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Review of Thermal Management, Techno-Economic and Environmental Sustainability of Photovoltaic Thermal Systems with Bibliometric

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Abstract: Photovoltaic thermal (PVT) systems have emerged as a promising solution for enhancing overall energy efficiency by simultaneously generating electricity and heat, addressing the performance limitations of conventional photovoltaic modules operating under elevated temperatures. This study reviews thermal management strategies, techno-economic feasibility, and environmental sustainability of PVT systems through a comprehensive bibliometric and technical analysis. A systematic approach was employed, integrating bibliometric mapping of global research trends with a detailed classification of thermal management technologies, including air cooling, water cooling, nanofluids, phase change materials (PCMs), heat pipes, and refrigerant-based systems. The review further examines cost performance trade-offs and life-cycle environmental impacts to evaluate the viability of large-scale implementation. Results indicate that advanced cooling approaches particularly nanofluid-enhanced systems and PCM composites effectively improve thermal conductivity and stabilize module temperatures, enabling combined electrical and thermal efficiencies exceeding 85% and, in some hybrid configurations, approaching 94%. Techno-economic assessments reveal that optimized system designs and integration with heat pumps can lower the levelized cost of energy and shorten payback periods, while environmental evaluations demonstrate reductions in carbon footprint and energy payback time. Despite these advantages, challenges persist regarding material stability, cost, and end-of-life recyclability. This study highlights the need for integrated optimization frameworks that account for energy, exergy, and life-cycle impacts. Future research should prioritize cost-effective nanomaterials, AI-driven control strategies, and advanced hybrid configurations to accelerate commercialization and support global decarbonization efforts.

Keywords: Thermal management; Techno-economic; Environmental; Sustainability; Bibliometric

1 Introduction

Thermal management of photovoltaic thermal (PVT) systems has gained significant attention and innovation, primarily driven by the growing demand for higher energy efficiency and improved performance of solar technologies. PVT systems simultaneously generate electrical and thermal energy, helping to mitigate the efficiency losses associated with the temperature-dependent performance of traditional photovoltaic (PV) modules. Lowering the operational temperature of PV modules not only enhances electrical efficiency but also produces usable thermal energy for various applications [1, 2]. A range of innovative approaches has emerged to improve thermal management in PVT systems. One notable advancement is the use of nanofluids as cooling media. Nanofluids engineered liquids containing nanoparticles exhibit superior thermal conductivity and heat transfer performance compared to conventional fluids. Numerous studies have reported significant improvements in PVT system performance when nanofluids are employed, owing to their enhanced ability to extract heat from PV modules [3]. By effectively reducing module temperatures, nanofluid-based cooling systems can substantially increase electrical efficiency [4].

Moreover, the architectural design of PVT systems, including airflow dynamics and channel configurations, plays a crucial role in thermal management. By employing dual- or multi-inlet designs, researchers have reported enhanced heat dissipation, thereby improving overall system performance. Such designs enable better air circulation and thermal stratification, which contribute to lower PV module temperatures and improved electrical output [5]. In addition to nanofluids and intelligent controls, the exploration of phase change materials (PCMs) offers another frontier in thermal management strategies. PCMs can absorb and release energy, helping stabilize the PV system's temperature across varying daily thermal profiles. These materials not only mitigate potential overheating but also improve energy recycling in PVT systems, thereby maximizing both thermal and electrical outputs [6].

This paper provides a comprehensive review of PVT systems by integrating three critical dimensions: thermal management strategies, techno-economic viability, and environmental sustainability, supported by a bibliometric analysis. The study begins by mapping global research trends and influential contributions through bibliometric techniques, offering insights into the evolution and future directions of PVT technology. It then systematically classifies thermal management technologies, such as passive cooling, active cooling, and hybrid approaches, and highlights their impact on system efficiency and operational reliability. Furthermore, the review delves into techno-economic assessments, evaluating cost-performance trade-offs, scalability, and market competitiveness, while also addressing environmental implications, including carbon footprint reduction and resource optimization. By combining quantitative bibliometric data with qualitative technical and sustainability perspectives, this paper serves as a holistic reference for researchers, policymakers, and industry stakeholders aiming to advance PVT systems toward sustainable energy solutions.

2 Bibliometric Approach

The Boolean search strategy combines key terms to identify relevant studies on PVT systems. It includes variations such as "photovoltaic thermal," "PV/T," and "PVT system," as well as "hybrid photovoltaic thermal," paired with concepts related to thermal management, such as heat dissipation, cooling techniques, and temperature control. Additional terms focus on performance outcomes, including efficiency improvement, energy yield, and thermal performance. To maintain relevance, the search excludes unrelated topics such as solar home systems, standalone PV, and concentrated solar power (CSP).

Data mining was conducted on December 2, 2026, using the Scopus database with the keyword "Thermal Management of Photovoltaic Thermal Systems." The initial identification process yielded 496 records. These records were carefully filtered to remove duplicates and entries that were not relevant to the research theme, resulting in 160 refined data points. This filtering ensured that only high-quality and relevant sources were considered for further analysis. From the refined dataset, 28 articles met the inclusion criteria, aligning with trending keywords such as thermal conductivity, heat transfer enhancement, and energy efficiency.

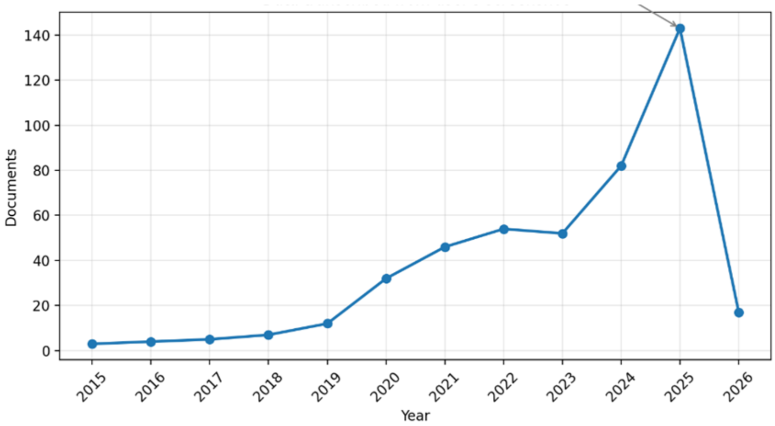

Figure 1. Number of documents by year indexed in Scopus

Figure 1 illustrates the annual document output in Scopus using the keyword query "Thermal Management of Photovoltaic Thermal." The trend from 2015 to 2026 shows clear growth: single-digit publications from 2015–2018 transition to steady expansion through 2019–2023, followed by an uptick in 2024 (82 documents) and a pronounced peak in 2025 (143 documents). The sharp drop in 2026 (17 documents) is likely due to the partial-year data effect rather than a genuine decline. This trajectory aligns with broader PVT bibliometric evidence indicating accelerated growth since the 2000s, with compound annual growth rates around 16% across PVT literature and expanding research topics ranging from performance modeling to integration and control.

The search covered publications from 2015 to 2026, and all available articles published in 2026 up to the date of data collection were included. To ensure consistency and avoid issues related to translation accuracy, the review was limited to English-language publications. This selection strategy ensured that the final dataset represented the most recent, relevant, and accessible body of research on thermal management technologies in PVT systems. The initial dataset comprised 74.2% journal articles, 12.1% conference papers, 11.9% reviews, 1.4% book chapters, and 0.2% conference reviews. These selected studies provide a strong foundation for exploring advancements in thermal management strategies for PVT systems as shown in Figure 2.

