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*Review*

# Hybrid Photovoltaic Thermal Systems: Present and Future Feasibilities for Industrial and Building Applications

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**Abstract:** The growing demands of modern life, industrialization, and technological progress have significantly increased energy requirements. However, this heightened need for energy has raised concerns about its impact on the environment and the rising costs associated with it. Therefore, the engineering sector is actively seeking sustainable and cost-effective energy solutions. Among the promising innovations in solving the problem is the photovoltaic thermal system (PVT), which aims to capture electrical and thermal energy from solar radiation. Despite its potential, the application of PVT systems is currently limited due to the unpredictable nature of solar energy and the absence of efficient thermal energy storage capabilities. To address these challenges, researchers have explored the use of phase change materials and nano-improved phase change materials (NEPCMs) to optimize energy extraction from solar systems. By incorporating these materials, the PVT system can maximize energy utilization. This article provides a comprehensive overview of the potential applications of PVT techniques in both industrial and building settings. It also offers a detailed assessment of their commercial and environmental aspects. The research findings highlight several advantages of PVT systems, including reduced electricity consumption, efficient utilization of cooling and heating loads during off-peak periods, improved temperature stability, and enhanced thermal comfort. Furthermore, the integration of NEPCMs in PVT systems has demonstrated superior thermal performance, enabling 8.3% more heat energy storage during charging and 25.1% more heat energy release during discharging. Additionally, the implementation of solar-assisted combined heating and power systems showed the potential to prevent the emission of 911 tons of $CO_2$ per year compared to conventional PV systems. These systems offer a promising pathway towards mitigating environmental impacts while meeting energy demands. Overall, this review article serves as a valuable resource for fellow researchers by providing detailed insights into the viability of PVT systems for various applications in the industrial and building sectors.

**Keywords:** thermal energy storage; phase change materials; hybrid photovoltaic thermal systems; buildings



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## 1. Introduction

The efficient utilization of solar energy, also known as insolation energy, holds the potential to significantly alleviate environmental conservation problems and address global energy demand [1,2]. Photovoltaic (PV) technology is specifically designed to directly convert solar energy into valuable electrical energy [3]. Despite having a higher initial investment than other renewable energy systems, solar PV is widely accepted worldwide due to its lower operational and maintenance costs [4]. Additionally, solar PV offers advantages such as higher efficiency and the generation of pollution-free electricity [5]. Figure 1 illustrates the global installation of solar PV systems, with an estimated installed capacity of 1523 GW by 2023. The installed capacities in 2022, 2021, and 2020 were 1208 GW, 940 GW, and 770 GW, respectively [6,7].

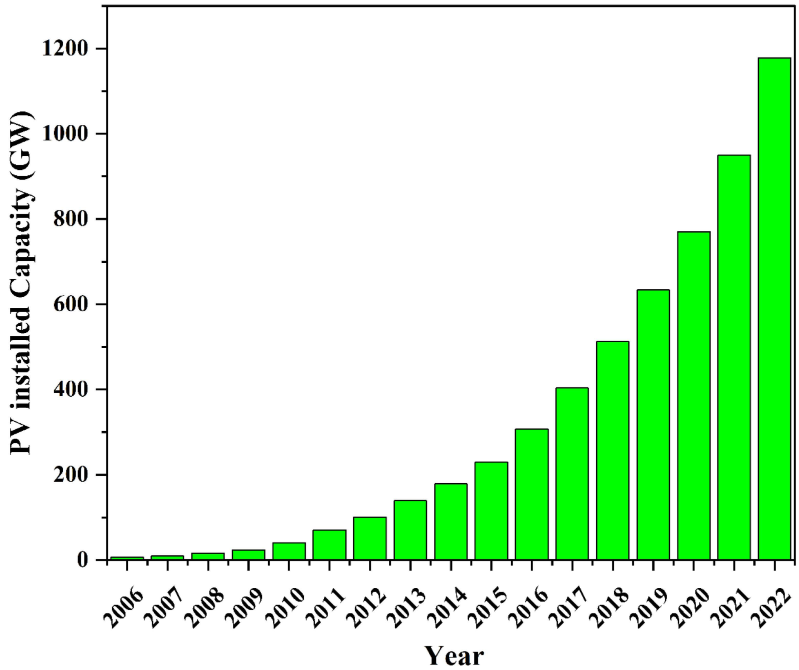


**Figure 1.** Global PV installed capacity [7].

The major limitation of photovoltaic panels is their capacity to convert a fraction of solar radiation into electrical energy, while the remaining energy increases the temperature of the PV cells, negatively impacting their performance. A mere 1 °C increase in the heat of PV cells can decrease electrical productivity by approximately 0.1% to 0.5%, significantly reducing the yield of PV cells, especially under continuous solar radiation [8,9]. Furthermore, increased circuit resistance caused by higher PV cell temperatures decreases electron velocity, affecting the open-circuit voltage and severely impacting the overall material performance of the cell. Therefore, the recommended operational temperature for PV cells is suggested to be within the range of 0 °C to 75 °C. The temperature co-efficient, which represents the rate of voltage decrease per unit temperature rise, defines the temperature dependence of the primary materials used in evaluating the performance of PV cells and highlights the strong relationship between output power and PV panel temperature [10].

For photovoltaic thermal (PVT) systems, where temperature control is crucial, it has been recommended that they incorporate cooling mechanisms into the solar collectors to improve their efficiency [11,12]. Thus, by introducing a heat transfer fluid (HTF) or cooling fluid into the solar collector, heat can be effectively removed from the PV cells, thereby increasing the photoelectric conversion efficiency and maximizing the utilization of waste heat [13,14]. PVT systems are designed to harvest electricity and heat energy simultaneously. The low-grade heat obtained can be used for various purposes, including space heating, industrial process heating, preheating household fluids, and crop drying [15–17]. Compared to conventional PV devices, PVT systems have lower manufacturing and installation costs per unit area and can be highly practical in efficient infrastructures such as buildings, hospitals, or factories [18,19]. This paper is focused on defining PVT systems based on different thermal transport strategies and exploring their integration into various potential frameworks [20]. The categorization of PVT systems for potential applications is based on different system parameters, including absorber plate configuration and fluid flow mechanisms (e.g., single-pass, double-pass, number of channels, normal and forced circulation) [21].

Given the significance of heat transfer and storage capacities in PVT systems, selecting suitable materials for storing heat energy during periods of solar power availability and releasing it when it is unavailable is crucial [22]. Phase change materials (PCMs), which are capable of efficiently storing and releasing heat energy through the process of melting and solidifying, are widely used in thermal energy storage (TES) applications [23,24]. However, the lower thermal conductivity of PCMs poses a challenge [25,26]. To overcome this limitation, researchers have suggested dispersing highly conductive nanomaterials, such as metals, metallic oxides, carbon nanotubes (CNTs), and graphene, within the PCMs. This new class of materials, known as nano-enriched phase change materials (NEPCMs), has become preferred for TES applications in PVT systems due to their higher heat transfer rates, higher storage density, and efficient energy release [27–31].

Multiple articles have been published that classify PVT systems and discuss experimental and numerical studies conducted on various PVT systems [32]. A comprehensive review has examined the performance, design, simulation, and experimental evaluation of different PVT systems, including air- and water-based collectors [33,34]. Studies have analyzed the seasonal performance of PVT systems under different climate conditions and found that simple cooling methods tend to outperform other systems [35]. Thorough analyses have highlighted the potential benefits of PVT systems in terms of energy efficiency, reliability, and long lifespan [36]. Extensive reviews have explored the application of PVT systems in solar water heaters and solar thermal systems with and without PCM for different temperature ranges and residential use [37–39]. Various cooling methods for PVT systems have also been reviewed, focusing on their accomplishments and applications [40,41]. The state-of-the-art solar-based heat pump PVT systems for meeting thermal energy demand in buildings have also been discussed, highlighting integration approaches, feasible arrangements, multiple foundations, and mechanism design [42]. Numerous ongoing scientific studies to enhance the reliability and application of this technology in decarbonizing buildings are also being reported [43]. However, based on the literature and Figure 2, there is a lack of review articles focusing on the industrial applications of PVT systems in terms of their environmental aspects. This article aimed to fill this gap by providing a general classification of PVT systems, discussing cooling methods, exploring industrial and building applications of PVT systems, and analyzing the environmental impacts based on previous studies conducted on various PVT devices. Moreover, this study aimed to assist engineers and researchers who are considering PVT systems for industrial and building facades, by providing them with a better understanding of the effects on electrical and thermal energy for heating and cooling applications.

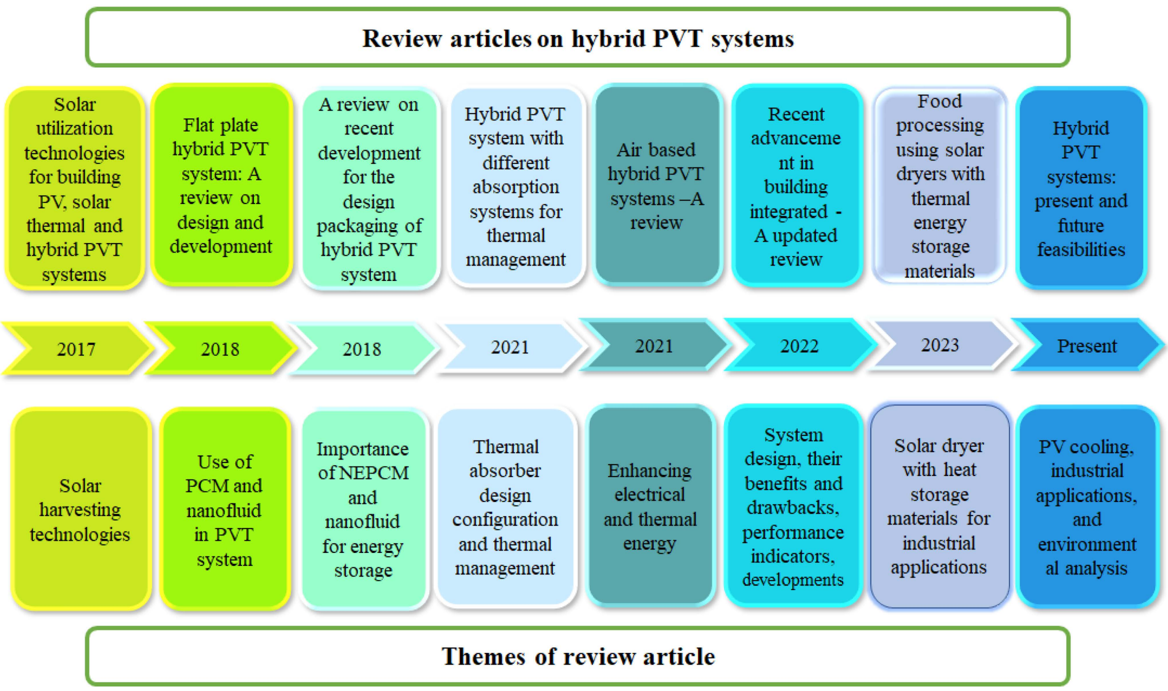


**Figure 2.** Previously published review articles on hybrid PVT system applications [20,44–50].

The present article also includes an analysis of liquid-based spectrum filters in PVT systems, a comparative analysis of PVT technology highlighting its key advantages, challenges, and future potential, and a thorough examination of the impact of PVT system output in industries, as it was noticed that there is a lack of revised and constructive analyses evaluating PVT system industrial applications from both approaches. To fill this gap, the research record on PVT system output was reviewed based on the industrial requirements, and the various factors considered in each analysis were categorized. The use of NEPCM has garnered significant attention due to its positive impact on the thermal regulation of PV units and its ability to improve electricity and thermal energy performance. Thus, this prospect was extensively reviewed based on in-depth articles. Furthermore, various PVT systems for enhancing electricity and thermal energy production were extensively discussed. The literature on experimental applications of hybrid PVT arrangements, with and without PCM, was surveyed, analyzed, and summarized for various industrial applications, including water heating, water desalination, thermal management in buildings, food processing, HVAC, agricultural processes, and thermal power plants. Even though a number of innovative techniques to improve the thermal and electrical performance of PVT systems have been described, it appears that the field of PVT systems that use PCMs and NEPCMs is continuing to grow. According to a search that used the keywords "PVT system, PCM, and NEPCM", it was discovered that the number of publications, which began in the year 2005, grew more than sixty times between the years 2020 and 2023. The specifics of the articles can be obtained from the "Web of Science, Scopus and Science Direct", as shown in Figure 3. From a total of 45,000 publications, approximately 130 articles were chosen for the present review article according to their applicability, suitability and significance. The remaining sections of the article are organized as follows: Section 2 provides a detailed understanding of PVT system behavior and classification, Section 3 focuses on the industrial applications of PVT systems, Section 4 discusses the environmental aspects of PVT systems, Section 5 outlines the technical tasks associated with PVT systems, and Section 6 concludes the article by summarizing the work and suggesting future prospects for this field.

