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Systematic Review of Flat Plate Photovoltaic Thermal Systems: Components, Efficiency, Monitoring, and Artificial Intelligence

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The use of hybrid solar panels represents a promising technology for the simultaneous generation of electrical and thermal energy from solar radiation. However, their implementation has been slow due to various technical challenges related to component optimization and the integration of new technologies. This article presents a review of flat-plate hybrid solar panels, focusing on four key aspects: system components, parameters affecting efficiency, monitoring, and applications of artificial intelligence. The analysis highlights the importance of the thermal absorber design and the heat transfer fluid, as well as the influence of environmental, operational, and design-related factors on overall system performance. Furthermore, the need for a comprehensive monitoring approach is emphasized, given that thermal performance is closely linked to the electrical behavior of the system. Regarding AI, its main applications in this field are discussed, particularly in efficiency and environmental variable prediction, design optimization, and the identification of optimal solar system configurations. The integration of AI and real-time monitoring, along with component improvements, can significantly enhance the impact of PVT systems in the energy transition, promoting their adoption in residential and commercial applications and contributing to global sustainability goals.

1. Introduction

The energy transition to renewable sources is not progressing at the pace necessary to meet the targets set in the Paris Agreement.[1,2] Although recent years have seen acceleration driven by government policies and industrial strategies, fossil fuels still dominate the major economies of the world.[1,2] While the capacity for clean energy generation continues to grow, its adoption and deployment are not uniform across all technologies or countries, creating additional challenges to achieve a global energy transition.[1,2] However, the implementation of key technologies such as photovoltaic (PV) solar, wind energy, nuclear energy, heat pumps, and electric vehicles has prevented CO_2 emissions from growing three times faster.[3]

In this context, solar energy plays a crucial role due to its versatility in generating electricity and heat. However, PV cells only convert a fraction of solar radiation into

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electricity, while the rest is either reflected or transformed into thermal energy, which is responsible for the increase in temperature within the module.[4–6] This heating is particularly problematic in tropical regions,[7] as it leads to a decrease in electrical efficiency and accelerates cell degradation.[8,9] In fact, for every 1 °C increase above the standard test temperature (20 °C−25 °C), electrical efficiency can decrease by between 0.3 and 0.65%.[9–12]

The concept of integrating a PV module with a solar thermal collector (STC) emerged in the 1970s,[13–15] leading to the development of photovoltaic thermal (PVT) panels. These devices combine electricity and heat generation, becoming a form of solar cogeneration.[11,16] It is important to clarify that PVT systems are also known as hybrid solar collectors or hybrid PVT solar collectors.[17] However, it is crucial not to confuse them with hybrid installations that use a separate PV panel and STC, as detailed in the studies.[18–21]

Although the most common design of PVT systems involves placing the PV module over the STC in a compact unit, some authors have proposed alternative configurations. In these designs, the PV module covers only part of the STC surface area,[22–24] either because its main function is to power auxiliary devices such as fans,[23,24] or because maximizing the STC surface is prioritized, as in applications intended for product drying.[24]

In addition to generating usable thermal energy, some authors[11,25–27] suggest that PVT systems were designed to eliminate the residual heat from photovoltaic modules. The integration of a thermal absorber with circulating fluid not only helps to cool the panels but also enables the recovery and use of residual heat,[25] thus improving the overall efficiency of the system.

PVT systems offer significant advantages: they are particularly suitable for applications with limited space[16,28] or those requiring low temperatures,[8] allow for a more uniform and aesthetically pleasing architectural integration compared to the separate installation of both systems,[29] and have the capacity to simultaneously capture thermal and electrical energy, enabling dual output.[16,30] In some cases, they are even more cost-effective than the combination of separate technologies.[29]

The first PVT system reached the market in 1991[31] and was primarily used in Israel for domestic hot water (DHW) and electricity generation. Since then, its adoption has gradually increased in various parts of the world. However, despite its potential, the growth of the PVT market slowed down in 2022 due to factors such as the reduction of subsidies and the rise of conventional photovoltaic installations, which led several companies to focus on traditional technologies.[32] Despite these challenges, by 2024, Europe became the continent with the largest installed PVT area, with France leading the market, followed by Germany and the Netherlands.[32]

In this regard, the International Energy Agency, through Task 60,[33] focused on the application of PVT collectors with the aim of evaluating existing solutions and developing new system solution principles where PVT technology truly offers advantages over the classic “side-by-side installations” of STCs and photovoltaic modules. Energy production, competitive costs, safety, and system reliability were within the scope of the task. This international effort has contributed to identifying the areas where PVT systems can outperform conventional technologies, promoting their adoption and optimization.

Regarding the scientific literature, review articles on PVT systems have addressed various aspects such as their background, classification, applications, performance, storage, emission mitigation analysis, concentrators, nanofluids (NF), and phase change materials (PCM).[13,16,34,35] Particularly noteworthy are the reviews focused on the classification of these systems, as they offer a better understanding of their technological diversity. Some of them[13,34] have proposed classification criteria based on the type of cover, photovoltaic cell type, cooling method, heat extraction medium, system structure, and working fluid. These contributions have been key to developing a comprehensive understanding of PVT systems, encompassing a wide variety of configurations and applications.

Among the different configuration types, PVT systems with flat plate STC stand out for offering a suitable temperature range[17] for applications such as DHW and space heating (SH).[5,36] Flat plate PVT systems have gained particular relevance due to the growth of the sector in commercial and public buildings,[32] where such applications are especially in demand. In this context, flat plate PVT systems are emerging as a highly promising option within the current solar technology market.

This type of PVT system has been studied from various perspectives,[31,37–39] including technologies, efficiencies, applications, classifications, advantages, limitations, and research opportunities. Recently, some studies[37] have also explored topics such as the use of NFs and PCMs, highlighting their impact on thermal efficiency and operational management.

However, to the best of this research team’s knowledge, no review article has been identified that focuses specifically on flat plate PVT systems in combination with monitoring and AI. Only two related works have been found: one that mentions machine learning (ML) applied to PVT systems,[40] and another that explores monitoring aspects in air-based PVT systems integrated into buildings.[41]

In this context, the aim of this article is to present an updated systematic review on flat plate PVT systems, focused on four main aspects (**Figure 1**): system components, parameters influencing efficiency, monitoring, and applications of AI.

The main contributions of this work for flat plate PVT systems are as follows. 1) **Classification based on structural components**: A classification is proposed according to the main elements of the system to facilitate comparison, analysis, and evaluation of different designs. 2) **Factors affecting efficiency**: A synthesis of the most relevant factors influencing system efficiency is presented. This information is key for the development and optimization of new designs. 3) **Monitoring**: Internationally applicable standards, the most commonly used parameters, and the most frequent measurement devices in experimental studies are compiled and described, offering a useful foundation for researchers interested in implementing monitoring systems. 4) **Artificial intelligence**: The most relevant applications and the dominant AI approaches are outlined.

The structure of this article is as follows: Section 2 details the methodology following PRISMA guidelines; Section 3 presents the results, including the analyzed articles organized according to the aforementioned categories; and Section 4 presents the conclusions.

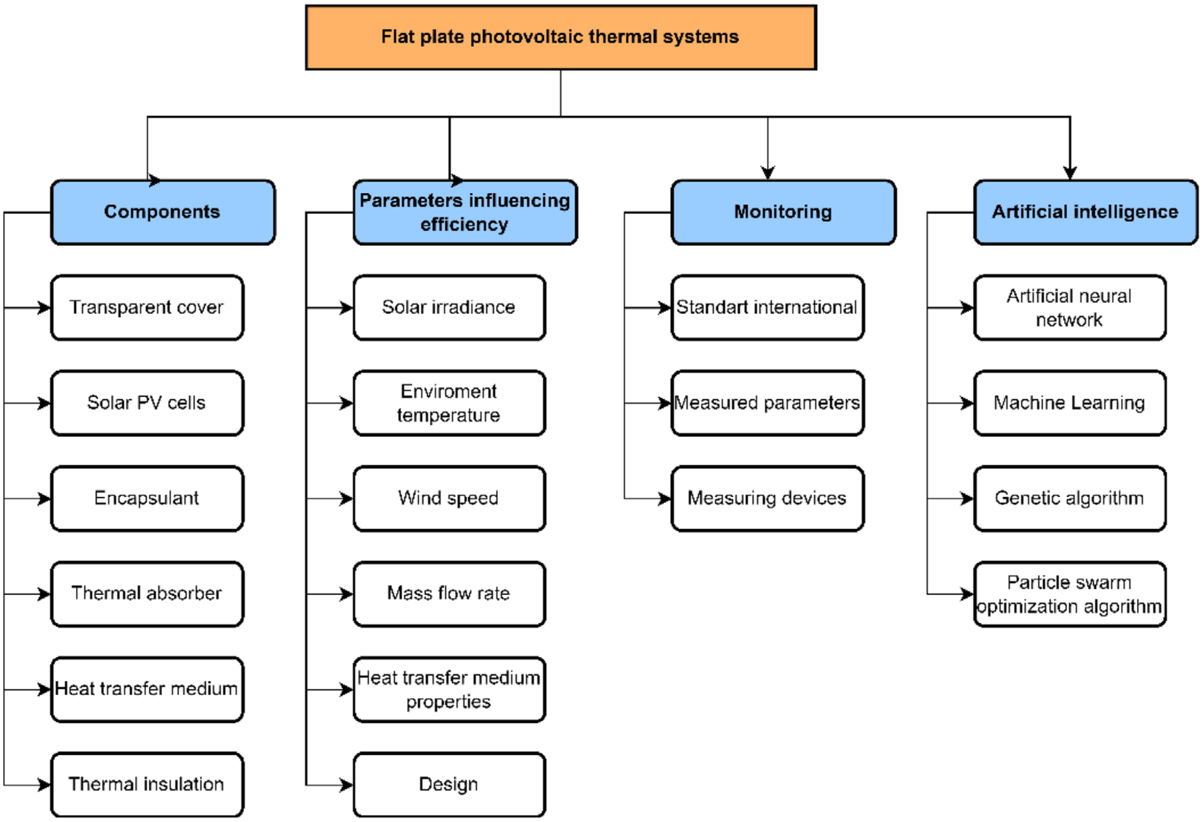

Figure 1. Classification of the reviewed studies, prepared by: author.

2. Experimental Section

This study was conducted following the guidelines established by the PRISMA statement,[42,43] a recognized standard for conducting systematic reviews.

Initially, searches were conducted in ScienceDirect, Scopus, and Web of Science databases using the keywords: "Photovoltaic," "Thermal," "Hybrid," and "Solar". However, these preliminary searches resulted in a large number of articles that were not relevant to the study's objectives.

To improve the accuracy of the results and refine the scope of the review, a combination of terms with Boolean operators was applied, resulting in a total of 584 studies retrieved from the selected databases. The search string used was: (Photovoltaic thermal hybrid solar) AND (Flat plate) AND (Efficiency OR Performance OR Operation OR Monitoring OR Maintenance OR Artificial Intelligence) NOT (Exergy OR Exergetic) AND NOT (Concentrator OR Concentrated).

The article selection process was conducted in three stages. First, an initial exclusion was performed, removing 359 articles that did not meet open-access requirements or were literature reviews. Subsequently, a screening phase was conducted, excluding 136 articles whose titles or abstracts were unrelated to the study's topic or were duplicates. Finally, the eligibility of the remaining studies was assessed by applying the predefined inclusion and exclusion criteria, leading to the exclusion of 18 additional articles. By the end of this process, 71 articles met all the established requirements and were included in the systematic review.

To minimize potential biases and ensure the inclusion of all relevant studies, a final search was conducted exclusively in the ScienceDirect database, as it had provided the highest-quality results in previous stages. In this search, the terms "Monitoring" and "Artificial Intelligence" were specifically explored in combination with the main keywords "photovoltaic thermal hybrid solar." This step led to the identification of additional studies, adding 10 more articles to the systematic review.

Figure 2 presents the PRISMA flow diagram, detailing the selection process of the included articles, reaching a final total of 81 studies analyzed in this review.

3. Results

This section presents the analysis of the selected articles following the PRISMA methodology. It begins with the subsection on system components, in which the different types, the most commonly used materials, their applications, and implemented improvements are described and compared. Next, key parameters affecting the PVT system and their impact on efficiency are analyzed. The following subsection focuses on the monitoring of PVT systems, detailing the parameters measured and the devices used for both measurement and data acquisition. Finally, the use of AI is discussed, highlighting its most common

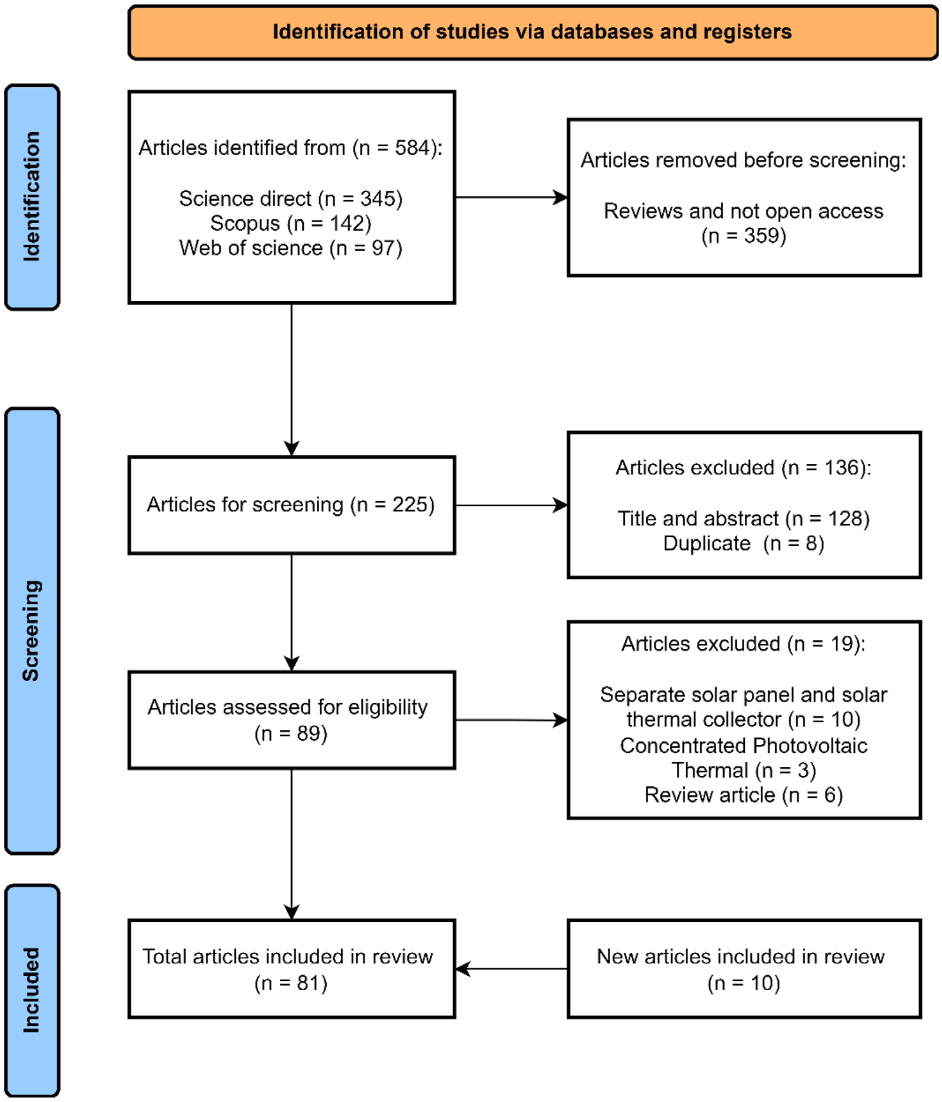

Figure 2. PRISMA flowchart. Figure created by the author based on sources:[42,43]

applications and the predominant AI approaches used in the PVT field.

