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CURRENT TRENDS IN PHOTOVOLTAIC THERMAL (PVT) SYSTEMS: A REVIEW OF TECHNOLOGIES AND SUSTAINABLE ENERGY SOLUTIONS

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ABSTRACT

This systematic review explores advancements and challenges in photovoltaic thermal (PVT) systems, focusing on efficiency improvements, cooling mechanisms, material innovations, Internet of Things (IoT) integration, and cost and environmental considerations. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, 45 articles were analyzed to provide a comprehensive understanding of current trends and future directions in PVT technology. Findings reveal that cooling mechanisms, particularly liquid-based and nanofluid-based systems, are essential for maintaining high PVT efficiency under diverse environmental conditions. Material advancements, including phase change materials (PCMs) and nanotechnology, have enhanced thermal management and energy storage capabilities, yet their high costs and environmental impacts remain significant barriers to broader adoption. IoT and smart grid integration have transformed PVT system functionality by enabling real-time monitoring, predictive maintenance, and energy flow adjustments within connected energy networks. However, persistent challenges—including high initial investment costs, environmental concerns related to materials, and the need for adaptable designs—highlight areas for future research. Advancements in adaptive materials, sustainable cooling solutions, and digital automation are essential for developing cost-effective, resilient PVT systems that contribute to global renewable energy goals. This review provides a foundation for future research to address the identified challenges and maximize the potential of PVT systems in sustainable energy production.

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KEYWORDS

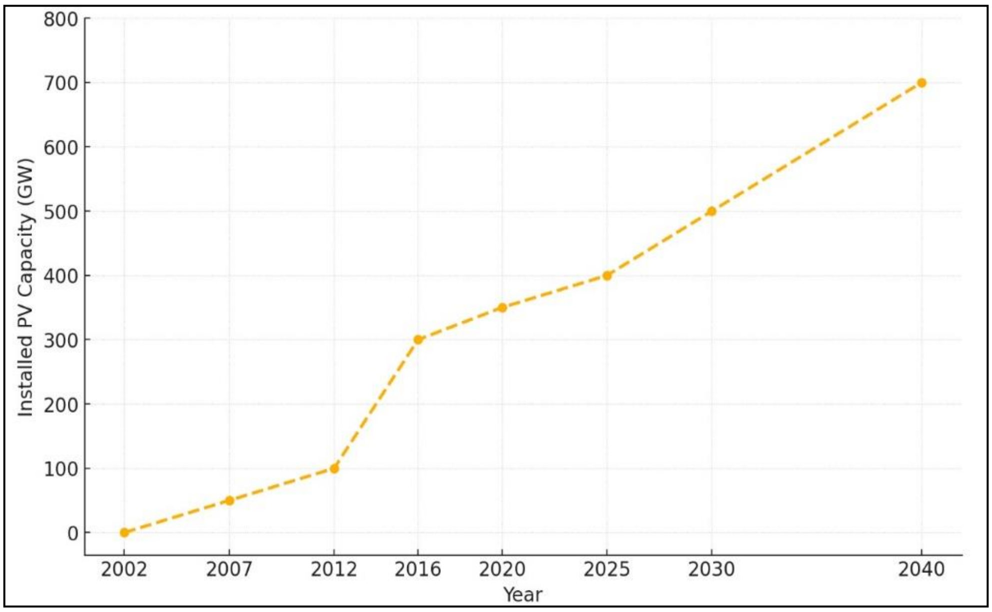
Photovoltaic Thermal Systems; Sustainable Energy; Energy Efficiency; Hybrid Solar Technology; Renewable Energy Solutions

1 Introduction

Photovoltaic thermal (PVT) systems represent an innovative approach to enhancing energy efficiency and harnessing renewable resources. By combining photovoltaic (PV) and thermal technologies, PVT systems aim to address the limitations of standalone PV panels and solar thermal collectors, providing a more efficient means of converting solar energy into both electricity and heat (Ghadiri et al., 2015). PVT systems have seen substantial development in recent years due to the increasing demand for sustainable energy solutions driven by concerns over climate change, resource depletion, and growing global energy needs (Singh et al., 2019). Initially, the technology emerged to improve the performance of traditional PV panels, which suffered from significant efficiency drops at higher temperatures. According to Lämmle et al. (2016), early attempts at PVT integration focused on using air-based systems for cooling PV modules. However, the evolution of materials and design has enabled more effective hybrid solutions that improve energy yield and system efficiency (Singh et al., 2015).

As PVT technology advanced, researchers explored the benefits of liquid-based cooling systems, which demonstrated higher heat transfer rates than air-based alternatives. For example, a study by Lamnatou and Chemisana (2017) highlighted that water-cooled PVT systems could achieve greater efficiency, as water's higher thermal capacity absorbs more heat from PV panels, reducing the temperature and thereby enhancing electrical output. Subsequent studies have also examined the potential of various coolants, including nanofluids, which improve the thermal conductivity of water, further optimizing the performance of liquid-cooled PVT systems (Zondag, 2008). This shift to liquid-based systems reflects a broader trend in PVT research toward maximizing energy output through design innovation and fluid dynamics improvements (Singh et al., 2014). More recently, the integration of advanced materials, such as phase change materials (PCMs) and thermoelectric components, has further diversified PVT configurations and improved efficiency. PCMs allow PVT systems to store excess thermal energy, which can then be released when solar irradiance is low, thus extending energy availability beyond sunlight hours (Tiwari & Gaur, 2014). This innovation aligns with broader trends in renewable energy systems, which increasingly focus on energy storage solutions to address intermittent supply issues (Lamnatou & Chemisana, 2017). Dimri et al. (2017) underscore the efficacy of PCMs in maintaining optimal PV module temperatures, thereby ensuring steady electrical output. This evolutionary phase reflects the ongoing demand for hybrid solar technologies capable of both power generation and heat management, bridging the gap between energy demand and

Figure 1: Global PV Installation Rate



intermittent supply challenges.

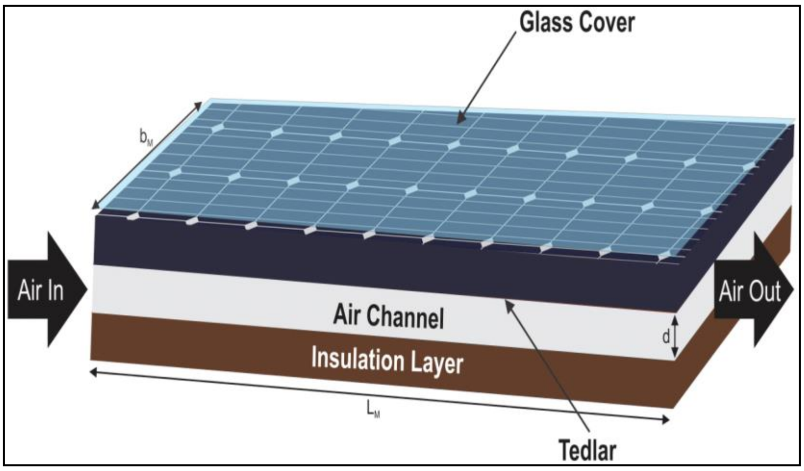
Another major trend in PVT system evolution involves incorporating hybrid solar thermal technologies for diverse applications. For instance, PVT collectors are now used not only in residential and commercial buildings but also in industrial settings where waste heat recovery is essential (Lamnatou & Chemisana, 2017). Researchers such as Dimri et al. (2019)have examined the industrial applications of PVT systems, where they contribute to process heating and cooling, thereby expanding their potential beyond traditional solar applications. Additionally, hybrid PVT systems are being designed to operate under varied climatic conditions, making them viable solutions in different geographic regions. This flexibility has driven more widespread adoption and interest in the technology, as PVT systems can now address energy needs across a broad spectrum of applications and climates (Jin et al, 2010).