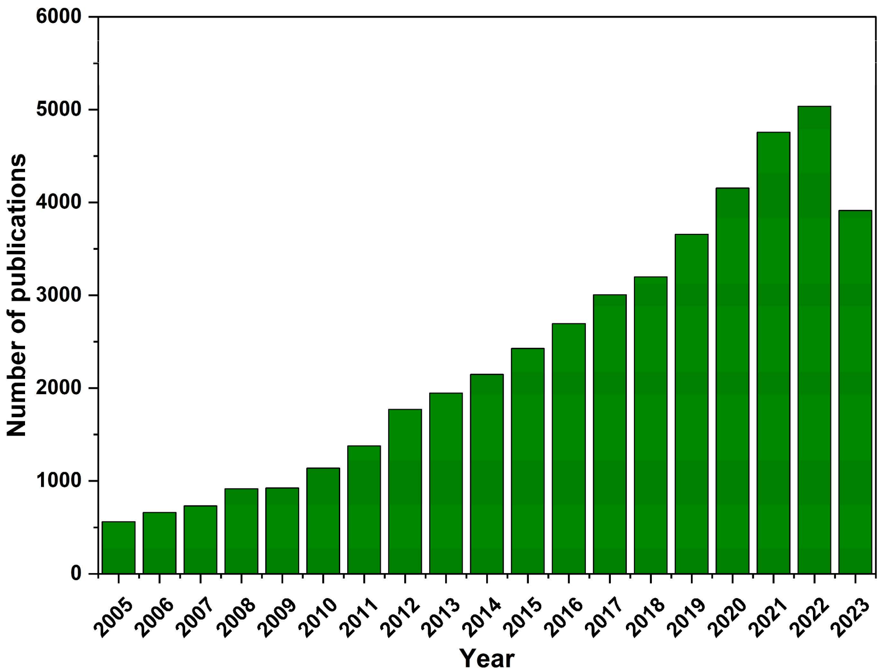


**Figure 3.** Number of journal publications related to PVT systems, PCMs, and NEPCMs for energy production and storage from 2005 to 2023. Sources: Scopus, Web of Science, and Science Direct.

## 2. PVT Systems and Their Performances

The PVT system combines photovoltaics with a thermal collector to convert both electrical and thermal energy simultaneously. This integration enhances solar energy utilization, allowing for greater electricity and thermal energy generation per unit area than standalone solar PV or thermal systems.

Various cooling methods are employed to regulate the temperature of PV panels, depending on whether they are passive or active techniques. A comprehensive and up-to-date exploration of cooling technologies is presented in the following sections, categorized according to the type of heat transfer mechanisms involved. The choice of heat transfer fluid (HTF) used in PVT systems determines their performance and implementation. Historically, air and water have been conventionally used as cooling fluids in PVT systems. In the past three to four decades, extensive research has focused on optimizing traditional fluid-based PVT systems, with numerous studies [51,52] conducted in this area. The following section evaluates the findings of these studies, highlighting the use of air and water as HTFs in PVT systems. The segment summarizes the key outcomes, various system configurations, and efficiencies in a tabular format, facilitating a better understanding of the subject matter. Figure 4 illustrates the classification of PVT systems, including air-based PVT systems, water-based PVT systems, bi-fluid PVT systems, heat-pipe-based PVT systems, and PCM-based PVT systems, all falling under the category of PVT.

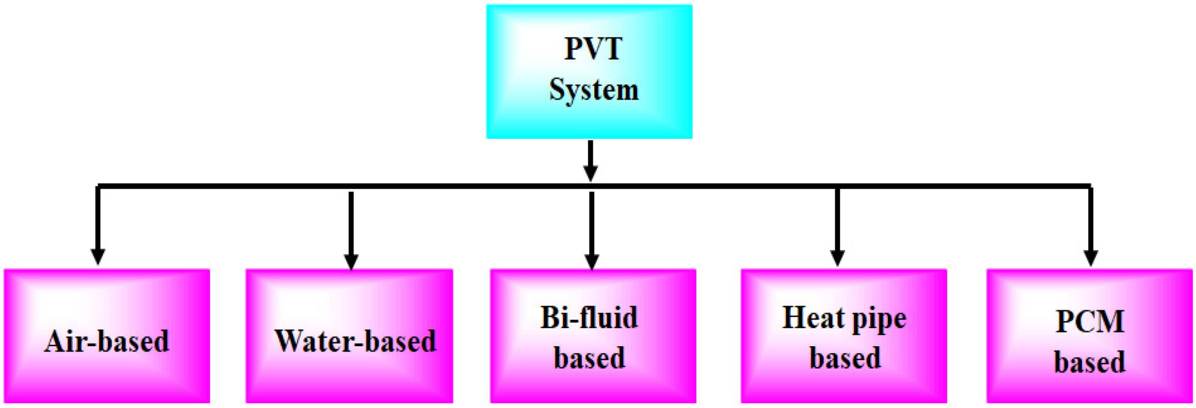


**Figure 4.** Classification of PVT systems.

### *2.1. Air-Based PVT Systems*

As shown in Figure 5, air-based PVT systems can actively or passively allow air to flow across the PV surface. These systems utilize single- or double-pass configurations and various absorber designs. Numerous researchers have been dedicated to enhancing the performance of conventional air-based PVT systems, including their architecture, operation, and materials [53–56]. Some studies have focused on simulating these systems using computational models to predict their potential performance. Researchers have also explored the energy and exergy approaches of air-based PVT systems.

Ozakin and Kaya conducted an ANSYS Fluent study to analyze the panel temperature and cooling channel air velocity [53]. Their findings were compared to real data, and it was discovered that using small and frequent fins improved the exergy performance of polycrystal panels by 70% and 30%, respectively, compared to empty fins. The thermal efficiencies also increased by approximately 55% and 70%. Furthermore, the PV temperature decreased by around 10% to 15% for all configurations [54].

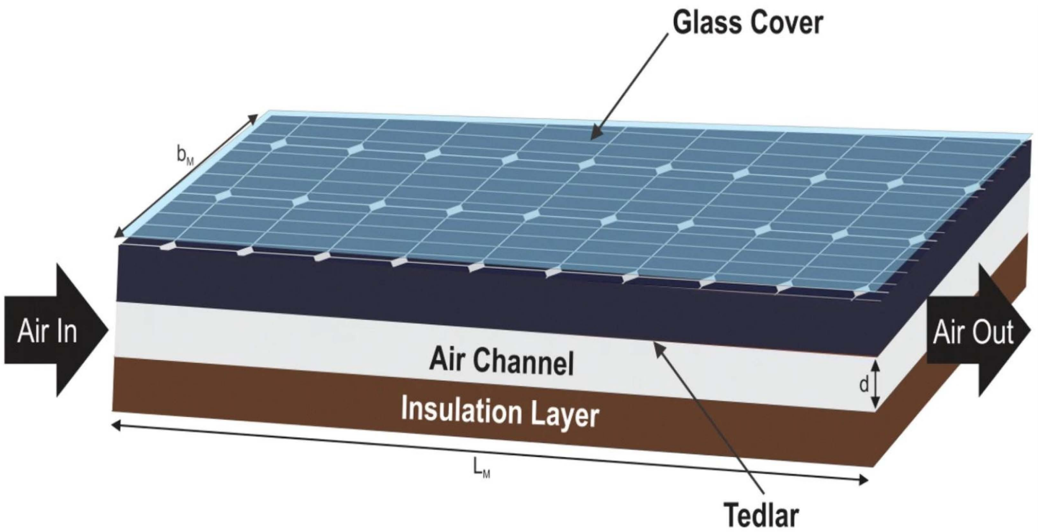


**Figure 5.** Air-based PVT systems [32].

Agrawal et al. examined a microchannel PV/T module featuring two types of panels: single-channel and multi-channel PV/T [55]. By maintaining a consistent airflow rate, they discovered that the multi-channel configuration exhibited improved thermal energy and exergy efficiency, achieving enhancements of 70.62% and 60.19%, respectively. Another study proposed the integration of a greenhouse solar dryer with a partially enclosed air-based PVT system designed for drying purposes [57]. The researchers evaluated the influence of flow rates on the system's thermal and electrical performance by varying the number of air collectors. As the number of collectors increased from 1 to 5, the equivalent thermal energy and thermal exergy efficiency rose from 3.24 kWh/day to 10.6 kWh/day. Air-based PVT systems require a sufficiently high airflow velocity to absorb the heat from the PV modules, especially during the daytime when temperatures are high [58]. To address this, a rotating airflow device is integrated into the channels to cool the modules. However, the output of air-based PVT systems fluctuates throughout the day due to temperature variations, and the heat absorption potential of air is at its lowest during the hottest hours. Thus, water-based PVT systems are employed to overcome these challenges and improve thermal management.

### 2.2. Water-Based PVT Systems

Air-cooled PVT devices generally have inferior thermal properties and are not very effective in high-temperature applications. Water, on the other hand, has higher thermal properties compared to air. Water-cooled PVT systems can be implemented in active and passive cooling. In both approaches, water tubes are installed behind the PV panel to allow water to flow through them. The water extracts heat from the PV unit, cooling the panel and producing heated water. This heated water can be utilized for various purposes. In one experimental setup, the water-based system consists of several main components: an exposed PVT collector, a storage tank, a forced water circulation circuit, and a pump (see Figure 6). The collector inlet is located at the bottom of the tank, while the heated water flows from the collector into the upper part of the tank. This arrangement creates stratification in the tank, with lower hot water density, improving thermal performance, and reducing the temperature of the photovoltaic cells [59].

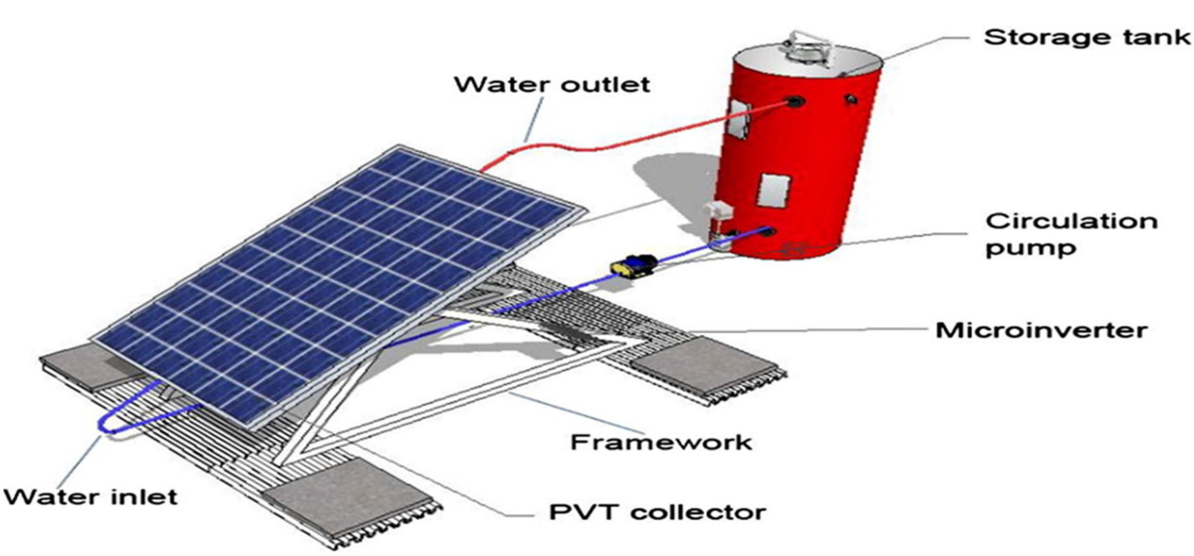


**Figure 6.** Water-based PVT systems [reproduced with permission from [60], Elsevier, 2016].

Previous studies have shown that water-based PVT systems [61] reach a maximum deflation temperature of 74.2 °C. This temperature level is considered safe in terms of overheating risk and PV efficiency. The PVT systems have also been proven suitable for domestic water preheating, with an average monthly output temperature of the PVT collector exceeding 45 °C for five months. It has also been demonstrated that an 8 $m^2$ PVT system is sufficient for heating a 300 L storage tank. Simulation results further indicate that the PVT surface area should be roughly double the size of a traditional thermal module to achieve the same thermal capacity. A dual oscillating absorber with a copper pipeline flow was developed and tested using water-based PVT systems. ANSYS 19.2 was used to predict the water outlet and surface temperatures under various irradiation and flow rate conditions [62]. The findings revealed an overall thermal efficiency of 59.6% for the PVT systems. At a mass flow rate of 6 LPM, the highest mean electrical performance values were 10.86% for the PV panel and 11.71% for the water-based PVT system. These results indicate that, as mass transfer improves, the electrical, thermal, and output capacity of PVT systems also increases.

