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FROM THERMAL ACCUMULATION TO HYBRID REGULATION: A COMPREHENSIVE REVIEW OF COOLING STRATEGIES IN PHOTOVOLTAIC AND PV/T SYSTEMS

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Abstract. *Both Photovoltaic (PV) and Photovoltaic/Thermal (PV/T) systems still remain significantly affected by thermal energy storage since around 70–80% of the sunlight absorbed turns into heat and not electricity. This leads to overheating and reduction of the systems' efficiency under hot weather conditions. The current research paper seeks to provide a critical review of some of the latest findings concerning thermal management solutions for PV and PV/T technologies while building a framework that connects cooling approaches to thermo-electrical performance. For the purpose of the research, a systematic analysis and comparison of more than 60 scientific papers, especially those written within the years 2022-2025, are considered alongside basic studies on the cooling of PV/T systems. Passive cooling includes methods such as using Phase Change Materials (PCMs). Active cooling technologies include air, water, and nanofluid cooling. Finally, hybrid solutions that involve PCMs and enhanced convective heat transfer are also studied. Comparative analysis shows that passive cooling with PCMs is relatively simple and highly efficient in terms of thermal energy storage while active cooling with nanofluids allows reaching up to 20 degrees centigrade decrease in temperatures and up to 15% efficiency improvement. In turn, hybrid solutions allow obtaining even better thermo-electrical efficiency at high levels of irradiation, up to 80%, due to up to 25°C temperature drop achieved in experiments. Yet, several challenges need to be addressed: pumping losses, nanofluids stability issues, PCMs performance in cycles, etc.*

Keywords: *PV/T systems; Thermal Regulation; Cooling Techniques; PCM; Hybrid Cooling.*

1. INTRODUCTION

The increase in the need for electricity and environmental issues has resulted in the swift rise of renewable energy sources, with solar energy becoming prominent owing to its abundant availability and cost reduction [1]. By the close of 2022, the installed capacity of PV exceeded 1.18 TW, amounting to an average increase of 240 GW annually, and the PV technology has played a vital role in reducing CO_2 emissions [2], [3]. However, traditional PV panels only utilize less than 25% of the incoming solar energy and waste the rest as heat [4].To improve thermal regulation and recover part of the dissipated heat, photovoltaic/thermal (PV/T) systems have been developed by integrating thermal collectors with PV modules [5]. These systems produce electricity and useful thermal energy simultaneously, with reported overall efficiencies greater than 60% depending on the operating conditions and system configuration [6]. Under high irradiance conditions, PV cell temperature may exceed 60–70 °C, especially in hot climates [7], [8]. Limited heat dissipation, non-uniformity of irradiance, and restricted airflow further intensify temperature accumulation within PV modules [9]. Such temperature elevation negatively affects semiconductor performance and reduces electrical efficiency. For crystalline silicon PV modules, an increase of 1°C may reduce electrical efficiency by approximately 0.1–0.5% [10]. Hence, efficient cooling strategies are essential to enhance the performance of PV and decrease the thermal stress [11].

Table 1. Temperature Coefficients of Power for Common Photovoltaic Cell Technologies

Source	Reported efficiency loss	Temperature coefficient (%/°C)	Cell technology
[10]	Electrical efficiency	−0.40 to −0.50	Monocrystalline Si
[10]	Electrical efficiency	−0.40 to −0.50	Polycrystalline Si
[12]	Electrical efficiency	−0.35 to −0.38	a-Si thin-film
[12]	Electrical efficiency	−0.25	CdTe thin-film
[12]	Electrical efficiency	−0.32 to −0.36	CIGS thin-film

The temperature coefficients of power for common photovoltaic technologies are shown in Table 1. The reported values show the high thermal sensitivity of PV systems under outdoor operating conditions. Several cooling techniques have been proposed to improve the thermal performance of PV and PV/T systems, including passive cooling, active cooling, and hybrid thermal regulation techniques [13], [14], [15]. This review provides a critical and comparative assessment of recent PV and PV/T cooling technologies with emphasis on thermal regulation under high-temperature operating conditions. This review used a systematic approach that involved screening, classifying, and evaluating peer-reviewed articles based on passive, active, and combined cooling techniques, with a focus on thermoelectric efficiency, engineering considerations, and application possibilities.

2. REVIEW METHODOLOGY

This review was developed from a systematic screening and comparison of studies on photovoltaic (PV) and photovoltaic/thermal (PV/T) cooling technologies. The literature survey was carried out using the major scientific databases like Scopus, ScienceDirect, Web of Science, IEEE Xplore, SpringerLink and Google Scholar. The review was primarily centered on peer-reviewed studies published in the period 2022–2025, with selected earlier studies to support the fundamental background of PV/T cooling technologies. The search process involves keywords such as “PV/T cooling”, “phase change material cooling”, “nanofluid cooling”, “hybrid PV/T systems” and “thermal regulation of photovoltaic systems”. The selected studies were experimental, numerical and review investigations on the cooling performance, electrical efficiency, thermal efficiency and engineering limitations of PV and PV/T systems.

