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Review

Photovoltaic-Thermal (PV-T) Systems for Combined Cooling, Heating and Power in Buildings: A Review

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Abstract: Heating and cooling (H/C) represent the largest share of energy consumption worldwide. Buildings are the main consumers of H/C, while the share of renewable energy for H/C provision still represents a low percentage, 22.0% in 2019. Hybrid photovoltaic-thermal (PV-T) systems are gaining increasing attention both in research and in applications, as they generate both electricity and useful heat simultaneously. The relevance and potential of PV-T collectors and their integration into wider systems are evident, but there is still a lack of review articles that address the potential of these systems in building applications in a comprehensive way. This work aims to review the state-of-the-art of PV-T collectors for building applications, as well as the corresponding PV-T systems for solar combined cooling, heating and power (S-CCHP) provision. The novelties of this work involve the comparison of these systems with conventional solar H/C technologies, the review of the market of H/C technologies, a summary of the challenges for the wider integration of S-CCHP systems and proposal lines of work to improve the cost-competitiveness of these systems. The first section summarises the focus and findings of previous reviews, followed by an overview of the current development status of the main types of PV-T collectors. Then, PV-T-based S-CCHP systems are reviewed, and the potential of PV-T systems' penetration in the built environment is evaluated and discussed.

Keywords: hybrid photovoltaic-thermal (PV-T) collector; solar energy; building energy provision; heating and cooling; heat and power

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1. Introduction

In recent decades there has been an increase in environmental awareness along with more consciousness of the need for reducing fossil fuel consumption to keep the rise in the average global temperature below 2 °C (above 20th-century pre-industrial levels). To achieve this goal, the global energy system should be transformed into a more sustainable energy system. Heating and cooling (H/C) is the largest energy-consuming application in Europe, responsible for 51% of the total final energy use (983 Mtoe in 2019) [1,2]. Most of the demand is for space heating (52%), process heating (30%) and water heating (10%), with space cooling demand still being limited but fast-growing [3]. Buildings are the main consumers of H/C: the residential sector is responsible for 45% of the energy for H/C, industry for 37% and services for 18% [2]. However, the share of renewable energy (RES) for H/C in 2016 was only 19.1%, and 22.0% in 2019 [1,4]. Therefore, the further development and implementation of renewable technologies for building H/C are essential for displacing the use of fossil fuels, reducing greenhouse gas (GHG) emissions and increasing the share of renewable energy sources (RES). In this context, solar heating and cooling (SHC) technologies arise as promising decarbonisation alternatives [5], as they can provide both heating (including space heating, SH, and domestic hot water, DHW) and cooling. The solar thermal contribution (2005–2050) to the low-temperature heat demand in Europe in three different scenarios is presented in Figure 1.

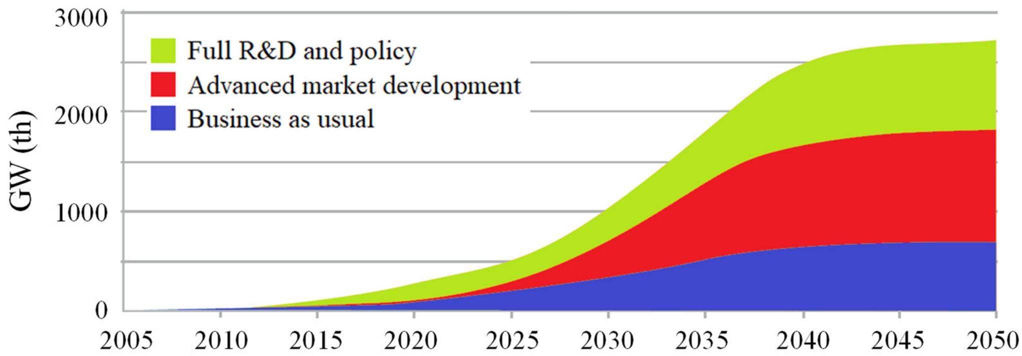

Figure 1. Development of solar thermal capacity in Europe according to 3 different scenarios (2005–2050). Raw data extracted from Ref. [6].