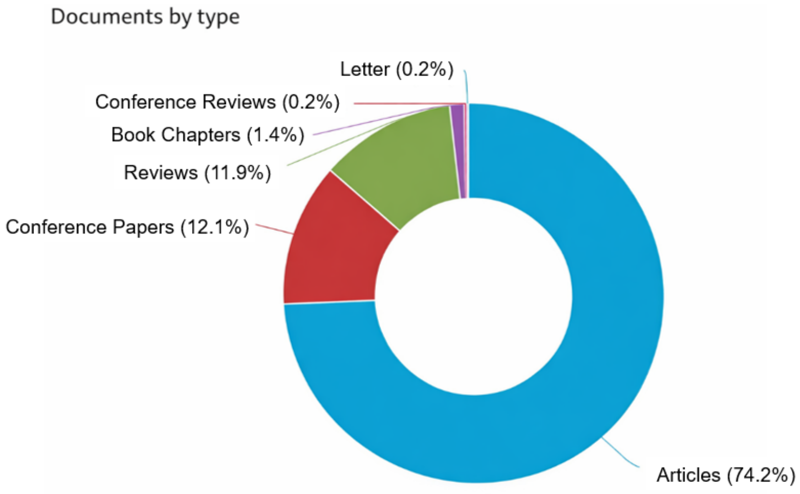

Figure 2. Percentage of different types of documents in Scopus

Eligible studies must address thermal management techniques for PVT systems, including passive and active cooling approaches, heat transfer mechanisms, and design modifications to control PV module temperature. Research that evaluates both thermal and electrical performance through experimental analysis, numerical simulations, case studies, or review articles will be considered. Publications from reputable sources such as peer-reviewed journals, conference proceedings, theses, and institutional reports are also included. The exclusion criteria: if they focus solely on conventional photovoltaic systems without thermal integration, or on solar thermal collectors without electrical generation. Research related to unrelated solar technologies, such as CSP or standalone PV systems, will not be considered. Non-technical publications, including news articles, editorials, commercial content, or papers lacking data on thermal performance or cooling techniques, are also excluded.

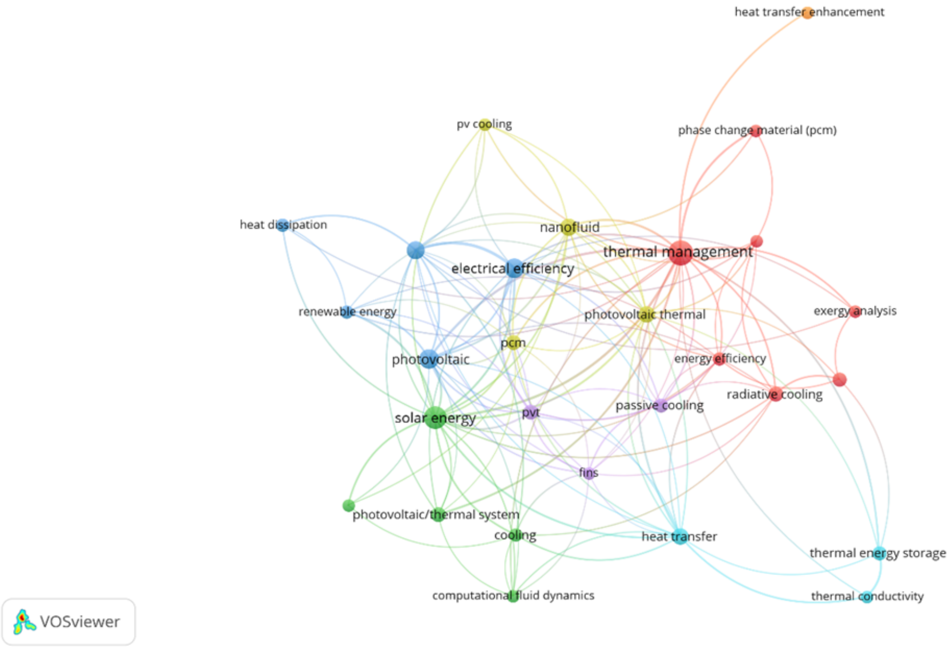

Figure 3. Network visualization

Figure 3 presents the network visualization generated in VOSviewer. In VOSviewer, a keyword co-occurrence map positions terms so that shorter distances indicate stronger relatedness, while colours represent clusters identified by the VOS (association-strength) normalization and layout algorithm. This distance-based approach is the standard method for bibliometric network visualization and is widely used in science mapping. Within the network, “thermal management” appears as the central hub, with dense connections to “PVT,” “PCM,” “radiative cooling,” “exergy analysis,” “electrical efficiency,” and “nanofluid,” highlighting that cooling strategies (active, passive, and hybrid) are thematically linked to performance and thermodynamic evaluation.

Cluster interpretation: the red cluster centers on thermal management, PCM, and exergy analysis; the blue cluster connects photovoltaic systems and electrical efficiency (including renewable energy); the green cluster groups solar energy, PVT systems, cooling, and computational fluid dynamics; the light-blue cluster associates thermal energy storage, thermal conductivity, and heat transfer; and the yellow cluster emphasizes nanofluid and PV cooling. These clusters reflect four active research streams: (1) hybrid PVT–PCM systems and storage design/optimization, often modeled and validated across climates; (2) optical/radiative cooling and spectrum management for passive temperature reduction; (3) nanofluid-based cooling for enhanced heat transfer; and (4) system-level building integration, computational fluid dynamics (CFD), and 4E (energy–exergy–environment–economy) assessments. Looking ahead, reviews stress durability, long-term viability, and commercialization gaps, and recommend a stronger exergy-centric evaluation, with priorities clearly represented as nodes in the map.

Table 1 displays the co-occurrence network of cluster keywords. The clustering pattern reveals a hierarchical structure in PVT research, with thermal management (red) as the dominant hub, integrating PCM storage, radiative cooling, and exergy analysis, underscoring its central role in performance optimization. Surrounding this core, electrical efficiency (blue) and solar energy/PVT systems (green) reflect system-level priorities that balance thermal regulation with power output. Meanwhile, nanofluid-based PV cooling (yellow) and heat transfer & storage (light blue) introduce material and thermal innovations, supported by CFD modeling (purple) for predictive design. Collectively, these clusters indicate a shift from isolated cooling techniques toward integrated, multi-physics solutions aimed at durability, scalability, and exergy-driven evaluation.

Table 1. Cluster keywords co-occurrence network

Cluster (Color)	**Keywords (per Cluster)**	**Average Link Strength per Keyword**
Thermal management (red)	Thermal management; PCM; heat transfer enhancement; exergy analysis; radiative cooling; PVT; energy efficiency; passive cooling	8
Electrical efficiency (blue)	Electrical efficiency; heat dissipation; renewable energy; photovoltaic	4
Solar energy/PVT system (green)	Solar energy; PVT system; cooling; thermal system	4
PV cooling/Nanofluid (yellow)	PV cooling; nanofluid; PVT	3
Heat transfer & storage (light blue)	Heat transfer; thermal energy storage; thermal conductivity	3
Computational fluid dynamics (purple)	Computational fluid dynamics	1

Note: PV = photovoltaic; PCM = phase change material; PVT = photovoltaic thermal.