3. CLASSIFICATION OF COOLING TECHNIQUES FOR PV/T SYSTEMS

The development of photovoltaic/thermal (PV/T) systems has led to a wide variety of cooling configurations for PV/T applications. Many cooling methods are used in PV/T systems, which requires a systematic classification for facilitating coherent technical and comparative evaluation [16]. However, with the growth of research activities associated with PV/T systems and the development of new cooling techniques, several review studies pointed out the increasing need to classify the cooling methods instead of evaluating each case study individually [17]. The recent reviews also highlighted the need for classifying cooling techniques to allow comparative technical assessment under different environmental conditions particularly under high solar irradiance conditions [18].

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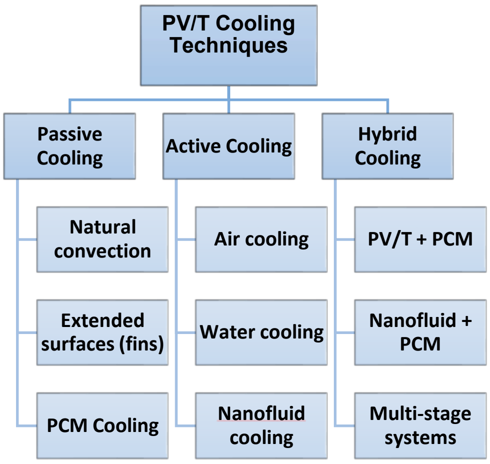

Fig. 1. Classification Framework of PV/T Cooling Techniques.

PV/T cooling technologies can be broadly classified into three categories: passive cooling, active cooling and hybrid cooling systems. Passive cooling systems employ natural heat dissipation mechanisms such as natural convection, extended surface cooling, and phase change materials (PCMs) without the use of external power [19]. Active cooling systems employ forced convection of coolants (e.g., air, water or nanofluids) to speed up the cooling process in comparison with natural convection [20]. Hybrid cooling systems employ two or more cooling mechanisms to enhance the reliability of the cooling system and the stability of the thermal regulation [21]. From an operational point of view, passive cooling systems refer to the reduction of the PV/T cell temperature by conductive, convective or latent heat absorption mechanisms for thermal relief depending on the environmental conditions [22]. Forced convection is employed in active cooling systems to improve heat removal, leading to better thermo-electrical energy harvesting compared to passive cooling methods [23]. Hybrid cooling systems have also been employed to enhance system stability and to improve temperature uniformity with respect to the individual cooling approaches [24].

Table 2 gives a general comparative overview of the three cooling categories.

Table 2. Comparative Classification of PV/T Cooling Strategies

Cooling Category	Operating Principle	Key Advantages	Main Limitations
Passive	Natural convection, conductive dissipation, or latent heat storage (PCM) without external power	Simple design, low operating cost, no auxiliary energy demand	Limited temperature control under high irradiance conditions
Active	Forced convective heat extraction using air, water, or nanofluids	Stronger thermal regulation, improved electrical performance, and controllable operation	Requires pumping or fan power, increased system complexity
Hybrid	A combination of passive storage and active forced convection mechanisms	Enhanced temperature uniformity, improved energy recovery, and better operational stability	Higher structural complexity and cost

In extending the aforementioned threefold categorisation scheme, the present review will first consider passive cooling methods, then active cooling techniques and finally hybrid cooling configurations, based on the general performance trends of these cooling approaches. This classification framework provides a systematic basis for evaluating PV/T cooling methods under high intensity solar operating conditions.

4. ACTIVE COOLING TECHNIQUES

4.1. ACTIVE COOLING AND ENERGY DEMAND

Active cooling in photovoltaic systems consists of the use of pumps or fans to produce forced convection of air or cooling fluids, which enhances the convective heat dissipation as compared to passive cooling systems [25]. Experimental and analytical studies have demonstrated the potential of active cooling for efficient reduction of the PV cell temperature and improvement of the electrical efficiency under different operating conditions [22]. However, active cooling systems require additional electrical energy to run pumps or fans, which has a direct impact on the overall system performance [25]. Therefore, the overall effectiveness of active cooling depends not only on the thermal and electrical enhancement, but also on the balance between the additional energy generated and the auxiliary energy required by the cooling components [22].