3.1. Components

This section describes the main components commonly used in flat plate PVT systems, as shown in **Figure 3**:[17,39,44,45] 1) transparent cover (optional); 2) solar PV cells; 3) encapsulant (optional); 4) thermal absorber, heat exchanger, or extracting heat device; 5) heat transfer medium or heat transfer fluid; and 6) thermal insulation (optional)

3.1.1. Transparent Cover

In PVT systems, the transparent cover plays a crucial role in influencing both the thermal and electrical efficiency of the

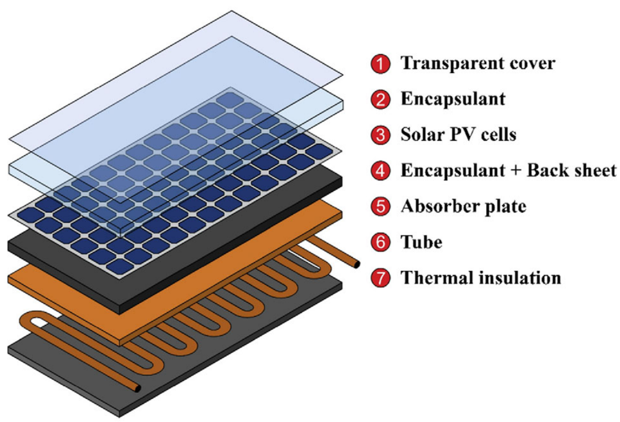

Figure 3. Schematic of a typical flat-plat PVT module. Figure created by the author based on sources:[45]

system. Its primary function is to block infrared radiation and protect photovoltaic cells from environmental factors such as wind, snow, hail, and acid rain.[17] The presence or absence of this cover determines two main configurations: Covered PVT, when the system includes a transparent cover, and Uncovered PVT or Unglazed PVT, when it lacks one. The latter is also known as unglazed or wind and/or infrared sensitive PVT collectors (WISC).[17] The inclusion of this cover is not mandatory and should be selected based on the specific energy requirements of the system.[46]

Studies on transparent covers in flat plate PVT systems have primarily focused on analyzing their impact on thermal and electrical performance. For instance,[46] compared the energy performance of both configurations and concluded that Uncovered PVT systems achieve higher electrical efficiency, while Covered PVT systems are more efficient in thermal energy production, particularly during winter. On the other hand, study[47] evaluated the performance of an Uncovered PVT system in different climate zones (Paris, Milan, and Athens) using a mathematical model in TRNSYS. The results showed that as annual solar irradiation increases, thermal efficiency improves, but electrical efficiency decreases due to the rise in module temperature.

Although these studies suggest that the differences in electrical and thermal efficiency between the two configurations are evident, research such as,[48] which developed 3D dynamic thermoelectric models to compare a flat plate STC with both Covered and Uncovered PVT systems, demonstrates that this difference cannot be attributed solely to the presence or absence of the transparent cover. The thermal and electrical behavior proves to be more complex and depends on operational and environmental factors, which will be addressed in the section dedicated to efficiency-influencing parameters.

Nevertheless, it can be generally stated that the use of a transparent cover reduces heat losses and enhances thermal energy production, although this may lead to an increase in solar cell temperature and, consequently, a reduction in electrical efficiency.[47] On the other hand, omitting the cover results in lower thermal output and greater dependency on environmental conditions such as wind speed or ambient temperature, which can limit performance in colder climates.[49] Therefore, the choice between a Covered or Uncovered system depends on the main objective of the PVT: maximizing thermal energy production, optimizing electrical efficiency, or achieving a balance between the two.

In Covered PVT systems, the cover is typically made of tempered glass or polymers. Some of the most commonly used materials include selective tempered glass,[29,49,50] tempered glass,[51] tempered soda lime glass,[52] and high transparency glass.[49] Some studies have also explored alternative materials such as transparent polyethylene terephthalate (PET).[8]

From an economic perspective, both Covered and Uncovered PVT systems have been studied. A comparative study[50] analyzed the performance of these systems against the conventional combination of PV and STC for energy supply and DHW applications in buildings. Economic viability was determined using the competitive specific price, an indicator based on energy savings and economic parameters. The results showed that, in 2013, commercially available Uncovered PVT systems were not economically competitive for DHW applications due to their high costs and lower efficiency compared to conventional solutions.

However, according to IEA data,[32] Uncovered PVT systems have dominated the global market, accounting for the largest cumulative installed area up to the end of 2023. Nevertheless, their market share decreased from 88% in 2022 to 78% in 2023. In contrast, Covered PVT systems experienced significant growth during the same period, increasing their global installed area from 11% in 2022 to 22% in 2023.

In terms of reported applications in the literature, Covered PVT systems have been documented for use in DHW, SH, and electricity generation in buildings,[46,49,50] as well as for similar purposes in the residential sector.[51,53,54] In the agricultural sector, they have been used for SH and DHW, particularly in pig farm greenhouses.[55]

These systems typically operate at temperatures ranging from 20 to 80 °C, making them suitable for use in swimming pools, which generally require water temperatures between 27 and 35 °C. For DHW systems, it is recommended to reach temperatures up to 60 °C to prevent legionella, although this temperature is usually reduced before supply. In SH systems, temperatures of up to 50 °C are required when heating is provided via underfloor systems.[17]

On the other hand, Uncovered PVT systems have been mainly studied for electricity generation and DHW applications in buildings.[46,48] However, since Uncovered PVT systems typically operate within a range of 0 to 40 °C, they have proven particularly suitable as a thermal source for heat pump systems due to their enhanced heat transfer to ambient air. When the heat pump source temperature is lower than the ambient temperature, the fluid can warm up to ambient levels even during sunless periods.[17]

Table 1 provides a summary of the highlights and applications of Covered and Uncovered PVT systems. It also shows that most studies focus on Covered PVT systems, indicating a growing interest in the use of transparent covers, which aligns with the increasing market share of Covered PVTs mentioned earlier.

3.1.2. Solar PV Cells

A key component in a flat plate PVT system is the solar PV cells, responsible for converting solar energy into electricity. These can be manufactured using different materials and production processes, allowing them to be classified into four generations:[56] 1) first generation: crystalline silicon (Si) cells (monocrystalline and polycrystalline); 2) second generation: thin-film cells made of amorphous Si, polycrystalline Si, cadmium telluride (CdTe), and copper indium diselenide (CIS); 3) third generation: organic solar cells and gallium arsenide (GaAs) cells; and 4) fourth generation: hybrid solar cells, such as perovskite cells.

Some studies have evaluated the performance of different solar cells in flat-plate PVT systems. For example,[57] analyzed CdS, CdTe, and GaAs cells in a high-vacuum PVT system incorporating a transparent conductive oxide (TCO) layer, which are key materials in photovoltaic energy as they serve as the front electrode in many solar cell technologies.[58] The results showed that the thermal efficiency of GaAs and CdTe is ≈60% at 323 K, while CdS cells, although exhibiting lower electrical efficiency,

Table 1. Highlights and applications of flat plate covered and Uncovered PVT. Prepared by: author.

PVT type	Highlights	Applications
Covered	• Protect photovoltaic cells from environmental factors and reduce infrared radiation losses.[17] • Implementation depends on the specific system requirements.[46] • Higher efficiency in thermal energy production, especially in cold climates,[46] with lower heat losses.[47] • Increased thermal output can raise cell temperature, reducing electrical efficiency.[47] • Materials used include selective tempered glass,[29,49,50] normal tempered glass,[51] tempered soda-lime glass,[52] high transparency glass,[49] and transparent PET[8] • Market trend shows growth from 11% (2022) to 22% (2023) installed area.[32]	• DHW, SH, and electricity generation in buildings[46,49,50] and residential sector.[51,53,54] • SH and DHW in pig farm greenhouses.[55] • Swimming pool heating requires temperatures between 27–35 °C.[17] • DHW systems requiring up to 60 °C to prevent legionellosis.[17] • SH requires temperatures up to 50 °C for underfloor heating.[17]
Uncovered	• Higher electrical energy generation efficiency compared to covered systems.[46] • Greater heat transfer to the fluid[48] but lower total thermal output.[50] • Performance significantly depends on climatic conditions.[50] • In 2013, not economically viable for DHW applications due to high costs compared to conventional alternatives.[50] • Despite dominating installed area, market share decreased from 88% (2022) to 78% (2023).[32]	• Electricity generation and DHW in buildings.[46,48] • Heat pump applications.[17]

offer higher thermal efficiency at 323 K, 353 K, and 373 K. Overall, all these technologies demonstrated better performance at low to medium operating temperatures. Regarding the use of the TCO layer, the study highlighted that the thermal emissivity of the material is a critical factor in achieving high thermal efficiency, especially when the operating temperature exceeds 75 °C.

On the other hand,[59] compared a PVT system with thin-film cells, combining amorphous and microcrystalline Si, against a conventional photovoltaic module. Although the PVT system's electrical output was slightly lower, its overall efficiency in terms of primary energy was higher, as it not only generated electricity but also produced thermal energy simultaneously.

A similar analysis was conducted in,[46] where two configurations were evaluated: an uncovered PVT system with polycrystalline cells and a covered PVT system with amorphous and microcrystalline Si thin-film cells. The results indicated that the uncovered PVT system with polycrystalline cells achieved higher annual primary energy efficiency. This is due to the lower electrical efficiency of microcrystalline Si; however, the thermal performance of the PVT system with amorphous and microcrystalline Si thin-film cells was superior, especially in winter. For amorphous Si, it is important to highlight the thermal annealing process,[46,59] which improves its electrical efficiency by up to 10% when exposed to temperatures between 50 °C and 100 °C,[60] this study has not considered this process in the analysis.

Additionally,[61] evaluated the performance of CIS thin-film solar cells, known for their high optical absorption coefficient. The results indicate that PVT systems with CIS thin-film solar cells surpass the thermal and electrical efficiency of monocrystalline Si cells.

Despite advancements in other technologies, monocrystalline Si remains the most widely used option in PVT systems due to its better cost-benefit ratio compared to polycrystalline Si, amorphous Si, and thin-film technologies.[62] However, its electrical efficiency is highly sensitive to temperature, which can affect its performance under high-irradiance conditions.

Study[9] analyzed a PVT system with monocrystalline cells and found that, at low levels of solar irradiance, the outlet fluid temperature from the collector is relatively low but increases with irradiance due to greater heat accumulation in the cooling fluid. Furthermore, it was observed that increasing the fluid flow rate by 10 L/h reduces the cell temperature and improves electricity generation. Conversely, study[8] demonstrates that although higher solar irradiance levels increase the thermal output of the PVT system, they also reduce the electrical efficiency of monocrystalline cells due to the rise in operating temperature. This highlights that higher irradiance enhances thermal utilization but decreases electrical efficiency.

Table 2 summarizes the highlights of the different types of photovoltaic cells used in flat-plate PVT studies. As can be observed, most works have focused on analyzing the thermal and electrical performance of monocrystalline silicon, polycrystalline silicon, and thin-film technologies based on amorphous and microcrystalline silicon. Additionally, thin-film cells using materials such as copper, indium, and selenium are included, as well as semiconductors with a high bandgap such as GaAs, CdS, and CdTe.

3.1.3. Encapsulant

The encapsulant is an essential component in PVT systems, as it protects and stabilizes the solar cells. In fact, it is one of the most critical layers in a PVT system, along with the PV module.[28] The encapsulant must possess the following characteristics: good thermal conductivity, high durability, resistance to expansion and shear stress, as well as a low temperature coefficient.[44] It can be located on both the top and bottom of the PV module. To improve the efficiency of the photovoltaic system, the contact surface between the PV module and the absorber must be optimized.[7,63,64] This is achieved when the encapsulant is combined with a back sheet, such as Tedlar,[6] which acts as an adhesive to secure the PV module to the thermal absorber and as a cushion to reinforce its structure.[8,45,65]

The most commonly used encapsulation material is a transparent ethylene-vinyl acetate (EVA) resin, manufactured by Dupont.[31] This material is widely used as a backsheet in

Table 2. Comparative highlights of photovoltaic cells used in flat-plate PVT systems. Prepared by: author.