Bevilacqua et al. [63] investigated the electrical performance of a PVT system using back surface spray cooling. They observed a 7.8% increase in electrical power and a 28.2% decrease in cell temperature compared to a non-cooled PV system. Similarly, Bevilacqua et al. [64] analyzed the electrical performance of a PVT system under different climate conditions. They developed a model to analyze panel surface temperature and power generation under various climate conditions. The model's accuracy was confirmed through statistical parameters, demonstrating good agreement between predicted and measured power and temperature. The experimental results were used to validate the simulation findings to evaluate the effectiveness of a novel dual oscillating absorber design for the PVT water system compared to a traditional PV device. The water-based PVT system's electrical, thermal, and overall efficiency were evaluated within an irradiation range of 500 to 1000 $W/m^2$ and flow rates ranging from 0.03 to 0.1 kg/s. The findings indicated that increasing either the flow rate or the amount of solar radiation can lead to improved thermal and overall efficiency. However, further increases result in a decline in efficiency after reaching an optimum value. Enhancing the cell's electrical efficiency requires lowering its temperature, which can be achieved by increasing the mass flow rate [65]. Bevilacqua et al. [66] compared three different cooling technologies under varying meteorological conditions and found that backside spray cooling provided the best temperature reduction and enhanced electrical performance compared to the other systems.

*2.3. Bi-Fluid-Based PVT Systems*

The performance of stand-alone air- or water-based PVT systems fell short of expectations, leading researchers to explore alternative approaches. One of the proposed approaches is using two fluids in a PVT unit, known as a bi-fluid-based PVT system (Figure 7). The aim was to overcome the limitations of the separate air-based and water-based PVT systems and simultaneously generate electricity, hot air, and water.

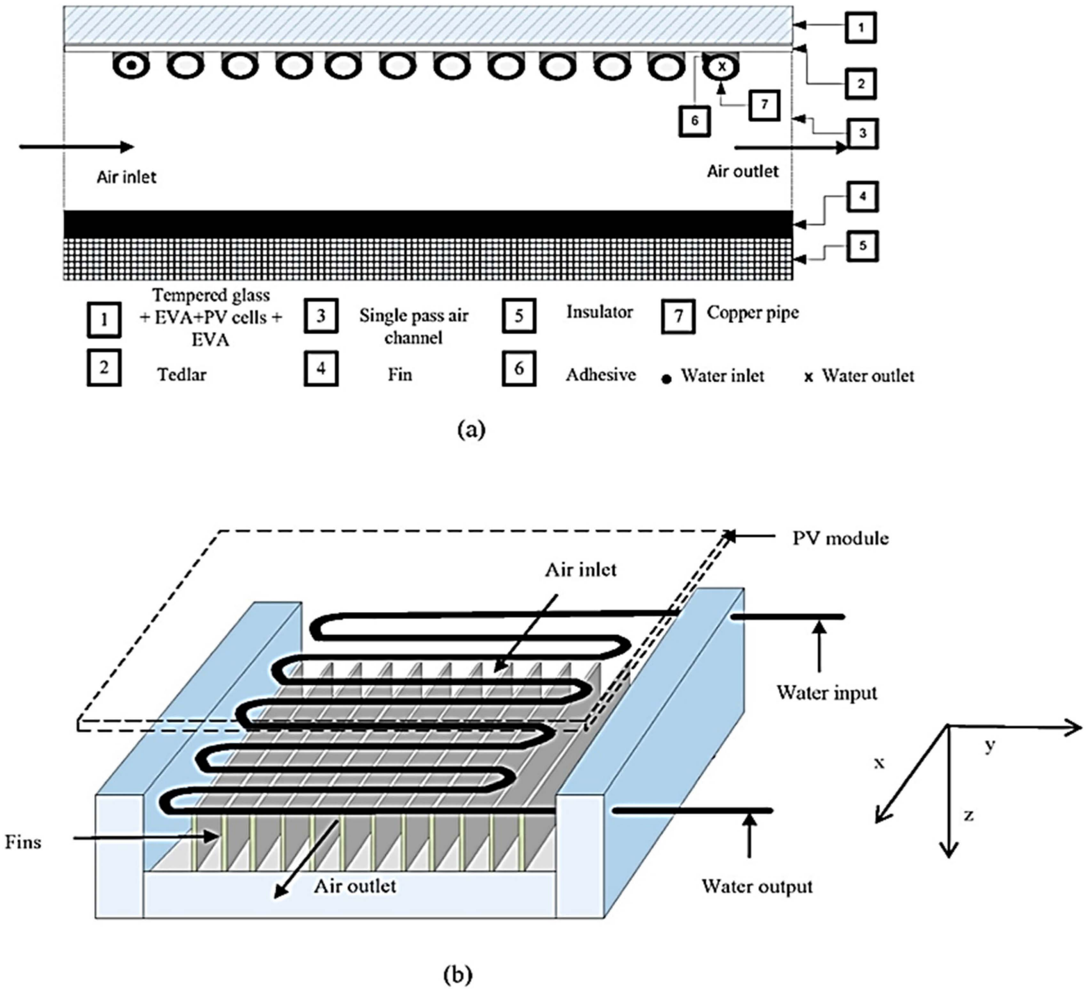


**Figure 7.** Bi-fluid-based PVT Systems (**a**) schematic illustration bi fluid PVT system (**b**) sectional view of fin and water tubes [reproduced with permission from [67], Elsevier, 2016].

A bi-fluid PVT system was developed, which incorporated a PV laminate, a serpentine copper tube for water heating, and a single-pass air channel for air heating [68]. To evaluate the efficiency of the developed bi-fluid collector, the fluids were analyzed both independently and concurrently using an established model. The simulated thermal and electrical efficiencies were found to be satisfactory when the bi-fluid collector operated independently. However, when the bi-fluid system operated simultaneously, the total performance reached a maximum of 76% efficiency at the specified parameters' maximum flow rate.

Furthermore, experimental analysis was conducted using two different fluids in various geometric channels [69]. Three different geometric forms were utilized as fluid movement channels: circular tube, half tube, and square tube. Pure water and an EG-W (60:40) mixture were used as heat transfer fluids to extract heat from the hybrid systems. The results indicated that the tube configuration was more efficient compared to circular and square tubes. Specifically, using the half-tube form at a mass flow rate of 0.04 kg/s improved the electrical efficiency of the hybrid collector by 0.53% and 1.16% compared to circular and square tubes, respectively. Additionally, the thermal efficiency showed an improvement of 1.17% and 2.6% for the same comparison.

### 2.4. Heat-Pipe-Based PVT Systems

Figure 8 illustrates a heat-pipe-based system that efficiently transfers heat between two solid surfaces without requiring external assistance. This system incorporates evaporation and condensation principles. Due to pressure variations in the adiabatic components, the working fluid transitions from a liquid phase to a vapor phase using heat from the ambient environment. This passive cooling technique, supported by a heat pipe, is known as a PVT-HP system. The vapor phase travels through the condenser, releasing heat and transitioning back to a liquid phase. It then returns to the evaporator through a wick structure.

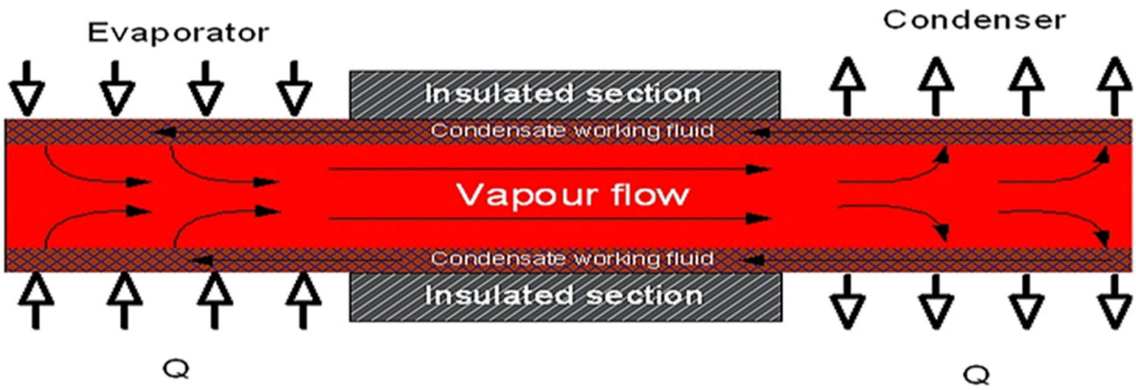


**Figure 8.** Heat-pipe working cycle [70].

The PVT-LHP system consists of several sub-models and an integrated model, which have been designed and analyzed [71]. The analysis revealed that under the given design conditions, the PV/LHP module achieved electrical, thermal, and overall performance of 12.2%, 55.6%, and 67.8%, respectively. The novel systems exhibited 28% higher efficiency and a 2.2 times higher coefficient of performance (COP) compared to traditional systems.

Another advanced system, the HP-PVT system, was developed to provide energy generation, water preheating, and load reduction in space air conditioning [72]. A dynamic prototype of the HP-PVT system was established and experimentally validated for numerical accuracy. Subsequently, the system's annual efficiency was assessed based on standard weather conditions in Hong Kong. Simulation results indicated that the average cumulative heat transfer through the outside wall could be reduced to less than a quarter of the usual level. The system achieved approximately 35% efficiency in water heating and 10% efficiency in power generation. Additionally, it was reported that the system saved an average of 315 kWh/year per unit surface area.

### 2.5. PCM-Based PVT Systems

The utilization of thermal energy storage (TES) is crucial to address the demand and availability of electricity at night [73]. Typically, batteries are employed to store electrical energy during the day, which can be used to meet the nighttime demand. Since solar energy is abundant, phase change materials (PCMs) offer an ideal solution for storing thermal energy [74]. PCMs possess desirable characteristics such as rapid charging and discharging capabilities and high performance. Additionally, they are cost-effective, readily available, and pose no toxicity or hazards. Various PCMs with different phase transition temperatures are commercially accessible [75]. These materials effectively reduce the temperature of solar panels during the day while storing the captured heat energy, which can then be released during the night. To enhance the efficiency of PCMs, techniques such as dispersing nanoparticles into the base PCM, encapsulating nano-sized particles with PCM, and creating nano-enhanced PCMs (NEPCMs) have been proposed [26,76–78]. These modifications improve heat transfer and increase thermal conductivity, thereby decreasing the temperature of photovoltaic (PV) panels and extending their lifespan. Figure 9 illustrates the integration of PCMs with a PVT unit.

PVT systems incorporating PCM-based collectors have been primarily used for cooling PV units [79]. Experimental studies have also focused on assessing their electrical performance. The implementation of PCM-based cooling for PV units has contributed to the preservation of their electrical efficiency. The peak efficiency achieved with this approach was reported to be approximately 13.7%, whereas traditional PV systems reached about 7.1% efficiency. The experimental findings also indicate an increase in electricity generation corresponding to the rise in solar irradiance. The cooling process facilitated by PCM integration results in higher power output. In conclusion, utilizing PCM for cooling PVT modules enhances their electrical efficiency [80].

(a)

(b)

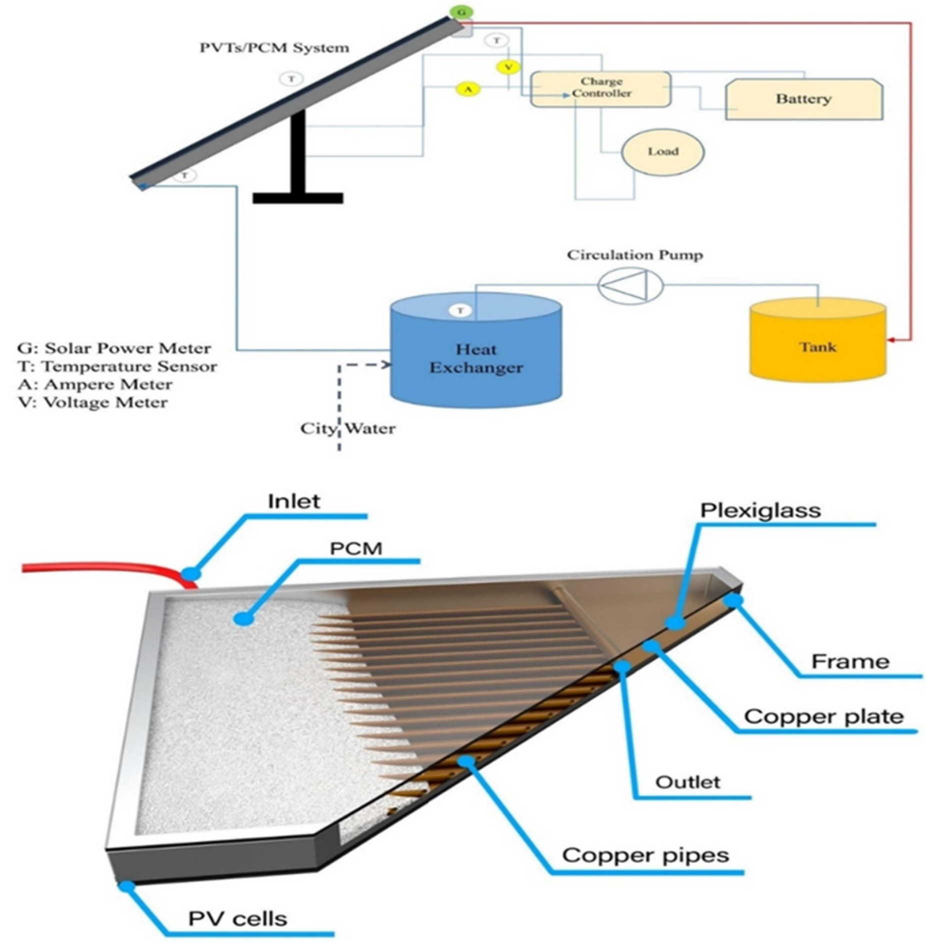


**Figure 9.** PCM-based PVT systems (**a**) schematic illustration of PCM-based PVT systems, (**b**) cut section of PVT system [reproduced with permission from [81], Elsevier, 2020].