4.2. AIR-BASED COOLING

Air-based photovoltaic cooling systems are based on rear air channels for improved convective heat dissipation by forced airflow [26]. CFD optimization showed that increasing the air mass flow rate from 0.01 kg/s to 0.035 kg/s decreased the outlet air temperature from 328.76 K to 307.97 K [26]. The best thermal performance was obtained with 18 guides inclined at 45°, even though the pressure loss was higher [26]. These results indicate that there is a trade-off between improved heat transfer and increased aerodynamic resistance for air-cooled PV systems.. Experimental studies also demonstrated that the duct configuration has a considerable effect on the thermal performance [27]. The reported air temperature increase reached 5.76 °C, 9.94 °C, and 10.87 °C for single-duct systems, dual-duct systems without turbulators, and dual-duct systems with turbulators, respectively [27]. In addition, the thermal efficiency increased by 88.7%, while the overall efficiency improved by 54.2% using the single-duct configuration [27].

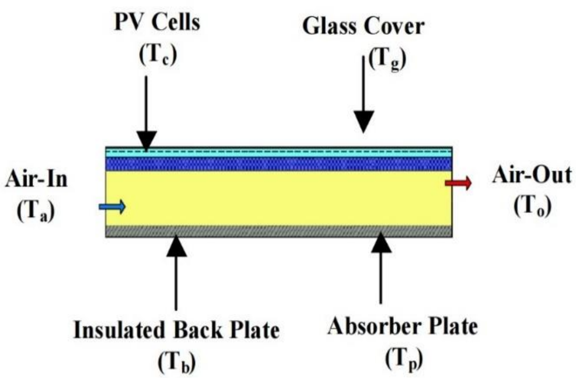

Fig. 2. Schematic Diagram of An Air-Based PV/T Cooling System Using Rear Forced Airflow [28].

4.3. WATER-BASED COOLING

Water-based cooling is considered as one of the most effective active cooling techniques for PV and PV/T systems because water has higher heat capacity and thermal conductivity in comparison to air [29]. Thus, water cooling improves heat removal from the rear side of PV modules and electrical stability [29]. In 2024, a comparative study proved that the combination of water channels at the back side of the PV modules improves the energy utilization efficiency by cooling the PV cells and improving electrical efficiency simultaneously [30]. The experimental investigations confirmed that the integration of backside cooling reduces the temperature gradients and thermal non-uniformity within the PV module [31]. A modified water-cooled tube design in 2025 increased the electrical efficiency from 16.13% for a standalone PV module to 17.57% for a PV/T system, while the overall efficiency reached 69.38% [32]. Another experimental study in 2025 demonstrated that improving hydraulic symmetry reduced the PV peak temperature from 62 °C to 43.7 °C and improved the electrical efficiency from 10.21% to 11.41% [33]. These results indicate that the cooling channel configuration and flow distribution have a significant effect on the thermo-electrical performance of water-based PV/T systems.

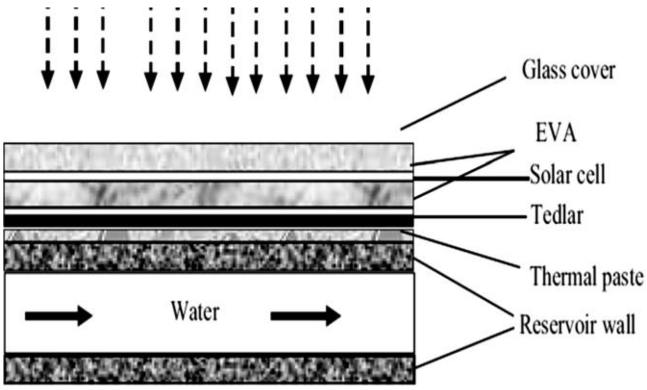

Fig. 3. Cross-Sectional Schematic of A Water-Based PV/T Cooling System [34].

Table 3. Quantitative Comparison of Air- and Water-Based Active PV/T Cooling Systems

Ref.	Cooling Type	System / Configuration	Operating Condition	Key Result
[26]	Air cooling	Air guides beneath PV module	CFD, 1 m/s airflow	Enhanced heat exchange and PV cooling
[27]	Air-based PV/T	Dual duct with semicircular turbulators	Outdoor experiment	ηoverall ↑ 54.2%
[32]	Water-based PV/T	Modified flat-contact cooling tubes	Experimental + numerical	ηe ↑ 17.57%; ηoverall = 69.38%
[33]	Water-based PV/T	16 parallel rear cooling tubes	Outdoor test, 48 L/h	Tpv ↓ 62→43.7 °C