Type of PV cell	Highlights
Monocrystalline	• It is the most widely used option due to its better cost-benefit ratio compared to polycrystalline Si, amorphous Si, and thin-film technologies.[62] • Its electrical efficiency is highly sensitive to temperature; although higher irradiance improves thermal performance, it reduces electrical efficiency.[9]
Policristalino	• Offers higher annual efficiency in terms of primary energy compared to thin-film technologies such as amorphous and microcrystalline Si, as the latter show lower electrical efficiency.[46]
Película delgada de Si que combina Si amorfo y microcristalino	• Microcrystalline Si has lower electrical efficiency than polycrystalline silicon[46] • It exhibits better thermal performance than polycrystalline Si, especially in winter.[46] • Amorphous Si can increase its electrical efficiency by up to 10% through thermal annealing when exposed to temperatures between 50 °C and 100 °C.[55]
Película delgada CIS	• Features a high optical absorption coefficient.[61] • It surpasses the thermal and electrical efficiency of monocrystalline Si.[61]
Semiconductores con banda prohibida alta GaAs, CdS y CdTe	• GaAs and CdTe exhibit higher electrical efficiency than CdS.[57] • CdS provides higher thermal efficiency, although with lower electrical efficiency.[57] • All these technologies show better performance at low to medium operating temperatures.[57] • The thermal emissivity of the TCO layer is a key factor in achieving high thermal efficiency, especially when operating temperatures exceed 75 °C.[57]

commercial Si-based solar modules. Study[28] have analyzed its impact on layer adhesion as well as the thermal and electrical efficiency of PVT systems. However, its thermal stability is a major limitation, as at temperatures above 80 °C, it can decompose into acetic acid,[50] leading to PV cell degradation, delamination, and discoloration. This prevents its use in covered PVT systems, where stagnation temperatures can reach between 120 °C and 180 °C.[50] Additionally, the high thermal resistance of backsheet layers in conventional photovoltaic encapsulation hinders heat transfer from the cell to the thermal fluid.[50]

To improve the stability and performance of PVT systems,[5] evaluated the use of two EVA layers: one above the photovoltaic cell and another between the cell and the thermal absorber, as shown in **Figure 4**. The latter layer serves to protect PV cells from moisture, electrical leakage, and potential scratches from neighboring layers. On the other hand, study[62] proposed replacing the lower EVA layer with a silicone gel, which not only bonds both components but also improves thermal conduction and electrical insulation.

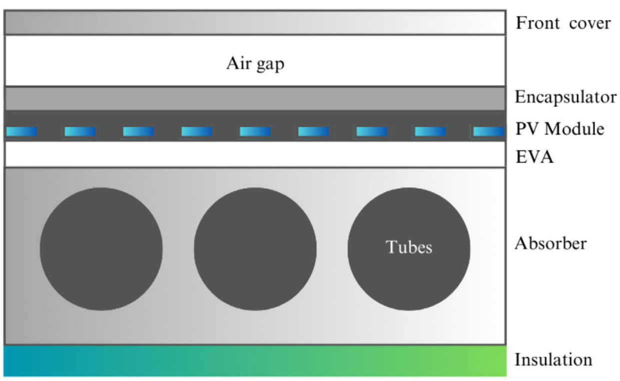

Figure 4. PVT with two EVA layers. Figure created by the author based on sources:[5]

Alternatively,[49] developed an encapsulation method with higher optical and thermal performance, replacing the glass cover with a front layer of low refractive index and substituting EVA with a low UV-absorption material, which increased the solar absorption coefficient compared to standard modules composed of glass, EVA, monocrystalline Si PV module, EVA, and Tedlar.

Another promising material is siloxane gel, which exhibits high thermal resistance (up to 250 °C), high transparency, the ability to compensate for thermal expansion stresses, and improved heat transfer between the photovoltaic cell and the PVT collector's heat exchanger.[50] A study[50] modeled in TRNSYS compared various configurations: PV, STC, and PVT with siloxane gel encapsulation and a selective glass transparent cover. The results showed that the PVT system with selective glass and siloxane gel achieved the highest heat savings for DHW preparation in buildings in Germany. However, the PV system proved to be more efficient in terms of electricity savings.

3.1.4. Thermal Absorber

The thermal absorber is a component that acts as a heat exchanger, transferring the thermal energy from the photovoltaic plate to the fluid circulating inside it.[66] It is important not to confuse this with the additional heat exchanger used in some studies,[54,67] which is used to transfer heat from the heated thermal fluid in the PVT to another circuit or storage system such as a hot water tank. This additional heat exchanger allows heat to be used in heating or DHW supply applications.

Materials used for PVT thermal absorbers include copper, aluminum, steel, and polymers.[44] However, for flat plate PVT systems, copper, aluminum alloy, laminated aluminum, polycarbonate (PC) polymer, polyamide polymer, combinations of various metallic substrates, galvanized steel, polyethylene, Twintex polymer, PMMA (polymethyl methacrylate), polypropylene, and selective solar material.

The most commonly used material is copper;[28] however, new research has been conducted to explore alternative options.

A study[28] compared different types of thermal absorbers, keeping all PVT parameters related to the various layers (dimensions, cover layers, PV cells, etc.) constant, while varying only the parameters associated with the absorber–heat exchanger. This allowed for a comparative analysis based on material type, as well as different pipe diameters and numbers.

The materials analyzed were copper, an aluminum alloy, and two polymers: PC and polyamide (PA). Since PA has low thermal conductivity, its performance was also evaluated with the addition of hexagonal boron nitride particles, an additive designed to enhance this property. However, the results showed that the use of additives significantly increases investment costs due to their high price. Therefore, nonadditivated PA emerges as a better option, as it can reduce investment costs by up to 22% and system weight by 10%, without significantly affecting performance.

In particular, the PC-based design demonstrated the greatest cost savings, positioning it as a viable alternative to copper and aluminum. Additionally, it was observed that for copper and aluminum PVTs, pipe diameter had little impact on thermal efficiency, while increasing the number of pipes significantly improved both thermal and electrical efficiencies. However, aluminum PVT is a strong alternative to copper as it maintains efficiencies while reducing both investment cost and weight.

On the other hand, study[68] also explored the use of a PC polymer known as Twintex, patented by Saint-Gobain, aiming to develop a lighter, more affordable, and easier-to-handle product. The results showed average efficiencies of 29% for the thermal system and 14% for the photovoltaic system. The use of this type of PC offers the advantage of reducing system weight to less than half that of a conventional metal-based collector while maintaining similar performance.

Studies on the use of metals and polymers as thermal absorber materials have also explored their combined application. In this context, study[69] proposed a hybrid absorber composed of PMMA and a copper sheet. The copper sheet, due to its high thermal conductivity, was incorporated to simplify the manufacturing process and reduce the degradation of the polymer material caused by continuous solar radiation exposure.

PMMA was selected for its excellent properties as a polymeric material, making it a promising component for solar energy technologies. The results demonstrated that it is possible to manufacture thermal absorbers combining these two materials, using a T-shaped piece that allows for joining without the need for welding. Furthermore, it was observed that this configuration can effectively cool the photovoltaic surface, contributing to an improvement in both the thermal and electrical efficiency of the PVT system.

Other studies, such as,[57] have integrated solar selective absorbers (SSAs), which are widely used in STCs. These materials are designed to efficiently absorb solar radiation while minimizing thermal emission.[70] In the mentioned study, a high-vacuum PVT system was analyzed, incorporating an SSA placed beneath the photovoltaic module. This allowed the system to capture the fraction of solar radiation not useful for electrical conversion and transform it into heat. Although the study highlights the importance of SSAs, its primary objective was to evaluate the system's performance at different operating temperatures and thermal emissivity levels of the TCO layer, as previously addressed in the subsection on solar cells.

In addition, materials resistant to specific conditions, such as seawater exposure, have also been investigated. For example, study[63] focused on desalination applications, proposed the use of polypropylene as the absorber material due to three main advantages over metals like copper or aluminum: high resistance to seawater, low cost, and reduced weight. Nevertheless, as previously mentioned, polymers have low thermal conductivity, which limits heat transfer efficiency from the photovoltaic cells to the working fluid. To overcome this limitation, the study emphasized the importance of optimizing the interface between the absorber and the photovoltaic module to enhance the thermal performance of the system.

Table 3 summarizes the materials used in flat-plate PVT thermal absorbers. It includes the studies in which each material has been used, as well as the main characteristics highlighted in the performance analysis of these systems. As previously mentioned, copper is the most commonly used material, as reflected in its frequent appearance in the reviewed literature. However, there is growing interest in finding alternatives to traditional metals, which has driven research into the use of polymers with improved properties and solar-selective materials, with the aim of optimizing thermal conductivity while reducing system cost and weight.

In flat plate PVT systems, the absorber can have different internal geometries, which we will classify as forms. **Figure 5** shows the main forms, including: serpentine, single-pass rectangular, honeycomb plate, parallel, grid with roller joints, honeycomb, dual oscillating, and spiral.

The pressure drop in the thermal absorber is the main factor of hydraulic resistance in a PVT liquid circuit, determining the fluid circulation mode in the collector.[71] Studies have explored various absorber configurations to optimize this aspect. For example, a laminated aluminum absorber with parallel tubes (known as a harp) demonstrated a reduction in hydraulic resistance and pressure drop[53] in initial tests, with a water tank positioned 1.2 m above the PVT system, natural circulation with a low flow rate and a temperature difference exceeding 20 °C was observed, negatively affecting the efficiency of the photovoltaic cells. When the tank was raised to 4 m, the flow rate improved significantly, reducing the temperature difference to ≈10 °C, making this system suitable for low-height rural housing. However, in other cases, mechanical circulation is required.[53]

In another study,[72] a similar design was analyzed using a commercial PVT system with a copper sheet absorber and parallel tubes, integrated with a pump to control the flow rate. In addition, manufacturing methods were evaluated to improve thermal contact between the photovoltaic layer and the absorber. The study highlighted that laminating both components into a single assembly is the most efficient method, as it ensures proper thermal insulation. As a simpler and more cost-effective alternative, some commercial collectors place the absorber in direct contact with the photovoltaic cell, using thin thermally conductive materials such as silicone adhesives, copper sheets, or adhesives filled with aluminum or silver. The quality of the thermal contact is key to PVT performance, as poor thermal contact reduces heat transfer to the circulating fluid, increases PV cell temperature, and

Table 3. Materials used for flat plate PVT thermal absorber, prepared by: author.

Type	Material	Studies	Highlights
Metal	Copper	[8,28,62,65,69,72,82,83]	• Most commonly used material.[28] • Pipe diameter has little effect on thermal efficiency.[28] • Increasing the number of pipes significantly improves both thermal and electrical efficiency.[28]
	Aluminum	[51,65,76]	• No detailed material analysis provided.
	Aluminum alloy	[28,30,60]	• Performs similarly to copper regarding pipe diameter and number effects.[28] • Alternative to copper with similar efficiency but lower cost and weight.[28]
	Laminated aluminum	[47,59,71]	• No detailed material analysis provided.
	Galvanized steel sheet	[11]	• No detailed material analysis provided.
Polymer	Polyethylene	[110,111]	• No detailed material analysis provided.
	PC	[28,91]	• Lower thermal conductivity compared to copper, aluminum alloy, and PA. Offers the greatest cost savings among the analyzed materials.[28]
	Twintex PC	[68]	• Patented by Saint-Gobain. • Reduces system weight to less than half that of conventional metal-based collectors while maintaining similar performance.
	Polypropylene	[63,64]	• High seawater resistance.[63] • Lower cost than copper and aluminum.[63] • Lightweight.[63] • Low thermal conductivity limits heat transfer.[63]
	PMMA combined with copper sheet	[69]	• Copper sheet improves thermal conductivity and simplifies fabrication. • PMMA shows favorable polymer properties. • Joined using a T-shaped piece without welding.
	Polyamide, with and without additives	[28]	• Low thermal conductivity. • Thermal conductivity improved with hexagonal boron nitride additives. • Additives significantly increase cost.
Other	Solar selective	[57]	• Captures unused solar radiation and converts it into heat.

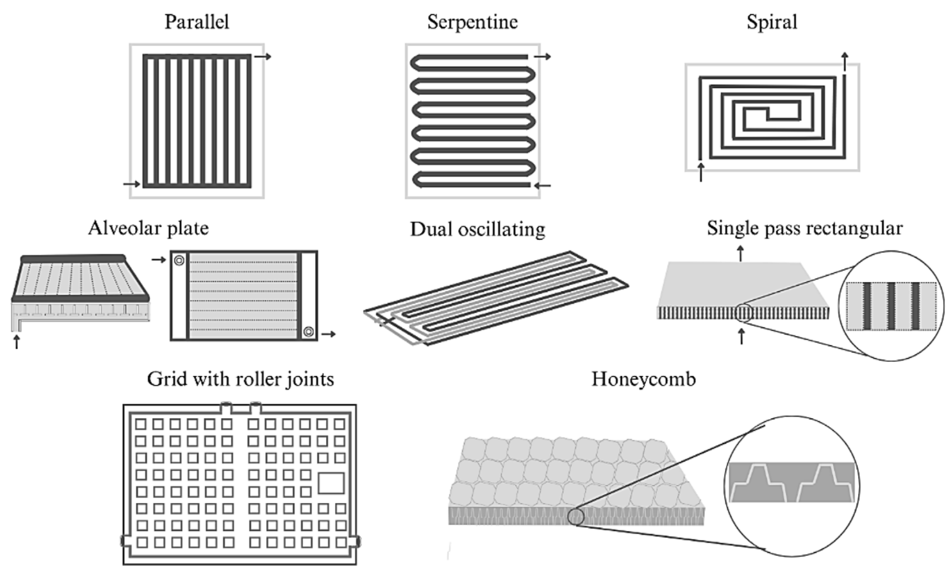

Figure 5. Forms of the flat plate PVT absorber. Figure created by the author based on sources:[7–9,29,63,82]

decreases electrical performance.[64,72] In the long term, this can accelerate the thermal degradation of the PV layer, affecting the system's lifespan.[72]

In addition to the parallel configuration, other internal geometries have been investigated. For instance, study[29] conducted an analysis using computational fluid dynamics (CFD) and compared serpentine and parallel absorbers. The results indicated that the parallel configuration offers a more homogeneous thermal distribution and maintains lower average temperatures, improving performance across all the evaluated electrical configurations. Similarly, study[71] compared a parallel absorber and a grid-shaped one with roller joints, using TRNSYS simulations and experimental tests. It was observed that the parallel configuration exhibits significantly lower pressure drops than the grid design, allowing it to operate with natural circulation at low flow rates or with reduced electricity consumption in mechanical circulation, as had already been demonstrated in.[53] In contrast, the grid design with roller joints requires the water tank to be at least 10 m above the collector to achieve a flow rate and temperature difference similar to the parallel system, which may be impractical. For this reason, its operation depends mainly on mechanical circulation. Despite this limitation, the experiments indicated that the grid-shaped absorber offers higher thermal and photovoltaic efficiencies compared to the harp-shaped one.