In the last few years, hybrid photovoltaic-thermal (PV-T) collectors have gained increasing attention both in research and in applications. Their main advantage is that they generate electrical and thermal outputs from the same aperture area simultaneously [7], thus presenting a higher overall conversion efficiency (which could be above 75% [8,9]) than separate PV and solar thermal systems [10–12]. Moreover, the integration of PV-T collectors with H/C technologies allows the simultaneous generation of DHW, space heating, cooling and electricity, and, thus, has the potential to cover a significant fraction of the energy demands of buildings [13]. Given the reality of global warming, it is likely that cooling needs will increase, while the heating demand in buildings might decrease. In this regard, SHC systems based on PV-T collectors appear to be a very suitable solution as these systems can be adapted to supply both heating and cooling depending on the specific needs while minimizing the impacts of global warming. This paper reviews different SHC technologies that can be used depending on the specific building demands.

The relevance and potential of PV-T collectors and their integration with other components to obtain new solutions in heating, ventilation and air conditioning (HVAC) systems were confirmed in Task 60 of PV-T systems of the SHC programme of the IEA, which ran in 2018–2020 [14]. However, most of the reviews found in the literature focus on SHC technologies that use solar thermal (ST) collectors such as flat-plate (FPC), evacuated tube (ETC) or parabolic through (PTC) collectors [15]. In addition, many of these reviews specifically focus on solar cooling [16–22]. To the best knowledge of the authors, very few SHC reviews specifically address PV-T collectors, and, when found, these works are mainly focused on stand-alone PV-T collectors [23] or solar cooling applications [24,25].

1.1. Previous Reviews

Previous reviews addressing PV-T collectors are presented here. The developments of flat-plate PV-T collectors during the decades before 2010, when the numbers of commercially available collectors and systems were still very limited, were reported in [26]. The development of flat-plate PV-T collectors during the same time was also addressed in [27], identifying that, at that time, not only were technical issues important but also certification, financing and integration issues, among others, were essential for the market growth of PV-T solutions.

In 2012, a global review and the market potential of ST, PV and PV-T technologies was presented [28] where the authors discussed the importance of PV-T collector demonstration in real buildings. Again, a brief overview of the different solar flat-plate PV-T technologies, their efficiencies, applications, advantages and limitations was published in 2015 [29] concluding that proper standards, regulations and continuous field testing are required to promote solar PV-T technologies and, therefore, facilitate their integration into the built environment. In the same year, advances in PV-T collectors, as well as various methods of thermal management of these systems, were reviewed [30].

A review of ST and PV-T collectors and their integration with heat pumps (HP) was presented in [31]. The authors of this work note that optimal control strategies are required when coupling PV-T collectors with an air-source heat pump (ASHP), and discuss the lack of research on combining air-based PV-T collectors with ASHP and thermal energy storage (TES). In 2017, a review of solar-driven absorption cooling with PV-T collectors was presented in [24]. This review includes experimental and computational work resulting in 50% of primary energy savings by using solar absorption cooling systems compared to vapour compression air conditioning systems.

A review of PV-T heat utilisation with low-temperature desiccant cooling and dehumidification was presented in [25], showing that obtainable outlet fluid temperatures from existing PV-T collectors nearly match the low-temperature desiccant cooling and dehumidification applications with reasonable electrical and thermal efficiencies. A review on the integration of solar collectors with absorption HPs and TES was presented in [21]; however, this work focuses on TES solutions for solar cooling and only a brief section is dedicated to the description of PV-T collectors.

A review of the economical assessment and applications of PV-T collectors, together with a description of flat-plate PV-T collectors was presented in [32]. Some of the opportunities identified by the authors for the further development of PV-T technology were: (i) the development of new feasible and energy-efficient collectors such as PCM-slurry-based PV-T collectors, (ii) to study the long-term dynamic performance of PV-T collectors, (iii) the demonstration of PV-T collectors in real buildings and (iv) economic and environmental analyses considering climatic conditions' long-term effects. Additionally published in 2017, a review on recent advancements in PV-T techniques [33] highlighted the very limited commercial PV-T collectors available on the market due to some major challenges, such as low thermal output, a lack of long-term performance information and compatibility of the thermal system with PV cells, among others.

A review on the development and applications of PV-T collectors was presented in 2019 [34], where the authors conclude that the production and installation costs of PV-T collectors are still expensive and some technological improvements are needed, including the research and development of novel materials, systems' stability improvements and the design of a supporting energy storage system. A review of recent advances and the role of nanofluids in solar PV-T collectors was presented in 2020 [35], which concludes that more theoretical and experimental research is required for a better understanding and development of the use of nanofluids in PV-T collectors. Finally, quite an interesting review was also published in 2020 [36], which addresses the current state of development of flat-plate building-integrated PV-T collectors, reporting the significant potential of nanoparticles and phase change materials (PCMs) for PV-T collectors, which could lead to thermal efficiencies above 70%. The review also highlights that building-integrated PV-T collectors could be easily integrated into façades and roofs for electrical and thermal energy generation.