4.4. *NANOFLUID-BASED COOLING*

The use of nanofluid-based cooling enhanced the thermal conductivity and convective heat transfer of PV/T systems, leading to a decrease in PV surface temperature and an increase in thermoelectric performance [35]. For the case of SiC/water nanofluid (0.5%), the electrical efficiency was improved by 25.3%, and the thermal efficiency by 98.6%, but the pumping power was flow regime dependent [36]. The use of Al_2O_3/water nanofluid (0.05% volume fraction, 0.07 kg/s) decreased the PV surface temperature by about 20 °C and improved the electrical efficiency by 15.5% [37]. Comparative studies with TiO_2, Al_2O_3, and ZnO nanofluids (0.5% volume fraction) demonstrated the best thermal performance for ZnO with a temperature drop of about 14 °C and an electrical efficiency enhancement of 4.7% [38]. Recent studies with MnO_2/water nanofluids (0.5–1.5 LPM) showed an electrical efficiency of 14.58% at PV surface temperatures ranging from 52–55 °C [39]. Similarly, hybrid MWCNT/ZnO nanofluids (0.2%) reduced the PV surface temperature by 16.6 °C and improved the thermal efficiency by 55.1%, while the overall system efficiency approached 60% with enhanced exergy performance [40].

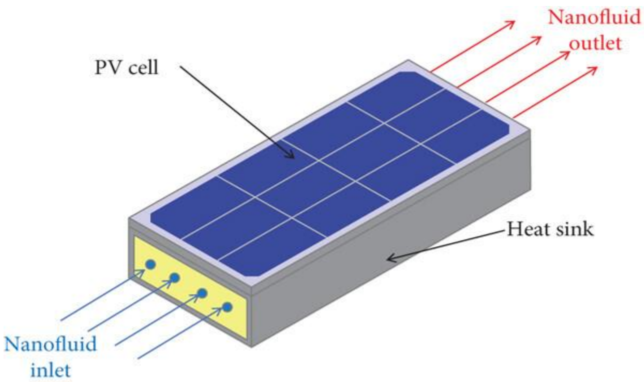

Fig. 4. Schematic Diagram of A Nanofluid-Based PV/T Cooling System [41].

Table 4. Quantitative Performance Comparison of Nanofluid-Based PV/T Cooling Systems

Ref.	Nanofluid	Conc./Flow Rate	Configuration	Key Result
[36]	SiC/water	0.5 wt.%	Experimental PV/T	ηth ↑ 98.6%; ηe ↑ 25.3%
[37]	Al_2O_3/water	0.05 vol.%, 0.07 kg/s	Serpentine outdoor PVT	Tpv ↓ 20 °C; ηe ↑ 15.5%
[38]	TiO_2, Al_2O_3, ZnO/water	0.5 vol.%	Rear rectangular/spiral HX	ZnO: Tpv ↓ 60→45 °C; ηe ↑ 4.7%
[39]	MnO_2/water	0.5–1.5 LPM	Experimental PVT + ML	ηe,max = 14.58%; R^2 = 0.96–0.97

4.5. *COMPARATIVE PERFORMANCE ANALYSIS*

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The comparative results demonstrate that the effectiveness of active PV/T cooling systems depends strongly on the cooling medium and flow configuration. Air-cooled thermal management systems are relatively simple and low-cost cooling means; but their cooling capability is limited by the limited thermal capacity of air and the increased aerodynamic drag with increasing velocity [26], [27]. Water-cooled thermal management systems offer more efficient solutions due to the high thermal capacity of water, but the efficiency is highly dependent on tube design, hydraulic, and backside thermal properties [29], [33]. Among the above-mentioned methods, nanofluid cooling is the best method for improving thermal enhancement, because the addition of nanoparticles increases the thermal conductivity and convection of the cooling medium [35], [39]. However, this thermal enhancement is usually accompanied by an increase in viscosity and power consumption. This means that the overall thermo-hydraulic effect should be considered, not just the cooling itself.

5. PASSIVE COOLING TECHNIQUES

5.1. CONVENTIONAL PASSIVE COOLING TECHNIQUES

Conventional passive cooling techniques for photovoltaic (PV) modules rely on natural convection and radiative heat dissipation without the need for external energy input [42]. Later, metallic fins were added to enhance the heat transfer but the cooling capability remained highly dependent on the ambient conditions and the natural heat transfer limits [43]. Experimental investigations further confirmed that the electrical efficiency of PV modules decreases when the temperature increases to about 48 °C compared to the standard operating conditions at 25 °C, demonstrating the thermal sensitivity of PV systems and the limited capability of conventional passive cooling only [44].