The PVT field continues to evolve through efforts to address system efficiency, durability, and integration with emerging energy technologies. Studies by Sardarabadi and Passandideh-Fard (2016) and Singh et al. (2019) reveal that future PVT advancements are likely to focus on smart grid compatibility, Internet of Things (IoT) integration, and remote monitoring capabilities, allowing for better energy management. These advancements indicate a shift toward creating sustainable, intelligent energy systems that can efficiently respond to fluctuating energy demands. As PVT technology matures, its role in sustainable energy production is anticipated to grow, with increasing emphasis on innovations that can cater to both small-scale and large-scale applications. The objective of this systematic review, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, is to provide a structured and comprehensive synthesis of current trends and advancements in photovoltaic thermal (PVT) systems, with a focus on technological innovations and sustainable energy applications. This review seeks to address key areas of PVT development, including improvements in efficiency, thermal management techniques, and adaptability across various environmental conditions and applications. Employing a systematic approach to identify, screen, and evaluate relevant literature, this review integrates findings on advanced materials, hybrid system configurations, and energy storage innovations that enhance the functionality and reliability of PVT systems. Furthermore, this study examines persistent challenges within PVT technology to outline future research directions, emphasizing the critical role of PVT systems in advancing global renewable energy objectives. This systematic synthesis will serve as a foundational resource for stakeholders interested in the sustainable development of PVT systems and their applications in diverse energy markets.

2 Literature Review

The literature on photovoltaic thermal (PVT) systems has evolved significantly, driven by the pressing need for efficient and sustainable energy solutions. Early

Figure 2: Layer diagram of PV/T air collector



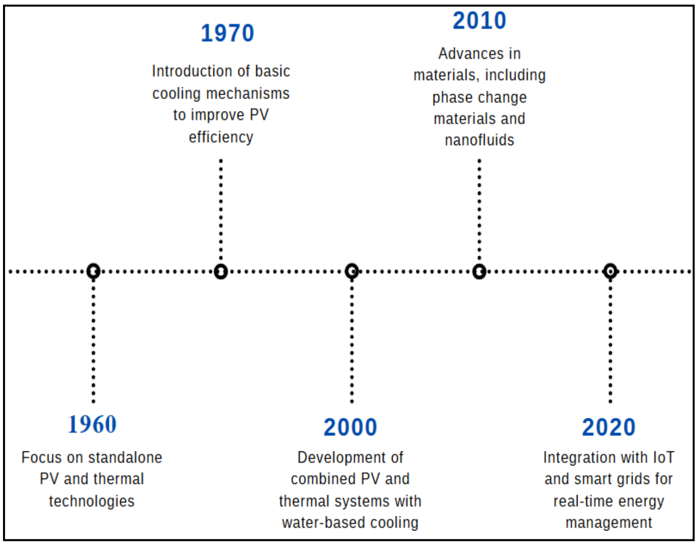
Source:Diwania et al. (2020)

research predominantly focused on enhancing the performance of standalone photovoltaic (PV) and thermal systems separately. However, with advancements in materials and energy management strategies, recent studies have shifted toward hybrid configurations that integrate both PV and thermal technologies to improve overall energy yield. This section provides a detailed review of the research contributions, focusing on the evolution of PVT systems, various cooling methods, advancements in materials and configurations, and application-based adaptations. By examining these core areas, this literature review aims to offer a comprehensive understanding of the factors contributing to PVT systems' development, including efficiency gains, implementation challenges, and future directions for optimizing performance.

2.1 Evolution of Photovoltaic Thermal (PVT) Systems

The development of photovoltaic thermal (PVT) systems has its roots in the mid-20th century, as researchers initially aimed to improve the efficiency of standalone photovoltaic (PV) and thermal solar technologies. Early studies primarily focused on enhancing either electrical or thermal output but rarely integrated both functions within a single system (Preet et al., 2017; Shahsavar & Ameri, 2010). Early efforts concentrated on mitigating PV efficiency losses at high temperatures by introducing cooling mechanisms (Fang et al., 2010). This era marked the foundation of PVT systems, as researchers began to investigate combined solutions to harness both thermal and electrical energy, setting the stage for the PVT concept to take shape (Ji et al., 2008; Preet et al., 2017). As the technology matured, researchers explored ways to enhance PVT systems through air and liquid-based cooling methods. Water-cooling mechanisms became increasingly popular due to their superior heat transfer capabilities, which helped maintain optimal PV efficiency (Michael et al., 2015; Wu et al., 2011). For instance, studies demonstrated that water-based PVT systems could achieve higher electrical and thermal efficiencies than air-based alternatives, establishing liquid cooling as a preferred approach (Zhou et al., 2019; Zondag, 2008). In addition, research by Amori and Abd-AlRaheem (2014) found that water-cooled systems not only stabilized PV temperatures but also allowed for efficient thermal energy utilization, which was especially beneficial in applications where both electricity and heat are in demand. This era of liquid-cooling innovation marked a significant phase in PVT evolution, transitioning from experimental integration to more practical applications with measurable performance improvements.

Figure 3: Evolution of Photovoltaic Thermal (PVT) Systems



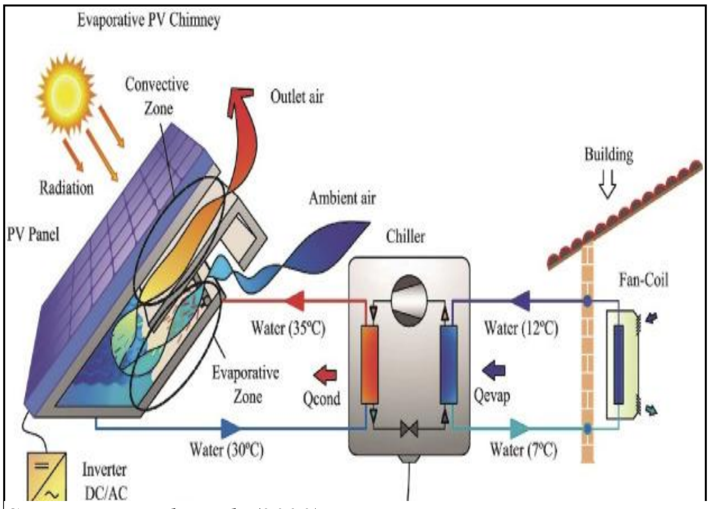
Further advancements in materials and configurations fueled the progress of PVT systems in the following decades. The introduction of advanced materials like phase change materials (PCMs) and nanofluids enhanced the thermal management capabilities of PVT systems, contributing to greater efficiency (Ji et al., 2008; Michael et al., 2015). Studies by Amori and Abd-AlRaheem (2014) and Michael et al. (2015); (Wu et al., 2011) demonstrated that PCMs provided improved thermal regulation, absorbing excess heat and releasing it when temperatures decreased, thus optimizing electrical output over extended periods. Nanofluids, which offered higher thermal conductivities than conventional fluids, also became an area of interest, as they further augmented the cooling efficiency of liquid-based systems (Alam, 2024; Ji et al., 2008). These material advancements illustrate the field's shift toward optimizing hybrid system configurations, aiming to enhance both efficiency and durability in varying climatic conditions. The modern phase of PVT system evolution emphasizes intelligent integration with smart grids and IoT, enabling real-time monitoring and control for optimal energy use. This integration aligns with broader trends in renewable energy systems, where digital technologies support efficient energy management and grid compatibility (Michael et al., 2015; Nandi et al., 2024; Rahman, 2024; Wu et al., 2011). Recent studies highlight how integrating IoT in PVT systems enables data-driven adjustments to maintain efficiency and manage energy flows based on demand (Ji et al., 2008; Yousefi et al., 2012). Additionally, the trend toward smart grid compatibility has positioned PVT systems as versatile solutions in residential, commercial, and industrial sectors. These technological advancements mark the latest phase in PVT evolution, where emphasis on smart integration and adaptability reflects the growing importance of PVT systems in achieving sustainable energy objectives globally.

2.2 Cooling Mechanisms in PVT Systems

Cooling mechanisms in photovoltaic thermal (PVT) systems play a pivotal role in enhancing system efficiency, as they help manage the heat generated during solar energy conversion. Early cooling solutions in PVT systems primarily employed air-based methods, where air circulated beneath PV panels to dissipate excess heat (Dorobanţu et al., 2013; Rajput & Yang, 2018). Although air-based cooling is simpler and cost-effective, it has limitations in thermal conductivity and heat transfer efficiency (Mojumder et al., 2016). Studies, such as those by Wu et al. (2017), highlight that while air-cooled systems are beneficial in low-cost applications, they offer limited temperature control compared to liquid-based methods. Consequently, air-based cooling is commonly applied in small-scale PVT systems where thermal efficiency is less critical. As the limitations of air cooling became apparent, research shifted toward liquid-based cooling systems, particularly water-based solutions, which demonstrate higher thermal conductivity and better cooling efficiency (Jin et al., 2010; Rodgers & Eveloy, 2013). Water-cooled PVT systems are effective at lowering PV panel temperatures, thus improving electrical efficiency and enabling effective thermal energy recovery (Dorobanţu et al., 2013). For example, studies by Rajput and Yang (2018) and Jin et al. (2010) found that water-cooled systems achieved higher energy outputs than air-based counterparts, making them suitable for applications where both electrical and thermal energy are needed. Additionally, research by Rajput and Yang (2018) demonstrated that water-based cooling contributes significantly to energy efficiency in climates with high solar irradiance, underlining its advantages in various geographic contexts.