Along the same lines, study[7] evaluated other types of absorbers, such as a spiral flow design with rectangular hollow stainless steel tubes, and another with a single-pass rectangular tunnel. The results indicate that the spiral flow absorber achieves its best performance at a PV module temperature of 55 °C, reaching a combined efficiency of 64%. On the other hand, the single-pass rectangular tunnel absorber showed its best performance at a surface temperature of 392 °C, reaching a combined efficiency of 55%.

Another study[67] also used the rectangular shape to carry out a comparative simulation and experimental analysis between a PVT module and a conventional PV module. Although it did not focus specifically on evaluating the impact of absorber geometry, it mentioned that this shape promotes natural fluid convection and provides a large thermal exchange surface between the PV module and the STC. The results showed that regardless of environmental conditions, the PVT system generated higher electrical power than the conventional PV module. Similarly, study[67] compares a PVT system with a dual-wavy absorber and a PV module. The results showed that the wavy design allowed for higher electrical and thermal efficiency, maintaining lower cell temperatures across all analyzed flow rates.

More studies have proposed other novel shapes. For example, study[9] presented an absorber based on an aluminum alveolar plate with 94 channels and two rectangular collectors. These collectors extend across the width of the plate to ensure water distribution in the channels. To analyze its behavior, a numerical model was developed using COMSOL software, based on the finite element method. The results indicate that the proposed PVT system offers good results in terms of thermal homogeneity and overall performance.

On the other hand, a honeycomb-shaped absorber has also been proposed as an original solution, particularly suitable for reverse osmosis desalination applications.[63] Although the material type was decisive for this application, the honeycomb shape was essential for achieving effective heat transfer between the absorber and the thermal fluid. Furthermore, the study concluded that this configuration shows better results than the rectangular shape.

Table 4 presents a summary of the shapes used in flat-plate PVT thermal absorbers. It lists the studies where these shapes

Table 4. Shapes of flat plate PVT thermal absorbers, prepared by: author.

Shapes	Studies in which it has been used	Highlights
Serpentine	[29,54,64,82,86,109]	• Common in commercial configurations.[82] • Higher flow rate improves the temperature difference between inlet and outlet, thus increasing efficiency.[82]
Single-pass rectangular	[7,67]	• Lower combined performance and efficiency than spiral geometry.[7] • Performs best at a high surface temperature (392 °C).[7] • Allows fluid flow by natural convection.[67] • Provides a large heat exchange surface between the PV module and the STC.[67]
Alveolar plate	[9]	• Good overall thermal performance. • Acceptable thermal heterogeneity.
Grid with roller joints	[71]	• Requires the water tank to be at least 10 m above the collector to achieve similar flow rate and temperature difference as the parallel configuration. • Relies on mechanical circulation. • Higher thermal and electrical efficiency than the parallel type.
Parallel or harp	[29,53,65,71,72,76]	• Reduces hydraulic resistance and pressure drop.[53] • Lower pressure drop than the grid-type absorber.[53] • Reduced power consumption thanks to natural circulation.[53,71] • Allows natural circulation at low flow rates.[53] • Performance improves by raising the tank.[53] • Suitable for low-rise rural homes.[53] • Laminating parallel tubes with a copper sheet ensures good thermal insulation, although adhesives can also be used.[72] • Thermal contact is crucial for system performance and longevity.[72] • Provides a more homogeneous thermal distribution and lower average temperatures, improving electrical performance.[29]
Honeycomb	[63]	• Suitable for reverse osmosis desalination. • Effective heat transfer between the absorber and the thermal fluid. • Performs better than the rectangular type.
Dual oscillating	[8]	• Higher electrical and thermal efficiency than a conventional PV module. • Maintains lower solar cell temperature across all flow rates.
Spiral	[7,69]	• Better combined performance and efficiency than the single-pass rectangular shape.[7]

have been used, as well as the main characteristics highlighted in the performance analysis of such systems. As shown in the table, serpentine and parallel configurations are the most widely used, which is reflected in their frequent appearance in the reviewed literature. However, there is a growing interest in exploring more novel shapes to enhance overall performance.

Flat plate PVT systems can be classified according to the configuration of their absorber, understood as its external arrangement. This classification differs from the absorber's form, which refers to the internal geometry of the channels or tubes through which the thermal fluid circulates. Among the most commonly used configurations are sheet and tube, channel or box, and combinations of these, including double absorber and channel (**Table 5**).

The sheet and tube configuration is one of the most studied and used in STCs.[28,73] However, the cylindrical geometry of the tubes does not optimally fit the flat structure of photovoltaic panels, which affects the system's efficiency.[36] Study[28] compared the thermal and electrical performance of two configurations: sheet and tube, and channel or box (**Figure 6**). The results indicate that box collectors, characterized by a thin absorbing plate, exhibit higher thermal and electrical efficiency due to their larger heat transfer area. Additionally, they distribute temperature more evenly across the photovoltaic cells, reducing hotspots and elevated temperatures. Regarding the sheet and tube configuration, it was found that the pipe diameter has minimal impact on thermal efficiency, while an increase in the number of upward tubes improves both thermal and electrical performance up to an optimal point between 20 and 25 tubes, beyond which the efficiencies stabilize.[28]

On the other hand, study[74] analyzed a PVT with a channel and passive cooling through a flat aluminum plate. It was found that adding more plates does not significantly improve heat transfer, suggesting a limit to their effectiveness. Additionally, the optimal distance between the back of the photovoltaic panel and the aluminum plate was found to be 3 cm, as it promotes air circulation, increasing flow velocity by 94%.

Other configurations include study[51] which proposed a PVT design with a double absorber, consisting of a PV module installed between a thermal collector with a glass cover and a thermal aluminum collector (**Figure 7**). The water circulates through both thermal collectors, that is, above and below the PV module and its connections are linked to a water tank. Another study[54] proposed a similar setup, but with two types of fluids circulating. The PVT includes a serpentine water tube and an air channel, allowing both to circulate simultaneously beneath the PV module. The water tube is connected to a heat exchanger that transfers heat to a storage tank, while the air channel is connected to a controller that ensures the air reaches the desired temperature.

Study[54] proposes a double channel configuration where the fluid circulates both above and below the solar panel (**Figure 8**). Unlike the double absorber configuration, this arrangement connects the top and bottom, allowing the fluid to remain in the system for a longer time and captures more heat. Similarly, study[75] presented the same configuration under the name "double pass."

Table 5. Configurations of the flat plate PVT thermal absorber. Prepared by: author.

Configuration	Description	Results	Articles
Sheet and Tube	Combination of a flat sheet and cylindrical tubes through which the thermal fluid circulates.	• The cylindrical geometry of the tubes is not optimal for the flat structure. • The tube diameter has a minimal impact, but an increase in the number of tubes improves performance up to an optimal point.	[5,28,29,36,48,62, 65,69,72,73,82]
Channel o box	Combination of a flat box collector and a thin absorber plate.	• Better thermal and electrical efficiency due to the larger heat transfer area. • Better thermal distribution over the photovoltaic cells. • Better distance between the photovoltaic panel and the aluminum plate.	[28,74]
Double Absorber	Design with a double absorber and a PV module between two thermal collectors.	• Improves heat transfer. • Fluid circulates above and below the PV module.	[51,54]
Double Channel	Fluid circulating above and below the solar panel, connecting both ends.	• Better thermal transfer and heat recovery than a single channel. • The arrangement optimizes thermal transfer.	[54,75]

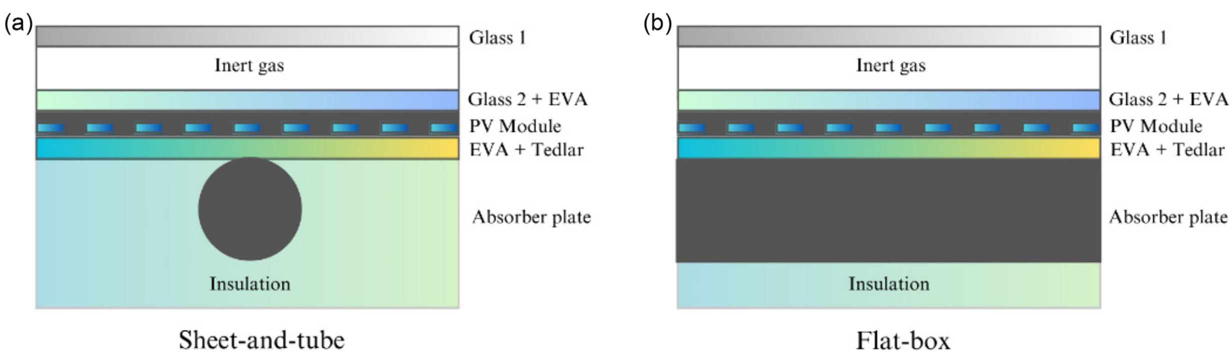

Figure 6. a) Sheet and tube configuration and b) box or channel. Figure created by the author based on sources:[28]

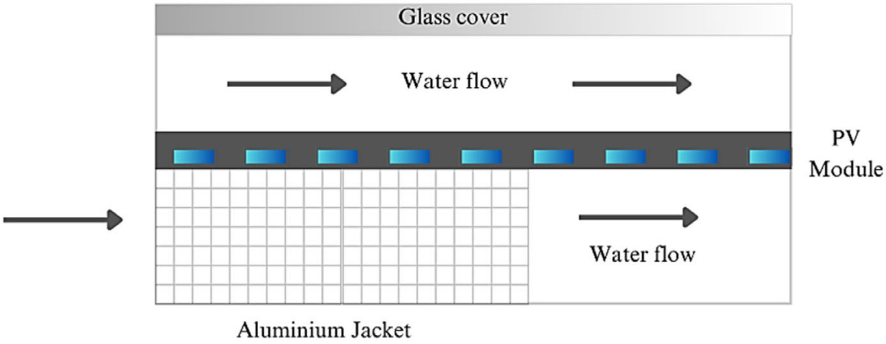

Figure 7. Double thermal absorber configuration. Figure created by the author based on sources:[51]

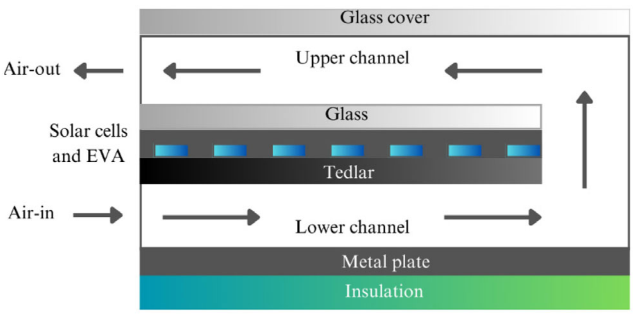

Figure 8. Double channel configuration. Figure created by the author based on sources:[54,75]

Both studies agree that this setup is more efficient than a single channel, as it optimizes thermal transfer and improves heat recovery.

As previously mentioned, the quality of the thermal contact between the photovoltaic layer and the absorber is a key factor for the system's efficiency. To address this limitation, study[36] proposes a thermal absorber designed to easily retrofit photovoltaic modules. As shown in **Figure 9**, this absorber is composed of two thin, parallel metal sheets: one of which is extruded using a mechanical mold to form mini corrugations, while the other remains smooth and is fixed beneath the panel using U-shaped metal clips. Both sheets are joined by laser welding, forming turbulent flow channels that enhance heat transfer. This compact structure not only optimizes thermal dissipation but also facilitates the quick conversion of a photovoltaic panel into a PVT system.

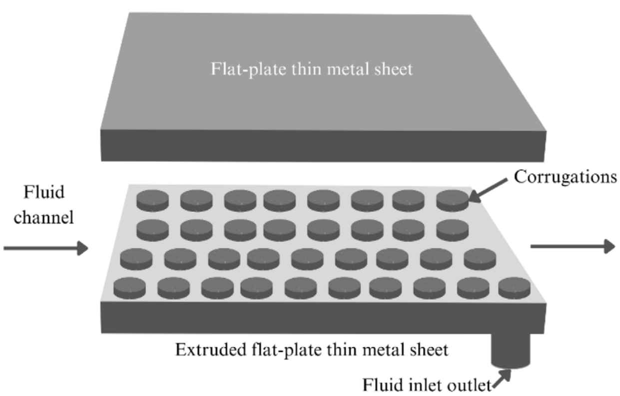

Figure 9. Thermal absorber with corrugations. Figure created by the author based on sources:[36]

On the other hand, the studies[30,60] propose the use of micro-heat pipes (MHPs), a new thermal conductivity component made of aluminum alloy. It features a seal, lower pressure difference, lower fill ratio, and a more compact structure. The liquid and vapor flow within the MHP can achieve uniform heat distribution, preventing the risk of local overheating. MHPs increase the heat transfer area in the heat pipe's evaporation and condensation sections. The rectangular shape of MHP significantly increases the heat transfer surface area, overcoming the limitations of cylindrical heat pipes and substantially reducing thermal resistance at the interface.

In addition to optimizing thermal contact between the photovoltaic layer and the absorber, another strategy to improve PVT system performance is the use of fins, which increase the heat exchange surface area with the surroundings and improve the heat transfer rate.[10]

Study[76] conducted a comparative evaluation of three bifluid PVT collector configurations, varying the number of aluminum fins. The first configuration does not incorporate fins in the tubes, the second integrates a total of 20 fins, and the third incorporates 40 fins. The results indicate that the latter is the most efficient, as it improves the cooling of the photovoltaic cells, allowing for higher electrical performance and greater thermal energy generation. Additionally, it recorded the lowest average surface temperature at the back of the panel, as the fluid stayed in contact with the surface for a longer time, increasing the heat exchange surface. **Figure 10** illustrates the bifluid PVT with fins, where water passes through the tubes and air through the channel.