To evaluate the energy performance of PVT systems incorporating PCMs, comparisons were made with standard PV modules based on electricity generation and overall energy performance [81]. Factors such as exergy destruction and external damages were considered in these measurements. The PVT-PCM system demonstrated the greatest relative improvement in energetic and exergetic efficiency. The PV module experienced a temperature drop of 12.6 °C, while the PVT-PCM system achieved a drop of 10.3 °C. The maximum electrical efficiency obtained was 13.72% for PV and 13.8% for PVT. Similarly, the electrical efficiency of PVT-PCM was numerically and experimentally determined to be 13.98% and 13.87%, respectively.

### 2.6. Summary

A study was conducted to examine the extraction of heat from PV units using various thermal fluids, cooling channel arrangements, and heat transfer enhancement techniques. Water-based PVT systems are commonly employed for dissipating heat from the backside of PV modules. The addition of water-based PVT systems could provide benefits for residential water heating and preheating water for industrial processes that currently use traditional solar collectors. However, the use of water-based systems may be limited in cold regions due to the risk of water freezing. Various methods were extensively discussed, such as glazing, heat pipes, coolant tubes, dual fluids and double channels, and PCMs. Water-based PVT units can also be extended to conventional water heating devices, preheating desalination water, and preheating water for industrial purposes. On the other hand, air-based PVT systems were found to be the least efficient and least effective method due to their low heat transfer properties.

It was observed that using water as a cooling medium for solar panels in PVT systems leads to higher efficiency rates. However, caution must be exercised when using this system in extremely cold environments, and there are other related complications that may cause damage. Both water- and air-based systems demonstrated more significant cooling of PV modules, but their design becomes increasingly complex and complicated when operating in passive mode. Furthermore, it was emphasized that the heat generated from PCMs must be effectively utilized to impact the thermal management system. It is recommended to use highly conductive nanoparticles enhanced nanofluid instead of conventional fluid to enhance the heat transfer rate between the PV panel and the cooling fluid. Moreover, the conductivity and absorption rate of the PCM plays a crucial role in the heat transfer rate and storage performance. Therefore, the use of carbon-based NEPCM (nano-enhanced phase change materials) is suggested to improve electrical performance, absorption rate, heat transfer rate, and storage performance. Implementing nano-enhanced PCMs in PVT systems allows for the extraction and storage of a greater amount of heat energy.

## 3. Industrial Applications of a Hybrid PVT System

Hybrid PVT systems are designed to generate both electricity and heat energy simultaneously. The heat energy obtained can be utilized for a wide range of applications, including water heating, space heating, drying, solar desalination, textiles, solar power plants, the agricultural sector, preservation of food and pharmaceutical products, automobiles, and medical applications [82].

Similarly, PCM-integrated PVT systems can produce both electricity and heat energy, which can also be stored. PCMs are suitable for energy conversion and heat transfer applications [2]. The stored heat energy can be effectively used for residential and industrial purposes. For instance, PCMs play a crucial role in urgent blood transport, and organ and cold therapies, as well as providing thermal protection for ice creams and food products [83]. Moreover, PCMs find applications in the development of high-performance electronic devices and textiles, cooking, industrial process heating, and regulating temperatures in chemical reactions [84]. This section extensively explores the diverse industrial applications of PVT systems.

### 3.1. Water Heating

Hot water is essential for a wide range of industrial and household uses. Industrial applications utilize hot water for curing, mixing, washing, cleaning, and sterilizing to facilitate product manufacturing. In a study by Abdallah et al. [85], it was found that adding conductive nanomaterials to the cooling fluid enhances the thermal properties of a PVT system. The cooling fluid reduces the temperature of the PV panel, leading to increased electrical production. Moreover, the nanomaterials in the fluid improve the overall performance of the PVT device by enhancing heat energy absorption for generating hot water for both household and industrial applications.

Researchers at Dalian University conducted a study [86] using a PVT heat pump and a water source heat pump for public hot water supply. They developed an innovative strategy to utilize multiple heat sources and established a calculation model to determine the system's heating characteristics. The study reported an 80% increase in public utility hot water supply and a 49% reduction in hot water production costs, resulting in improved economic performance.

Jafari et al. [87] conducted a thermodynamic investigation on a newly proposed PVT system that incorporated a fuel cell and battery. The excess electrical energy generated by the PVT system was used for hydrogen production. The produced hydrogen was then utilized in the fuel cell to generate electrical energy and heated water. The study revealed an overall electrical energy efficiency of 9% and an electrical energy production cost of USD 0.286/kWh. The PVT system's exergy and energy efficiencies were measured at 16.91% and 14.5%, respectively. Additionally, the combined system demonstrated a total energy efficiency of 41.80%. Kumar et al. [88] developed a model and simulation for industrial solar-assisted process heating (SAPH) applications. The study showed that the maximum heat gain, thermal efficiency, and exergy efficiency were 1420 W, 75%, and 12.72%, respectively. The SAPH system exhibited excellent performance under higher solar irradiation and lower mass flow rates.

A PVT system designed for hostel students, providing hot water and meeting a portion of the electrical requirements, was analyzed by Somasundaram and Tay [89]. The researchers compared two types of PVT systems, unglazed and glazed, as shown in Figure 10. The study indicated that the glazed PVT unit outperformed the unglazed arrangement. The payback period for the system was determined to be 12.5 years, with an electricity cost of USD 0.26 per kW/h.

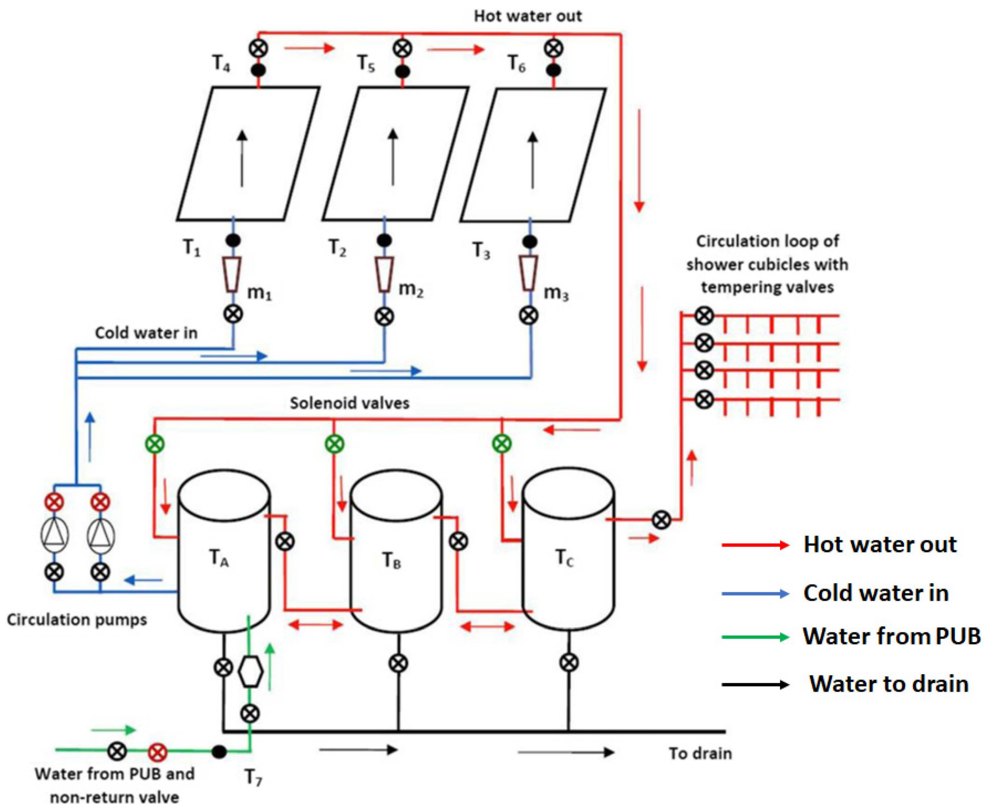


**Figure 10.** Line diagram of PVT system for water heating [89].

Maatallah et al. [90] conducted an exergoeconomic investigation of a PCM integrated water-based PVT system in Kerala, India, under various weather conditions. The research reported an overall performance of 41.0%. Furthermore, the water-based PVT system exhibited an extended life cycle conversion efficiency compared to conventional systems, with an improvement of 27.0%. The generated hot water was deemed suitable for both household and industrial applications.

Naghdbishi et al. [81] explored the impact of MWCNTs (multi-walled carbon nanotubes)-based nanofluids on a hybrid PVT system incorporating a PCM system. The dispersion of MWCNTs in water was found to enhance the thermal and electrical performance by 23.6% and 4.20%, respectively, compared to conventional water-cooled PVT systems. However, the use of the hybrid system led to higher exergy losses due to heat dissipation, resulting in an overall increase of 76% in exergy destruction.

Rajoria et al. [91] conducted an enviroeconomic and exergetic analysis of hybrid PVT systems, considering two cases based on the flow and design of PVT arrays. Case 2 demonstrated improved performance with lower cell temperature, higher outlet air temperature, and higher electrical efficiency compared to Case 1. The annual extenuation in terms of overall exergy gain and thermal energy gain was higher in Case 2. Additionally, the study evaluated the environmental cost associated with overall exergy and thermal energy for both cases.

Yandri et al. [92] evaluated the thermal performance of a hybrid PVT system, including Joule heating, to enhance thermal energy. The results showed a 13% improvement in thermal performance, suggesting wider applications in areas such as swimming pool water heating, floor heating, and medium-temperature heat pumps. Antony et al. [93] conducted a detailed analysis of a PVT system, considering various parameters such as solar irradiance, operational temperature, heat and electricity demand, thermal storage capacity, rate of flow, and ambient temperature over an entire year, as shown in Figure 11a. The study found that factors like heat removal, flow rate, location (longitude and latitude), tilt angles, and the choice of heat dissipation fluid significantly influenced the system's performance. The analyzed PVT system was recommended for industrial-scale water heating applications.

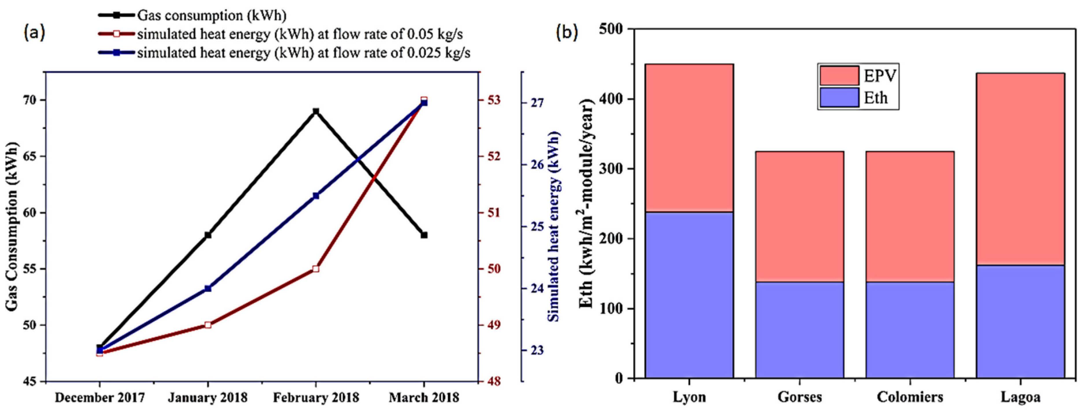


**Figure 11.** (**a**) Heat demand and supply in winter season [reproduced with permission from [93], Elsevier, 2019], (**b**) yearly thermal (Eth) and photovoltaic (Epv) energies per surface module [reproduced with permission from [61], Elsevier, 2020].