The VOSviewer overlay visualization illustrates keyword trends in the thermal and energy research domain, where node size represents overall frequency, node color indicates the average publication year, and link thickness reflects co-occurrence strength. Based on this figure, heat transfer enhancement appears in bright yellow, suggesting it is a relatively recent and emerging topic gaining attention between 2023 and 2025, often linked to PCMs and thermal management. In contrast, energy efficiency is shown as a large, greenish node positioned centrally, indicating it is a consistently important and widely connected concept with steady relevance rather than a sudden surge. Meanwhile, thermal conductivity appears in blue tones, signifying an older average publication year and a more foundational role, with incremental rather than rapid growth in recent years. These visual indicators color recency, size for overall importance, and connectivity for thematic integration, supporting qualitative assessments of keyword trends, as shown in Figure 3.

Figure 4 shows the overlay visualization in Vosviewer. The keyword emerging in recent years is heat transfer enhancement, as shown in Figure 4. A significant approach to enhancing heat transfer in PVT systems involves the use of PCMs. According to recent studies, PCMs can absorb excess heat and release it when temperatures drop, thus stabilizing operating temperatures in photovoltaic modules. An integrated thermal management system that combines PCM with conventional water cooling extends thermal management times and improves thermal performance, especially under the extreme summer conditions of Baghdad, where PCM configurations outperformed traditional systems [7, 8].

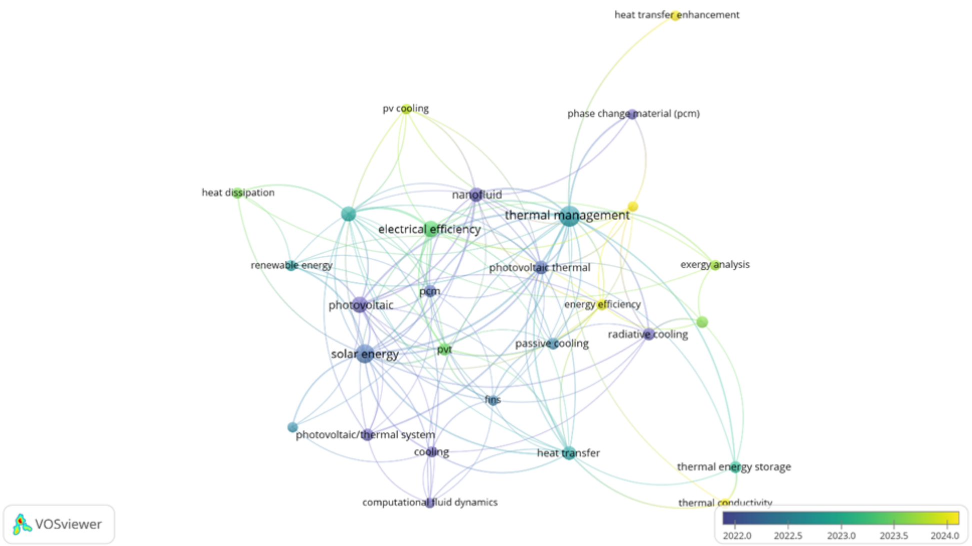

Figure 4. Overlay visualization

Innovations in fluid dynamics and nanofluid applications have also attracted attention for improving heat transfer between the cooling medium and PV cells. Research indicates that incorporating nanofluid suspensions of nanoparticles into a base fluid can enhance thermal conductivity compared to conventional fluids such as water [3, 9]. For example, an experimental setup using CuO-based nanofluids demonstrated significant improvements in thermal regulation within PVT systems [10]. Additionally, a study showed that using carbon nanotubes in cooling fluids improved heat transfer in magnetohydrodynamic environments, further optimizing cooling systems for photovoltaic applications [11].

Structural modifications, such as wavy channels in thermal collectors, can increase contact area between the working fluid and surfaces, generating secondary flows that enhance convective heat transfer [12]. Modifications in heat exchanger designs, such as incorporating fins or varying channel configurations, have demonstrated improvements in overall system thermal performance [13]. These design optimizations are crucial for achieving higher thermal outputs while ensuring that PV modules operate within optimal temperature ranges.

Moreover, a review of comparative cooling techniques underscores the importance of balancing both electrical and thermal demands in PVT configurations. Researchers have identified water as a highly effective working fluid for cooling due to its abundance and high specific heat capacity, and advanced systems, such as evaporative cooling, further demonstrate its potential to optimize module performance [14, 15]. The advancement of thermoelectric technologies presents another promising avenue, with integrating thermoelectric generators with PVT systems suggested as a way to leverage waste heat for additional power generation. This dual-output system offers potential improvements in the energy yield of solar installations and aligns with the increasing demand for energy efficiency [16, 17].

The second keyword emerging in recent years is thermal conductivity, as shown in Figure 4. One central aspect of thermal management in PV systems is the integration of PCMs. PCMs are known for their ability to absorb, store, and release thermal energy, thereby stabilizing temperature fluctuations in PV cells. A study indicates that the use of PCMs with a thermal conductivity of approximately 19 W/m·K significantly improves the thermal regulation of dual-concentrated photovoltaic systems, ensuring optimal performance even under varying environmental conditions [18]. Similar findings indicate that PCMs are critical for minimizing thermal degradation in PV modules and enhancing performance metrics, such as solar-to-hydrogen conversion efficiency, when applied to photovoltaic-electrocatalysis systems [19].

Furthermore, research has shown that the thermal conductivity of materials used in photovoltaic systems, such as microencapsulated PCMs, can significantly affect thermal management effectiveness. For example, the introduction of microencapsulated PCMs provides a thermal management solution that enables PV modules to maintain optimal operating temperatures, thereby improving both thermal and electrical efficiency [8]. This finding is particularly significant, as conventional PV cells exhibit reduced efficiency with increasing temperature; thus, effective thermal management systems are essential for maximizing energy output [20].

Recent advances also highlight the performance benefits of hybrid systems, particularly PVT technologies, which leverage both electrical and thermal energy. These systems have shown promising results, achieving thermal efficiencies of up to 86%, compared to lower rates in conventional PV systems. A comparative study demonstrates that incorporating PVT-PCM configurations improves thermalization of collector systems, further enhancing overall system performance [21]. This dual functionality not only increases energy efficiency but also extends PV panel lifespan by mitigating excessive heat buildup. Additionally, the challenges posed by thermal management in extreme climates cannot be understated. Studies suggest that integrating ventilation strategies with PCMs can significantly improve performance under high-temperature conditions, which are prevalent in areas like Baghdad, Iraq [7]. The combination of these techniques results in optimized thermal management, effectively enhancing the operational lifespan and reliability of PV systems in harsh environments [22].

The third keyword emerging in recent years is energy efficiency, as shown in Figure 4. The energy efficiency of PVT systems has become increasingly vital in the quest for sustainable energy solutions. PVT systems integrate photovoltaic solar energy generation with thermal heat collection, thus improving overall energy efficiency. These systems harness both electricity and heat, addressing the common issue of performance degradation due to excess heat accumulation in photovoltaic modules [23]. Research highlights various methods to enhance thermal management within PVT systems, particularly through innovative cooling techniques. Passive cooling methods, such as rear ventilation and PCMs, have shown promise in maintaining lower module temperatures, consequently improving electrical output and extending the modules' lifespan [24]. Active cooling strategies, including water-cooled designs and nanofluid-enhanced systems, have gained traction due to their higher heat-extraction efficiency compared to passive methods [25]. Certain configurations have achieved overall system efficiencies of up to 89.6% [24].