5.2. PCM COOLING

Phase Change Materials (PCMs) have been widely used as latent heat-based passive cooling strategies to reduce the temperature rise of PVs by absorbing heat during melting and releasing heat during solidification [45]. For crystalline silicon PV systems, a 1 K increase in temperature can decrease the electrical output by around 0.45%, and a 15 K increase can lead to an efficiency loss of about 7% [45]. In 2023, experimental studies showed that fin-assisted PCM configurations improved internal heat diffusion and phase uniformity, leading to a PV temperature reduction of 13.1 °C and an electrical efficiency improvement of 6.85% [46]. Another experimental implementation using RT-42 paraffin PCM reported that a 3 cm PCM thickness increased electrical power output by 15.8% compared to the reference PV module under similar outdoor conditions [47]. The thickness of PCM also plays a significant role in the charging time and thermal control in peak solar hours, as confirmed in the study [47]. The climatic studies in 2024 showed that the effectiveness of PCM is highly dependent on environmental conditions and phase cycling behaviour [48]. In hot regions, the complete melting-solidification cycles increase the annual energy generation by around 1.4–3%, while the incomplete phase cycling reduces the effectiveness of PCM in moderate climates [48]. The long-term thermal stability may also be affected by repeated melting-solidification cycles, especially in the case of organic PCM materials working outdoors continuously [49]. Further analytical assessments also revealed that the optimum choice of PCM depends on melting temperature (Tm), latent heat capacity (L), thermal conductivity (k), and cycling stability [49]. The thermal conductivity of most of the organic PCMs is less than 0.5 W/m·K, which hinders the heat

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diffusion unless techniques for conductivity improvement are adopted, e.g., metallic fins, graphite matrices, encapsulation, or porous metal foams [49].

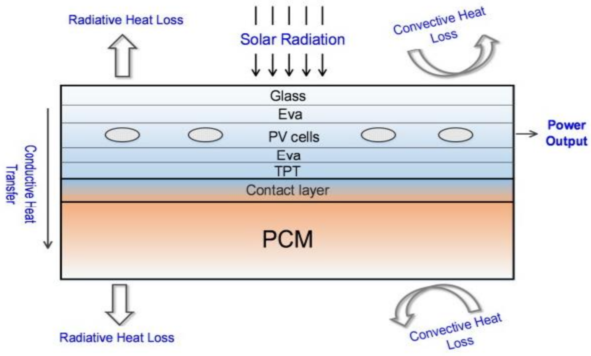

Fig. 5. Schematic Diagram Of Thermal Regulation With PCM-Integration In PV/T Systems [50].

Table 5. Thermophysical Properties of Selected Phase Change Materials (PCMs) for PV Thermal Applications

Ref.	PCM / Material	Tm (°C)	L (kJ/kg)	k (W/m·K)	ρ (kg/m³)
[45]	Soy wax	43.9–45.06	100.9–127.2	0.25–0.324	900
[45]	Paraffin	57–60.8	134.9–135.35	0.186–0.320	760–910
[45]	Beeswax	61.3–64.2	141.4–177	0.25–0.41	811–907
[47]	RT-42 paraffin	38–43	N/A	0.2	880
[48]	Paraffin/EG composite	41.5	177.7	2.7	950

Table 5 shows that most organic PCMs are in the common operating temperature range of PV modules but their low thermal conductivity is a major limitation which affects heat diffusion during charging. Comparative results also show that expanded graphite greatly enhances the thermal conductivity and thermal regulation ability of PCM.

Table 6. Summary of Experimental PCM-Based PV Cooling Investigations

Ref.	PCM Type	Integration Method	ΔT (°C)	Electrical Improvement
[45]	Beeswax	Rear passive PCM layer	8.2	ηe ↑ 0.94%
[46]	PCM + Al fins	Rear fin-assisted PCM container	13.1	ηe ↑ 6.85%
[47]	RT-42 paraffin	Rear PCM layer (3 cm)	—	Pele ↑ 15.8%

The comparison in Table 6 shows that fin-assisted PCM configurations offer better thermal regulation than traditional passive PCM layers, due to the enhanced internal heat diffusion and phase uniformity.

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Table 7. PCM Enhancement Techniques for PV Cooling Systems Validated Experimentally

Ref.	Enhancement Technique	Main Function	Reported Effect
[46]	Aluminum fins	Enhanced heat transfer within PCM	ΔT ↓ 13.1 °C
[47]	PCM thickness optimization	Increased latent heat storage capacity	Pele ↑ 15.8%
[48]	Expanded graphite composite PCM (EG-PCM)	Increased thermal conductivity (k)	Annual power generation ↑ 1.4–3%
[49]	Metal foams / graphite matrices	Enhanced PCM thermal conductivity	Improved heat-transfer performance

Table 7 indicates that the PCM cooling performance depends strongly on the heat transfer enhancement techniques, not only on the PCM selection. Enhanced thermal conductivity and optimised PCM geometry significantly improve the thermo-electrical performance and temperature regulation in PV cooling applications.

6. HYBRID COOLING SYSTEMS IN PV/T APPLICATIONS

6.1. *THERMODYNAMIC BASIS OF HYBRID THERMAL REGULATION IN PV/T SYSTEMS*

Hybrid cooling methods in PV/T systems are mainly aimed at combining latent heat storage with advanced convective heat transfer to improve thermal regulation under high solar irradiation. In these systems, phase change materials (PCM) store excess thermal energy during peak operating periods, thereby reducing transient temperature fluctuations and delaying rapid PV temperature rise [51]. At the same time, nanofluids raise the convective heat dissipation due to their high thermal conductivity and heat transfer ability in comparison with conventional cooling fluids [52]. The synergistic effect of latent heat storage and nanofluid cooling enhances the thermo-electrical stability and improves the overall energy recovery capability of PV/T systems [53]. Outdoor studies also supported the high influence of the operating conditions, coolant flow stability and environmental changes on the thermal efficiency of hybrid systems under real climatic environments [54].