There are also reviews addressing solar technologies and systems where PV-T collectors are mentioned, but they are not specifically considered in detail. A review of ST collectors and TES in solar thermal applications was presented in 2013 [37], where a variety of non-concentrating and concentrating solar collectors were discussed, briefly mentioning PV-T collectors as the ones with the best overall performance among the non-concentrating collectors. In the same year, a review on dynamic thermal models and computational fluid dynamics (CFD) analysis for flat-plate ST collectors was presented in [38], only including a very brief reference to PV-T collectors, but no CFD models considering PV-T were described.

A review of the advancements in the field of solar thermal technologies with a focus on techniques employed for its performance enhancement was presented in 2015 [39]. Regarding PV-T collectors, the authors of this work refer to previously published material proposing the use and challenges of certain nanofluids for thermal performance improvement. In 2016, a systematic review of solar-assisted heat pump systems for low-temperature water heating applications was presented [40]. The review was limited to ST collectors and concluded that combined ST and HP technologies are a promising potential alternative for different climates with modifiable configurations. The status and future development of SHC technologies presented in [15] mentioned the scarce work on PV-T collectors in SHC systems.

In the overview of the main solar technologies presented in [41], PV-T collectors as part of wider SHC systems are mentioned. The review concludes that the system location and particular application determine which would be the best technology for each case. Additionally in 2018, a comprehensive review of research and developments on solar-assisted compression heat pump systems was presented in [42]. The authors mention that the performance of a conventional solar-assisted compression HP unit is improved by integrating it with a PV-T collector and report modelling research on solar PV-T heat pumps. Finally, a systematic review of ASHP systems assisted by ST, PV and PV-T collectors was presented in 2020 [43].

As mentioned above, most reviews found considering solar technologies for H/C focus on solar cooling systems. The most relevant reviews published on solar cooling systems in the last decade are presented here in chronological order. Just a few of the reviews below discuss the integration of PV-T collectors within wider solar cooling systems [44]. A review on solar cold production through absorption technology was presented in [45] and a review of a new approach to minimize the cost of solar-assisted absorption cooling system was presented in [46]. These works focus on the absorption system integrated with ST collectors, with no specific mention of PV-T collectors. Other authors [46] conclude that a solar-assisted single-effect absorption cooling system would be competitive with a compression cooling system if they were compared for long-term operation.

A detailed review of different solar refrigeration and cooling methods [16] also refers to solar hybrid cooling systems with heterogeneous composite pairs and compared various solar cooling systems; however, PV-T collectors are not mentioned. A review of solar thermal air conditioning technologies [44] briefly mentions the integration of PV-T collectors within solar cooling systems. The work concludes that there is a need for efficiency improvement in solar thermally-operated cooling technologies. In a techno-economic review of solar cooling technologies [47], the authors compare the performance and cost of ST and PV-based cooling systems, concluding that vapour compression cycles in combination with PV panels appear to be the best option; hybrid PV-T collectors are not evaluated in this work.

Solar thermally-driven refrigeration (absorption, adsorption and desiccant cooling systems), solar electric refrigeration and hybrid systems with ST collectors or PV modules are extensively reviewed and compared in [48]. Meanwhile, in [49], only solar thermo-mechanical refrigeration and cooling methods considering ST collectors are reviewed. The review presented in [18] is also limited to solar thermal cooling technologies, as well as the work presented in [50]; the latter work also reviews research on solar cooling systems' simulation. All these reviews agree on the potential of solar cooling processes; however, they highlight that major obstacles limiting their worldwide implementation are the high installation cost and the low performance.

More recent reviews on solar cooling focus on experimental studies and ST collectors combined with absorption chillers [19,51], presenting similar conclusions to previous reviews and not considering PV-T collectors. A global review of solar thermal cooling technologies was presented in [22]. This work focuses on ST collectors, but it also mentions concentrated PV-T (CPV-T) collectors (although no flat-plate PV-T collectors), which the authors believe could drive both electric vapour compression and sorption low-temperature thermal chillers, achieving high performances, thanks to their very efficient solar conversion rate (2017).

