewed articles, researchers have claimed a significant enhancement in heat extraction from PV panels and that this excess heat may be utilized in various applications. In a few considered conditions, the thermal η of PCM and water-cooled PV/T systems may reach as high as 90%. This conclusion is highly suitable for cold regions, but for sunny regions like areas of the middle east, which is a highly needed area for PV/T systems, the authors have not seen researchers' interest in heat extracted via cooling media from PV cells and the applications that can be used. We recommend exploring these areas.
- ➢ It is recommended to calculate the impact of cooling and heating cycles on overall latent heat and heat transfer of nanofluid and nano-PCM.
- ➢ It is recommended to analyze the long-term nanofluid circulation impact on its stability and thermophysical properties. The same research is required for a nano-PCM-cooled PV/T system as well.
- ➢ It is not recommended to use reflectors in PV panels without the cooling system, as further temperature rises will occur.
- ➢ Valuable research for the optimization of the parameters affecting thermal and electrical efficiencies and geometry of the PV/T systems needs to be explored.

VII. CONCLUSION

The purpose of PV/T system is to recover heat and improve the efficiency of solar cells. This study gives a vivid analysis of the field of heat extraction of the PV/T systems via research activities performed in the last decade. Exergy and energy aspects are vividly considered in this review article. The exergy η increases with reducing ambient temperature and increasing solar insolation. The energy η is enhanced via glazing the PV/T systems but reduces the exergy η. Among several types of cooling media for PV/T systems, air-cooled, water-cooled, and nanofluid-cooled PV/T systems have gained more attention. Moreover, by analyzing the literature published in the field of exergy, the thermoelectric-driven cooling performance of PV/T systems has obtained the least attention. It must be mentioned that thermoelectric devices are gaining much attention nowadays, and several research is presently dealing with the energetic assessment of thermoelectric-PV integrated devices.

From the rigorous review it is noted that in the air-cooled PV/T system, optimal air channel depth, optimal air inlet velocity, and optimal air collector length are present, which optimize the exergy η. The electrical η of PV/T systems enhances by water-cooled via copper finned tubes, water spray cooled, wet absorbent, via reflector and airflow in the optimal diffuser by 6%, 2%, 15%, 10%, and 20%, respectively. In a water-cooled PV/T system, optimal inlet water velocity, optimal mass flow rate, optimal pipe numbers, optimal inlet water temperature, and optimal pipe diameter are present to optimize exergy η. Enhancing the nanofluid concentration enhances the exergy η of nanofluid-cooled PV/T systems. The liquid PCM-cooled PV/T systems provide enhanced η compared to liquid-cooled PV/T systems. Moreover, PCM-cooled PV/T systems provide 15-23% higher electrical η than PV panels. Compared to single and dual fluid cooling, the electrical η of the PCM cooling system is more elevated.

Using nanofluids as cooling media in micro-channels, spiral channels, and direct channels enhanced the electrical η by 27%, 37.67%, and 20.55%, respectively. Thermal η of PCM cooled PV/T system for different PCMs such as capric acid, uric acid, and nanofluid/nano-PCM were calculated as 69.84%, 90%, and 72%. The utilization of nanofluid in PCM enhances the power output, voltage difference, and thermal η by twice. Finally, it is concluded that thermal η is directly associated with the number of channels and increases with enhancing channel output area. For future prospect of heat extraction methodologies, the exergoeconomics analysis must be included. Exergoeconomics i.e., exergy costing, means the inculcation of economic analysis with exergy analysis, which is missing in this study. Hence, it must be the future scope of the work to investigate these items from an exergoeconomics viewpoint in future studies.

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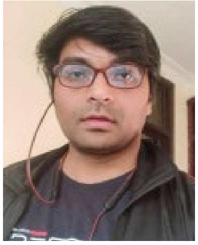

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