The role of nanomaterials has introduced additional avenues for improvement. Nanofluids, engineered fluids containing nanoparticles, exhibit enhanced thermal conductivity, thereby improving heat transfer within PVT systems [26]. Their application has led to improvements in both electrical and thermal efficiencies, allowing more efficient cooling and thermal regulation of the photovoltaic components [27]. Additionally, integrating these materials can mitigate the rise in operating temperatures that typically hinder performance [28]. Researchers have explored recent advancements in hybrid collector designs, such as combining PVT with innovative cooling technologies. These hybrids can utilize efficiencies from both electrical generation and thermal energy recovery [29, 30]. Studies suggest that PVT systems generally outperform conventional solar collectors in high-temperature zones, resulting in better overall energy utilization [22]. However, there are trade-offs between electrical and thermal efficiencies, emphasizing the need for optimal design parameters to achieve balanced performance [7].

Figure 5 shows the documents by country or territory. Based on the Scopus database, the top contributors are China (110) and India (107), followed by Saudi Arabia (70), Malaysia (48), Egypt (46), Iraq (42), Iran (38), Turkey (30), the United Kingdom (27), and the United States (23). Taken together, these 10 countries account for 541 documents, with rough shares of 20.3% for China and 19.8% for India, highlighting an Asia/MENA concentration of PVT thermal-management research. This geographic pattern is consistent with prior PVT bibliometric studies that reported strong growth post-2000 and identified Asian countries as leading contributors, as well as with recent technology reviews emphasizing cooling strategies (e.g., nanofluids, PCM, radiative cooling) that are especially relevant to hot-climate testbeds.

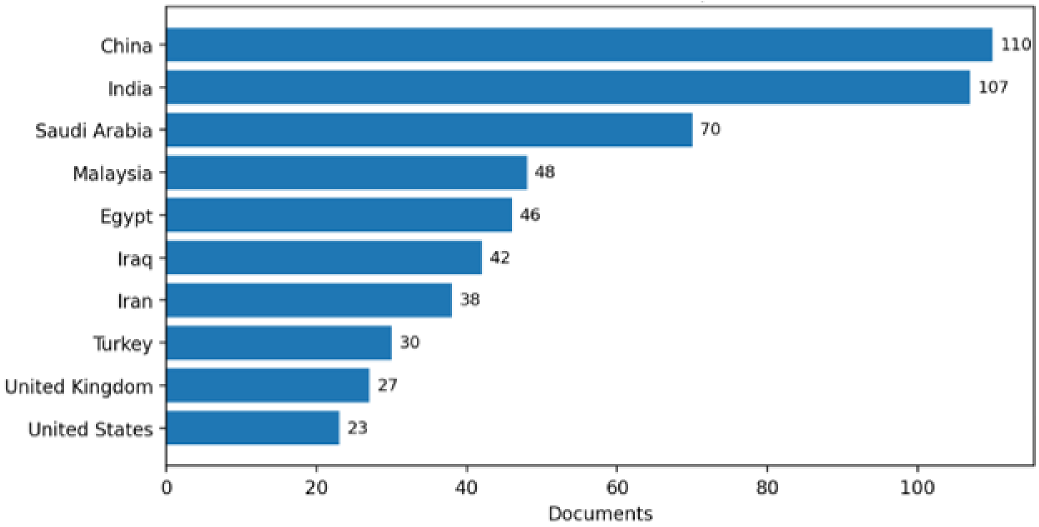

Figure 5. Number of documents by country or territory

3 Classification of Thermal Management Technologies in Photovoltaic Thermal

Figure 6 shows the classification of thermal management technologies in PVT. The integration of photovoltaic and thermal technologies, or PVT systems, enables simultaneous electricity and heat production within a single unit, significantly enhancing overall energy efficiency compared to standalone PV or solar thermal systems. This combined approach also minimizes space requirements, making it an attractive solution for applications with limited areas such as urban buildings and rooftops. To optimize performance, thermal management methods in PVT systems are categorized into several types, including water-based cooling, air cooling, nanofluid systems, refrigerants, PCM, and heat pipes, each offering unique advantages for maintaining stable, efficient operating temperatures.

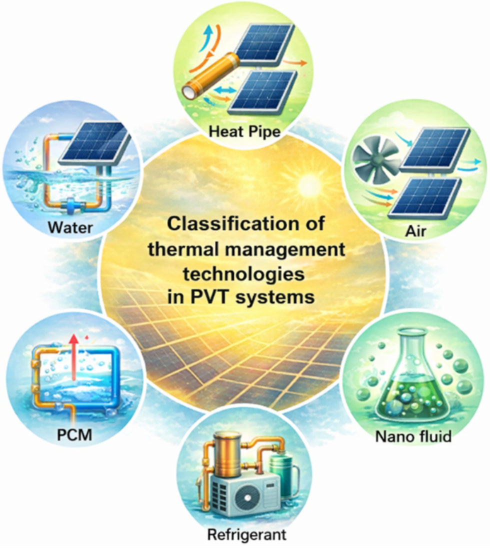

Figure 6. Classification of thermal management technologies in PVT
Note: PCM = phase change material; PVT = photovoltaic thermal.

3.1 Air-Cooled Photovoltaic Thermal Systems

Air-cooled PVT systems utilize ambient air as a cooling medium for PV modules while simultaneously recovering waste heat for thermal applications. This configuration offers several practical advantages, including simplicity, low cost, and resistance to leakage or freezing issues, making it particularly suitable for cold or remote regions. Although the cooling capacity of air is inherently lower than that of liquid-based systems, air-cooled PVT units are easier to integrate with building ventilation systems and enhance operational safety. Recent studies have demonstrated that coupling PVT systems with heat recovery ventilators can improve PV electrical output by approximately 5.4% and reduce space heating energy demand by up to 15.4% [31]. Furthermore, integrating air-source heat pumps (ASHPs) can significantly increase annual energy efficiency, highlighting the potential of hybrid configurations for building energy systems [32].

Current research emphasizes airflow optimization through improved duct design and ventilation strategies. Researchers have reported that closed-loop configurations with dedicated air channels minimize convective heat losses and stabilize the outlet air temperature, thereby enhancing thermal recovery [33]. Increasing inlet air velocity and employing active ventilation using fans or blowers further improves thermal power output and overall system efficiency [31]. Among active cooling techniques, jet impingement using multiple nozzles has demonstrated substantial performance gains, with electrical output improvements of up to 26% [34].

Passive design modifications also play a critical role in improving heat transfer. Researchers have shown that incorporating baffles, perforated plates, porous media, fins, and vortex generators significantly enhances convective heat transfer. For instance, the use of porous copper plates resulted in electrical and thermal efficiencies of 15.63% and 43.68%, respectively. Similarly, metal foam integration increased electrical efficiency by approximately 4% and thermal efficiency by 10–40% [35]. Hybrid approaches combining jet impingement with ring fins have yielded synergistic improvements in both electrical and thermal performance [36].