A recent review of solar PV cooling systems also mentioned the integration of PV-T collectors [52]. The main conclusions of this review were: (i) the overall performance of cooling systems based on nanofluids is better than baseline systems, (ii) PCMs within PV-T collectors allow cooling of PV modules and also serve as a storage medium by extending the effective period of heat transfer, and (iii) using nanomaterials in PV-T collectors based on PCMs there is an improvement in the collector thermal behaviour. Finally, a review of thermal solar sorption cooling systems compared different solar cooling technologies, mentioning the possibility of PV-T collectors' integration, and concluding that the absorption cooling system is the most efficient one among the analysed systems [53].

1.2. Aim and Structure of the Work

Having discussed the main focus and findings of previous reviews, to the best knowledge of the authors there is still a lack of review articles that address the potential of PV-T collectors in building applications in a comprehensive way. Therefore, this work aims to review the state-of-the-art PV-T collectors for building applications, as well as the corresponding PV-T systems for combined cooling, heating and power provision in the built environment. The novelties of this work involve the comparison of these systems with conventional SHC technologies, the review of the current market of H/C technologies (e.g., heat pumps and absorption chillers), a summary of the challenges for the wider integration of S-CCHP systems based on PV-T collectors and a proposal of lines of work to improve the cost competitiveness of these systems.

In Section 2, a brief overview of the main types of PV-T collectors for building applications and their current development status is presented, together with their market penetration. PV-T collectors for building applications are divided into non-integrated and building-integrated collectors. Section 3 summarizes the main works on solar combined cooling, heating and power (S-CCHP) systems based on PV-T collectors, differentiating also between non-integrated and building-integrated systems. Section 4 summarizes the major advancements and suggests further work on PV-T collectors and systems for building applications. Section 5 analyzes the potential of S-CCHP systems based on PV-T collectors, compares their performance with alternative SHC systems, addresses the current market and proposes potential lines of work. Section 6 summarizes the main conclusions of this review.

2. PV-T Collectors for Building Applications

There are several classifications of hybrid PV-T collectors depending on different factors: the heat extraction mode (air, liquid, dual air-water, heat-pipe, thermoelectric), the PV-T collector cover(s), the type of PV technology (a-Si, m-Si, thin-film, multi-junction cells, etc.), the cooling method of the PV module (active vs. passive) or the system structure (flat-plate, concentrated, building integrated).

This review classifies and summarizes previous works differentiating between standalone PV-T collectors (Section 2.1) and building-integrated PV-T (BIPV-T) collectors (Section 2.2). The first section addresses the most common types of PV-T collectors installed in buildings: air-based (Section 2.1.1), liquid-based (including both water and refrigerant PV-T collectors) (Section 2.1.2) and low-concentrated PV-T collectors (Section 2.1.3). Meanwhile, Section 2.2 is further divided depending on the transparency level of the BIPV-T collector, reviewing within these subsections PV-T systems based on air, liquid (including both water and refrigerant), heat-pipe and dual air-water. The review also addresses different PV-T collector covers, PV technologies and cooling methods.

2.1. Non-Integrated PV-T Collectors

2.1.1. Air-Based PV-T Collectors

Air-based PV-T collectors are the simplest solution for PV cooling and consist of circulating air above or below the PV cells. This arises as an attractive solution when water is limited. The main applications are ventilation and air pre- or space heating and can be installed as an independent component on the roof [27] or integrated into roofs and building façades [54,55] (see Section 2.2).

The heat transfer properties (e.g., thermal conductivity and specific heat capacity) of air are smaller than those of liquids used in PV-T collectors (such as water), so air-based PV-T collectors present overall efficiencies (electrical plus thermal) in the range of 20% to 40% [56]. However, air-based PV-T collectors are in general cheaper than liquid-based PV-T collectors and are particularly suitable for building applications in cold regions [9].

There are different configurations of air-based PV-T collectors according to several factors [56,57]. For example, depending on how the air flows through the collector, there are natural and forced circulation collectors. Natural circulation is simpler and has lower costs than forced circulation, while forced circulation is more efficient, although the energy necessary to drive the fan decreases the net electricity gain of the collector [58]. In addition, air can flow at the back and/or the front surfaces of the PV cells. When air is flowing through the front surface, extra glazing is required to form a passage. This allows a better heat extraction, but it also increases the PV cell temperature and imposes another reflection loss for the incoming solar radiation.