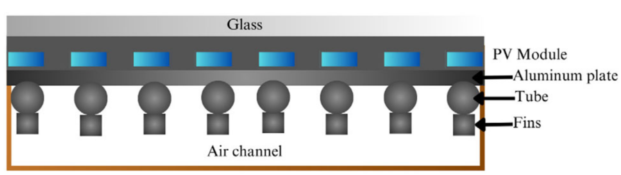

Figure 10. Thermal absorber with fins. Figure created by the author based on sources:[76]

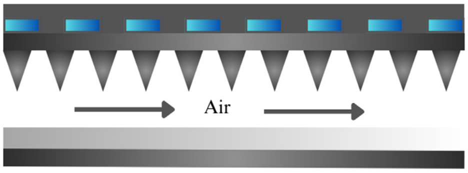

Figure 11. Thermal absorber with GRIPMetal. Figure created by the author based on sources:[10]

A recent study[10] designed a PVT system using an absorber called GRIPMetal, shown in **Figure 11**. This absorber incorporates peaks and cavities to optimize heat transfer in the air channel. This design was made possible through an innovative manufacturing method that allows the creation of hook-shaped grooves on the surface of different metallic substrates, generating a unique surface texture.

The results indicate that the use of GRIPMetal plates significantly reduces the average temperature of the photovoltaic panel and improves heat transfer by convection in the air channel.[10] Consequently, both electrical and thermal efficiency are enhanced compared to a conventional flat plate PVT collector.[10]

Another improvement to the absorber is the use of obstacles in the fluid path, as it allows for increased heat exchange with the absorber.[22] Thus, study[77] proposes a thermal absorber prototype, where linear obstacles (**Figure 12**) have been added to distribute the flow evenly across the back surface and maximize the thermal interaction between the air flow and the PV cells.

Another study[22] examines the use of thin wooden baffles as obstacles in the air space of the absorber, as shown in **Figure 13**. These elements, inserted into heat transfer devices, extend the thermal fluid's path, and optimize the exchange surface. Their incorporation increases the air residence time in the collector, improving heat transfer and system efficiency. However, they also cause flow separation and reattachment, resulting in pressure losses. Therefore, it is crucial to determine the optimal number of baffles to minimize such losses and avoid high operational costs.

Another study[78] evaluates five absorber tube configurations: smooth tube, ribbed and petaled arrangement tube, ribbed and petaled arrangement tube integrated with a coil, ribbed and petaled arrangement tube integrated with a twisted tape, and ribbed and petaled arrangement tube integrated with a helical twisted tape. The research focuses on enhancing the thermal absorber surface by incorporating ribs, which are roughness elements on the tube surface.[79] These roughness elements generate flow turbulence, increase the contact area, and optimize fluid distribution, thereby improving heat transfer efficiency and overall thermal performance.[78]

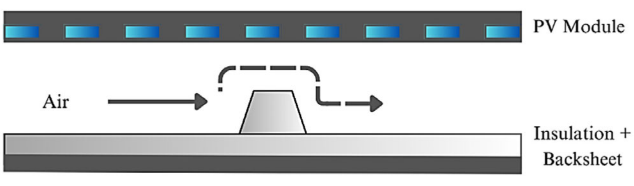

Figure 12. Thermal absorber with obstacles. Figure created by the author based on sources:[77]

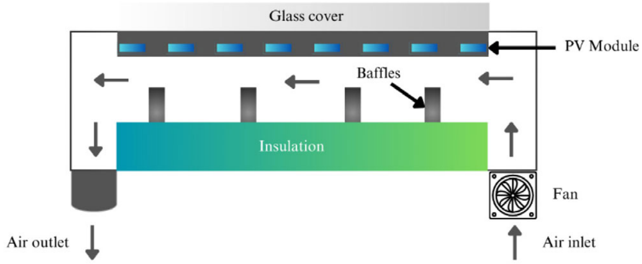

Figure 13. Thermal absorber with baffles. Figure created by the author based on sources:[22]

In addition, a petal arrangement is integrated over the ribs to further boost performance. This configuration not only increases contact area and turbulence, as ribs do, but also disrupts thermal boundary layers, significantly enhancing heat transfer. Another key innovation is the integration of twisted tapes and coils within the tube, which promote vortex formation and thus increase heat transfer. Furthermore, a helical twisted tape is introduced to combine these enhancements and achieve superior performance. The data show that the new design achieves a maximum thermohydraulic improvement of 1.5 times compared to a smooth tube collector, along with a 20.4% increase in thermal efficiency. **Figure 14** illustrates the aforementioned improvements.

Table 6 summarizes the main improvements in thermal absorbers, including the use of corrugations, microtubes, fins, obstacles, deflectors and ribs, petal, twisted tape, and spring. Each of these modifications contributes to improving heat transfer and PVT system efficiency.

3.1.5. Heat Transfer Medium

The heat transfer medium is the component responsible for extracting thermal energy from the system and cooling the absorber. It can be liquid, gaseous, or bifluid, and its flow can be positioned above, below, or on both sides of the PV module simultaneously.[51]

The fluid circulation can be natural (passive) or forced (active).[10,77] In passive circulation, heat is transferred through convection, conduction, or radiation between the PV cells and the environment. In contrast, in active circulation, the fluid moves continuously via a pump (in liquid systems) or a fan (in gaseous systems), allowing for more efficient heat dissipation.[10,77]

In PVT systems with air as the working fluid, the absorber is usually located at the top of the air channel, near the back of the panel, where the temperature is higher.[10] These systems are

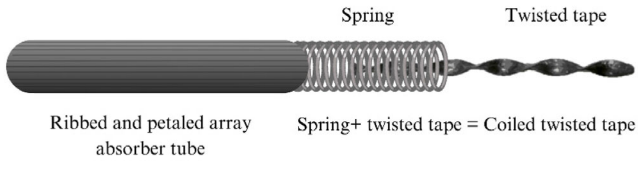

Figure 14. Ribbed and petaled array absorber tube, spring, twisted tape and coiled twisted tape, Figure created by the author based on sources:[78,90]

Table 6. Summary of improvements in thermal absorbers to optimize the efficiency of PVT systems. Prepared by: author.

Improvement	Description	Benefits
Absorber with mini corrugations[36]	Two metal sheets, one with corrugations and the other smooth, joined by laser welding.	Improves thermal dissipation and facilitates the conversion of PV panels to PVT.
MHPs[30,60]	Aluminum conduits with liquid-vapor flow for uniform heat distribution.	Increases the transfer area, prevents overheating, and reduces thermal resistance.
Fins[64,76]	Absorber with rectangular devices 1 mm thick, fixed to pipes and located in the air channel.	Increases the exchange surface, improves the heat transfer rate, and increases the contact time of the fluid with the panel.
Use of fins (GRIPMetal)[10]	Absorber with peaks and cavities on its surface, manufactured using an innovative method.	Improves heat transfer by convection and reduces the average temperature of the panel.
Linear obstacles in the flow[77]	Elements on the back surface of the absorber to uniformly distribute the flow.	Increases thermal interaction between the air and the PV cells.
Internal deflectors[22,91]	Thin barriers in the air space of the absorber.	Extends the fluid path, increases residence time, and improves thermal efficiency.
Ribbed and petaled arrangement tube[78]	Surface modifications on the inner wall of the tube.	Enhance flow turbulence, increase contact surface area, and optimize fluid distribution, thereby improving heat transfer efficiency and overall thermal performance.
Spring and helical twisted tape [78]	Elements inserted inside the tube.	Promote vortex formation, which contributes to enhanced heat transfer.

used in SH, ventilation, and industrial applications, such as food drying.[77] Their main advantage is freeze resistance and the absence of fluid leaks, although their efficiency decreases in cold climates.[54]

An experimental study[77] analyzed an air-based PVT system in which air extracted from the panels is channeled into a building using a centrifugal fan. Depending on the internal temperature of the office, the warm air is directed to the office or released into the environment through discharge vents. The results showed that the thermal efficiency of the system depends on the air flow rate and the temperature difference between the inlet and the back photovoltaic laminate, while the external wind speed has a lesser impact.

Another study[80] analyzed a PVT consisting of solar panels on a perforated metal sheet, installed vertically on a building facade or horizontally on a roof to absorb solar radiation (**Figure 15**). The metal heats up quickly and transfers the heat to the air, which is forced to circulate through the perforations and sucked into the air space between the solar wall and the building. The analysis compared two sizes of photovoltaic panels installed separately on the sheet: large and small. The results showed that, with a wind speed of 3 m/s, the system achieved higher electrical efficiency, which increased with suction velocity. Furthermore, the small photovoltaic modules exhibited slightly higher overall efficiency compared to the larger modules covering the same area.

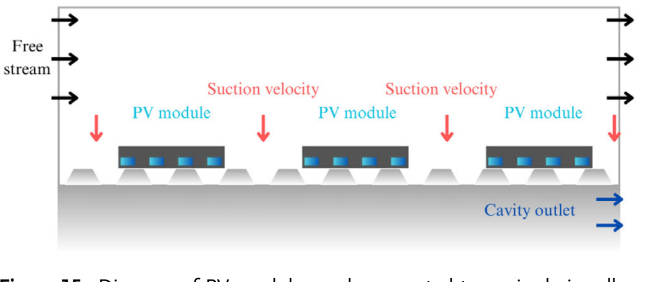

Figure 15. Diagram of PV modules and corrugated transpired air collectors. Figure created by the author based on sources:[80]

Air has been one of the most popular and studied fluids,[7] but its use is less compared to water-based PVTs. In fact, as previously mentioned, trends in 2023 indicate that these almost disappeared from the market.[32]

Water is the most commonly used heat transfer fluid in PVT systems, as it offers higher efficiencies compared to air due to its higher heat capacity and thermal conductivity.[54,59,81] However, these systems have certain limitations, such as the risk of severe damage in case of leaks.[77,82] To mitigate these issues, water is often mixed with glycol, which helps prevent corrosion and freeze in cold climates.[54] In addition, the use of NFs has been explored. These are advanced fluids containing suspended nanoparticles, typically made of metals or metal oxides, to enhance heat transfer efficiency and, consequently, the overall system performance.[78,81]

Study[49] evaluated the performance of a PVT prototype that used glycolic water as part of a real domestic hot water (DHW) system. The results showed high performance under real weather conditions, reaching a combined thermal and electrical efficiency of 44.5%. Another study[36] used a working fluid composed of 95% water and 5% glycol to prevent potential freezing issues.

The PVT liquid-based market has been limited to the uncovered PVT types due to issues with the EVA layer of the PV modules,[50] as they can decompose into acetic acid at temperatures above 80 °C, causing delamination, discoloration, and photovoltaic cell degradation due to the acid. Therefore, conventional photovoltaic laminates cannot withstand stagnation temperatures in glazed collectors, which typically range from 120 °C to 180 °C. Moreover, the thermal resistance of the rear layers of conventional photovoltaic laminates is quite high to achieve a good heat transfer rate from the photovoltaic cell to the liquid.[50]

Study[82] evaluated the performance of a PVT using water and an Al_2O_3 NF at various concentrations and flow rates. The results showed that the thermal efficiency of the system depends on the volumetric flow rate of the working medium, with the NF being more efficient than water. The greatest improvement in thermal efficiency, 79.4%, was obtained with a flow rate of 2.0 LPM and a volume fraction of 1% Al_2O_3, which increased thermal conductivity by 1.98%. In general, the water-based NF demonstrated superior performance under all conditions evaluated.

Another study[83] investigates a heat sink simulated to align with the back plate of a photovoltaic cell through jet impingement cooling. Specifically, it examines the impacts of pulsating cooling and nanoparticle size in hybrid NFs, which consist of combinations of Al2O3 and multiwalled carbon nanotubes (MWCNT) in water, with varying NF volume fraction and Reynolds (Re) number of flow. The key findings reveal significant influences of nanoparticle size, NF concentration, and pulsating flow on heat transfer performance.

Another study[78] analyzes the use of NFs, specifically silicon carbide (SiC) nanoparticles at volumetric concentrations of 0.3%, 0.6%, and 0.9%. The results show that thermal efficiency significantly improves with the incorporation of these NFs. In an earlier work,[78] the same author expands on this research line by combining NFs with PCMs. These materials absorb or release thermal energy during their physical state transitions.[84] Additionally, the study introduces nanophase changing materials (NPCMs), a variant that incorporates nanoparticles (generally metallic or metal oxides) to optimize the thermophysical properties of the system. In this case, an NPCM was synthesized by mixing SiC with melted paraffin wax. The results revealed that the maximum electrical efficiency was achieved with a 0.6% concentration of SiC, both in the NF and the NPCM. However, the study observed that the decreasing performance trend under high solar irradiance persists even with the use of NFs, reinforcing the need to use NPCMs to mitigate this effect. Moreover, it was found that increasing the NF concentration led to higher energy consumption by the pump due to the greater pressure drop in the system.

Another type of liquid that can be used as a heat transfer medium is seawater. Study[63] developed a seawater-resistant PVT using a polymer thermal absorber for reverse osmosis desalination applications. In reverse osmosis desalination, water production increases by 2% to 3% per K. Therefore, due to the preheating of seawater in the study, a reverse osmosis plant could produce ≈10% more freshwater. The results showed that one of the most important design parameters is the optical efficiency of the collector. Optical efficiency is defined as the ratio between the energy absorbed by the receiver and the energy incident on the concentrator aperture.[85] Since seawater temperatures, and thus the collector inlet temperatures, are often lower than or equal to ambient temperature, the PVT collector operates near optical efficiency.

In a bifluid collector, both water and air flow simultaneously, combining the advantages of both air and water collectors. However, these collectors are slightly more expensive and complex than typical air or water-based collectors.[54] Study[54] presents different configurations, including a bifluid PVT where water and air flow simultaneously beneath the PV module. The results indicate that it stands out as the highest performing in electricity generation. This is attributed to its unique characteristic of simultaneous fluid circulation, which effectively maintains lower cell temperatures. The use of two fluids combines the advantages, and this combination not only enhances thermal production but also effectively reduces the temperature of the photovoltaic cell. Another study[86] also uses a bifluid but examined the behavior of three cases classified based on the absorber design attached to the air channels used for heat extraction from the back surface of the solar cell.

Another fluid that can be used is refrigerant R141b[30,60] as it has advantages such as lower corrosivity, greater stability, and better compatibility with aluminum alloys compared to acetone. The results show that using R141b as the working fluid in heat pipes leads to higher average thermal conversion efficiency and average energy collection efficiency. Another study[60] also uses R141b due to its favorable attributes for operation in cold climates.