Brottier and Bennacer [61] analyzed the performance of residential water heaters in Western Europe using 28 hybrid non-overglazed PVT systems in France, Portugal, and Switzerland. The study concluded that the PVT systems were suitable for residential water heating, providing an average temperature of 45 °C with five months of autonomy per year. The yearly thermal and electrical energies per surface module are shown in Figure 11b. It was noted that non-overglazed PVT systems exhibited the highest stagnation temperature of 74.2 °C.

Dannemand et al. [94] evaluated the performance of heat-pump-based PVT systems for cold buffer and hot water storage. Amo et al. [84] theoretically analyzed a heat-pump-based PVT system for seasonal storage in educational buildings. Both studies demonstrated high solar coverage of up to 98% for the proposed systems, indicating their economic and technical feasibility.

In summary, various studies have explored different aspects of PVT systems, including the enhancement of thermal properties through the use of nanomaterials, integration with fuel cells and batteries, exergoeconomic analysis, utilization of PCMs, and the evaluation of system performance for different applications. These investigations contribute to the advancement of PVT technology for efficient hot water generation in industrial and household settings.

*3.2. Water Desalination*

Water salt removal is a process that involves heating saline water to produce water vapor, which is then condensed to obtain pure water. This purification process requires hot water or heat energy. In the context of a PVT system, the hot water outlet can be utilized for the desalination and production of pure water. Mittelman et al. [95] conducted an analysis of a concentrated PVT system for a water desalination setup, as depicted in Figure 12. This hybrid system generates electricity and desalinated water. The designed CPVT solar collectors are capable of operating at high temperatures, enabling the use of more advanced desalination techniques such as vapor-compression or absorption refrigeration systems. Monjezi et al. [96] evaluated a solar-powered osmosis desalination system integrated with a photovoltaic thermal system to produce fresh water. The study found that the specific energy consumption (SEC) for reverse osmosis desalination systems was 4.15 kWh/m$^3$ with PVT systems and 4.27 kWh/m$^3$ without PVT systems. Additionally, the novel PVT system with seawater cooling resulted in a 0.12 kWh/m$^3$ reduction in SEC and a 65% reduction in panel area.

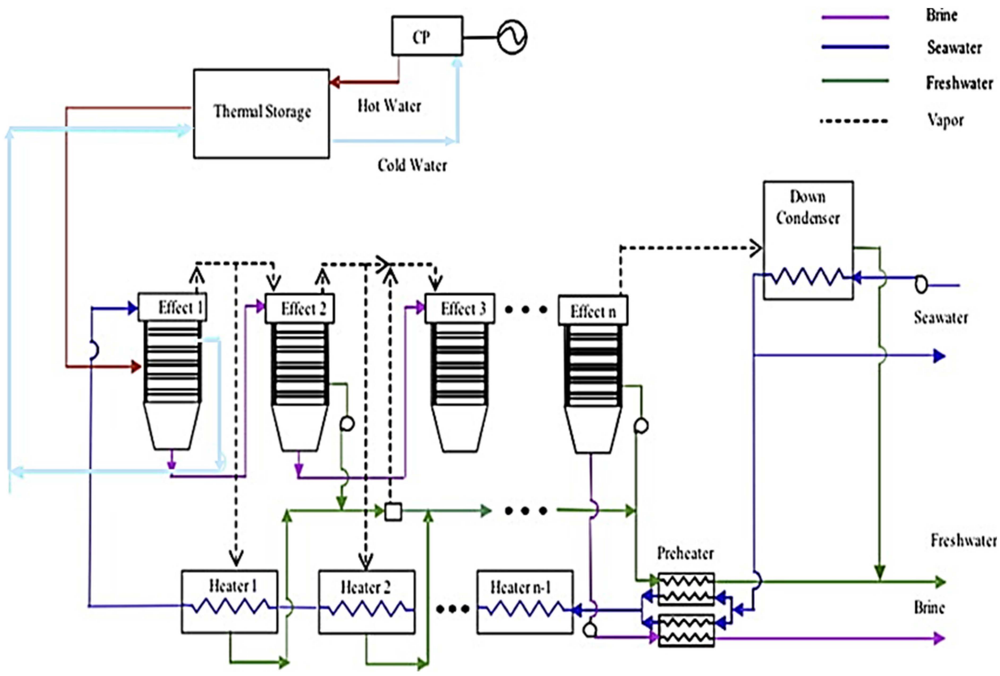


**Figure 12.** Schematic diagram of CPVT and multiple-effect evaporation plant [reproduced with permission from [95], Elsevier, 2009].

Ong et al. [97] investigated the desalination of water using waste heat obtained from CPVT systems. This hybrid system also generates electrical energy and desalinated water. The results demonstrated that the approach is highly optimized and that effective minimization of heat energy utilization is achievable. Abdelgaied et al. [98] proposed a system that combines PV panels with thermal collectors, a solar dish concentrator, and a reverse osmosis salt removal system with an energy recovery device. They installed a PV unit with a thermal recovery device and a dish concentrator with a solar thermal receiver to power the reverse osmosis desalination process. The dish concentration and PV panels were also used to preheat the purification system. Preheating the input water before pumping it to the reverse osmosis plant resulted in SEC savings ranging from 18.7% to 22.9% for treated seawater and from 24.3% to 35.8% for brackish water, compared to systems without solar preheating. Calise et al. [99] studied a poly-generation system for generating potable water, which includes a PVT system, a single-stage absorber chiller, a multi-effect distillation system, and other components. The PVT system generates electrical and thermal energy, with the electrical energy being sent to the grid. The thermal energy can be utilized to power an air-to-water heat pump that produces chilled water for air conditioning. Finally, the multi-effect distillation system can employ both solar energy and thermal energy from an additional biomass-fired heater to transform seawater into potable water.

Xiao et al. [100] designed a desalination system integrated with a PVT system. The PVT system generates electricity and heat energy, which is used to preheat the saline water in the desalination system, as illustrated in Figure 13a. Potable water production depends on the bottom channel's height, with a deeper channel resulting in decreased water production. As the water quantity increases, the evaporation rate decreases. The use of a PVT system increases the heat transfer rate from the absorber plate to the saltwater by 44%. However, pure water production decreases by 17% when the height of the bottom tank is 0.03 m instead of 0.01 m. Alnaimat et al. [101] designed a solar-diffusion-driving desalination unit, as shown in Figure 13b. This system can generate 100 litres of fresh water daily with an SEC of 3.6 kWh/m$^3$, using 2 m$^2$ panels in different weather conditions. Xinxin et al. [102] designed three solar still systems with different glass angles integrated with a concentrated parabolic PVT system, as depicted in Figure 13c. The researchers found that higher solar irradiation increases freshwater generation, electrical efficiency, and thermal efficacy. The temperature difference between the saltwater and the condenser glass is a key factor in freshwater generation. Additionally, the angle of the condenser affects the production of freshwater.

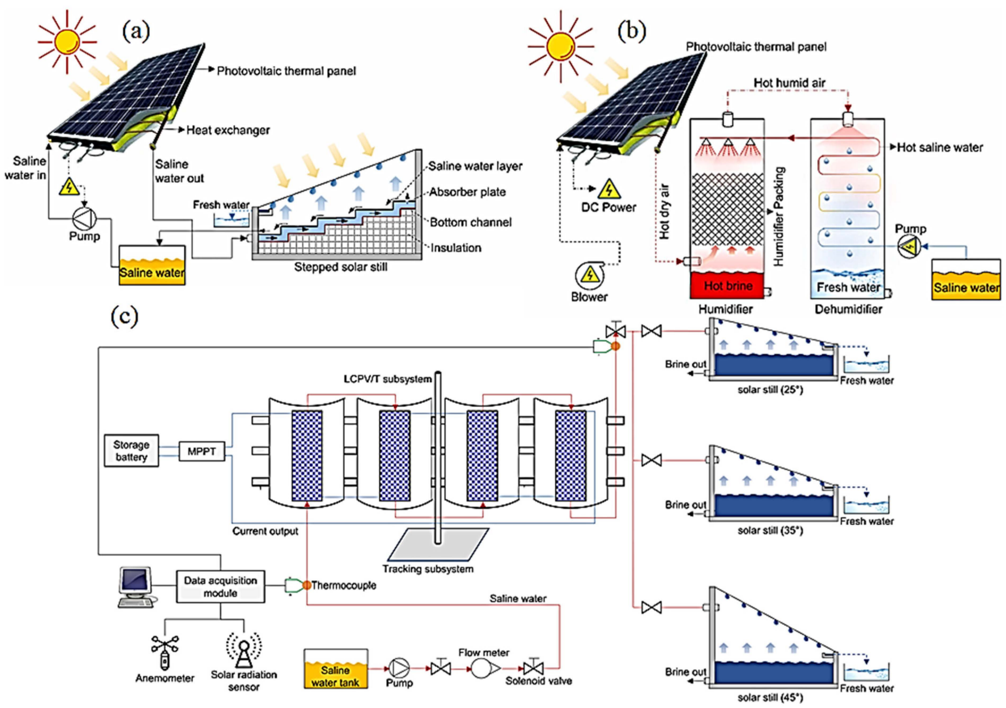


**Figure 13.** Different configurations of PVT-based solar desalination systems (**a**) stepped solar still with PVT system [reproduced with permission from [100], Elsevier, 2019], (**b**) air assisted PVT integrated desalination [reproduced with permission from [101], Elsevier, 2012], (**c**) low concentration ratio CPC-PVT desalination system [reproduced with permission from [102], Elsevier, 2019].

### 3.3. Thermal Management in Buildings

The integration of latent heat storage in building materials plays a significant role in building energy management, facilitated by TES technology. Thermal management is crucial in construction to ensure human comfort and the functionality of various structures, from everyday devices to industrial installations [103]. In a study by Zarei et al. [104], a hybrid photovoltaic thermal system was analyzed for eco-friendly solar heating and cooling applications. The system employed two refrigerants, R600 and R290, to reduce global warming potential, replacing R134a. The study found that the outlet water temperature ranged from 31.7 °C to 46.7 °C. Furthermore, using the R290 refrigeration cycle and cooling the panel resulted in an 11.1% improvement in the coefficient of performance (COP), a 9.17 °C increase in the outlet water temperature, and a 60.17% reduction in refrigerant flow rate compared to a system without panel cooling that used R134a refrigerant.

Braun et al. [105] conducted an analysis of a hybrid PVT system for zero-energy office buildings, providing electrical, heating, and cooling functions (trigeneration). The simulation study demonstrated the technical feasibility of the system. Additionally, the proposed PVT system with a heat pump (HP) exhibited higher energy potential for incorporating renewable energies, lower energy production costs, and increased self-consumption of locally generated energy. Hassan et al. [3] investigated the thermal management and regulation of PVT systems integrated with nanofluid-based (PCMs). Three PVT systems were compared: PVT/PCM, PV/PCM, and conventional PV systems. The study revealed that the addition of a 0.1 wt% graphene water nanofluid at a flow rate of 40 LPM improved the overall thermal and electrical efficiency by 14.1%, 20.8%, and 14.5%, respectively, compared to a water-based PV system. An increase in flow rate was found to enhance the electrical and thermal effectiveness of the systems.

Behzadi et al. [83] conducted a techno-economic investigation of PVT systems for building energy management. The study reported a 4.03% increase in exergy, a reduction of EUR 3.64 per Wh in total cost, and a decrease in capital cost achieved by eliminating the battery component. Chemisana et al. [106] analyzed the impact of immersing PVT systems directly in liquids for building applications. The study concluded that immersing the PVT system in a mixture of isopropyl alcohol and deionized water yielded the best results in terms of electrical, thermal, operational, and optical behavior.

Compared to building-integrated photovoltaic (BIPV) systems, building-integrated photovoltaic-thermal (BIPVT) systems offer additional advantages as they can generate both electrical and thermal energy. Debbarma et al. [80] reviewed the thermal performance of BIPVT systems through exergy analysis, highlighting their ability to partially or completely fulfil a building’s energy needs.

A PCM-integrated hybrid PVT system was experimentally analyzed to study building thermal management [107]. The system utilized an organic PCM called RT42 for thermal energy storage. The experiment demonstrated a 7.7% improvement in the PCM’s electrical energy and a 4.45 V increase in Voc (voltage at open circuit) at an irradiance of 100 $W/m^2$, validating the effective contribution of PCM in thermal management within buildings.