Depending on the air channel configuration, there are four main types [26]: channel above the PV cells, channel below the PV, PV cells between single-pass channels and double-pass design [59] (see Figure 2). Air-based PV-T collectors can be unglazed [60] or glazed [61,62]. A previous work [63] concluded that a glass cover improves the thermal efficiency of the collector but reduces the electrical efficiency. Other authors have also proposed double-glass PV-T collectors [28] or the addition of a suspended metal sheet in the middle of the air channel to improve the performance [55]. Other studies have proposed the addition of fins and metal sheets in the flow channel to improve the collector performance [64,65].

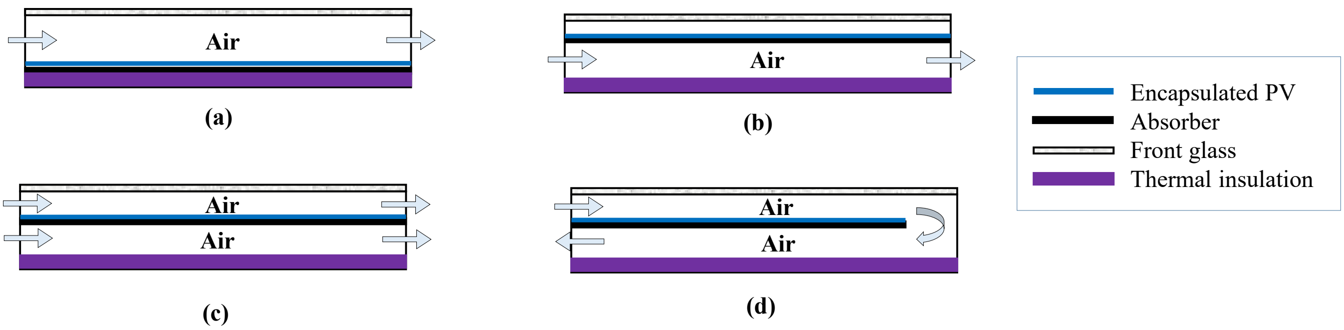

Figure 2. Four main types of air-based PV-T collector designs depending on the air channel configuration. (**a**) Channel above PV, (**b**) channel below PV, (**c**) PV between single-pass channels and (**d**) double-pass design. (Adapted with permission from [26]. Copyright 2009 Elsevier Ltd.).

2.1.2. Liquid-Based PV-T Collectors

Using a liquid instead of air allows more efficient use of the heat extracted in PV-T collectors. This occurs due to the higher thermal conductivity and better heat transfer coefficient of liquids, also allowing the desired operating temperature of the PV cells to be maintained with fewer temperature fluctuations [26,28,66]. The two main types of heat transfer fluids (HTF) employed are water, or a mixture of water-glycol to avoid freezing [34,55], and refrigerants [29,55]. The basic liquid-based design uses one or several channels to allow the fluid to flow below the PV cells (see Figure 3).

Water-based PV-T collectors are considered the most efficient mode of preheating water all year long at locations with high solar irradiance and relatively high ambient temperature (low latitudes) [26,54]. From the different designs found in the literature, the main design concepts are the following [28,67]: (i) sheet-and-tube: parallel pipes [7,68], serpentine [69], parallel-serpentine [67,70], spiral [67,70]; (ii) free flow [71]; (iii) channel above the PV cells [72,73]; (iv) two-absorber collector [72,74].

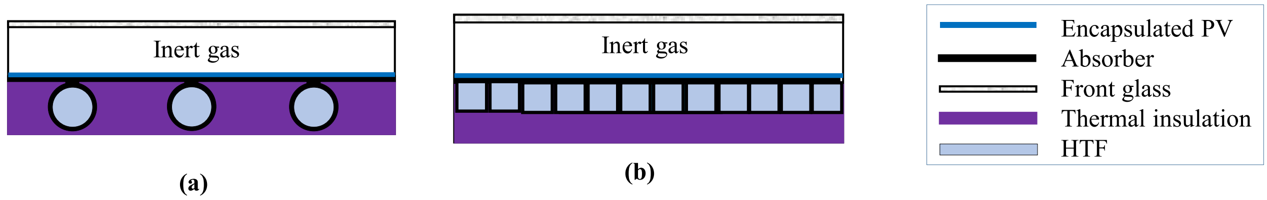

Figure 3. Basic liquid-based PV-T collector designs: (**a**) sheet-and-tube and (**b**) flat-box channel. (Adapted with permission from [26]. Copyright 2009 Elsevier Ltd.).