Despite these advancements, research on air-cooled PVT systems remains incomplete. The similarities between PVT/air systems and conventional solar air heaters suggest opportunities for further development, particularly in optimizing ventilation modes, airflow rates, and duct configurations to achieve a balanced trade-off between electrical and thermal energy conversion [31]. Future studies should also explore machine learning-based predictive models for performance optimization, as demonstrated in recent computational approaches [34].

3.2 Water-Cooled Photovoltaic Thermal Systems

Water-cooled PVT systems have gained significant attention due to the high specific heat capacity and widespread availability of water, which enables effective thermal management and energy recovery. The overall performance of these systems is influenced by external factors such as solar irradiance, ambient temperature, and coolant flow rate, as well as internal design parameters including pipe diameter, plate thickness, and insulation characteristics [37, 38]. Lower inlet water temperature and increased flow rate generally enhance PV electrical efficiency by reducing cell temperature. However, beyond a certain threshold, the marginal benefits diminish due to increased pumping power and pressure drop, necessitating optimized channel design to balance thermal performance and hydraulic losses [39]. Insulation thickness above 0.14 m provides negligible improvement, whereas increasing the pipe diameter and reducing the back plate thickness significantly improve heat dissipation [40]. Additionally, past studies have shown that low wind speeds are associated with higher thermal efficiency, and an optimal solar irradiance level exists at which combined electrical and thermal performance is maximized [37].

Recent innovations in heat exchanger design have demonstrated substantial performance gains. For example, external serpentine coils reduced PV cell temperature by approximately 15 °C, increasing electrical efficiency from 12.32% to 14.58% and thermal efficiency up to 58.8% [40]. Incorporating turbulence promoters, such as twisted tapes or porous media, into the flow channels improved heat transfer and increased overall efficiency by more than 5% [41, 42]. Similarly, optimized bi-symmetrical flat-channel geometries achieved electrical and thermal efficiencies of 18% and 63.1%, respectively, under specific flow conditions [43].

Beyond conventional designs, advanced cooling techniques have emerged to address limitations in heat transfer and fouling. Fine water mist spraying simultaneously reduces surface temperature, removes dust accumulation, and enhances energy efficiency by up to 83.3% [44]. Biomimetic strategies inspired by natural structures, such as leaf-vein and micro- and nano-textured surfaces, offer promising solutions for improved heat dissipation, chemical resistance, and anti-icing functionality. These approaches also mitigate challenges associated with low thermal conductivity in PCMs and channel fouling, positioning them as sustainable alternatives for next-generation PVT systems [45, 46].

Despite notable progress, several research gaps remain. Comprehensive optimization frameworks that integrate thermal, hydraulic, and exergy analyses are essential for achieving balanced performance across varying climatic conditions. Furthermore, hybrid cooling strategies combining biomimetic channel designs with turbulence-enhancing inserts and mist-assisted cleaning warrant further investigation to maximize energy yield and system durability. Future studies should also explore predictive modeling and real-time control algorithms to adaptively regulate flow and temperature, thereby improving annual energy performance [39].

3.3 Nanofluid-Cooled Photovoltaic Thermal Systems

Nanofluid-based cooling in PVT systems has emerged as a promising approach to enhance thermal conductivity, accelerate heat transfer, reduce PV cell temperature, and improve both electrical and thermal efficiencies. In addition to its superior heat transfer properties, nanofluid can act as an optical filter, selectively absorbing non-useful wavelengths and thereby optimizing energy conversion [47, 48]. Experimental studies have demonstrated that nanoparticle concentration, flow rate, and particle size significantly influence system performance, while external factors such as solar irradiance and ambient temperature also play a role [49]. For instance, a water–CuO nanofluid-based PVT system reduced cell temperature by up to 23.7 °C, resulting in electrical and thermal efficiencies of 17.61% and 71.17%, respectively [48]. Advanced nanomaterials such as metal oxides, graphene, and MXene have pushed total system efficiency to as high as 94.31%, underscoring their potential for next-generation PVT applications [50, 51].

While higher nanoparticle concentrations improve thermal performance, they also increase fluid viscosity and pumping power requirements, necessitating careful optimization [52]. Studies have shown that structural enhancements such as dual-channel configurations, fin integration, and mechanical stirring can boost efficiency by 5–13% [53]. Hybrid nanofluids, such as multi-walled carbon nanotubes (MWCNT)/ZnO blends, and core-shell particles (e.g., SiO_2@Au) offer additional benefits, including improved optical filtration (up to 89.45%) and enhanced electrical and thermal performance [52, 54].

Despite these advantages, nanofluid-based systems face challenges related to particle agglomeration, sedimentation, and high material costs. Recent research has focused on hybrid nanofluids and surface-engineered particles to improve stability and durability [53]. Furthermore, biomimetic channel designs inspired by natural structures, combined with AI-driven optimization and low-cost synthesis methods, are being explored to overcome limitations in thermal conductivity and fouling resistance [45, 46].

Future work should prioritize integrated optimization frameworks that account for energy, exergy, and environmental and economic factors, as demonstrated in recent studies [51]. Additionally, coupling nanofluid cooling with advanced optical filtering and solar-tracking strategies could further enhance overall system performance [54]. The development of cost-effective, stable nanofluids and adaptive control algorithms will be critical for large-scale deployment in building-integrated and industrial applications.

3.4 Phase Change Material-Cooled Photovoltaic Thermal Systems

Passive cooling via natural convection offers energy savings but is generally insufficient to maintain optimal PV cell temperatures, whereas active cooling methods, although effective, are energy-intensive and costly. PCMs offer a promising alternative by absorbing latent heat during phase change, thereby stabilizing module temperature and improving overall system performance [55, 56]. Experimental studies confirm that PCM integration reduces PV cell temperature and enhances both electrical and thermal efficiencies. For example, paraffin-based PCM (RT-30) improved thermal efficiency by 26.87% and electrical efficiency by 17.33% compared to conventional systems [56]. Critical design factors include PCM layer thickness and melting point, which exert a greater influence on performance than latent heat capacity [57, 58]. Optimal PCM thickness typically ranges from 5 to 20 mm, while blending PCMs with different melting points extends the operational range and improves thermoelectric performance [59].

Despite their benefits, pure PCMs suffer from low thermal conductivity, supercooling, and leakage issues. Recent innovations address these limitations through composite structures such as microencapsulated PCM (MePCM), nano-enhanced PCM (NePCM), and porous-supported PCM (PSPCM). MePCM improves stability and prevents leakage, achieving system efficiencies exceeding 80% [60, 61]. NePCM, incorporating nanoparticles such as SiC, CuO, ZnO, and Ag, significantly enhances thermal conductivity, accelerates heat storage/release cycles, and raises total efficiency to approximately 85.7% [62]. PSPCM utilizes metal foams or carbon substrates to create stable thermal networks; for instance, copper/RT-50 composites reduced PV temperature by about 30 °C and achieved thermal efficiency of 72.74% [63].

Persistent challenges include long-term stability, corrosion, and volumetric expansion during phase transitions. Future research should focus on PCMs with tunable supercooling characteristics, corrosion-resistant support matrices, and advanced nano-composite formulations to ensure durability and thermal reliability [57, 58]. Additionally, integrating PCM with AI-based optimization and hybrid cooling strategies could further enhance energy yield and economic viability for building-integrated applications.