In recent years, researchers have introduced nanofluids as an innovative coolant for liquid-based PVT systems. Nanofluids, which are engineered by dispersing nanoparticles in base fluids like water, exhibit superior thermal conductivity compared to traditional fluids (Nasim et al., 2016; Sharma, 2011). Studies by Lin et al. (2014); Slimani et al. (2017) indicate that nanofluids can improve the cooling efficiency of PVT systems, particularly in high-temperature environments where traditional coolants might fall short. Ji et al. (2009) and (Zhang et al., 2014) further found that the integration of nanofluids can increase energy transfer rates, enhancing both thermal and electrical output in PVT systems. This trend toward nanofluid cooling exemplifies the continuous innovation in PVT cooling solutions aimed at maximizing energy efficiency and reliability. Hybrid cooling solutions represent the latest evolution in PVT cooling mechanisms, combining air and liquid-based methods to leverage the strengths of both approaches. These systems, often referred to as dual-mode cooling, use liquid cooling during peak sunlight hours to maintain panel efficiency while using air cooling when thermal demand is lower (Lämmle et al., 2016; Nasim et al., 2016). Research by Song et al. (2018) and Chow et al. (2009) shows that hybrid cooling systems can dynamically respond to changing environmental conditions, thereby optimizing performance across various climates and applications. Hybrid cooling

Figure 4:PVT System with Evaporative Cooling and Chiller Integration



Source: Dwivedi et al. (2020)

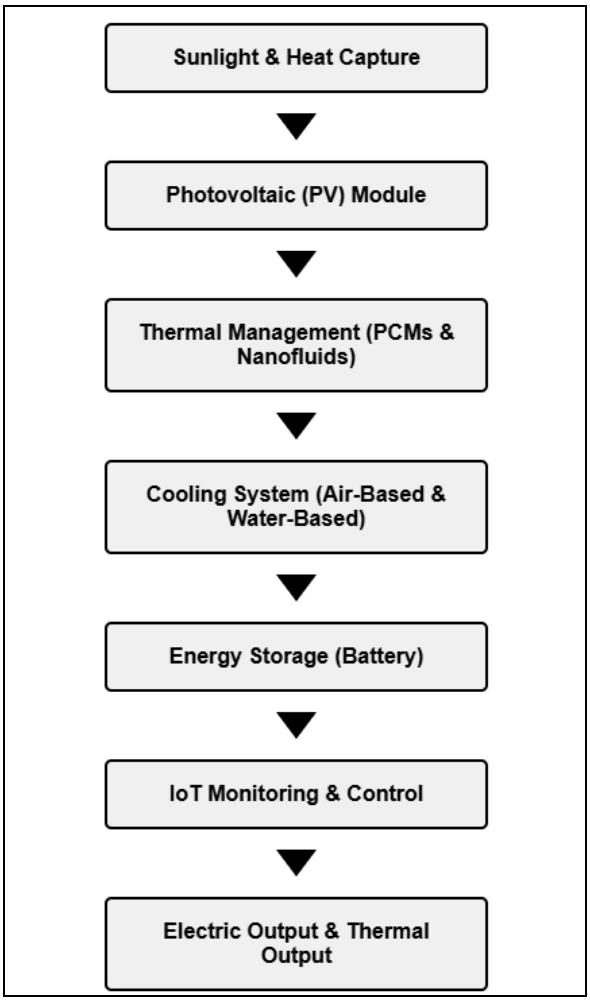
solutions highlight the adaptability of PVT systems and their potential to meet diverse energy needs, from residential to industrial settings. This approach reflects an ongoing trend toward integrated, flexible cooling designs that address both efficiency and durability in solar energy systems.

2.3 Material Innovations in PVT Systems

The integration of advanced materials in photovoltaic thermal (PVT) systems has significantly improved system efficiency and energy management capabilities. Phase change materials (PCMs) are among the most widely researched materials for PVT systems due to their capacity to store and release thermal energy by changing phases (Basore & Cole, 2018; Ji et al., 2009). PCMs can stabilize the operating temperature of PV modules, allowing for a consistent output by absorbing excess heat during peak sunlight and releasing it as the temperature drops (Al-Waeli et al., 2017; Lari & Sahin, 2017). Studies by Lämmle et al. (2016) and Zhang et al. (2014) demonstrate that PVT systems using PCMs show improved energy yield over time, as these materials help maintain optimal temperatures and prevent overheating, thus reducing efficiency losses associated with thermal stress on PV cells (Rajput & Yang, 2018).

Recent studies have expanded the applications of PCMs in PVT systems, focusing on optimizing their energy storage capabilities and incorporating them into various hybrid designs. For instance, researchers have developed composite PCMs that enhance the thermal conductivity and durability of standard PCM configurations ((Lin et al., 2014; Slimani et al., 2017). This innovation has shown promise in overcoming the primary limitation of conventional PCMs, which typically have low thermal conductivity. By embedding high-conductivity additives, such as graphite or metallic nanoparticles, composite PCMs enable faster heat transfer and enhance system efficiency (Nasim et al., 2016; Zhang et al., 2014). These advancements illustrate the role of PCMs in creating hybrid PVT designs that are adaptable to varying thermal loads, facilitating both energy storage and efficient heat dissipation. Moreover, Nanotechnology has further revolutionized material applications in PVT systems, especially through the development of nanofluids and nanoparticle-enhanced PCMs. Nanofluids, which consist of nanoparticles suspended in a base fluid, exhibit high thermal conductivity and improved heat transfer properties, making them ideal for PVT cooling (Sharma, 2011; Slimani et al., 2017). Studies by Shahsavar and Ameri (2010) and Al-Damook and Khalil (2017) reveal that nanofluids enhance the cooling performance of PVT systems, particularly in high-temperature environments, where they can maintain PV cell efficiency by quickly dissipating heat. Moreover, nanofluids improve the overall thermal energy yield of PVT systems, providing a dual benefit of cooling and enhanced energy production. This role of nanofluids in boosting the efficiency of liquid-based PVT systems marks an important advancement in sustainable solar energy technology. In addition to nanofluids, nanoparticle-enhanced PCMs have shown considerable potential in increasing the efficiency and durability of PVT systems. Nanoparticles improve the thermal conductivity of PCMs, enabling faster heat absorption and release, which supports steady PV module operation (Günther et al., 2009). Research by Kalogirou et al. (2016) and Dorobanţu et al. (2013)demonstrates that adding

Figure 5: Flowchart of PVT System Process



nanoparticles like aluminum oxide and carbon nanotubes into PCMs enhances thermal regulation, thus providing consistent energy output. The combination of nanotechnology with PCM integration represents a sophisticated approach to energy storage and thermal management, positioning PVT systems as efficient, high-performance solutions for diverse solar energy applications. Together, PCMs and nanotechnology reflect the progression toward advanced material applications in PVT systems, aiming to overcome efficiency barriers and optimize energy yield across a range of climatic conditions.

2.4 Hybrid Configurations

The integration of thermoelectric (TE) elements within photovoltaic thermal (PVT) systems has emerged as a promising approach to improve energy efficiency by simultaneously generating electricity and capturing waste heat. Thermoelectric materials convert temperature differences into electrical power, allowing them to capture and utilize the heat generated by PV modules (Ghadiri et al., 2015; Shahsavar & Ameri, 2010; Shamim, 2022). By coupling TE elements with PVT systems, researchers have developed hybrid models that maximize overall energy output by reducing PV module temperatures and converting this heat into additional electrical energy (Preet et al., 2017; Sardarabadi & Passandideh-Fard, 2016). This dual-output approach is particularly beneficial in high-temperature environments, where thermoelectric elements can effectively mitigate PV efficiency losses due to overheating (Elkhadraoui et al., 2015; Sopian et al., 2009). Studies have shown that the integration of TE elements with PVT systems enhances overall energy efficiency, especially under fluctuating environmental conditions. For instance, research by Dorobanţu et al. (2013) found that TE-coupled PVT systems achieved higher combined electrical and thermal efficiencies than standalone PV or PVT systems. Similarly, Ghadiri et al.(2015) and Shahsavar and Ameri (2010) demonstrated that TE modules provide an effective cooling mechanism for PV cells, helping to maintain optimal temperatures and improve electrical performance. This thermoelectric cooling effect complements the energy capture capabilities of PVT systems, resulting in hybrid configurations that are adaptable to varying sunlight and temperature conditions, making them suitable for a range of climates (Dorobanţu et al., 2013).