Balaji et al. [108] discussed the design features of BIPV and BIPVT technologies. They presented two setups, BIPV-wall/facade, where PV panels were vertically mounted on walls, and the BIPV roof, which is suitable for high-rise buildings with increased airflow for efficient PV panel cooling, as shown in Figure 14. The study emphasized several crucial parameters to consider when integrating PV systems into building roofs/facades, including design, buildability, compliance with regulations, safety, maintenance, environmental factors, durability, and performance.

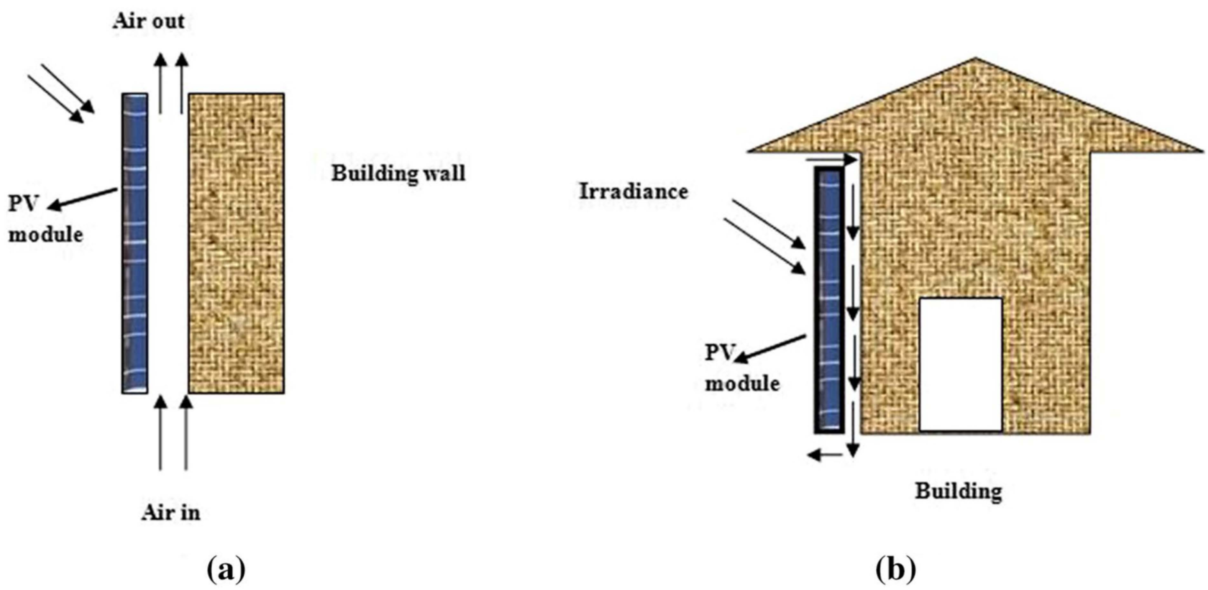


**Figure 14.** (**a**) Staggered configuration of BIPVT, (**b**) PVT system integrated in building [reproduced with permission from [108], Elsevier, 2016].

### 3.4. Agricultural Processes Solar Drier

The agricultural industry predominantly utilizes solar dryers to reduce moisture levels and prevent deterioration during storage. A recent experiment [109] involved using a mixed-mode air-based PVT system to dry tomatoes. The initial moisture content of the tomatoes was 91.9%, and they were successfully dried to 23.3% in the mixed-mode solar dryer and to 30.15% in the open-mode solar dryer within a period of 44 h. The maximum thermal and electrical performance achieved was 65% and 12.31%, respectively.

Tiwari et al. explored energy and exergy analysis for solar dryer applications in five different cities: Mumbai, New Delhi, Bangalore, Jodhpur, and Srinagar [110]. They found that the solar dryer's air temperature depends on the air's inlet velocity. This investigation demonstrated self-sustainability and applicability to remote areas, with excellent agreement between numerical and experimental outcomes.

The thermal performance of a PVT arrangement with a desiccant wheel was numerically analyzed, and the produced hot air was utilized for the drying process. By employing the desiccant wheel, the temperature increased from 65 °C to 80 °C, while the humidity ratio of the air decreased from 15 kg water/kg dry air to 8.8 kg water/kg dry air, compared to without the desiccant wheel [111]. Tiwari et al. discussed various types of air-assisted hybrid PVT arrangements with solar greenhouse dryers [57]. They reported an overall thermal output of 26.68% and an electrical output of 11.26% at a flow rate of 0.01 kg/s. Ziaforoughi et al. [112] investigated a novel hybrid PVT system for improving the performance of potato slice drying and agricultural processes in industries. Drying potato slices with thicknesses of 3 mm, 5 mm, and 7 mm at temperatures of 50.0 °C, 60.0 °C, and 70.0 °C, respectively, their system achieved a reduction in electrical consumption of 40% to 69% and a decrease in drying time by 31% to 52%.

Tiwari et al. [113] conducted an experimental study on an optimized drying method using a PVT air collector, which proved beneficial for crop preservation, and is illustrated in Figure 15. The study found that forced convection mode was more efficient for crops with high moisture content, while natural convection mode was better suited for crops with low moisture content. A hybrid PVT system integrated with an indirect solar dryer was analyzed for drying agricultural products [114]. A thermal balance equation was developed and examined using various heat transfer and electric parameters. The numerical analysis demonstrated a 70% improvement in thermal performance, a 10.50% improvement in electrical performance, and an overall performance enhancement of 90.0% at a flow rate of

0.0155 kg/s. Effective crop drying is crucial in rural areas to remove moisture content and prevent quality deterioration.

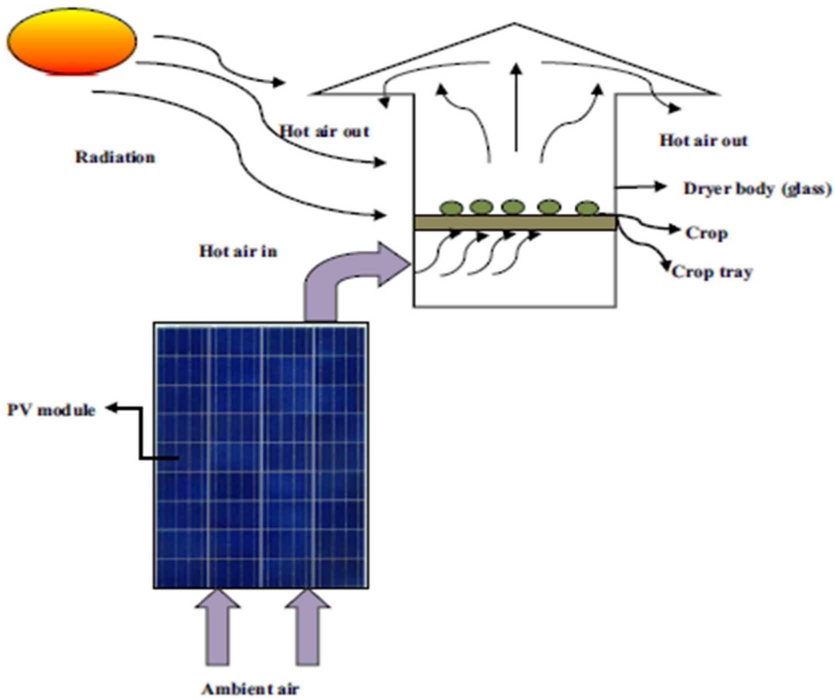


**Figure 15.** Greenhouse dryer [reproduced with permission from [113], Elsevier, 2018].

The exergoeconomic analysis of hybrid PVT systems, such as that shown in Figure 16 under the forced mode, was conducted, considering parameters such as PV cell temperature, outlet temperature, greenhouse temperature, and crop temperature, at the Indian Institute of Technology in India [115]. Findings revealed the system's efficiency decreased as the PV panel temperature increased. The annual energy outputs were 191.53 kWh for electrical energy, 1182.19 kWh for thermal energy, and 1686.22 kWh for overall energy. The thermal exergy and overall exergy were determined to be 16.52 kWh and 208.05 kWh, respectively. The researchers concluded that the solar dryer was suitable for all climate conditions as it effectively utilized both direct and diffuse radiation.

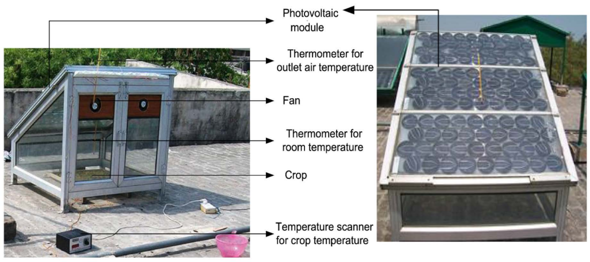


**Figure 16.** Greenhouse dryer apparatus [reproduced with permission from [115], Elsevier, 2016].

### 3.5. Food Processing

The food processing industry commonly relies on conventional heating sources like hot air and steam. However, the heat energy generated by PVT systems can also be effectively utilized in this industry. Steam and hot air have been the traditional choices for heating in various food processing applications. However, alternative heating methods such as infrared, ohmic, and microwave heating have gained attention due to their high energy efficiency. In recent years, PVT-based heating systems have gained popularity as a more energy-efficient option.

A theoretical analysis conducted by Herrando et al. [116] examined the heating, cooling, and electrical demands of food industries in Spain. The study identified the optimal number (N) of solar collectors that minimizes the payback time for the solar system. In the case of a solar-powered combined cooling, heating and power PVT system, the payback time decreases exponentially with the system's size when N is less than 120. This optimization leads to significant savings in electrical power consumption and increased annual savings overall.

### 3.6. Heating, Ventilation, and Air Conditioning

The HVAC system, responsible for heating, ventilation, and air conditioning, is crucial for maintaining human comfort and ensuring the protection of goods in residential and commercial buildings. It regulates temperature by heating and cooling the air while aiming to provide high-quality indoor air. During winter, the HVAC system utilizes thermal energy from the PVT system to heat the air. Zarei et al. [104] conducted an analysis of a hybrid PVT system for eco-friendly solar heating and cooling applications. Instead of using R134a, they employed two different refrigerants, R600 and R290, to reduce global warming potential. The study found that the outlet water temperature ranged between 31.7 °C and 46.7 °C. Furthermore, it concluded that the COP of the R290 refrigeration system improved by 11.1%, reducing the refrigerant flow rate by 60.17% and increasing the water temperature by 9.17%.

Braun et al. [105] studied a hybrid PVT system for zero-energy office buildings, focusing on trigeneration (electrical, heating, and cooling) capabilities. Through simulation, they determined that this system was technically feasible. The proposed PVT system with heat pumps exhibited higher energy potential, lower energy production costs, and greater self-consumption of locally generated energy. Zhou et al. [117] enhanced the performance of a PCM-combined hybrid PVT system by incorporating cooling and ventilation. This hybrid system integrated a ventilator, radiative cooling, active PV cooling, and PCM storage. The study showed that the radiant cooling system effectively maintained indoor temperatures while offering significant energy-saving potential. The new hybrid system demonstrated superior energy efficiency compared to conventional systems.

In India, a BIPVT system was analyszed with and without the PVT arrangement [118]. The electrical performance of the BIPVT system with an air duct was reported to be 13.11%, while without the air duct it was 12%. The experimental results aligned well with the theoretical findings. The impact of water flow in a BIPVT system with heat capacity was also investigated in India [119]. The study revealed a significant temperature drop in the PV cell temperature, resulting in a 23.7% improvement in electrical efficiency. Meanwhile, in Portugal, one study focused on the solar-absorption heating and cooling of buildings, considering the energy, economic, and environmental aspects [120]. The research explored three cities—Rome, Lisbon, and Berlin—to investigate solar heating and cooling theoretically. The results indicated that integrated solar systems showed higher economic efficiency in single-family houses and in hotels.

### 3.7. Thermal Powerplants

Electricity is generated from heat energy in thermal power plants. These power plants typically heat water to produce steam, which then drives steam turbines to generate electrical energy. In a study by Shah et al. [121], the thermal and electrical efficiency of hybrid PVT systems under standard testing conditions (STCs) was examined. These systems generate both electrical and thermal energy, which thermal power plants can utilize. The research findings indicated that employing an active cooling method improved the electrical energy output of the PVT system drastically.

Another study conducted by Wang et al. [122] investigated hybrid PVT systems for solar-powered combined heating and power in power plants and dairy farms (as depicted in Figure 17). The S-CHP hybrid PVT system was found to fulfil 52.0% of the steam demand and 40.0% of the hot water demand. Additionally, the system achieved an electrical efficiency equivalent to 14% of the total electrical demand. Based on the energy consumption of dairy farms, this implementation was projected to reduce 890 tonnes of $CO_2$ emissions per year. Of this total, 720 tonnes would stem from decreased natural gas consumption, while the remaining 100 would result from displaced electricity.