3.5 Heat Pipe-Cooled Photovoltaic Thermal Systems

Heat pipes have emerged as an effective thermal management solution for PVT systems due to their extremely low thermal resistance and phase-change-based heat transfer mechanism. This technology ensures uniform PV cell temperature distribution, thereby improving both electrical and thermal efficiencies [64, 65]. Common heat pipe configurations include conventional thermosyphon heat pipes (CTHP), loop heat pipes (LHP), pulsating heat pipes (PHP), two-phase closed thermosyphon (TPCT), and miniaturized heat pipes (MHP), each employing distinct condensate-return mechanisms [66].

CTHPs use capillary wicks for stable operation and have demonstrated improved cooling when integrated with PCM or nanofluids, thereby reducing PV cell temperature and enhancing efficiency [67]. LHPs overcome limitations related to distance and orientation, achieving thermal efficiencies up to 71.7% [66]. PHPs, leveraging liquid-vapour oscillations for heat transport, have demonstrated PV temperature reductions of approximately 16.1 °C and improvements in electrical output of 18% [68]. TPCT systems rely on gravity, making inclination angle and working fluid selection critical to performance [69]. MHPs, designed for compact applications, typically deliver seasonal thermal efficiencies of 30–50% [70].

Recent advancements focus on enhancing heat pipe performance through nanofluid charging, optimized inclination angles, and micro-channel designs. For instance, a PHP filled with a graphene oxide nanofluid achieved a total efficiency of 74.4%, while a micro-channel loop heat pipe assembly maintained indoor temperatures above 16 °C under extreme cold conditions and generated electricity [68, 69]. Hybrid systems combining PCM and nanofluid with heat pipes have further improved thermal regulation and energy yield, demonstrating synergistic effects that reduce thermal resistance and accelerate heat transport [67].

Despite their advantages, heat-pipe-based PVT systems face challenges such as secondary heat exchanger inefficiencies, sensitivity to vapor pressure fluctuations, and high material costs. Future research should prioritize hybrid designs integrating PCM and nanofluids to enhance heat transfer capacity while reducing production costs. Additionally, machine learning-based predictive models for performance optimization and cost-reduction strategies for advanced heat pipe configurations are promising directions for large-scale deployment [64, 70].

3.6 Refrigerant-Cooled Photovoltaic Thermal Systems

Refrigerant-based cooling in PVT systems leverages phase-change processes, evaporation and condensation to regulate PV module temperature while simultaneously recovering thermal energy. Among the most widely adopted configurations is the direct-expansion PVT heat pump (DX-PVT-HP), in which the solar collector serves as the evaporator. This arrangement offers rapid thermal response and high operational stability, particularly under low-solar-irradiance conditions [71, 72]. Early studies employing conventional refrigerants such as R134a, R410A, and R22 reported significant thermal improvements, with PV module temperature reductions of up to 23.3 °C and annual electrical output gains of approximately 9.67% [73, 74]. Integration of DX-PVT-HP systems with advanced heat transfer technologies, such as micro-channel heat pipe assemblies (MHPA), has further expanded heat exchange areas and improved thermal performance [75].

Recent trends emphasize the adoption of low-global-warming-potential (GWP) refrigerants, including R290, R600a, R407C, R32, and next-generation fluids such as R1234yf and R152a, to mitigate environmental impact [76]. Experimental results indicate that R290/R600a blends can increase the coefficient of performance (COP) by up to 7.9% and electrical output by 10.3% compared to conventional refrigerants [74]. Moreover, CO_2-based systems have demonstrated COP improvements of approximately 30% compared with air-source systems, highlighting their potential for high-efficiency applications [77].

Despite their advantages, refrigerant-based PVT systems face challenges related to flammability risks associated with hydrocarbons and the high cost of premium low-GWP alternatives. Future research should focus on developing safe, cost-effective refrigerants with superior thermophysical properties, alongside adaptive control strategies to ensure operational stability and optimize energy performance under variable climatic conditions [78, 79]. Additionally, hybrid designs integrating thermoelectric modules and advanced heat pipes with DX-PVT-HP systems offer promising opportunities to enhance energy efficiency and reduce environmental impact [75].

Table 2. Comparative analysis of the characteristics of various thermal management technologies applied to PVT systems [80]

Type of Cooling	Efficiency	Features	Recommendation
Air	Thermal: 10–45% and Electrical: 6–15%	Appropriate for applications in buildings, heat pump systems, and drying equipment, this system offers high reliability with no risk of liquid leakage. Its design is straightforward, resulting in low installation costs and facilitating easy operation and maintenance.	Low-cost, small-scale applications where simplicity and reliability are priorities.
Water	Thermal: 20–70% and Electrical: 6–18%	Achieving an overall efficiency of up to 95%, making it well-suited for high-temperature industrial applications. In addition, it provides significantly enhanced heat transfer performance compared with conventional working fluids.	Medium- to large-scale systems requiring stable, efficient thermal management.
Nanofluid	Thermal: 20–85% and Electrical: 10–22%	It can achieve an overall efficiency of up to 95%, making it suitable for high-temperature industrial applications, while offering superior heat transfer performance compared to conventional fluids.	High-performance industrial applications where cost is less critical.
PCM	Thermal: 20–83% and Electrical: 10–18%	It enables time-shifting and thermal buffering, supports passive cooling with a more uniform temperature distribution, and can be integrated with other cooling strategies. In addition, it is well-suited for cross-temporal heating applications.	Systems requiring thermal storage and passive cooling.
Heat Pipe	Thermal: 20–75% and Electrical: 10–22%	It consumes no energy, exhibits excellent isothermal characteristics, and provides high thermal conductivity for effective long-distance heat transfer, making it well-suited for applications requiring precise temperature control.	Precision cooling applications and long-distance heat transfer scenarios.
Refrigerant	Thermal: 20–80% and Electrical: 10–18%	It enables rapid temperature regulation, maintains a stable low-temperature environment, and is suitable for industrial applications and integration with heat pump systems.	Industrial systems that require fast, stable cooling.

Note: PCM = phase change material; PVT = photovoltaic thermal.

Table 2 presents a comparative analysis of the characteristics of various thermal management technologies applied to PVT systems. The comparative analysis of thermal management technologies for PVT systems reveals that reported efficiencies cannot be directly compared due to variations in climate conditions, testing protocols, and data sources, which include both simulations and experimental results. Air cooling offers simplicity and reliability at low cost, making it suitable for small-scale applications, while water cooling provides superior heat transfer and overall efficiency for medium to large-scale systems. Nanofluids further enhance thermal performance, positioning them as an option for high-performance industrial applications where cost is less critical. PCM-based systems offer thermal storage and passive cooling, ideal for applications that require temperature buffering. Heat pipes deliver excellent isothermal characteristics and passive operation, making them suitable for precision cooling and long-distance heat transfer. Finally, refrigerant-based cooling enables rapid, stable temperature regulation, serving industrial systems that demand fast, consistent cooling. Each technology presents distinct advantages and limitations, emphasizing the need for context-specific selection rather than direct efficiency comparison. The thermal and electrical efficiency values in Table 2 represent system level PVT efficiencies (total heat and electricity output relative to solar input) measured during operation with different cooling technologies. They do not represent incremental improvements or cooling-system efficiencies; they reflect the overall PVT performance achieved under each thermal management method according to the reported studies.