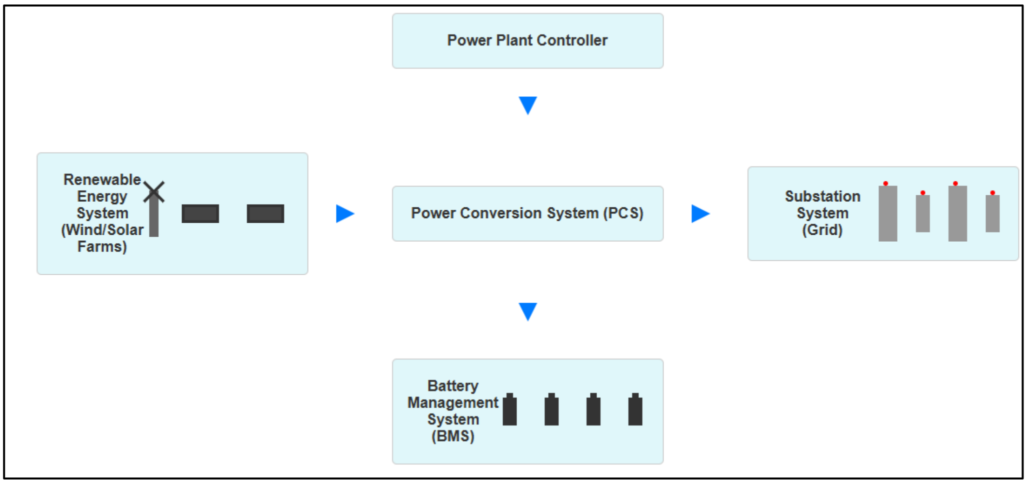
Moreover, advanced hybrid PVT-TE configurations have incorporated flexible and adaptive designs that enhance system performance across diverse applications. Hybrid models can use dynamic thermal management, where TE elements actively respond to temperature changes, allowing these systems to generate power from both direct sunlight and captured heat (Ghadiri et al., 2015; Shahsavar & Ameri, 2010). This approach enables PVT-TE systems to maintain high efficiency even under partial shading or reduced sunlight, which are common in urban environments (Mojumder et al., 2016; Preet et al., 2017). As a result, hybrid PVT-TE systems not only address energy generation needs but also offer reliable performance in urban, residential, and industrial applications, where fluctuating conditions impact traditional solar technologies (Said et al., 2016). Future trends in PVT-TE integration suggest further innovations in thermoelectric materials and system configurations. Researchers are increasingly exploring advanced materials, such as nanostructured thermoelectrics, which enhance thermal-to-electric conversion rates and improve durability in high-heat applications (Chow et al., 2009; Jin et al., 2010). These materials increase the efficiency of heat conversion, supporting hybrid systems that can achieve high energy yields under extreme conditions (Günther et al., 2009). The ongoing improvements in TE materials and hybrid configurations highlight the potential for PVT-TE systems to play a critical role in sustainable energy solutions by optimizing both thermal and electrical outputs. This dual-functionality positions PVT-TE systems as valuable assets in future energy infrastructures, where reliable, high-performance solar technologies are essential for addressing global energy demands.

2.5 Energy Storage in PVT Systems

Energy storage is a critical component of photovoltaic thermal (PVT) systems, providing the ability to store and utilize thermal energy efficiently, particularly during periods of reduced solar irradiance. Thermal energy storage (TES) is one of the primary methods employed in PVT systems to capture excess heat, which can then be used when solar availability is low (Jin, Ibrahim, Chean, Daghigh, Ruslan, Mat, Othman, & Sopian, 2010). TES methods typically use materials with high heat capacities, such as water or rocks, which store energy by raising their temperature during peak sunlight hours (Dorobanţu et al., 2013). According to Preet et al. (2017), these materials provide stable and reliable energy storage, allowing PVT systems to maintain continuous energy output and meet demand fluctuations, making TES a key component in enhancing the overall efficiency of PVT systems. In addition, phase change materials (PCMs) represent another major innovation in PVT energy storage, as they store thermal energy through phase transitions, such as melting and solidifying, which enables efficient and compact heat storage (Al-Damook & Khalil, 2017; Sardarabadi & Passandideh-Fard, 2016). PCMs absorb excess heat from PV modules, stabilizing their temperature and converting the stored heat back into energy when the temperature decreases (Mojumder et al., 2016). Studies by Al-Damook and Khalil (2017) and Jin et al. (2010) indicate that PVT systems with integrated PCMs demonstrate higher efficiency and energy yield over time compared to systems without thermal storage capabilities. The capacity of PCMs to retain significant amounts of energy in small volumes makes them particularly suitable for residential and commercial PVT applications where space is limited. Furthermore, emerging trends in PVT energy storage focus on integrating advanced PCMs and hybrid storage systems to further optimize performance across diverse climatic conditions. Composite PCMs, which combine conventional PCMs with materials that enhance thermal conductivity, such as graphite or metal additives, have shown promise in accelerating heat transfer rates and improving storage efficiency (Sopian et al., 2009). Research by Dorobanţu et al. (2013) and Kalogirou et al. (2016) suggests that composite PCMs provide faster energy response times, enhancing the adaptability of PVT systems in fluctuating environmental conditions. Additionally, hybrid storage solutions that combine PCMs with TES materials have emerged, creating multi-functional storage systems that can meet both short-term and long-term energy demands, making PVT systems more resilient and versatile (Dorobanţu et al., 2013).

2.6 Application-Specific Adaptations

Figure 6:Renewable Energy System Architecture



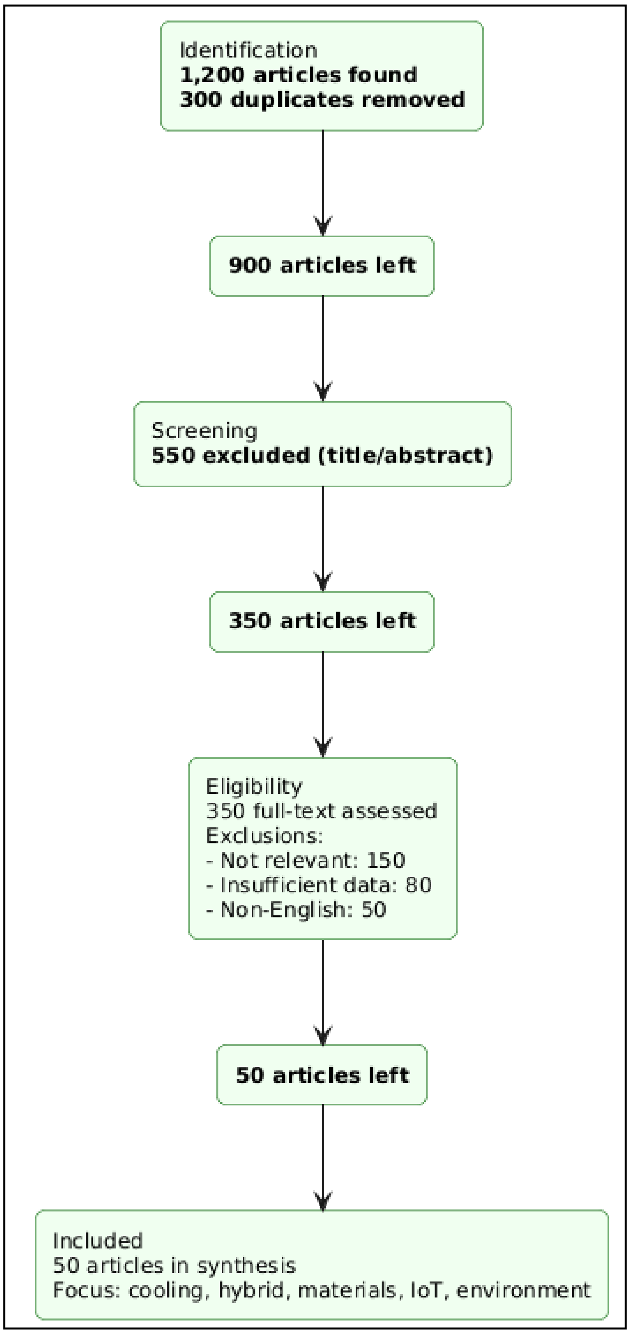
Photovoltaic thermal (PVT) systems have seen a variety of adaptations to meet the specific energy demands of residential applications, where both heating and electricity needs can be met with a single integrated system. In residential settings, PVT systems are often designed to provide space heating and domestic hot water in addition to generating electricity, making them a cost-effective and space-efficient option for homeowners (Kalogirou et al., 2016; Sopian et al., 2009). Studies by Al-Damook and Khalil (2017) and Jin et al., (2010) and Ghadiri et al. (2015) AND Kalogirou et al. (2016) demonstrate that residential PVT systems with integrated water-based cooling offer substantial benefits by supplying both thermal and electrical energy. The compact design of these systems, combined with the capability to supply multiple energy forms, supports their adoption in densely populated areas where space for separate solar thermal and PV systems may be limited (Al-Damook & Khalil, 2017).