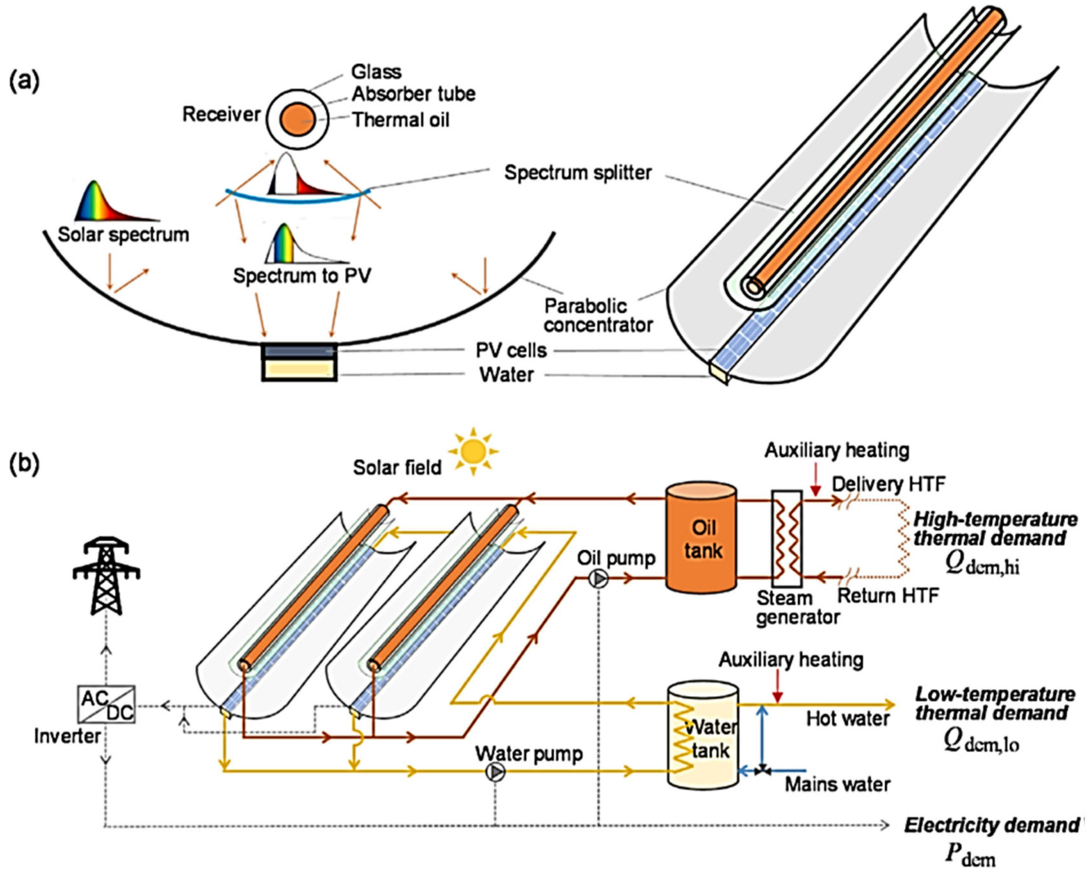


**Figure 17.** (**a**) Concentrating spectral-splitting hybrid PVT collector (**b**) schematic diagram of S-CHP hybrid PVT system [reproduced with permission from [122], Elsevier, 2020].

### *3.8. Summary of Hybrid PVT System Applications*

Table 1 presents a summary of the performance and industrial applications of various PVT systems across different fields. PVT setups have found utility in water heating, solar salt removal, farming, HVAC, power plants, building heating/cooling, and swimming pool heating. Hybrid PVT systems are particularly suitable for medium-temperature applications like water heating and residential rooftops, as they serve as reliable energy sources for maximizing energy production. Among these systems, the inorganic PCM-integrated PVT system demonstrated superior performance compared to the reference system, achieving a maximum electrical efficiency of 14.99% and a thermal efficiency of 80%. Furthermore, the nanofluid-based PVT system exhibited a remarkable 33.95% improvement in electrical efficiency while effectively reducing the panel's temperature.

**Table 1.** Hybrid PVT system performances and applications.

| Type of System | PCM | Thermal Efficiency | Electrical Efficiency | Overall Efficiency | Place of Study | Observations | Applications | References |
|---|---|---|---|---|---|---|---|---|
| Water-cooled PVT system | NA | NA | Increased by 7% | 75.8% | Iran | The COP of the system improved by 11%, and the water temperature increased by 9.17 °C. | Solar heating applications | [104] |
| Nanofluid-based PVT system | NA | NA | Increased by 33.95% | 83.26% | Egypt | The PV unit temperature reduced by 12 °C. Water heating applications. | Water heating | [85] |
| Water-based PVT system | NA | NA | 14% | 61% | Denmark | Exergy efficiency was increased by 4.03%, and total cost reduced by EUR 3.64/MWh. | Water heating | [83] |
| Solar combined heating cooling and power-based PVT system | NA | 55.1% | 8.62% | NA | Italy | Heating, cooling, and power systems for buildings. | Heating and cooling | [123] |
| Solar combined heating cooling and power-based PVT system | NA | 45.4% | 6.7–7.9% | - | Spain | Higher efficiency, lower fuel cost and higher reduction of $CO_2$ emission. | Food processing, beer brewery, pig slaughterhouse, vegetable and fruit processing, and canning plant | [116] |
| Water-cooled PVT system | NA | NA | 9% | 41.8% | Iran | The developed system is convenient for all seasons because the produced power satisfies the demand at all times. | Water heating | [87] |
| Water-based PVT system | NA | 30% | 10.4% | NA | Singapore | Glazed PVT system had higher performance than unglazed PVT system. | Hot water for student hostel | [89] |
| Water-based hybrid PVT system | NA | 80% | 7.9% | NA | Japan | PVT system with PMMA absorber and copper plate provides 80% thermal efficiency, significant cooling effect, and 0.03%/°C reduction in electrical efficiency. | Water heating, swimming pool water heating | [124] |
| Water-based hybrid PVT system | NA | 13% enhanced | NA | NA | Japan | In a moderate wind speed (less than 1 m/s), negligible or no loss in thermal efficiency. | Swimming pool heating, floor heating | [92] |
| Water-based hybrid PVT system | NA | 450 kWh/m$^2$–module/year | 275 kWh/m$^2$–module/year | NA | Western Europe | The developed non-overglazed PVT system's stagnation temperature is always lower than 74.5 °C, which is lower the chance of overheating the PV panel. | Water heating | [61] |

**Table 1.** *Cont.*

| Type of System | PCM | Thermal Efficiency | Electrical Efficiency | Overall Efficiency | Place of Study | Observations | Applications | References |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Air-based PVT system | NA | 65% | 12.31% | NA | Tunisia | The developed prototype system reduces the moisture content from 91.2% to 22.32% for tray 1, 28.9% for tray 2 and 30.15% for using sunlight. | Drying tomatoes | [109] |
| Air-based PVT system | NA | NA | 13.11% | 42% | India | The electrical efficiency and temperature with and without air duct is 13.11%, 12% and 10.1 °C, 25 °C, respectively. | Space heating | [118] |
| Water-based PVT system | NA | NA | 15.5% | NA | Egypt | The developed system reduces electricity consumption by 0.12 $kWh/m^3$. | Solar desalination | [96] |
| Nanofluid-based PVT system | RT-35HC (35 °C) | Enhanced by 20.8% | Enhanced by 14.5% | Enhanced by 14.1% | Pakistan | PCM-integrated nanofluid-based PVT system increases the thermal and overall energy by 17.50% and 12.0% compared to the water-based PCM-integrated PVT system. | Thermal management in buildings | [3] |
| Water-based PVT system | Paraffin wax (57 °C) | 26.8% | 17.33 | 40.59% | Kottayam, India | Heating water during night time, cooling PV cell during day time. | Water heating | [90] |
| Nanofluid-based PVT system | Paraffin wax (57–60 °C) | Enhanced by 23.52% | Enhanced by 4.22% | NA | Tehran, Iran | Heating water during night time. Reduces the PV panel temperature by 16–21%. | Water heating | [81] |
| Water-based hybrid PVT system | $CaCl_2$.6H2O (22–26 °C) | 80% | 14.99% | NA | China | PCM and active water cooling systems are technically feasible in terms of thermal and electrical energy enhancement. | Heating and ventilation in buildings | [117] |
| Air-based PCM-integrated PVT system | RT42 (42 °C) | NA | Enhanced by 7.7% | NA | UK | The electrical efficiency improved by 7.7% and the reduction in cell temperature increased by 3.8 °C for PCM embedded PV system. | Building heating/cooling | [107] |

CPVT systems were employed for higher-temperature applications such as thermal power plants and solar desalination. The nanofluid PVT arrangement demonstrated higher overall thermal and electrical efficiency among the various PVT configurations. The advantage of PCM-based PVT systems lies in their ability to store thermal energy in the PCM, enabling utilization when solar energy is not available. This stored heat energy can be effectively utilized for water heating, space heating, and crop drying applications. Additionally, grid-connected and building-integrated PVT systems offer a seamless appearance, eliminating the need for separate thermal collectors and PV modules. It is recommended to improve the thermal conductivity of PCMs to enhance thermal energy storage and the heat transfer rate. This can be achieved by incorporating highly conductive nanoparticles into the PCM, further enhancing the heat transfer rate and storage capacity.

### *3.9. Discussion and Inferences About Hybrid PVT Systems*

Hybrid photovoltaic thermal (PVT) systems have found widespread use in various industrial applications, with efficiency being the most crucial factor in PVT technologies. The performance of a hybrid PVT system is influenced by several factors, as shown in Figure 18. In evaluating the electrical, thermal, and overall performance of the PVT system, three operational parameters are considered: design, climate conditions, and operating characteristics.

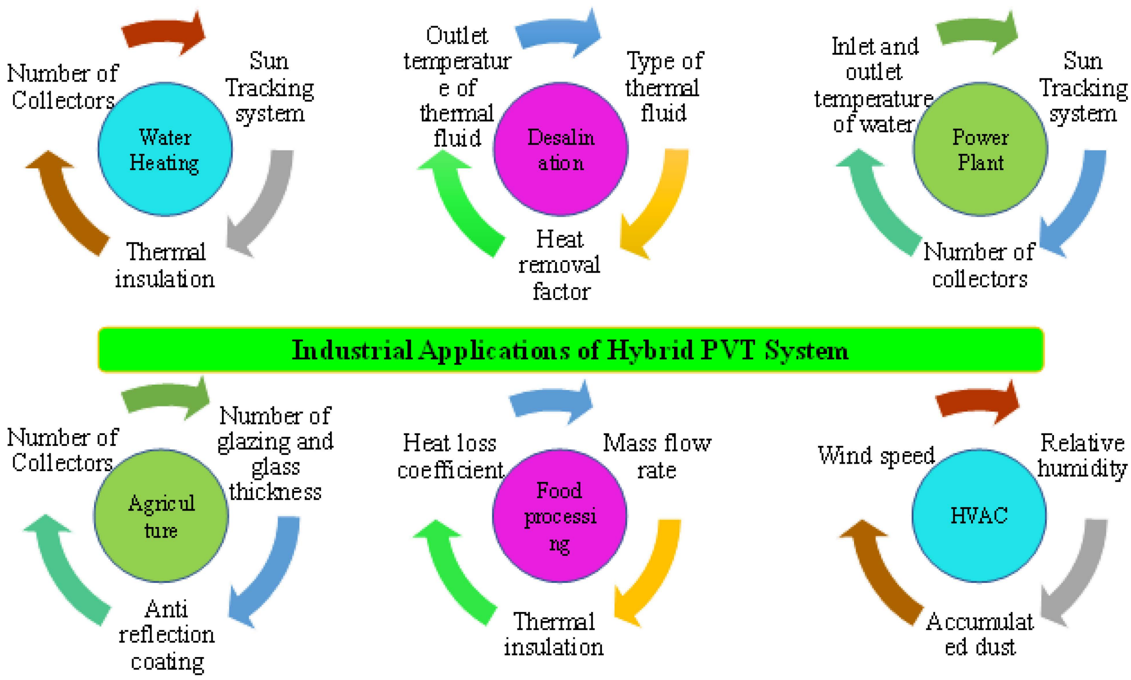


**Figure 18.** Inferences on hybrid PVT system.

The thermal efficiency of the PVT system decreases as the ambient temperature, inlet water temperature, channel depth, duct length, packing factor, thermal resistance, and flow rate increase. Once the optimal value is exceeded, improving the velocity of the inlet flow rate, tilt angle, wind speed, heat loss coefficient, and thermal conductivity of insulation can enhance the system's performance. Also, the thermal efficiency increases with higher solar irradiation, tilt angles close to the latitude, tracking systems, absorber quality, and supporting metal bars. PV materials play a significant role in enhancing the system's electrical efficiency.