While both water cooling and nanofluid cooling provide high heat-removal capability and can achieve similar ranges of overall efficiency, nanofluids offer specific performance advantages that distinguish them from conventional water-based systems. In particular, nanofluids incorporate suspended nanoparticles (e.g., Al_2O_3, CuO, TiO_2), which increase the thermal conductivity, convective heat-transfer coefficient, and overall cooling rate of the working fluid. This enhanced heat-transfer capability enables faster and more uniform PV temperature reduction, allowing PVT systems to maintain higher electrical output under elevated irradiance conditions. Water cooling remains a cost-effective and reliable option, but nanofluids are better suited for high-performance applications where maximizing thermal extraction and efficiency is prioritized over cost and simplicity.

Table 2 reviews six thermal management techniques used in PVT systems air, water, nanofluid, PCM, heat pipe, and refrigerant cooling. It summarizes the thermal and electrical efficiency ranges, technical characteristics, suitable integration contexts, and limitations of each method based on existing research. This comparison provides a useful reference for researchers selecting the most appropriate cooling strategy for specific climatic and environmental conditions. Overall, the six techniques are complementary rather than mutually exclusive. Nanofluid and heat pipe systems exhibit the highest thermal conductivity, followed by refrigerant-based and water-cooling methods, while PCM and air cooling offer lower conductivity, although PCMs excel in latent heat storage capability. In terms of cost, air cooling is the most economical option, followed by water cooling and PCM, whereas heat pipe, refrigerant, and nanofluid systems generally involve higher investment. PCM, refrigerant, heat pipe, and nanofluid methods also provide more precise temperature regulation. Total energy efficiency can reach approximately 95% with nanofluids, around 60% with air cooling, and roughly 80% with the other methods. These variations indicate that hybrid configurations can effectively optimize performance by combining the strengths of each technique.

Thermal management technologies in PVT systems face substantial engineering constraints, primarily due to trade-offs between heat transfer effectiveness, structural complexity, and integration requirements. Air-cooled systems offer low-cost simplicity but suffer from limited cooling capacity, while water and nanofluid cooling introduce hydraulic losses, fouling, leakage risks, and pumping-power penalties that require careful channel and flow optimization. Low thermal conductivity, supercooling effects, and long-term material stability concerns constrain PCM-based cooling. Heat pipe systems require precise geometric configuration and are sensitive to orientation, vapour pressure fluctuations, and secondary heat exchanger inefficiencies. Refrigerant-based systems add complexity through phase-change control, compressor reliability, and safety concerns, especially with low-GWP but flammable refrigerants. These technologies also differ in scalability: air cooling scales easily but experiences diminishing performance in high-density installations; water and nanofluids cooling scale well for larger systems but incur higher operational costs and maintenance loads; PCM and heat pipes scale poorly for very large collectors due to material costs, volume requirements, and thermal saturation; and refrigerant systems scale effectively for industrial applications but require specialized components and regulatory compliance.

From an operational standpoint, maintainability and stability challenges strongly influence long-term performance and costs. Water and nanofluid systems require continual monitoring to prevent corrosion, sedimentation, and nanoparticle agglomeration, while PCM systems face issues such as long-term degradation, leakage, and cycling fatigue. Heat pipes and refrigerant systems introduce higher mechanical complexity, demanding periodic inspections, precise charge control, and robust sealing to prevent working-fluid loss. These factors directly affect commercial maturity: air and water cooling are the most mature and widely deployed, benefitting from well-established components and low technical risk; PCM and heat pipes occupy a mid-maturity tier with promising performance but limited real-world testing and unresolved durability issues; nanofluids remain at a pre-commercial research stage due to cost, stability, and environmental concerns; and refrigerant-based PVT systems, despite their high performance, remain constrained by safety regulations, cost, and system complexity. Overall, while each technology offers distinct advantages, none represents a universally optimal solution. Commercialization depends heavily on application context, economic trade-offs, and long-term reliability considerations.

4 Techno-Economic and Environmental Sustainability

The techno-economic evaluation of PVT systems reveals that both technical efficiency and financial metrics strongly influence their viability. The analysis indicates that improvements in thermo-electrical performance alone are insufficient to guarantee widespread adoption; economic feasibility remains a critical determinant. Key indicators, including initial capital cost (ICC), life-cycle cost (LCC), levelized cost of energy (LCOE), and payback period (PBP), were assessed to provide a comprehensive understanding of cost competitiveness. The LCC analysis, which incorporates investment, operation, maintenance, and energy revenue streams, offers a robust basis for technology selection and investment decisions. Herrando et al. [81] demonstrated that financial incentives and variations in economic parameters significantly affect the competitiveness of PVT systems, particularly in combined heating and power applications. Similarly, Abdul-Ganiyu et al. [82] highlighted that exergy-based assessments can further refine economic evaluations by linking thermodynamic efficiency to cost performance.

Calculating LCOE and the levelized cost of heat (LCOH) enables cross-technology comparisons, positioning PVT systems against conventional PV and solar thermal alternatives. Recent studies by Behzadi et al. [83] and Chae et al. [84] confirm that integrated designs, such as coupling PVT with heat pumps or smart building systems, can reduce LCOE and shorten PBP, thereby enhancing economic attractiveness. However, Zhang et al. [85] noted that site-specific factors, including ground thermal effects and climatic conditions, introduce variability in cost metrics, underscoring the need for localized optimization strategies.

Across recent studies, the economic viability of PVT hinges as much on contextual economics as on thermo-electrical performance. Herrando et al. [81] show that identical PVT-based S-CHP designs optimized for single-family homes yield markedly different payback times (PBP) across Athens, London, and Chae et al. [84], driven primarily by local electricity prices rather than collector performance, underscoring how incentives and market conditions dominate adoption prospects even in sunny climates. In their analysis, the optimized system's PBP reaches 15.6 years in Athens versus 11.6 years in Zaragoza, despite similar solar resources, due to lower Greek tariffs. The study directly links shorter PBPs to higher energy prices and, by implication, to supportive policies (e.g., FIT/RHI) when present. Complementing this, Abdul-Ganiyu et al. [82] introduce Levelized Cost of Exergy (LCOEx) to price combined heat and electricity services consistently; in Ghana's climate ($\approx$ 4.6 peak sun hours), they find LCOEx $\approx$ 0.33 \$/kWh for PVT vs 0.45 \$/kWh for PV, with improvements under higher insolation (up to 11–18% reduction when Sh rises to 6.5 h), highlighting how integrated designs can be economically advantaged when both thermal and electric outputs are valued and storage is considered.

Integrated, multi-generation configurations can further compress costs and payback. Chae et al. [84] report that coupling PVT with an ASHP for zero-energy buildings in Busan achieves high seasonal COPs and indicates potential capital advantages versus ground-source variants, aligning with other findings that smart building integration is a practical route to lower LCOE/PBP. However, explicit cost metrics vary by case and assumptions. In a more aggressive integration, Gado et al. [86] evaluate a PVT-powered adsorption chiller plus PEM electrolyzer in Alexandria (cooling + DHW + green H_2) and report an exceptionally short payback $\approx$ 0.8 years alongside sizable annual outputs of cooling, heat, and hydrogen; while such figures depend on assumed component costs and local pricing of electricity, cooling, and hydrogen credits, they illustrate how PVT's economic case strengthens when multiple revenue streams (and decarbonization benefits) are monetized. Overall, the evidence supports combining PVT with heat pumps or multi-generation subsystems to lower LCOE/LCOH and raise PBP (faster recovery), but results remain site-sensitive (tariffs, climate, and incentive architecture) and should be localized.