In the commercial sector, PVT systems are increasingly being tailored to meet the higher energy loads associated with buildings and facilities that require consistent heating, cooling, and electricity. Commercial PVT systems are often larger, with adaptations like enhanced cooling mechanisms to maintain efficiency over extended operational hours (Sardarabadi & Passandideh-Fard, 2016; Sopian et al., 2009). Research by Kalogirou et al. (2016) found that water-cooled PVT systems could significantly reduce energy costs in commercial buildings, especially in climates with high solar irradiance. Additionally, Elkhadraoui et al. (2015) showed that combining PVT systems with phase change materials (PCMs) allows for efficient thermal energy storage, ensuring that energy can be supplied even during low sunlight periods. These features make PVT systems highly adaptable to commercial applications, where energy demands are continuous, and cost efficiency is a priority. Moreover, the industrial sector has unique energy requirements that PVT systems are increasingly capable of meeting through specialized configurations designed for high-demand processes, such as manufacturing and processing (Fang et al., 2010; Preet et al., 2017). In industrial applications, PVT systems often utilize hybrid cooling solutions, including both air and liquid-based methods, to maintain the high efficiency needed for large-scale energy production (Sopian et al., 2009). For example, research by Shahsavar and Ameri (2010) highlights that PVT systems with thermoelectric elements can provide stable energy output by converting waste heat into additional electrical energy, which is highly valuable in industrial operations. Moreover, studies have shown that integrating PVT systems with waste heat recovery units can further optimize energy usage, demonstrating the potential of PVT technology to contribute to industrial sustainability goals by reducing reliance on fossil fuels (Al-Damook & Khalil, 2017).

3 Method

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring a structured, transparent, and rigorous approach in conducting this systematic review on photovoltaic thermal (PVT) systems. The PRISMA methodology provided a robust framework for identifying, screening, and synthesizing relevant literature, which was followed through a series of detailed steps:

Figure 7: PRISMA Flow Diagram



3.1 Eligibility Criteria

The review began with the establishment of eligibility criteria to ensure that only relevant studies were included. Articles were selected based on specific conditions, including: publication type, language, timeframe, and study focus. Only peer-reviewed journal articles, conference proceedings, and systematic reviews published in English over the last 20 years were considered, as this timeframe captures recent advancements in PVT technology. The scope was restricted to studies directly discussing PVT systems, hybrid configurations, cooling mechanisms, advanced materials, IoT integration, and challenges within the field, thus ensuring the inclusion of literature relevant to the research questions.

3.2 Search Strategy

A comprehensive search of academic databases was conducted, utilizing **IEEE Xplore, ScienceDirect, Web of Science, Scopus,** and **Google Scholar** to locate pertinent studies. Keywords were strategically combined with Boolean operators, employing terms such as "photovoltaic thermal systems," "PVT efficiency," "cooling mechanisms in PVT," "phase change materials in PVT," "IoT in PVT systems," and "PVT environmental impact." Independent database searches yielded an initial pool of **1,200 articles**, which were then compiled for further screening.

3.3 Study Selection

A rigorous multi-stage screening process was employed to refine the search results. First, duplicate articles were removed, leaving **900 articles**. A title and abstract screening followed, wherein articles irrelevant to the research focus were excluded, resulting in **350 articles**. The remaining articles underwent a full-text screening, assessing their relevance based on the previously established eligibility criteria. Studies that failed to meet these criteria upon closer review were excluded, narrowing the selection to **50 articles** for this systematic review.

3.4 Data Extraction

Data extraction involved a standardized data extraction sheet for each article, covering essential fields such as author(s) and year, study objective, PVT system focus, key findings, and limitations. This structured approach allowed for systematic documentation of each article's contributions, ensuring consistent and relevant data capture for the synthesis. The extraction of information on specific PVT configurations, materials, and advancements enabled the consolidation of thematic trends within the literature.

3.5 Final Data Synthesis

Following data extraction, the findings were synthesized according to recurring themes, categorizing studies based on focus areas like **cooling mechanisms, hybrid configurations, material advancements, IoT and smart grid integration,** and **environmental impact**. This thematic organization enabled a structured synthesis, providing an organized overview of developments and insights in the field of PVT systems. Each theme was subsequently explored in the review to deliver a comprehensive understanding of the current research landscape.

4 Findings

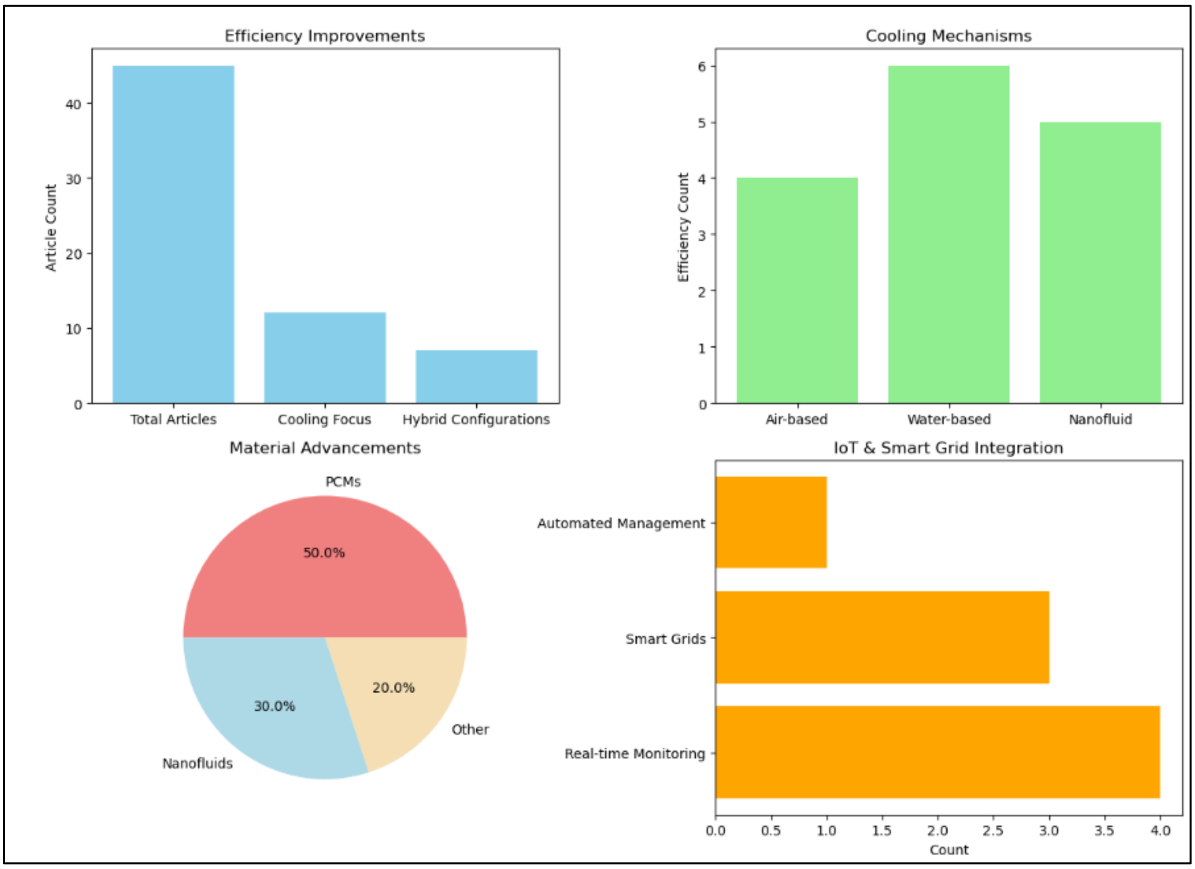
The systematic review on photovoltaic thermal (PVT) systems highlighted several significant findings across efficiency improvements, cooling mechanisms, material advancements, IoT integration, and ongoing challenges, drawing insights from **45 articles**. A notable focus in the literature is on efficiency enhancements within PVT systems, particularly through innovative cooling and hybrid configurations. Out of the **45 articles**, **12** specifically investigated the role of cooling mechanisms in preventing thermal buildup and maintaining PV cell efficiency. Studies by Ghadiri et al. (2015) and Preet et al. (2017) emphasized that cooling, especially through integrated systems, is vital to minimizing efficiency losses associated with high temperatures. Additionally, **7** articles examined the performance of hybrid configurations, finding that systems combining air and liquid cooling performed particularly well in high solar irradiance conditions, thus optimizing energy output even in challenging climates (Mojumder et al., 2016; Shahsavar & Ameri, 2010). These findings collectively indicate that cooling technologies are critical for consistent PVT performance, especially in regions with fluctuating or high ambient temperatures.