Table 7 presents the main characteristics of the heat transfer mediums mentioned, along with a classification of the articles based on the type of fluid used in each study.

3.1.6. Thermal Insulation

Thermal insulation is essential to reduce heat losses and maintain the hydrophobic surface, so it should have low thermal conductivity, be insect-resistant, not outgas, and be nonflammable.[44] The most common materials used are mineral wool and foam. In study,[83] NFs were used as heat transfer fluids in a PVT system to minimize thermal losses, using polytetrafluoroethylene (PTFE) in the experimental design to obtain precise measurements. Similarly, another study[50] used 40 mm of mineral wool at the back for the same purpose. Although the use of insulation is optional, its absence does not negatively impact system performance, especially when operating near or below ambient temperatures. Other studies also use polystyrene insulation.[8]

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3.2. Parameters Affecting Efficiency

This section analyzes the main parameters affecting PVT systems, highlighting their effects on electrical, thermal, and overall efficiencies. While several of these aspects were already addressed from a construction perspective in the components section, here they are examined in an integrated manner, emphasizing their operational and comparative impact. Among the most relevant factors are environmental conditions (solar irradiance, ambient temperature, and wind speed), operational conditions (mass flow rate and properties of the working fluid), as well as the PVT design.

Table 7. Characteristics of the heat transfer medium in PVT. Prepared by: author.

Classification	Characteristics	Articles
Water	• More efficient than air due to its higher heat capacity and thermal conductivity. • Risk of severe damage in case of leaks. • Corrosion. • Requires a pump for forced circulation. • Problems with the EVA layer, which may decompose into acetic acid at temperatures above 80 °C, causing delamination, discoloration, and degradation of photovoltaic cells due to the acid. • Problems with stagnation temperatures typically ranging from 120 °C to 180 °C.	[4,8,9,25,28,29,48,49,51,53,59,64, 65,68,69,71,89,111–118]
Seawater	• Used in reverse osmosis desalination systems. • Increase the production of fresh water. • High optical efficiency. • May require corrosion-resistant materials for the absorber, such as polymers.	[63]
Water + NF	• Higher thermal efficiency compared to water. • Higher thermal conductivity and better heat dissipation. • The size and concentration of nanoparticles affect thermal transfer. • An increase in NF concentration raises the pump's energy consumption due to the higher pressure drop in the system. • Use of NPCM to mitigate the low performance effect under high solar irradiance.	[78,82,83,90]
Water + Glycol	• Mixture used to prevent freezing water and prevent corrosion.	[36,49]
Air	• Freeze-resistant. • Absence of fluid leaks. • Low efficiency in cold climates. • Requires a fan for forced circulation. • These systems are used in SH, ventilation, and industrial applications such as food drying. • Trends in 2023 indicate that these systems have almost disappeared from the market.	[6,10,11,22,54,74,75,77, 80,99,119–124]
Bifluids	• Simultaneous circulation of air and water to improve heat dissipation. • Slightly more expensive and complex than single-fluid systems.	[54,76,86,109]
R141b	• Working fluid with lower corrosivity and better stability than acetone. • Higher thermal conversion efficiency, compatible with aluminum alloys. • May be less accessible or more expensive.	[30,60]

3.2.1. Environmental Conditions

Solar irradiance and ambient temperature are key factors influencing the electrical parameters of the current-voltage (I–V) curve, particularly the open-circuit voltage (Voc), short-circuit current (Isc), and maximum power (Pmax).[56] The electrical power generated mainly depends on the irradiance incident on the photovoltaic module. However, an increase in cell temperature reduces Voc, which decreases the generated power.[9,87,88] This behavior is described by temperature coefficients provided by manufacturers, which quantify the variation of Isc, Voc, and Pmax as a function of operating temperature.[88]

A comparative study[67] clearly analyzed this phenomenon by examining a flat-plate PVT system with a glass cover against a conventional PV module under variable conditions for 8 h. Results showed that while the PVT solar cell temperature increased rapidly during the first two hours before stabilizing, the conventional module exhibited a continuous thermal rise. This difference translated into a distinctive electrical behavior: with increases in irradiance (0–1200 W m^{-2}), the PVT system increased its voltage, whereas the conventional one experienced a decrease. Similarly, when ambient temperature rose from 25 °C to 35 °C, both systems showed decreases in their maximum electrical energy, but the PVT maintained a constant and superior overall efficiency, demonstrating the advantage of its hybrid design. The PVT stands out for its ability to compensate for electrical losses by recovering heat and transferring it to a thermal fluid, thus improving its overall energy efficiency.[89]

In this context, there are also studies analyzing the relationship between irradiance and temperature with the thermal part of the PVT. For example, the numerical study by,[9] carried out in COMSOL Multiphysics, showed that an increase in irradiance raises both the module surface temperature and the temperature of the working fluid, enhancing thermal output and consequently the overall system efficiency. Similar results were reported by[55] in an experiment at a pig farm, where higher irradiances increased the generated thermal energy, observing a direct correlation between the fluid outlet temperature, thermal power, and ambient temperature.

However, the behavior of the thermal and electrical parts is not always linear. The study by,[90] which evaluated absorbers with NF and NPCM, found that electrical and thermal efficiencies increase with irradiances between 400 and 800 W m^{-2} but sharply decrease beyond 1000 W m^{-2}. This is attributed to insufficient cooling capacity at high irradiance conditions, even when using NF. Additionally, the I–V curve analysis in[90] revealed that, for the same flow rate and irradiance, SiC NF and NPCM reduced Isc but increased Voc and power, highlighting the role of materials in operational response.

Another environmental parameter significantly influencing PVT system efficiency is wind speed, as strong winds can drastically reduce thermal performance, especially near the collector stagnation point.[63] When selecting the mounting type to integrate a PVT in a building, this factor must be considered. In an inroof mounting, where the collector is installed close to the building envelope with an air gap, thermal losses increase due to wind circulation in the space between insulation and collector, although to a lesser extent than other mounting types.[64] On the other hand, in a free-attached mounting, where the PVT is exposed to ambient air on all sides (such as in shading devices or protective roofs), thermal efficiency depends more on wind, decreasing significantly as heat losses increase.[64]

The impact of wind varies depending on the PVT application. In SH applications, higher wind speeds reduce thermal efficiency, while in cooling applications it may aid heat dissipation.[63] However, if the fluid temperature is lower than ambient, wind can reduce overall performance.[64]

3.2.2. Operating Conditions

Mass flow rate is another parameter playing a fundamental role. Study[69] evaluated the cooling effect on the photovoltaic module surface temperature and efficiency under constant irradiance conditions with varying mass flow rates. At the experiment's start, all configurations had similar electrical efficiency (7.92%), but after 60 min, significant differences were observed: systems with higher flow rates maintained slightly higher electrical efficiency than lower flow systems, due to more effective cooling. However, in all cases, electrical efficiency progressively decreased as the module surface temperature rose. In contrast, thermal efficiency showed an inverse behavior, starting at 0% and gradually increasing, reaching ≈80% by the experiment's end, slightly higher for the higher flow case. Overall, the study confirms that the thermal part of the system helps maintain photovoltaic cell temperature at optimal levels, thus favoring electrical production.

Nonetheless, this effect depends on adequate fluid circulation.[71] If the system operates without circulation, heat accumulates, reducing electrical efficiency. This effect was studied in,[90] where results indicated that high flow ranges positively affect electrical efficiency because faster fluid circulation brings cold water into contact with hot surfaces sooner. Complementarily, study[9] demonstrated that an increase of 10 L/h in fluid flow causes an approximate reduction of 0.885 °C in cell temperature, a 1.98 °C decrease in fluid outlet temperature, and an increase of 0.798 W in electrical energy generated. These findings highlight the importance of fluid circulation in PVT systems to maximize electrical efficiency and avoid negative effects from overheating.

While the relationship between mass flow, thermal efficiency, and fluid outlet temperature was previously mentioned, study[82] offers a more detailed analysis. In this study, authors evaluated a copper sheet and tube absorber in a serpentine shape, operating from 08:00 to 17:00 h with four different flow levels. Results showed that fluid inlet temperature matched ambient temperature in all cases, and the temperature difference between inlet and outlet depended directly on mass flow rate. Specifically, higher flow generated a greater temperature difference, which translated into higher system thermal efficiency. However, it was observed that as the day progressed and the fluid absorbed solar energy over prolonged periods, its temperature increased, causing a significant rise in heat losses to the environment.

Besides mass flow rate, fluid properties also affect PVT system performance. As mentioned earlier, the heat transfer medium (air, water, NFs, refrigerants, or two-phase systems) directly impacts thermal and electrical efficiency. Among these, water remains the most used fluid due to its high heat capacity and thermal conductivity, resulting in better thermal performance.[54,59,81]

However, alternatives like NFs (Al_2O_3, SiC, or hybrids with MWCNT) have been explored, offering higher thermal conductivity and thus improving heat transfer and overall efficiency.[82,83] Their effectiveness depends on factors such as particle size, concentration, and flow type.[82,83] Another option is two-phase systems, combining advantages of two media (e.g., water and air), achieving greater integral efficiency.[54]

Fluid selection and optimization represent an opportunity to improve PVT system performance, though their effectiveness remains conditioned by environmental and operational factors.

3.2.3. PVT Design

Finally, the design of the PVT system also plays an essential role in its efficiency. Factors such as the number of tubes, the cover, and the thermal contact between the absorber and the PV module are key.

In a study,[28] different PVT designs were analyzed and compared with a commercial model. Results showed that increasing the number of tubes improves both thermal and electrical efficiency, although this benefit has limits since more tubes imply higher system weight and cost. In this regard, the author suggests aluminum designs as a better alternative, improving efficiency without significantly increasing cost or weight. The same study indicated that tube diameter does not significantly affect thermal efficiency, and that for the same design and configuration, copper systems perform better due to higher thermal conductivity. Also, flat-box designs outperform sheet-and-tube designs in efficiency because they provide greater thermal contact area between absorber and fluid, compensating for lower polymer thermal conductivity. Moreover, flat-box designs show more uniform temperature distribution over photovoltaic cells, reducing hot spots and helping maintain lower cell temperatures, thus increasing electrical efficiency.

Another key design aspect is the presence or absence of a transparent cover. Study[46] compared overall efficiency between covered and uncovered PVT systems. Although overall efficiency was similar in both cases, separate analysis showed that uncovered PVTs have higher electrical efficiency, while covered PVTs excel in thermal efficiency since the cover helps reduce thermal losses and raise outlet fluid temperature, improving thermal output.

Although studies show general trends, the influence of the cover on system efficiency is complex and depends on multiple operational and environmental variables.[48] In this context, study[48] compared covered and uncovered PVTs with STC for flat-plate and PV modules. The authors concluded that while covered PVTs usually achieve higher thermal efficiency, this advantage may vanish when ambient temperature is high and inlet fluid temperature is low. Regarding electrical efficiency, it is generally higher in uncovered PVTs. However, this may change if the working fluid temperature is high, since in that case, the PV module temperature in uncovered PVTs may exceed that of conventional PV modules, reducing electrical efficiency.

This behavior was also experimentally confirmed by,[72] who evaluated various PVT designs under outdoor conditions. It was confirmed that glass covers significantly improve thermal efficiency compared to uncovered PVTs. However, glass was also reported to reduce electrical efficiency due to reflection losses, an effect that can be mitigated using high-transmittance glass.

Another relevant factor affecting system efficiency is the quality of thermal contact between the photovoltaic module and the thermal absorber. The same study[72] emphasized that poor thermal contact decreases heat transfer to the fluid, increasing cell temperature and reducing electrical efficiency. As a solution, the application of thermally conductive silicon paste was proposed. Although no significant improvement in thermal efficiency was recorded, the cell temperature was reduced, resulting in better electrical performance.

The analyzed studies show the complexity of PVT systems, as many parameters can positively or negatively influence performance. Therefore, there is growing interest in better understanding how each factor affects the system and in finding strategies to optimize both electrical and thermal production. **Table 8** summarizes the mentioned parameters and their effects on electrical, thermal, and overall efficiencies.

3.3. Monitoring

Monitoring a solar installation is essential for tracking energy performance, evaluating system efficiency, and identifying design faults or failures in a timely manner.[91] In the case of PVT systems, monitoring must consider both electrical and thermal performance, as they are interrelated: an increase in panel temperature reduces electrical efficiency but increases thermal output.[69,89] Therefore, an effective monitoring system must evaluate both components in an integrated manner.[91]

For photovoltaic systems, the standard UNE-EN IEC 61 724-1:2022[92] establishes the key parameters to measure, such as in-plane irradiance, ambient temperature, wind speed, output voltage and current, generated power, module temperature, and grid voltage and current, as well as load and storage values.[91] Additionally, it classifies monitoring systems into Class A (for large installations) and Class B (for smaller systems).[92]

In conventional thermal systems, monitoring is performed using mechanical thermostats in the thermal storage tank, temperature sensors to measure stored heat, and current transducers to verify the operation of pumps or auxiliary systems.[91,93] However, in PVT systems, complexity increases due to the interaction between electrical and thermal components.[91] Effective monitoring must detect the efficiency of both subsystems and avoid errors when calculating overall efficiency, simply adding individual efficiencies without considering energy quality, according to the second law of thermodynamics, is insufficient.[91]

Some studies have developed experimental test benches following the ISO 9806:2017 standard, which establishes test methods for STCs.[77] These test benches include sensors to measure temperatures (air, fluid, and cells), pressure drops, volumetric flow, and generated current, along with weather stations to record environmental conditions.[77]

In the article,[94] a PVT installation was implemented to produce DHW and electricity in the residential sector. Monitoring verified that the relationship between storage volume and collector area is appropriate, avoiding issues such as system overheating, which occurs when the fluid temperature exceeds operational limits, potentially damaging components and

Table 8. Parameters affecting PVT efficiency. Prepared by: author.