6.2. HYBRID PCM–NANOFLUID COOLING CONFIGURATIONS

The integration of nanofluid cooling with PCM has been demonstrated to possess better thermal regulation capability than conventional passive or single-fluid cooling methods in PV/T systems. Experimental investigations showed that Al_2O_3/TiO_2 nanofluids integrated with PCM thermal storage significantly reduced PV operating temperature and improved electrical efficiency under controlled solar conditions [55]. Nano-enhanced PCM structures were additionally reported to improve thermal conductivity and accelerate melting behaviour within PV/T thermal regulation systems [56]. Hybrid configurations employing rGO/H_2O nanofluids, serpentine geometries, and paraffin PCM further enhanced thermo-electrical performance through improved heat extraction capability [57]. Significant thermal enhancement was also achieved using SiC nanofluids integrated with nano-PCM, twisted tapes, and micro-fin tubes [58]. Hybrid TiO_2–Fe_2O_3 nanofluids additionally improved thermal, electrical, and exergy performance because of enhanced heat transfer characteristics within serpentine-tube PV/T systems [59]. Numerical investigations employing MWCNT nanofluids with fin-assisted PCM structures demonstrated improved melting behaviour and enhanced thermal regulation under different flow conditions [60]. Other hybrid nanoparticle-integrated PCM structures further improved thermal transport

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behaviour and PV electrical performance [61], [62]. Outdoor investigations additionally confirmed that dual-fluid and NePCM–nanofluid cooling systems effectively reduced PV peak temperature and improved overall PV/T thermo-electrical performance under realistic climatic conditions [63], [64]. Overall, hybrid PCM–nanofluid cooling systems provide more stable thermal regulation and higher energy recovery capability than conventional PV/T cooling approaches; however, their performance remains strongly dependent on nanoparticle stability, hydraulic losses, flow conditions, and long-term thermo-hydraulic operating requirements.

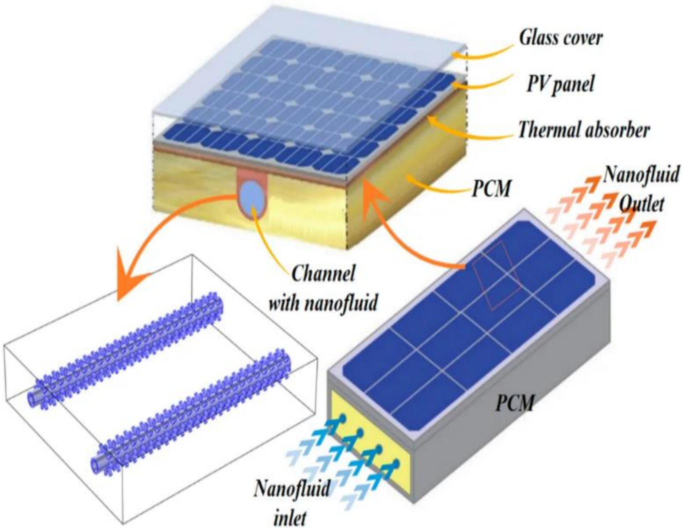

Fig. 6. Schematic Diagram of A Hybrid PV/T Cooling System Integrating PCM And Nanofluid Circulation [65].

Table 8. Quantitative Performance Comparison of Hybrid PV/T Cooling Systems

Ref.	Hybrid Configuration	Main Thermal Result	Electrical / Overall Performance
[55]	Al_2O_3/TiO_2 nanofluid + PCM	PV temperature reduced by ~25%	ηe improved by ~10.3%
[56]	Nano-enhanced PCM	Improved thermal conductivity	Faster melting response
[57]	rGO/H_2O nanofluid + PCM + serpentine geometry	PV temperature reduced by 21.55 K	ηth ≈ 69.2%
[58]	Nano-enhanced PCM + SiC nanofluid + twisted tape	Enhanced thermal dissipation	ηth = 83.3%; electrical power +44.5%
[59]	TiO_2–Fe_2O_3 hybrid nanofluid	Improved thermo-electrical performance	ηe = 12.62%
[60]	MWCNT nanofluid + PCM + fins	Improved melting characteristics	Enhanced electrical performance
[61]	MgO–Al_2O_3 hybrid nanoparticles + PCM	Enhanced thermal transport	PV efficiency increased to 24%
[62]	Hybrid MgO/MWCNT nanofluid + PCM	Reduced PV surface temperature	Improved overall energy efficiency
[63]	Dual-fluid nanofluid PV/T system	Enhanced thermal management	PV/T efficiency ≈ 85%
[64]	NePCM–nanofluid cooling system	Peak PV temperature reduced by 25.7 °C	ηth = 40–70%