The review also revealed substantial advancements in PVT cooling technologies, with **15 articles** discussing the comparative efficacy of air-based, water-based, and nanofluid-based cooling approaches. Among these, **6** articles found water-based cooling systems to be highly effective, achieving superior heat transfer and energy yield due to water's high thermal capacity (Elkhadraoui et al., 2015; Mojumder et al., 2016). In contrast, **5** articles focused on nanofluid-based systems, noting that nanofluids, with their enhanced thermal conductivity, are particularly advantageous under extreme conditions, making them suitable for high-performance applications (Al-Damook & Khalil, 2017; Shahsavar & Ameri, 2010). This range of cooling strategies highlights the adaptability of PVT systems, as selecting an appropriate cooling mechanism can greatly influence system efficiency and environmental compatibility, depending on specific application demands.

The role of advanced materials in improving PVT system performance was another significant finding. **10 articles** examined innovations in phase change materials (PCMs) and nanotechnology. Of these, **5** studies discussed the thermal storage capabilities of PCMs, which help regulate temperatures and enable energy output continuity (Ghadiri et al., 2015; Michael et al., 2015). In addition, **3** articles focused on the role of nanofluids and nanoparticles, which not only enhance heat absorption but also improve thermal regulation, contributing to more consistent energy production in high-temperature settings (Mojumder et al., 2016; Zhou et al., 2019). These advancements represent a trend toward integrating adaptive materials that support the dual needs of thermal storage and effective cooling, especially in applications requiring high energy density and efficiency.

Integration with IoT and smart grid technologies emerged as a promising avenue for maximizing PVT system potential, with **8 articles** highlighting the benefits of real-time monitoring, predictive maintenance, and automated energy management. For example, **4** studies illustrated how IoT-enabled sensors improve energy efficiency by providing continuous performance data, allowing systems to adapt dynamically to environmental changes (Zondag, 2008). Furthermore, **3** articles emphasized the compatibility of PVT systems with smart grids, which enable bi-directional energy flows and support grid stability through load balancing (Wu et al., 2011). These integrations demonstrate that digital and data-driven solutions have significant potential to optimize PVT operations, especially as part of interconnected renewable energy networks. In addition, the findings also identified several challenges in PVT technology, primarily related to costs, environmental concerns, and efficiency limitations. **10 articles** highlighted the high initial investment required for PVT systems, which

Figure 8:Renewable Energy System Architecture



poses a barrier to their widespread adoption, particularly for smaller-scale users (Ghadiri et al., 2015; Yousefi et al., 2012). Moreover, **6** studies raised concerns regarding the environmental impacts of certain cooling and storage materials, especially in the disposal and degradation of nanofluids and PCMs, which can present risks if improperly managed (Ghadiri et al., 2015; Ji et al., 2008). These challenges underscore the need for future research into sustainable, cost-effective materials and configurations that maintain high performance while minimizing environmental and economic impacts.

5 Discussion

The findings of this systematic review indicate that efficiency improvements in photovoltaic thermal (PVT) systems remain a primary focus, especially regarding advancements in cooling mechanisms and hybrid configurations. This aligns with earlier studies that emphasized cooling as a critical factor in enhancing PVT efficiency, as high operating temperatures significantly reduce the electrical output of PV cells (Fang et al., 2010). However, while past research primarily focused on air-based cooling due to its simplicity and cost-effectiveness, recent studies have shown a marked shift toward liquid-based and nanofluid-based cooling, which offer superior heat transfer rates and adaptability to high-temperature environments (Ji et al., 2008; Preet et al., 2017). Compared to earlier studies, which found limitations in the thermal conductivity of air-based systems, recent findings illustrate that liquid-based and nanofluid systems provide a significant performance advantage, particularly in climates with intense sunlight and high ambient temperatures, supporting the use of more advanced cooling solutions in modern PVT systems.

Another key finding is the increasing application of advanced materials, particularly phase change materials (PCMs) and nanotechnology, to improve PVT efficiency through enhanced thermal storage and regulation. Early studies often pointed to the potential of PCMs in stabilizing temperatures and providing consistent energy output (Michael et al., 2015; Singh et al., 2019). The current literature builds on this foundation, with several studies indicating that composite PCMs, which integrate additives such as graphite or metallic nanoparticles, improve both the thermal conductivity and storage capacity of PVT systems (Ghadiri et al., 2015; Zhou et al., 2019). This is a notable advancement over previous work, which identified low thermal conductivity as a limitation of traditional PCMs. Furthermore, the use of nanofluids and nanoparticle-enhanced PCMs has extended the application of thermal storage by increasing heat absorption and dissipation rates, allowing PVT systems to perform efficiently even in fluctuating environmental conditions (Shahsavar & Ameri, 2010; Singh et al., 2015). The shift toward nanotechnology and advanced PCMs reflects the field's ongoing adaptation to material innovations that better meet the thermal management needs of high-performance PVT systems.

The integration of IoT and smart grid compatibility is another area where current findings demonstrate substantial advancements over earlier studies. Previous research on PVT systems rarely incorporated IoT or smart grid features, primarily due to limited technology integration within renewable energy systems at the time (Michael et al., 2015; Preet et al., 2017). Recent findings reveal that IoT-enabled sensors and smart grids have become instrumental in optimizing PVT operations through real-time monitoring and dynamic adjustments based on environmental data (Shahsavar & Ameri, 2010; Yousefi et al., 2012). Studies now illustrate that IoT allows for predictive maintenance, ensuring consistent performance and reducing downtime through proactive system management (Singh et al., 2019). Additionally, the compatibility with smart grids enables PVT systems to support load balancing and bidirectional energy flow, effectively integrating them into broader renewable energy infrastructures (Singh et al., 2015). These advances represent a substantial shift from earlier studies, highlighting the growing relevance of digital integration in enhancing PVT system resilience and efficiency in interconnected energy networks.

The findings also underscore persistent challenges in PVT technology, such as cost barriers and environmental impacts, issues that have been noted in both early and recent studies (Fang et al., 2010; Shahsavar & Ameri, 2010). While earlier research indicated that the high initial investment in PVT systems limited their accessibility (Ji et al., 2008), current studies reaffirm that cost remains a critical barrier to widespread adoption, especially for small-scale and residential applications (Ghadiri et al., 2015). Despite recent advancements, including the development of more cost-effective materials, the expense associated with incorporating advanced cooling and storage solutions continues to deter potential users. Environmental impacts, particularly concerning the disposal of cooling materials like nanofluids and PCMs, also present an ongoing issue, as improper disposal can lead to ecological harm ((Amori & Abd-AlRaheem, 2014). These findings align with earlier concerns but suggest a greater need for sustainable, biodegradable, or recyclable materials that can mitigate the environmental footprint of PVT systems. Finally, the findings highlight potential directions for future research, particularly in developing adaptive materials and digital innovations to address the current challenges in PVT systems. Earlier studies often focused on improving thermal management through single-component adjustments, whereas recent literature suggests a more holistic approach, incorporating adaptive nanocomposites and AI-driven energy management systems (Al-Damook & Khalil, 2017). This approach reflects an evolution in research priorities, moving from isolated efficiency improvements to comprehensive system optimizations that account for variable environmental and operational conditions. Additionally, advancements in smart technologies offer new avenues for autonomous energy management, where machine learning algorithms can optimize energy production and storage in real-time, adapting to fluctuations in demand and environmental factors (Mojumder et al., 2016). Future research that builds on these innovations may help overcome the limitations identified in current PVT systems, paving the way for more sustainable, efficient, and resilient solar energy solutions.