Parameter	Effect on efficiency	Reference
Solar irradiance	• The short-circuit current and power increase with irradiance, improving electrical generation. • Higher irradiance increases the fluid temperature, enhancing thermal output and overall efficiency. • High irradiance levels can reduce electrical and thermal efficiency due to insufficient cooling capacity.	[9,55,67,87,88,90]
Ambient temperature	• Maximum electrical energy decreases with increasing ambient temperature.	
Wind speed	• Reduces thermal efficiency, especially during stagnation. • Important factor when selecting mounting type on buildings.	[9,48,54,59,63,64,67]
Mass flow rate	• Higher mass flow rate improves both electrical and thermal efficiency. • If the system operates without circulation, heat accumulates, reducing electrical efficiency.	[9,69,71,82,90]
Properties of heat transfer medium	• Water shows higher thermal efficiency due to its high specific heat and thermal conductivity.	[54,59,81]
	• NFs enhance heat transfer thanks to their higher thermal conductivity.	[82,83]
	• The use of bifluid combines the thermal advantages of two fluids, improving overall system efficiency.	[54]
PVT system design	• Increasing the number of tubes improves efficiency but is limited by the absorber material as it can significantly raise cost and weight. • Tube diameter does not affect thermal efficiency. • Larger thermal contact area provides more uniform temperature distribution, reducing hot spots and improving electrical efficiency.	[28]
	• A cover improves thermal efficiency by reducing losses but may decrease electrical efficiency due to reflection and increased temperature. Its impact depends on environmental and operational conditions.	[46,48,72]
	• Poor thermal contact between the photovoltaic module and the absorber limits heat transfer to the fluid, increasing cell temperature and thereby reducing electrical efficiency.	[28,72]

reducing efficiency. Additionally, the data obtained were compared with a simulation model developed in TRNSYS, which serves as a valuable tool for manufacturers during predesign, optimization, and troubleshooting of PVT systems.

On the other hand, article[91] proposes a modular monitoring and control architecture for solar systems (PV, ST, and PVT), based on a web application that enables remote control, notifications, reporting, and data export. This system has detected issues such as module soiling, high battery resistance, and sensor detachment. Furthermore, data analysis allowed for improvements in the initial design, such as the installation of stationary batteries to optimize energy performance.

The selection of parameters to measure is crucial and should be based on the minimum acquisition rate required to obtain meaningful results. The UNE-EN IEC 61 724 standard[92] recommends sampling intervals of 5 s for large PV systems and 1 min for small PV systems, with recording intervals of 5−15 min depending on the system type. Key parameters include solar radiation, ambient temperature, module, and fluid temperature, current, voltage, mass flow, wind speed and direction, relative humidity, and pressure.[91]

The International Energy Agency, through Task 35,[95] presents a standardized framework for the characterization and monitoring of PVT systems, emphasizing the importance of uniformly representing electrical and thermal production to facilitate comparisons between systems. Three classification schemes are proposed: the design scheme, which is the most detailed and suitable for research; the rating scheme, which allows for practical comparisons and annual performance estimates; and the market scheme, aimed at policy documents and marketing.[95] Additionally, the need to adhere to existing standards for photovoltaic modules (IEC 61 215) and thermal modules (EN 12 975) is emphasized, and it is recommended to base thermal efficiency on the collector's aperture area and express electrical output in peak watts.[95] Furthermore, it is recommended to use primary energy as a metric to evaluate the combined performance of PVT systems, as this indicator accurately reflects the amount of fossil fuel saved, a fundamental goal of renewable energy systems.[95]

To measure these variables, various devices are used. Solar radiation is recorded using pyranometers, while temperature is measured with sensors such as PT100, thermocouples, integrated sensors (LM35), or immersion sensors. Mass or volumetric flow is quantified using flow meters, current is measured with Hall effect transducers, and the electrical characterization of modules is performed with IV curve tracers. Additionally, weather stations allow for the recording of multiple environmental variables relevant to system performance.

Data logging in PVT systems is conducted using data loggers such as Data Taker DT80, Omega DAQPRO-5300, Graphtec GL220, Graphtec GL820, TES 1333 R, and Campbell Scientific CR300. Data acquisition systems like the National Instruments Field Point RT 2000 with LabVIEW software, ET-7017-10 (ICPDAS), and ADAM 4019 are also used, as well as platforms based on Arduino or microcontrollers, which enable the precise collection of multiple parameters.

Real-time monitoring is a common practice in these systems, utilizing computers with specialized software such as LabVIEW and programmable logic controllers (PLCs) like the Modicon 241 for continuous data visualization and management. **Table 9** summarizes the studies that have implemented monitoring systems, specifying the measured parameters, devices used, measurement intervals, and data logging methods.

Since the performance of PVT systems depends on the interaction between their electrical and thermal components, precise and continuous monitoring is essential to ensure reliable operation. Early detection of faults or low-efficiency conditions not only improves system reliability but also reduces operational costs and maximizes the utilization of renewable energy.[91]

3.4. Artificial Intelligence

This section analyzes the main applications of AI in flat-plate PVT systems. In the reviewed literature, notable approaches include artificial neural networks (ANN), group method of data handling (GMDH), ML, genetic algorithms (GAs), and particle swarm optimization (PSO).

AI is defined as the ability of a machine or program to think and learn similarly to a human being.[96] As shown in **Figure 16**, for AI to function and perform adequately, it relies on two key areas: ML and deep learning (DL).[96]

ML gives computers the ability to solve problems through algorithms that learn from analyzing large volumes of data.[97] DL is a subfield of ML and uses ANN that mimic the information processing of the human brain.[97]

Regardless of the algorithm used, evaluating the accuracy of AI models is essential. To do so, specific metrics are used, which can be classified into three main categories:[76,98] 1) regression metrics, such as R-squared (R^2), root mean square error (RMSE), and mean absolute error (MAE), which measure the accuracy of predictions against actual values; 2) clustering metrics, such as the sum of squared errors (SSE), which evaluate the cohesion and separation of groups; and 3) classification metrics, such as precision, recall, and F-measure, used to analyze the relevance and retrieval of observations.

These metrics are essential when applying AI to complex systems such as PVTs, as they allow the evaluation of the model used. Traditionally, PVT efficiency has been modeled using mathematical equations, but these methods have limitations due to the complexity and uncertainty of some parameters.[81]

To overcome these inaccuracies, advances in computing have supported the use of ML techniques, offering a more accurate and efficient alternative for predicting PVT system performance.[81] Over the past decade, ML has been widely implemented in solar systems due to its ability to predict performance with high accuracy without requiring physical modeling.[99]

3.4.1. ANNs

ANNs learn to perform tasks by analyzing patterns and relationships within a training dataset.[66] These networks can predict outcomes, such as the efficiency of solar systems, by adjusting their internal connections through a training process.[99,100]

Compared to mechanistic models, ANNs offer fast and cost-effective simulations, as well as more efficient multiobjective optimization analysis, facilitating performance evaluation and

Table 9. Flat plate PVT with monitoring system. Prepared by: author.

Article	Year	Monitoring system description
[112]	1980	• **Measurement device:** flow meter, pyranometer, and thermocouple.
[7]	2009	• **Measured parameters:** current, voltage, short-circuit current, open-circuit voltage, and temperature.
[119]	2012	• **Real-time data:** LabVIEW software as an interface. • **Measured parameters:** Global solar radiation, ambient air temperature, wind direction and speed, humidity, solar cell temperature, glass cover of the air collector and the absorber plate, inlet and outlet water temperatures, storage water temperature, etc. • **Data logging:** data logger (National Instruments Field Point RT 2000) with a FARLAP operating system
[52]	2012	• A device was designed to change operating conditions and monitor results.
[49]	2014	• **Measured parameters:** Meteorological data (total radiation on the tilted plane, ambient temperature, and wind speed), inlet and outlet fluid temperatures, module surface temperatures, flow rates, photovoltaic electrical production, and auxiliary SH consumption.
[64]	2015	• Uses the ISO 9806:2013 procedure. • **Measured parameters:** Wind speed and direction, barometric pressure, ambient temperature, and relative humidity. Also measures global radiation and volumetric flow rate. • **Measurement devices:** Weather station.
[59]	2015	• Real-time monitoring. • **Measured parameters:** Irradiance, temperature, and pressure.
[91]	2015	• **Measured parameters:** PV and battery output current, dummy load current of the plant, PV voltage, module temperature, inlet and outlet water temperature, ambient temperature, relative humidity, and solar irradiance. • **Measurement devices:** Closed-loop Hall effect transducers LEM LA100-P, precision integrated circuit sensors LM35 from National Semiconductors, TO-220 package sensors, precision voltage dividers, Honeywell HIH-4030 sensor, and Davis solar radiation sensor. • **Data acquisition system:** ET-7017-10 produced by ICPDAS.
[47]	2016	• **Measured parameters:** Solar irradiance, PV laminate temperatures, inlet and outlet fluid temperatures, channel pressure drop, ambient temperature. • **Measurement devices:** Solar irradiation sensors, PT 100 temperature sensors, immersion temperature sensors, pressure gauges, weather station, voltage, and current sensors.
[89]	2016	• Real-time monitoring. • **Measurement devices:** Flow meter, pyranometer, resistance thermometers, thermocouples, power optimizer.
[125]	2016	• **Measured parameters:** Irradiance, wind speed and air temperature, average photovoltaic cell temperature, water temperatures at module inlets and outlets, panel currents and voltages, lead-acid battery state of charge. • **Measurement devices:** SPN1 thermopile pyranometer, RM Young and Campbell scientific sensors, five type-E thermocouples, type-K thermocouples, charge controller. • **Data recording:** Data Taker DT80, then transferred to a computer for storage and later analysis at the end of each day.
[123]	2017	• System monitoring is discussed through an Arduino-based controller, suggesting an approach towards automation and data collection.
[11]	2017	• **Measured parameters:** Ambient temperature, panel temperature, solar irradiance, current and voltage recording, injected air temperature and flow rate, absorber temperature. • **Measurement device:** Solarimeter.
[94]	2017	• **Measured parameters:** Solar irradiance, surrounding indoor and outdoor air temperature, fluid mass flow, tank temperature, fluid inlet temperature at the solar panel, outlet temperature from the panel.
[48]	2018	• The article mentions system monitoring using sensors and a data acquisition system.
[72]	2019	• **Measured parameters:** Flow rate, current-voltage characteristics of the PVT module, electrical output power at the maximum power point. • **Measurement devices:** Analog volumetric flow meter, PVPM 254°C, thermocouples, and pyranometer. • **Data recording:** Portable data acquisition unit Omega DAQPRO-5300.
[69]	2019	• **Measured parameters:** PV electrical data such as voltage, current, and power. • **Measurement device:** Analog-to-digital converter (WE1C, Fuji Electric). • **Data recording:** Data logger (GL220, Graphtec) connected to a personal computer.
[71]	2019	• Evaluate benches with sensors and monitoring devices.
[53]	2019	• **Measurement devices:** Included flow sensors, resistance temperature detectors, an IV curve tracer, and pyranometers.
[124]	2020	• **Measured parameters:** Solar radiation. Measurement device: Solar energy meter with data logging TES 1333 R. Uses Max6675 and LM35 sensors. • **Data recording:** Data logger prototype developed based on a microcontroller, battery-powered, and equipped with internal memory storage, real-time clock (RTC), and sensors.
[65]	2020	• **Data recording:** Programmable data logger (CR300, Campbell Scientific, Logan, UT, USA) to record meteorological and module performance data.
[8]	2020	• **Measured parameters:** Temperature of the outlet pipe wall, inlet pipe wall, back of the system, and photovoltaic panel surface. Also, water flow, wind speed on the collector surface, solar intensity. • **Measurement devices:** Apogee pyranometer, cup anemometer, fifteen type-K thermocouples (surface thermocouples, immersion thermocouple), F-400 flow meter, flow control valve. • **Data recording:** DT80 immediately connected to the computer system.

Table 9. Continued.

Article	Year	Monitoring system description
		• **Data acquisition system:** ADAM 4019, including a precision integrated processor and various modules for smart sensor-computer interfacing, featuring an embedded microprocessor. All measurement units were transmitted to the data acquisition unit and recorded values.
[62]	2022	• **Measured parameters:** Total solar radiation on the front surface of the collector, maximum power, short-circuit current, open-circuit current, water flow rate. Also, temperature parameters of inlet and outlet water in the collector and tank, rear surface of photovoltaic cells, front surface of a thermal absorber, and outer tube surface, from top to bottom in the tank and ambient air. • **Measurement devices:** Pyranometer, IV curve tracer, flow meter, copper thermocouples. • **Data recording:** GL820.
[12]	2022	• **Real-time data:** LabVIEW software as an interface. • **Measured parameters:** Water tank temperature, ambient air, and thermal fluid properties. • **Measurement device:** Thermogravimetric sensor.
[77]	2023	• **Measured parameters:** Environmental conditions, air temperature (inlet and outlet of each panel), cell temperature in the central panel, system pressure drops, volumetric flow, and DC current generated in the panels. • **Measurement devices:** Weather station (pyranometer, anemometer, and humidity meter), Pt100 temperature sensor, Gems pressure sensor, Testo 405i volumetric flow sensor, Darrera wind speed sensor, SEM160i relative humidity sensor, HT-RS-0 current sensor, Herten SL, and In-home voltage sensor. • **Data recording:** Data continuously monitored in a Modicon 241 PLC and recorded on a computer for post-processing.
[86]	2023	• **Real-time data:** A desktop computer was used to run display modes to monitor sensor values. • **Measured parameters:** Solar radiation, module temperatures, flow rate, current, voltage, and temperature.
[6]	2023	• **Real-time data:** LabVIEW software as an interface. • **Measured parameters:** Radiation, air velocity in the air channel. • Measurement device: Pyranometer (MS-42, Eko), anemometer, I-V tracer, pyranometer, thermocouple, hot-wire anemometer SDL 350 from Extech Instruments. • **Data logging:** The system collected digital data from the sensors and transferred it directly to the computer for recording and analysis using software. • **Data acquisition system:** ADAM saved the data in a CSV file format and analyzed it with Microsoft Excel.
[30]	2024	• **Real-time data** • **Measured parameters:** PVT surface temperature, water temperature inside the insulated water tank, water flow rate, incident solar irradiance, ambient wind speed. • **Measurement device:** Patch-type temperature sensors, probe-type temperature sensors, flowmeter, solar radiometer JTBQ-2, hot-film anemometer. • **Data logging:** Agilent 34 970
[51]	2024	• **Measured parameters:** Temperature, irradiance, voltage, current, and PV surface temperature. • **Measurement device:** Thermocouple, solarimeter, multimeter, and IR thermal gun.
[22]	2024	• **Measured parameters:** Mass flow rate of air, fan speed, solar radiation, ambient temperature, wind speed, temperature (air inlet, central air, absorber, inner glass surface, air outlet, and Tedlar). • **Measurement device:** Weather station, Kipp & Zonen CMP21 pyranometer, Testo 425 hot-wire anemometer, CS215 probe from Campbell Scientific, K-type thermocouples (Ni-Cr). • **Data logging:** Fluke 2638 A Hydra Series III
[83]	2025	• **Measured parameters:** coolant fluid temperature out and upper surface temperature. • **Measurement device:** Thermocouples.

improvement.[101] Additionally, they are capable of identifying nonlinear patterns and require fewer computational resources and hyperparameter adjustments than other ML algorithms, such as support vector machines (SVMs) or random forest (RF) algorithms.[101]

Despite their effectiveness in capturing complex relationships between data, ANNs depend on large volumes of high-quality data.[99,100] Alternatively, the least squares SVM (LS-SVM) can predict the performance of solar systems with a lower risk of overfitting, as they use a regression function to map inputs to outputs and optimize the calculation process compared to traditional SVM.[99,102]

In the case of flat-plate PVT systems, study[99] applied ANNs to predict the electrical and thermal efficiencies of an air-based PVT system, using two accurate, experimentally validated modeling techniques, which resulted in high precision. The modeled efficiency values were used to train and test the ANN-based predictive model, using meteorological data as input. Various combinations of meteorological variables were considered to evaluate the model's performance. The ANN model achieved a MAE of 0.0078% for electrical efficiency and 3.3607% for thermal efficiency, indicating greater accuracy in predicting electrical efficiency. Furthermore, the ANN outperformed LS-SVM in predicting the performance of the air PVT collector.