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6.3. COMPARATIVE ANALYSIS AND ENGINEERING TRADE-OFFS

Hybrid PV/T cooling systems can enhance thermal management by incorporating latent heat storage and upgraded convective heat transfer mechanisms. Nano-enhanced PCM structures improve thermal conductivity and heat storage behaviour while geometry-assisted configurations with serpentine channels, twisted tapes, fins and micro-fin tubes intensify heat extraction and thermo-electrical performance in PV/T systems [56] – [60]. The hybrid nanofluids enhance the thermal and exergy performance further due to their higher heat transfer ability than that of the conventional cooling fluids [59]. Outdoor investigations also confirmed that NePCM and dual-fluid nanofluid systems provide more stable thermal regulation under realistic climatic conditions [63], [64]. However, hybrid PV/T systems are still faced with hydraulic losses, nanoparticle stability issues, need for PCM containment and increased structural complexity. Therefore, the practical use of hybrid cooling systems depends on finding an optimal trade-off between thermal enhancement, operational stability, hydraulic performance and long-term system reliability.

7. COMPARATIVE ANALYSIS AND DISCUSSION

The comparative evaluation of PV/T cooling systems should consider thermo-electrical performance, auxiliary energy demand, complexity, maintenance, and climatic suitability rather than relying only on individual efficiency values. The results summarized in Tables 3, 5, and 8 indicate that cooling performance strongly depends on the thermal regulation mechanism and operating conditions. Passive PCM-based systems provide simple thermal regulation with low operational requirements. However, their performance is limited by the low thermal conductivity of PCM materials under high solar irradiation conditions. Nevertheless, passive configurations achieved electrical efficiency enhancement approaching 15.8% under optimized conditions. Active cooling systems (water or nanofluids) can offer additional temperature reduction and better convective heat transfer than passive systems. Active cooling decreased PV temperature by about 20 °C and improved electrical efficiency by more than 15% under similar irradiance ranges. Nanofluid systems also enhanced thermal conductivity, but increased viscosity and auxiliary pumping requirements at higher concentrations. The best thermo-electrical performance was achieved for the hybrid PV/T systems due to the combined effects of latent heat storage and enhanced convective heat transfer. Under similar operating conditions, the hybrid systems reduced the PV peak temperature by up to 25.7 °C while the overall efficiency reached 84%. Hybrid configurations also improved the thermal stability under fluctuating solar irradiation conditions. However, despite the advantages, hybrid systems are still related to hydraulic losses, nanoparticle stability, PCM containment needs, and higher system complexity. Hence, the best PV/T cooling approach is a matter of balancing thermal enhancement, operational stability, economic viability, and climatic suitability.

Table 9. Multi-Criteria Evaluation Framework for PV/T Cooling Systems

Cooling Technique	ΔT Reduction	ηe Enhancement	ηth / ηoverall	Auxiliary Energy	Complexity	Maintenance	Scalability
Passive Cooling (PCM)	Moderate	Moderate	Moderate	Very low	Low	Low	High
Active Cooling (Water/Nanofluid)	High	High	High	Moderate	Moderate	Moderate	Moderate
Hybrid Cooling (PCM + Nanofluid)	Very high	Very high	Very high	High	High	High	Moderate

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The multi-criteria evaluation demonstrates that hybrid PV/T systems provide the highest thermo-electrical performance under severe thermal loading, whereas passive and active systems remain more practical for moderate climatic and operational conditions.

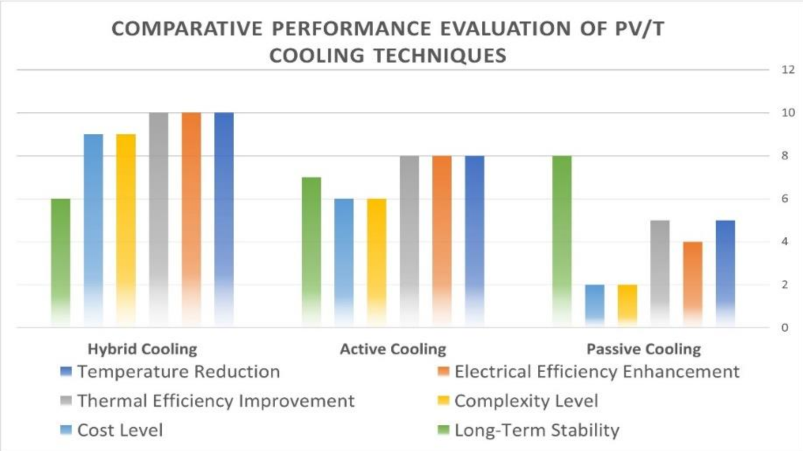

Fig. 7. Comparative Performance Evaluation of Passive, Active, And Hybrid PV/T Cooling Techniques