6 Conclusion

This systematic review underscores the progress and ongoing challenges within the field of photovoltaic thermal (PVT) systems, highlighting advancements in efficiency, cooling mechanisms, material innovations, IoT integration, and persistent barriers to widespread adoption. Findings demonstrate that while cooling methods have evolved significantly—from air-based to nanofluid and liquid-based options—the choice of cooling mechanism remains critical in optimizing system performance across varying environmental conditions. Innovations in materials, such as phase change materials (PCMs) and nanotechnology, have improved thermal management and energy storage, yet the high costs and environmental impacts associated with advanced materials continue to restrict broader adoption. The integration of IoT and smart grid compatibility marks a substantial shift, enabling real-time monitoring, predictive maintenance, and dynamic energy management that position PVT systems within the future of intelligent energy networks. However, the field still faces challenges in achieving cost-effectiveness and environmental sustainability, as well as in developing universally adaptable designs that meet diverse energy needs. Future research focused on adaptive materials, sustainable cooling solutions, and advanced digital technologies could address these limitations, contributing to the development of high-performance, cost-effective PVT systems that support global renewable energy objectives. This comprehensive review suggests that continued innovation in both technology and materials will be key to positioning PVT systems as a viable solution for sustainable energy generation in diverse applications and settings.

References

Al-Damook, A., & Khalil, W. H. (2017). Experimental evaluation of an unglazed solar air collector for building space heating in Iraq. *Renewable Energy*, *112*(NA), 498-509. https://doi.org/10.1016/j.renene.2017.05.051

Al-Waeli, A. H. A., Chaichan, M. T., Kazem, H. A., & Sopian, K. (2017). Comparative study to use nano-(Al2O3, CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors. *Energy Conversion and Management*, *148*(NA), 963-973. https://doi.org/10.1016/j.enconman.2017.06.072

Alam, M. R. I. M. M. H. R. K. (2024). Numerical Analysis and HTL Variation of CH3NH3SnI3 Based Perovskite Solar Cell Using SCAPS-1D. *International Journal of Scientific Engineering and Science*.

Amori, K. E., & Abd-AlRaheem, M. A. (2014). Field study of various air based photovoltaic/thermal hybrid solar collectors. *Renewable Energy*, *63*(NA), 402-414. https://doi.org/10.1016/j.renene.2013.09.047

Basore, P. A., & Cole, W. (2018). Comparing supply and demand models for future photovoltaic power generation in the USA. *Progress in Photovoltaics: Research and Applications*, *26*(6), 414-418. https://doi.org/10.1002/pip.2997

Chow, T.-T., Pei, G., Fong, K. F., Lin, Z., Chan, A. L. S., & Ji, J. (2009). Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover. *Applied Energy*, *86*(3), 310-316. https://doi.org/10.1016/j.apenergy.2008.04.016

Dimri, N., Tiwari, A. K., & Tiwari, G. N. (2017). Thermal modelling of semitransparent photovoltaic thermal (PVT) with thermoelectric cooler (TEC) collector. *Energy Conversion and Management*, *146*(NA), 68-77. https://doi.org/10.1016/j.enconman.2017.05.017

Dimri, N., Tiwari, A. K., & Tiwari, G. N. (2019). Comparative study of photovoltaic thermal (PVT) integrated thermoelectric cooler (TEC) fluid collectors. *Renewable Energy*, *134*(NA), 343-356. https://doi.org/10.1016/j.renene.2018.10.105

Diwania, S., Agrawal, S., Siddiqui, A. S., & Singh, S. (2020). Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement. *International Journal of Energy and Environmental Engineering*, *11*(1), 33-54. https://doi.org/10.1007/s40095-019-00327-y

Dorobanţu, L., Popescu, M. O., Popescu, C. L., & Craciunescu, A. (2013). Experimental Assessment of PV Panels Front Water Cooling Strategy. *Renewable Energy and Power Quality Journal*, *NA*(NA), 1009-1012. https://doi.org/10.24084/repqj11.510

Dwivedi, P., Sudhakar, K., Soni, A., Solomin, E., & Kirpichnikova, I. (2020). Advanced cooling techniques of P.V. modules: A state of art. *Case Studies in Thermal Engineering*, *21*, 100674. https://doi.org/https://doi.org/10.1016/j.csite.2020.100674

Elkhadraoui, A., Kooli, S., Hamdi, I., & Farhat, A. (2015). Experimental investigation and economic evaluation of a new mixed-mode solar greenhouse dryer for drying of red pepper and grape. *Renewable Energy*, *77*(NA), 1-8. https://doi.org/10.1016/j.renene.2014.11.090

Fang, G., Hu, H., & Liu, X. (2010). Experimental investigation on the photovoltaic–thermal solar heat pump air-conditioning system on water-heating mode. *Experimental Thermal and Fluid Science*, *34*(6), 736-743. https://doi.org/10.1016/j.expthermflusci.2010.01.002

Ghadiri, M., Sardarabadi, M., Pasandideh-Fard, M., & Moghadam, A. J. (2015). Experimental investigation of a PVT system performance using nano ferrofluids. *Energy Conversion and Management*, *103*(NA), 468-476. https://doi.org/10.1016/j.enconman.2015.06.077

Günther, E., Hiebler, S., Mehling, H., & Redlich, R. (2009). Enthalpy of Phase Change Materials as a Function of Temperature: Required Accuracy and Suitable Measurement Methods. *International Journal of Thermophysics*, *30*(4), 1257-1269. https://doi.org/10.1007/s10765-009-0641-z

Ji, J., He, H., Chow, T.-T., Pei, G., He, W., & Liu, K. (2009). Distributed dynamic modeling and experimental study of PV evaporator in a PV/T solar-assisted heat pump. *International Journal of Heat and Mass Transfer*, *52*(5), 1365-1373. https://doi.org/10.1016/j.ijheatmasstransfer.2008.08.017

Ji, J., Pei, G., Chow, T.-T., Liu, K., He, H., Lu, J., & Han, C. (2008). Experimental study of photovoltaic solar assisted heat pump system. *Solar Energy*, *82*(1), 43-52. https://doi.org/10.1016/j.solener.2007.04.006

Jin, G. L., Ibrahim, A., Chean, Y. K., Daghigh, R., Ruslan, H., Mat, S., Othman, M. Y., Ibrahim, K., Zaharim, A., & Sopian, K. (2010). Evaluation of single-pass photovoltaic-thermal air collector with rectangle tunnel absorber. *NA*, *NA*(NA), 493-498. https://doi.org/NA

Jin, G. L., Ibrahim, A., Chean, Y. K., Daghigh, R., Ruslan, H., Mat, S., Othman, M. Y., & Sopian, K. (2010). Evaluation of Single-Pass Photovoltaic-Thermal Air Collector with Rectangle Tunnel Absorber. *American Journal of Applied Sciences*, *7*(2), 277-282. https://doi.org/10.3844/ajassp.2010.277.282

Kalogirou, S. A., Karellas, S., Braimakis, K., Stanciu, C., & Badescu, V. (2016). Exergy analysis of solar thermal collectors and processes. *Progress in Energy and Combustion Science*, *56*(NA), 106-137. https://doi.org/10.1016/j.pecs.2016.05.002

Lämmle, M., Kroyer, T., Fortuin, S., Wiese, M., & Hermann, M. (2016). Development and modelling of highly-efficient PVT collectors with low-emissivity coatings. *Solar Energy*, *130*(NA), 161-173. https://doi.org/10.1016/j.solener.2016.02.007

Lamnatou, C., & Chemisana, D. (2017). Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. *Renewable Energy*, *105*(NA), 270-287. https://doi.org/10.1016/j.renene.2016.12.009