Study,[76] on the other hand, proposed a new AI-based approach to predict the performance of bifluid PVT systems with a double absorber. A comparative evaluation was carried out to assess three distinct bifluid PVT collector configurations, focusing on the varying number of fins. The proposed AI system consists of three main stages: data collection, data preparation, and prediction. In the data collection stage, experimental data were obtained from the three configurations, considering the fin arrangement, water mass flow rate, and solar irradiance values. The data were then standardized and split into two sets: 80% for

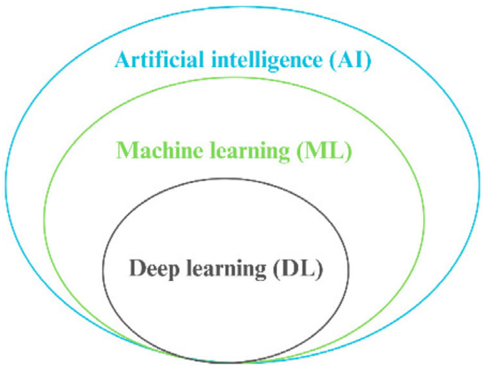

Figure 16. AI, ML, DL. Prepared by: author. Source:[97]

training and 20% for testing. In the prediction phase, an advanced model based on optimized deep neural networks (ODNNs) was developed to identify the most efficient design for water, air, and electrical efficiency. The results showed that this system outperformed other ML algorithms in terms of MAE, MSE, and R^2.

GMDH is a method based on polynomial neural networks that allows automatic modeling of multiparametric datasets. Its inductive approach finds interactions within the data and optimizes the model structure, improving accuracy and reliability. Its main feature is the self-organization of the structure and the number of neurons in the hidden layers. GMDH uses second-order polynomials to estimate target values from multiple input variables. The method divides the data into training and testing sets, iterating to minimize errors and improve prediction accuracy.

Study[66] analyzes the benefits of a corrugated absorber tube in a PVT system using a water-based NF with Al_2O_3 at different concentrations. 3D numerical calculations were performed for laminar forced convection of the NF at four Re numbers. To estimate the overall efficiency of the system without resorting to extensive numerical calculations, a GMDH-type ANN model was developed. The network was trained with two-thirds of the data obtained and validated with the remaining third.

The main input parameters of the model were the Reynolds number and the nanoparticle concentration. The model achieved performance coefficients of $R^2 = 0.99602$, $RMSE = 0.0077$, and $EMEAN = 0.0063$, indicating a high trend and accuracy of the model in determining the overall efficiency of the PVT system.

3.4.2. ML

In flat-plate PVT systems, the most commonly used ML algorithms in the literature include multilayer perceptron (MLP), RF, and support vector regression (SVR).

Study[81] evaluated the predictive capabilities of these three methods to estimate the electrical efficiency of PVT systems. Additionally, explainable AI methods were used to visualize and interpret the ML model results using SHapley Additive exPlanations (SHAP). The models were trained with over 380 datasets extracted from the literature, using input variables such as mass flow rate, solar radiation, ambient temperature, wind speed, fluid inlet temperature, PVT surface area, and pipe inner diameter. The analysis showed that SVR achieved the lowest mean relative error, while RF offered a balance between accuracy and stability. In general, all models showed variable performance depending on the parameters analyzed, highlighting the complex relationship between input variables and PVT efficiency.

Meanwhile, study[83] explored the use of ML to analyze the relationship between key parameters in a PVT system using hybrid NF, focusing on the Re number, NF volume fraction, and nusselt number (Nu). ML classifiers were used to identify critical thermal performance parameters, and the Reynolds number was identified as the most significant factor influencing heat transfer. RF and gradient boosting classifiers demonstrated high accuracy in predicting Nu, highlighting the usefulness of ML techniques in optimizing thermal management and improving heat dissipation on the rear plates of photovoltaic cells.

3.4.3. GA

GAs are also part of AI and stand out as an optimization technique inspired by natural selection and genetic principles.[101,103] Following Darwin's principle of "survival of the fittest," these algorithms operate on a population of candidate solutions that evolve over several generations.[101,104] Using historical information, GAs explore new search points to find optimal solutions,[103] making them one of the most popular optimization techniques in energy system applications, alongside methods such as direct search, simulated annealing, and PSO.[4] A GA has five basic principles:[105] 1) initialization: the set of sample points for the entire population is marked as GA initialization; 2) selection: subset from the previous step to categorize data; 3) crossover/recombination: to create logical relationships between sets and reduce randomness between sets; 4) mutation: to generate genetic diversity; and 5) acceptance: generation of new offspring after mutation. This stage also involves elimination.

Study[25] uses a GA to optimize the absorber channel geometry, aiming to maximize heat transfer to the fluid. For this, the Nu number, a dimensionless parameter describing convective heat transfer between a solid surface and a fluid,[106] and the comparative effectiveness, defined as the ratio of the heat flow eliminated by a modular dissipator to the flow dissipated in a flat-walled channel with the same hydraulic resistance,[25] are analyzed. The results show that fourth-order profiles (modeled using fourth-degree polynomials) are the most efficient in terms of the Nu number. However, when pressure loss and module weight restrictions are imposed, the system's efficiency decreases compared to the case without such limitations.

On the other hand, article[4] compares a conventional reference system (national grid and gas boiler) with four combined solar energy configurations: 1) PV modules with solar-assisted heat pump, 2) national grid supplemented with STC, 3) combination of PV panels and STC, and 4) PVT.

For each configuration, the design is optimized considering the number of solar panels and the capacities of electrical and thermal storage. The optimization is performed using GA based on the total unit cost of the product as a fitness function, using MATLAB 2019b. Additionally, metrics such as solar self-production and self-consumption, energy generated by the panels, grid consumption, and fuel savings are analyzed.[4]

Table 10. Application of artificial intelligence in PVT. Prepared by: author.

Artificial intelligence	Application	Reference
ANNs	Prediction of electrical and thermal efficiency of air-based PVT systems	[99]
• Deep optimized ANNs	Performance prediction of bifluid PVT and evaluation of thermal absorber configurations	[76]
• Two-layer feedforward ANNs	Prediction of hourly solar radiation and ambient temperature using historical meteorological data	[101]
GMDH (based on polynomial ANNs)	Prediction of overall efficiency of PVT with NFs and corrugated absorber tube	[66]
ML • MLP, RF, and support vector regression	Prediction of electrical efficiency of PVT systems	[81]
• RF and gradient boosting	Identification of critical parameters for thermal performance	[83]
GA	Optimization of absorber channel geometry	[25]
	Optimization of the design of combined solar energy configurations (PV, STC, PVT), considering the number of solar panels and electrical and thermal storage capacities	[4]
• Nondominated sorting GA II	Maximization of total efficiency and net thermal energy while minimizing plant area	[101]
PSO algorithm + controlador de lógica difusa	Prediction of fluid outlet temperatures using control variables such as collector dimensions and fluid velocity	[109]

The optimization process uses an initial population of 50 individuals and a maximum of 200 generations. Sparse crossover and Gaussian mutation techniques are applied for solution evolution. Although the main goal is to minimize costs, a slight increase is considered acceptable if it results in lower grid dependence or higher solar self-production. These factors are evaluated to select the most suitable configuration in each case.[4]

Study[101] presents comprehensive modeling, seasonal performance optimization, and techno-economic analysis of a PVT system integrated into buildings to supply electricity and SH in residential buildings. Parameters such as panel temperature, electrical and thermal efficiencies, thermoelectric energy production, and required plant size for a typical household were calculated. Furthermore, a multiobjective optimization based on a second nondominated sorting GAs (NSGA-II) was implemented to maximize total efficiency and net thermal energy while minimizing plant area. Finally, a forward-propagating ANN model with two layers was developed to predict hourly solar radiation and ambient temperature using historical meteorological data. The simulation results obtained in this study match previous findings reported in the literature.

3.4.4. PSO Algorithm

PSO is based on the on the food-searching behavior of birds and offers advantages over other AI algorithms, such as GA. PSO requires less computation time, memory, and parameter adjustment and is easier to program.[107,108]

Study[109] proposes a method to optimize the fuzzy logic controller (FLC) technique by integrating the optimized output of PSO as an input for the FLC. This hybrid PSO-FLC algorithm is applied to PVT systems to predict the fluid outlet temperatures, using control variables such as collector dimensions and fluid velocity. The results of the PSO, FLC, and PSO-FLC algorithms were compared, showing that the hybrid provides values closest to the experimental ones, followed by the PSO method, and finally the FLC.

Table 10 presents a summary of AI applications in PVT systems. According to the reviewed literature, these applications have mainly focused on predicting the electrical, thermal, or overall efficiency of the system; evaluating different thermal absorber configurations; and identifying critical parameters that affect heat transfer. AI has also been used to optimize absorber channel geometry, combine different solar configurations to maximize efficiency and reduce the required area, as well as to predict variables such as fluid outlet temperature, hourly solar radiation, and ambient temperature.

4. Conclusions

PVT systems represent a promising technology for the simultaneous generation of electrical and thermal energy from solar radiation. However, their market growth has been limited by the reduction of subsidies and a general preference for conventional photovoltaic installations, which has led many companies to focus on traditional technologies. Despite this, current trends show a growing number of installations, indicating renewed interest in their research and development.

This review article contributes to the field by offering a classification of flat-plate PVT systems based on their components, a synthesis of the most relevant factors influencing their efficiency, a description of monitoring strategies, and an overview of the application of artificial intelligence in this area. Altogether, this provides a solid foundation for future research aimed at developing, optimizing, or evaluating these systems.

From the analysis conducted, the following conclusions are highlighted. 1) The integration of PVT system components remains a technical challenge. Nevertheless, the reviewed literature shows notable progress, especially in the design of the thermal absorber and the heat transfer media. 2) Design improvements have been achieved through the use of alternative materials such as aluminum and polymers, which are viable options compared to copper due to lower costs and better structural integration without compromising performance. 3) Different internal geometries of the thermal absorber directly affect pressure drop, temperature distribution, and overall system efficiency. 4) External configurations are also crucial: the sheet-and-tube design presents geometric limitations, while box-type and dual-absorber or channel configurations increase heat recovery and thermal exchange area. 5) Innovations such as MHPs, high-conductivity films, corrugated surfaces, GRIPMetal, rib-type roughness, petal-like arrangements, and vortex generators (twisted tapes, springs) have been incorporated to enhance heat transfer and thereby improve thermal efficiency. 6) Thermal absorber design emerges as one of the most innovative aspects of PVT systems, offering a wide variety of materials, shapes, and configurations to optimize both thermal and electrical performance, as well as to reduce weight and costs. 7) The use of NFs and bifluids has proven effective in enhancing thermal transfer and thus improving overall system performance. 8) Thermal insulation and encapsulation techniques have been implemented to minimize heat losses and extend system lifespan. 9) PVT system performance is highly influenced by environmental and operational conditions. An appropriate combination of thermal design and operational management is key to maximizing efficiency. 10) Monitoring systems based on advanced sensors and real-time data acquisition enable more precise fault detection and performance optimization. 11) There is currently no specific international standard for PVT system monitoring; instead, standards for photovoltaic and thermal systems are applied separately. The International Energy Agency has proposed a unified framework to address this need. 12) Artificial intelligence, particularly ANNs and ML, has proven effective in predicting both electrical and thermal efficiency, outperforming traditional models. In addition, algorithms such as GAs help optimize absorber design and the selection of suitable technological configurations. 13) Although significant work has been carried out in the study of PVT systems, key challenges remain. 1) Most monitoring strategies rely on separate standards for photovoltaic and thermal systems, highlighting the need for unified methodologies tailored to hybrid systems. 2) Poor thermal contact between the photovoltaic module and the absorber continues to be a major technical challenge. 3) Based on the conclusions and identified challenges, the following research lines are recommended: 1) development of standardized testing and monitoring protocols specifically designed for PVT systems, 2) innovations in design to improve thermal coupling between the photovoltaic module and the absorber, and 3) integration of advanced monitoring systems and artificial intelligence to develop smart control strategies and enable early fault detection.

In summary, the integration of artificial intelligence and real-time monitoring, along with the optimization of system components, can enhance the impact of PVT systems in the energy transition. These improvements will facilitate their adoption in residential and commercial applications, strengthening the efficiency of photovoltaic technologies and contributing to the achievement of global sustainability goals.

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Conflict of Interest

The authors declare no conflict of interest.

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artificial intelligence, efficiencies, flat plates, heat transfer medium, monitoring, photovoltaic thermal, thermal absorbers

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