The performance of a water-based PVT system depends on factors such as the type of heat transfer fluid used, solar radiation intensity, and the entry and exit temperatures of the heat transfer fluid. Therefore, using a heat transfer fluid with higher thermal conductivity is advisable. In a solar desalination system, performance relies on solar irradiation, the heat transfer fluid's entry temperature, the absorber plate's quality, and thermal insulation. The use of high-thermal-conductivity fluids like nanofluids can effectively remove heat from the PVT system, utilizing that energy to evaporate salty water in salt removal systems. However, many systems lack proper thermal insulation and higher-thermal conductivity heat transfer fluids. This issue is also relevant in PVT systems used in thermal power stations, where water is heated to generate steam. To improve the performance of thermal power plants, it is necessary to incorporate proper thermal insulation and higher-thermal conductivity heat transfer fluids. The rate of steam production is a critical factor influencing power plant performance. Furthermore, hot air is required for food processing and HVAC systems to enhance their performance. Therefore, optimizing the air flow rate, glazing thickness, and ensuring proper thermal insulation is recommended.

The fluid used in a PVT system can be air, liquid, or a combination of both. Air is a cost-effective and environmentally friendly option that can be used in various locations. However, water is the least expensive and most commonly used fluid due to its purity and usability. Additionally, air-based PVT systems require less maintenance compared to water-based ones. However, certain applications may necessitate the use of different fluids, requiring specific designs or configurations.

## 4. Environmental Analysis of PVT Systems

Factors such as population growth, industrialization, and technological advancements make it inevitable that greenhouse gas emissions will continue to rise. The primary greenhouse gases of concern include carbon dioxide, methane, sulfur hexafluoride, carbon monoxide, nitrous oxide, and chlorofluorocarbons. To mitigate the release of these gases into the atmosphere, the implementation of PVT systems could be an effective solution. This section explores the significant environmental parameters associated with the impact of PVT systems on the environment.

The introduction of carbon tax and emission trading systems by many nations will impose additional costs on energy usage due to $CO_2$ emissions [125]. Exposure to greenhouse gases, particularly carbon dioxide, is known to have adverse effects on human health and the environment. Therefore, an analysis was conducted to investigate the reduction of $CO_2$ emissions from using PVT systems using Equation (1).

$$\bar{\omega}_{ov} = \lambda_{CO_2*}\dot{E}_{ov} \tag{1}$$

$\bar{\omega}_{ov}$ is $CO_2$ emission ($mtCO_2$), $\lambda_{CO_2*}$ is electrical equivalent intensity (grams $CO_2$ equ. per kWh electricity), and $\dot{E}_{ov}$ is overall energy or exergy generation (W).

The overall energy production of the PVT system is estimated using Equation (2).

$$\dot{E}_{ov} = \dot{E}_{el} + \dot{E}_{th} * 0.38 \tag{2}$$

$\dot{E}_{el}$ denotes the electrical power in watts and $\dot{E}_{th}$ is the thermal power in Watts.

Studies have shown that a PV unit can contribute to a reduction of 16.3 kg of $CO_2$ over a three-month period. Similarly, PCM-embedded PVT systems with water, EG 50%, and EG 100% have demonstrated reductions of 52.56%, 51.38%, and 49.69%, respectively, over the same duration [126]. The implementation of a PVT system with nanofluid in Saudi Arabia could potentially reduce $CO_2$ emissions by 16,975 tonnes [127]. In another case, a PVT system with air as the working fluid prevented the release of 1.98 kg/h of $CO_2$ emissions from a solar dryer into the atmosphere [128]. An environmental analysis of a solar-assisted combined cooling, heating, and power (S-CCHP) system revealed that it could prevent the emission of 911 tons of $CO_2$ per year, which is 16% higher than a similar PV system [123].

The environmental impact assessment of a combined cooling, heating, and power (CCHP) system, coupled with PVT, micro gas turbine, and absorption chiller, was conducted. The analysis divided the proposed CCHP system into three subsystems: power generation mode with MGT, CHP mode combined with PVT cycle, and CCHP mode with MGT combined with absorption systems. The $CO_2$ emissions from these subsystems were computed using equations (Equations (3)–(5)). The proposed system was found to emit 0.16 (ton/MWh) of $CO_2$ annually, which is relatively low compared to other methods [129].

$$\varepsilon_{em,GT} = \frac{\dot{m}_{CO_2,emitted}}{\dot{W}_{GT}} \tag{3}$$

$$\varepsilon_{em,CHP} = \frac{\dot{m}_{CO_2,emitted}}{\dot{W}_{GT} + \dot{Q}_{heating}} \tag{4}$$

$$\varepsilon_{em,CCHP} = \frac{\dot{m}_{CO_2,emitted}}{\dot{W}_{GT} + \dot{Q}_{heating} + \dot{Q}_{cooling}} \tag{5}$$

The yearly reduction (ER) in $CO_2$ emission of the proposed PVT system at the University Sports Center of Bari, Italy, was evaluated based on $CO_2$ discharge factors of natural gas $(f_{ng})$ and electricity $(f_{el})$. Equation (6) was used for the assessment. The yearly reduction in cost of $CO_2$ emission per unit was found to vary from EUR 120/t$CO_2$ to a value less than EUR 1/t$CO_2$.

$$ER = \frac{Q_{COV}}{\eta_{boil}} f_{ng} \tag{6}$$

$$ER_{el} = (E_{COV} + E_{exc}) \cdot f_{el} \tag{7}$$

$$ER_{tot} = ER_{ng} + ER_{el} \tag{8}$$

$ER_{tot}$ denotes the total emission reduction (Equation (7)), $ER_{ng}$ denotes the emission reduction due to displaced natural gas, $ER_{el}$ denotes the emission reduction due to displaced electricity (Equation (8)).

Furthermore, a hybrid PV-ETC system could achieve an annual reduction of 317 tons of $CO_2$ emissions, while a novel PVT S-CHP system demonstrated a reduction of 445 tons of $CO_2$ emissions per year. In contrast, an ICE-CHP system only achieved a reduction of 25 tons of $CO_2$ emissions per year. An ultra-low-cost PVT collector design was found to reduce annual $CO_2$ emissions by 183.8 kg, and over a 20-year lifespan it could reduce emissions by 3.7 metric tons of $CO_2$ per square meter of PVT collector installed [130]. Therefore, the implementation of this system can contribute to the European Union's goal of achieving a 40% reduction in carbon emissions by 2030 [8].

The environmental impacts of different configurations of water/carbon nanotube-based PVT systems were examined, revealing the potential to prevent emissions of $CO_2$, $SO_2$, NOx, CO, and particulate matter [131]. Additionally, the use of aluminum foam in PCM-integrated PVT systems was found to effectively reduce $CO_2$ emissions [132].

However, the incorporation of nanomaterials in the cooling fluid can enhance the performance of PVT systems and improve their environmental parameters. It should be noted that while nanofluid-based solar systems can reduce greenhouse gas emissions more effectively and generate higher energy outputs compared to conventional cooling fluids, the production of nanoparticles may also pose contamination risks to other natural sources such as soil and water.

## 5. Technical Challenges and Limitations

This comprehensive review article delves into the extensive applications of hybrid photovoltaic thermal (PVT) systems. Each type of PVT system holds its own significance and value, depending on its intended use and environmental feasibility. However, for these systems to truly compete with established solar thermal and PVT systems in the commercial market, they require significant upgrades.

One of the challenges associated with conventional working fluids used in PVT systems is their inferior thermal behavior in relation to their expected application. Researchers have been actively searching for improved working fluids with enhanced thermal properties to overcome this. In particular, the freezing of water in cold regions restricts the use of water-based PVT systems, making air-based PVT systems more suitable for heating applications in such areas. Therefore, it is imperative to develop appropriate water-based systems tailored for cold regions.

In terms of system design, active PVT systems necessitate more pumping power compared to passive systems. PVT systems employing natural circulation are more cost-effective than those relying on forced circulation. Water supply availability limits the application of water-based PVT systems, whereas air is readily accessible for air-based PVT systems. The choice of medium depends heavily on the intended application of the PVT system.

The use of conductive adhesives can improve heat transfer and system efficiency. Introducing multiple air inputs into air-based PVT systems is considered beneficial. Moreover, single-laminated PVT units, referred to as TESPI systems, have the potential to reduce thermal resistance provided by tedlers, encapsulant materials, and adhesives, although they have yet to be commercialized. Another approach to enhance thermal performance is to partially cover the absorber layer with PV modules rather than entirely covering it. However, it should be noted that the addition of glazing in PVT systems increases thermal efficiency at the expense of electrical performance.

Despite the promising applications of PVT technology, its commercialization is still limited. To facilitate widespread adoption, focusing on and improving these systems' initial and operating costs is crucial. Additionally, extensive research is required in emerging areas of PVT technology, such as optimizing auxiliary power usage (e.g., pumps or blowers), reducing materials costs, and exploring the utilization of smart materials.

In conclusion, hybrid PVT systems offer diverse applications, but their market penetration requires substantial upgrades and cost improvements. Continued research and development efforts are essential to fully unlock the potential of PVT technology and facilitate its commercial viability.

## 6. Conclusions and Recommendations

The present research analyzed and summarized the literature on experimental applications of hybrid PVT systems with and without PCMs for various industrial applications and buildings. Industrial applications, such as water heating, water desalination, thermal management in buildings, food processing, HVAC, agricultural processes, and thermal power plants, were taken into consideration. This technology offers benefits such as reduced electrical consumption, shifting of cooling and heating peak loads to off-peak periods, minimized temperature fluctuations, and improved thermal comfort. Additionally, the incorporation of nanoparticles into PCMs has been shown to enhance the performance of PVT systems.

The present study discussed the various types of cooling systems of PVT systems. The thermal management system bi-fluid cooling system performs better than other systems. Also, the PCM-integrated PVT system has the advantages of cooling the PVT system and storing excess thermal energy. The stored energy can be used when solar energy is unavailable. Studies have demonstrated that PVT systems incorporating NEPCMs exhibit higher thermal performance. During charging, these systems stored 8.3% more heat energy; during discharging, they released 25.1% more heat energy than traditional PVT systems. Moreover, employing a solar-powered combined cooling, heating, and power (S-CCHP) system instead of a conventional PV system can prevent the emission of 911 tons of $CO_2$ per year. Enhancing the overall efficiency of hybrid PVT systems leads to reduced payback periods and $CO_2$ emissions.

Based on the analysis conducted in this article, the following recommendations for future research in the field of hybrid PVT systems are presented:

- Investigate the impact of dust and dirt on the efficiency of PVT systems under various weather conditions, as most previous research has focused on clean conditions with low occurrence and intensity of rain.
- Conduct experiments that simultaneously explore the use of nanofluid as the heat transfer fluid (HTF) and PCM/NEPCM as the cooling method, as this area has received limited attention compared to studies on nanofluid- and water-based PVT systems.
- Perform long-term tests to assess the performance of PVT devices over extended periods, including the examination of the effects of prolonged solar exposure on adhesives, glazes, selective coating materials, and other components.
- Explore alternative heat transfer techniques, such as PCMs and NEPCMs, as cooling media in PVT systems, as the majority of the existing literature primarily focuses on water and air as the cooling mediums. Investigate various PCM and NEPCM options for PVT systems.
- It is necessary to work on flame retardant and leakage-preventable PCMs to avoid leakage during the phase transition of the PCM-integrated PVT system.
- Consider studying nano-fluid-based jet impingement systems, as they have the potential to generate a greater amount of heat energy and electricity.

By addressing these recommendations, future research can further advance the understanding and effectiveness of hybrid PVT systems in industrial applications.

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## Nomenclature

| | |
|---|---|
| ALCC | Annualized life cycle cost |
| ALCS | Annualized life cycle savings |
| COP | Coefficient of performance |
| CPVT | Concentrated photovoltaic thermal |
| ECS | Electricity savings |
| EG | Ethylene glycol |
| Epv | Photovoltaic energy |
| Et | Thermal energy |
| HTF | Heat transfer fluid |
| LCC | Life cycle cost |
| LPM | Liters per minute |
| MC | Maintenance cost |
| N | Optimum number |
| NCOT | Nominal cell operating temperature |
| NEPCM | Nano-enhanced phase change material |
| PCM | Phase change materials |
| PMMA | Polymethyl methacrylate |
| PV | Photovoltaic |
| PVT | Photovoltaic thermal |
| PWF | Present worth factor |
| SAH | Solar air heater |
| STC | Standard temperature conditions |
| $tCO_2$ | Tonne of carbon dioxide |
| Tmean | Mean temperature |
| V | Volt |
| VAR | Vapor absorption refrigeration |
| Voc | Open circuit voltage |
| W | Watts |

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