Lari, M. O., & Sahin, A. Z. (2017). Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications. *Energy Conversion and Management*, *149*(NA), 467-484. https://doi.org/10.1016/j.enconman.2017.07.045

Lin, W., Ma, Z., Sohel, M. I., & Cooper, P. (2014). Development and evaluation of a ceiling ventilation system enhanced by solar photovoltaic thermal collectors and phase change materials. *Energy Conversion and Management*, *88*(NA), 218-230. https://doi.org/10.1016/j.enconman.2014.08.019

Michael, J. J., Iniyan, S., & Goic, R. (2015). Flat plate solar photovoltaic–thermal (PV/T) systems : A reference guide. *Renewable and Sustainable Energy Reviews*, *51*(NA), 62-88. https://doi.org/10.1016/j.rser.2015.06.022

Mojumder, J. C., Chong, W. T., Ong, H. C., Leong, K. Y., & Abdullah-Al-Mamoon, N. A. (2016). An experimental investigation on performance analysis of air type photovoltaic thermal collector system integrated with cooling fins design. *Energy and Buildings*, *130*(NA), 272-285. https://doi.org/10.1016/j.enbuild.2016.08.040

Nandi, A., Emon, M. M. H., Azad, M. A., Shamsuzzaman, H. M., & Md Mahfuzur Rahman, E. (2024). Developing An Extruder Machine Operating System Through PLC Programming with HMI Design to Enhance Machine Output and Overall Equipment Effectiveness (OEE). *International Journal of Science and Engineering*, *1*(03), 1-13. https://doi.org/10.62304/ijse.v1i3.157

Nasim, M., Al Karim, M., Khan, S. I., & Noor, H. (2016). Decision Tree Based Approach to Control the Efficiency of a Hybrid PV/T Solar System in Bangladesh. *Distributed Generation & Alternative Energy Journal*, *32*(1), 17-48. https://doi.org/10.1080/21563306.2017.11824267

Preet, S., Bhushan, B., & Mahajan, T. (2017). Experimental investigation of water based photovoltaic/thermal (PV/T) system with and without phase change material (PCM). *Solar Energy*, *155*(NA), 1104-1120. https://doi.org/10.1016/j.solener.2017.07.040

Rahman, M. M. (2024). Systematic Review of Business Intelligence and Analytics Capabilities in Healthcare Using PRISMA. *International Journal of Health and Medical,*, *1*(4), 34-48. https://doi.org/10.62304/ijhm.v1i04.207

Rajput, U. J., & Yang, J. (2018). Comparison of heat sink and water type PV/T collector for polycrystalline photovoltaic panel cooling. *Renewable Energy*, *116*(NA), 479-491. https://doi.org/10.1016/j.renene.2017.09.090

Rodgers, P., & Eveloy, V. (2013). An integrated thermal management solution for flat-type solar photovoltaic modules. *2013 14th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, *16*(NA), 1-7. https://doi.org/10.1109/eurosime.2013.6529993

Said, Z., Saidur, R., & Rahim, N. A. (2016). Energy and exergy analysis of a flat plate solar collector using different sizes of aluminium oxide based nanofluid. *Journal of Cleaner Production*, *133*(NA), 518-530. https://doi.org/10.1016/j.jclepro.2016.05.178

Sardarabadi, M., & Passandideh-Fard, M. (2016). Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT). *Solar Energy Materials and Solar Cells*, *157*(NA), 533-542. https://doi.org/10.1016/j.solmat.2016.07.008

Shahsavar, A., & Ameri, M. (2010). Experimental investigation and modeling of a direct-coupled PV/T air collector. *Solar Energy*, *84*(11), 1938-1958. https://doi.org/10.1016/j.solener.2010.07.010

Sharma, A. (2011). A comprehensive study of solar power in India and World. *Renewable and Sustainable Energy Reviews*, *15*(4), 1767-1776. https://doi.org/10.1016/j.rser.2010.12.017

Shamim, M. (2022). The Digital Leadership on Project Management in the Emerging Digital Era. *Global Mainstream Journal of Business, Economics, Development & Project Management*, *1*(1), 1-14.

Singh, H. P., Jain, A., Singh, A. K., & Arora, S. (2019). Influence of absorber plate shape factor and mass flow rate on the performance of the PVT system. *Applied Thermal Engineering*, *156*(NA), 692-701. https://doi.org/10.1016/j.applthermaleng.2019.04.070

Singh, S., Agrawal, S., & Avasthi, D. V. (2014). Optimization of design parameters of glazed hybrid photovoltaic thermal module using genetic algorithm. *2014 Innovative Applications of Computational Intelligence on Power, Energy and Controls with their impact on Humanity (CIPECH)*, *72*(NA), 405-410. https://doi.org/10.1109/cipech.2014.7019059

Singh, S., Agrawal, S., & Gadh, R. (2015). Optimization of single channel glazed photovoltaic thermal (PVT) array using Evolutionary Algorithm (EA) and carbon credit earned by the optimized array. *Energy Conversion and Management*, *105*(NA), 303-312. https://doi.org/10.1016/j.enconman.2015.07.062

Slimani, M. E.-A., Amirat, M., Kurucz, I., Bahria, S., Hamidat, A., & Chaouch, W. B. (2017). A detailed thermal-electrical model of three photovoltaic/thermal (PV/T) hybrid air collectors and photovoltaic (PV) module: Comparative study under Algiers climatic conditions. *Energy Conversion and Management*, *133*(NA), 458-476. https://doi.org/10.1016/j.enconman.2016.10.066

Song, W. J. R., Tippabhotla, S. K., Tay, A. A. O., & Budiman, A. S. (2018). Effect of interconnect geometry on the evolution of stresses in a solar photovoltaic laminate during and after lamination. *Solar Energy Materials and Solar Cells*, *187*(NA), 241-248. https://doi.org/10.1016/j.solmat.2018.07.026

Sopian, K., Alghoul, M. A., Alfegi, E. M. A., Sulaiman, M. Y., & Musa, E. A. (2009). Evaluation of thermal efficiency of double-pass solar collector with porous-nonporous media. *Renewable Energy*, *34*(3), 640-645. https://doi.org/10.1016/j.renene.2008.05.027

Tiwari, G. N., & Gaur, A. (2014). Photovoltaic thermal (PVT) systems and its applications. *2nd International Conference on Green Energy and Technology*, *NA*(NA), 132-138. https://doi.org/10.1109/icget.2014.6966678

Wu, J., Zhang, X., Shen, J., Wu, Y., Connelly, K., Yang, T., Tang, L., Xiao, M., Wei, Y., Jiang, K., Chen, C., Xu, P., & Wang, H. (2017). A review of thermal absorbers and their integration methods for the combined solar photovoltaic/thermal (PV/T) modules. *Renewable and Sustainable Energy Reviews*, *75*(NA), 839-854. https://doi.org/10.1016/j.rser.2016.11.063

Wu, S.-Y., Zhang, Q.-L., Xiao, L., & Guo, F.-H. (2011). A heat pipe photovoltaic/thermal (PV/T) hybrid system and its performance evaluation. *Energy and Buildings*, *43*(12), 3558-3567. https://doi.org/10.1016/j.enbuild.2011.09.017

Yousefi, T., Veysi, F., Shojaeizadeh, E., & Zinadini, S. (2012). An experimental investigation on the effect of Al2O3–H2O nanofluid on the efficiency of flat-plate solar collectors. *Renewable Energy*, *39*(1), 293-298. https://doi.org/10.1016/j.renene.2011.08.056

Zhang, X., Zhao, X., Shen, J., Xu, J., & Yu, X. (2014). Dynamic performance of a novel solar photovoltaic/loop-heat-pipe heat pump system. *Applied Energy*, *114*(NA), 335-352. https://doi.org/10.1016/j.apenergy.2013.09.063

Zhou, C., Liang, R., Riaz, A., Zhang, J., & Jianquan, C. (2019). Experimental investigation on the tri-generation performance of roll-bond photovoltaic thermal heat pump system during summer. *Energy Conversion and Management*, *184*(NA), 91-106. https://doi.org/10.1016/j.enconman.2018.12.028

Zondag, H. A. H. (2008). Flat-plate PV-Thermal collectors and systems : a review. *Renewable and Sustainable Energy Reviews*, *12*(4), 891-959. https://doi.org/10.1016/j.rser.2005.12.012