8. CHALLENGES, RESEARCH GAPS, AND FUTURE DIRECTIONS

8.1. TECHNICAL CHALLENGES

Although hybrid PV/T systems have high thermo-electrical performance, several technical limitations remain. The thermal response and heat diffusion of PCM-based systems are limited by their low thermal conductivity. While nano-enhanced PCM improves conductive heat transfer, it also increases system complexity. Nanofluid cooling systems improve convective heat transfer and PV/T performance; however, higher nanoparticle concentrations may increase viscosity and auxiliary pumping power. In addition, long-term nanoparticle stability during cyclic operation remains insufficiently validated outdoors. Hybrid nanofluid-PCM systems are more effective in temperature regulation than the individual cooling methods but they are still prone to hydraulic losses, nanoparticle agglomeration, PCM containment issues and more complex structure. Thus, practical implementation depends on the balance between thermal enhancement, operational reliability and energy consumption.

8.2. RESEARCH GAPS

Although PV/T cooling technologies have been developed rapidly, some important research gaps still exist. Direct comparison between studies is problematic because of the lack of standardised testing procedures; irradiance levels, flow rates and operating conditions vary widely. Furthermore, the long-term durability of nanofluids and nano-enhanced PCM systems has not been well validated, particularly under repeated thermal cycling and outdoor conditions. In addition, the assessment of the overall system efficiency often neglects auxiliary pumping power and hydraulic penalties. Long-term outdoor validation studies are still rare compared to laboratory-scale studies. The scalability of hybrid PV/T systems is still unclear, with most studies being performed on small-scale systems. Moreover, techno-economic analysis and optimisation of the cost-performance are still under-explored in the existing PV/T literature.

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8.3. FUTURE DIRECTIONS

Future studies are recommended to standardise testing procedures for PV/T cooling systems to ensure consistent comparison. More work is required to improve the long-term stability of nanofluids and reliability of thermal cycling under real outdoor conditions. Further studies are needed to optimise the nanoparticle concentration and flow conditions in order to minimise the hydraulic penalties and the auxiliary energy consumption. Large scale outdoor investigations are also required to assess the scalability and operational durability of hybrid PV/T systems. Finally, the future development of PV/T should integrate the thermo-hydraulic optimisation with techno-economic and life-cycle analysis to make sure that hybrid cooling systems are practical and commercially viable.

Table 10. Prioritized Research Gaps and Future Directions for Hybrid PV/T Systems

Priority	Research Gap	Main Challenge	Suggested Future Direction	Expected Impact
1	Standardization	Difficulty in cross-study comparison	Develop unified testing protocols	Reliable benchmarking
2	Long-term stability	Nanoparticle degradation and agglomeration	Long-duration outdoor validation	Improved operational reliability
3	Pumping penalties	Increased auxiliary energy consumption	Optimize flow regime and concentration	Balanced net efficiency
4	Outdoor validation	Limited realistic climatic assessment	Multi-season field monitoring	Realistic performance evaluation
5	Scalability	Limited large-scale implementation	Pilot-scale PV/T investigations	Practical deployment potential
6	Cost-performance analysis	Uncertain economic feasibility	Integrate techno-economic assessment	Commercial viability
7	Thermal cycling reliability	PCM degradation during repeated cycles	Cycling-stability investigations	Improved long-term durability

9. CONCLUSIONS

Under high solar irradiation conditions, thermal management has a strong influence on the thermo-electrical performance of PV and PV/T systems. Passive PCM based cooling offers a simple solution for thermal buffering with low operation requirements. However, the effectiveness of such solutions is still restricted by the low thermal conductivity of PCM materials. The active cooling systems with water and

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nanofluids provide better convective heat transfer and temperature reduction than the passive ones. Active cooling in similar operating conditions lowered PV temperature by about 20 °C and improved electrical efficiency by over 15%. However, the auxiliary pumping power and the hydraulic penalties should be considered for the overall system performance. The configurations tested showed the best thermo-electrical performance for hybrid PV/T systems with latent heat storage and enhanced convective heat transfer. The maximum PV temperature was reduced to 25.7 °C for hybrid systems and the overall efficiency reached approximately 84% at optimised conditions. Hybrid systems, however, still have higher structural complexity, stability of the nanoparticles and higher maintenance requirements. The best PV/T cooling strategy is a compromise on thermal enhancement, operational robustness, economic viability and climatic suitability. The future development of PV/T should focus on long-term operational reliability, techno-economic feasibility, and scalable outdoor demonstration.

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