From an environmental perspective, the assessment focused on carbon mitigation potential, energy payback time (EPBT), life-cycle climate performance (LCCP), and life-cycle assessment (LCA). EPBT serves as a critical indicator of energy sustainability, representing the time required for the system to offset the energy consumed during manufacturing, transportation, and installation. Abadeh et al. [87] reported that incorporating nanofluids into PVT systems can reduce EPBT by enhancing thermal efficiency, though concerns regarding nanoparticle waste and recyclability persist. LCCP analysis provides a holistic view of greenhouse gas emissions throughout the system's life cycle. Gado et al. [86] demonstrated that advanced PVT configurations, such as adsorption-electrolyzer integration for cooling and hydrogen production, can significantly reduce LCCP values, advancing broader decarbonization goals. Nevertheless, Herrando et al. [81] emphasized that environmental benefits are highly sensitive to material selection and end-of-life management practices.

Life cycle assessment remains indispensable for evaluating environmental trade-offs, encompassing raw material extraction, operational impacts, and disposal. Current findings indicate that while PVT systems generally outperform conventional PV in terms of combined energy output and carbon reduction, challenges related to material degradation, nanoparticle waste, and recycling limitations require urgent attention. Future research should expand LCA boundaries to include additional impact categories such as acidification potential, eutrophication, and water consumption, as suggested by Chae et al [84]. Furthermore, sustainable design strategies such as low-impact material selection, eco-friendly synthesis routes, and improved recycling protocols are essential to enhance the ecological profile of PVT technologies.

LCA of PVT systems typically adopts a functional unit of 1 kWh of combined energy output (electricity + heat) delivered over the system's lifetime, although some studies use per m^2 of collector area per year for design comparisons. This choice ensures that environmental impacts are normalized to useful energy services rather than physical size alone. Regarding system boundaries, most recent analyses use a cradle-to-grave approach that encompasses raw material extraction, manufacturing, transportation, installation, operation, and end-of-life phases. For example, Herrando et al. [81] include end-of-life recycling of aluminum frames and glass, while Abadeh et al. [87] explicitly account for nanofluid disposal and potential nanoparticle waste management. In contrast, some earlier studies adopt cradle-to-gate boundaries, excluding disposal and recycling, which can underestimate impacts such as greenhouse gas emissions and resource depletion. Explicitly defining these boundaries, especially whether working-fluid disposal and material recovery are included, is critical for comparability and for identifying opportunities for sustainable design improvement.

The integration of techno-economic and environmental analyses underscores the need for a multidimensional evaluation framework for PVT systems. While recent advancements demonstrate promising reductions in cost and environmental impact, large-scale deployment will depend on continued innovation in system design, material sustainability, and policy support. Future studies should prioritize dynamic economic modelling under varying market conditions, coupled with comprehensive LCAs that address emerging environmental concerns. Such efforts will facilitate informed decision-making and accelerate the transition toward sustainable energy systems.

Linking technical performance with cost and environmental externalities, air and water-cooled PVT (especially when integrated with heat pumps or smart building systems) are the most economically feasible at scale due to mature components, predictable O&M, and demonstrated LCOE/PBP improvements in site-optimized deployments; refrigerant DX-PVT-HP can also be viable for industrial/large-building applications where rapid, stable temperature control yields high utilization, provided safety/regulatory costs are effectively managed. Environmental risks concentrate in working fluids and materials: nanofluids (agglomeration, end-of-life nanoparticle disposal), PCM composites (leakage, microplastic/nano-additive release, corrosion of supports, recycling barriers), refrigerants (GWP/flammability and leakage), and water loops (corrosion, biogrowth, and antifreeze disposal), with system-wide impacts hinging on cradle to grave boundaries, fluid handling, and material recovery processes. Consequently, short-term deployment routes prioritize air/water PVT coupled with ASHPs and building energy management, selective heat-pipe add-ons for precision/isothermal needs, and refrigerant-based systems where codes and technician capacity are established. Long-term research should focus on cost-stable, recyclable nanofluids and NePCM/MePCM/PSPCM with verified durability and take back pathways, hybridized heat pipes + PCM for passive reliability. Ai-driven control with exergy-aware optimization to co-minimize LCOE/LCOH and life cycle impact, ensuring that technical gains translate into bankable economics without shifting burdens to end of life or environmental risk.

5 Conclusions

The review underscores that selecting an optimal thermal management strategy for PVT systems is not solely about maximizing efficiency but about balancing performance, cost, and sustainability. Air cooling remains the most practical route for small-scale and building-integrated applications due to its simplicity, low maintenance, and absence of leakage risks, even though its thermal efficiency is modest. Water-based systems dominate medium-to-large installations because of their stability and strong heat transfer, but they introduce higher installation complexity and pumping costs. Advanced options such as nanofluids and PCM composites deliver superior thermal performance and enable buffering, yet their scalability is constrained by material cost, long-term stability, and environmental concerns, particularly nanoparticle disposal and recyclability. Heat pipes offer passive, precise cooling with minimal energy input, making them attractive for niche applications that require uniform temperature control, while refrigerant-based systems excel at rapid cooling but raise concerns about refrigerant leakage and global warming potential.

From an economic perspective, cost drivers differ across classes: air systems are dominated by installation simplicity, water systems by pumping and heat exchanger costs, and nanofluid/PCM systems by material synthesis and lifecycle durability. Environmental trade-offs focus on material selection and end-of-life management (aluminium and glass recycling for conventional systems), nanoparticle handling for nanofluids, and refrigerant choice for vapour-compression designs. These findings suggest that decision-making should weigh integration feasibility, lifecycle cost, and ecological footprint rather than focusing solely on peak efficiency. Future research should prioritize durable, low-impact materials, closed-loop fluid recovery, and policy frameworks that incentivize multi-generation configurations, as these strategies offer the greatest promise for scaling PVT technologies sustainably.

This study contributes to the existing body of knowledge by providing a comprehensive classification of thermal management strategies and by linking technical performance to techno-economic and environmental assessments. It underscores the importance of integrated optimization frameworks that account for energy, exergy, and life-cycle impacts. Future research should focus on: developing cost-effective, durable nanofluids and PCM composites with high thermal conductivity, exploring AI-driven predictive control for real-time optimization of hybrid cooling systems, expanding life cycle assessments to include broader environmental impact categories, and investigating hybrid configurations combining thermoelectric modules, heat pipes, and advanced optical filtering for next-generation PVT systems. By addressing these gaps, PVT technology can transition from niche applications to mainstream adoption, thereby supporting global decarbonization and energy-efficiency goals.

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Author Contributions

Conceptualization, S.H., P.H.A., and M.Z.; methodology, S.H.; software, P.H.A.; validation, S.H., P.H.A., and M.Z.; formal analysis, S.H.; investigation, P.H.A.; resources, S.H.; data curation, P.H.A.; writing—original draft preparation, S.H. and P.H.A.; writing—review and editing, M.Z.; visualization, S.H.; supervision, S.H. and M.Z.; project administration, P.H.A.; funding acquisition, S.H. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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