Regarding the material/s used for the channels, copper is the most widespread due to its high thermal conductivity, among other reasons [29,75]. However, some authors have proposed web-flow, direct-flow or spiral-flow designs made of stainless steel [67,70], or sheet-and-tube collectors made of extruded aluminium [76], while others studies [77,78] have proposed polycarbonate (PC) to lower the cost and weight of the PV-T collector. Furthermore, loading the polymer with different additives can also improve its thermal conductivity [79,80]. However, recent works concluded that the small improvement in thermal performance might not compensate for the higher complexity and costs of loading the polymer with additives [10].

There are also several glazing configurations [29,72]: uncovered [68,81], with one [82,83] or two covers [72,84] or with or without a gap between the cover and the PV cells [83,85], as well as different filling gases: air, inert gases or a vacuum [63,85]. The use of one or more covers reduces thermal losses, increasing the thermal efficiency [86,87], but it also reduces the electrical efficiency due to an increase in the PV cells' temperature and the reflection losses [88–90].

The range of applications of water-based PV-T collectors can be divided into [91]: (i) low-temperature applications (below 50 °C), including swimming pool heating or spas (~27–35 °C), space heating via radiant underfloor heating or integration with low-temperature heat pumps; (ii) medium temperature applications (up to 80 °C), for space heating via conventional water radiators or DHW provision (up to 60 °C [92]); (iii) high-temperature applications, larger than 80 °C, for cooling purposes through refrigeration cycles such as absorption chillers or for certain industrial processes [91,93] (see Figure 4).

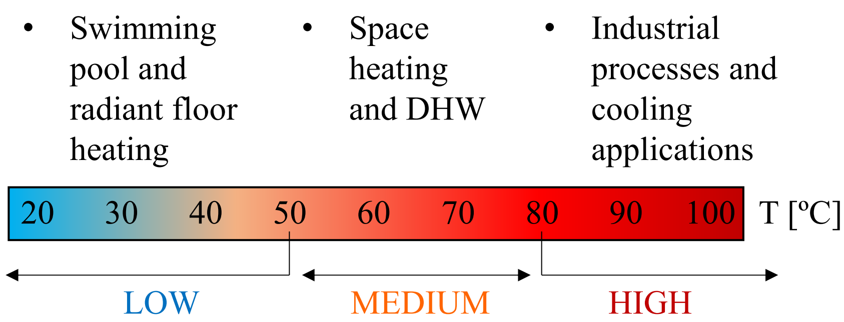

Figure 4. Temperature range of the main applications of water-based PV-T collectors. Raw data extracted from [91].

Despite the fact that water-based PV-T collectors can also be used to meet the heating and power demands of swimming pools [94–96] or to provide space heating [97–99], most of the studies found in the literature focus on the supply of DHW demand in buildings [100–104].

Water-based PV-T collectors can be configured as direct systems, such as thermosiphon systems [105,106], in which potable water is directly heated in the PV-T collectors, or as indirect systems, where potable water is heated through a heat exchanger with the hot water circulating in the solar closed-loop circuit [12,83,107].

In refrigerant-based PV-T collectors, the PV-T collector usually acts as the evaporator of a heat pump [108,109], to maximize the solar energy utilization and at the same time enhance the coefficient of performance (COP) of the heat pump [31,32]. These systems are also called PV-T solar-assisted heat pump (SAHP) systems [110] and are used to provide space heating in buildings [111]. These collectors typically present a serpentine design made of copper coils [112] with diameters between 6 and 10 mm [113–116]. There are also other configurations such as multi-port copper tubes assembled in parallel [117] or serpentine micro-channels integrated into an opaque ventilated façade [118]. In this line, other authors proposed multi-port flat extruded aluminium tubes of 3.35 × 3 mm channels [119], or micro-channel rectangular pipes (2 × 6 mm) [108]. More recently, other authors have proposed a roll-bond design with serpentine aluminium coils as the thermal absorber of the refrigerant-based PV-T collector [120,121].

Several works [116,122] concluded that a refrigerant-based PV-T can improve the electrical efficiency by >20% compared with that of a conventional PV module due to the lower operating temperatures of the PV cells. Refrigerant-based PV-T collectors usually have higher electrical efficiencies than air- or water-based PV-T collectors due to the lower operating temperature of the PV cells [28,34]. However, refrigerant-based PV-T collectors have some disadvantages, such as uneven refrigerant distribution in evaporation tubes [123,124] and the high risk of refrigerant leakage [28].

2.1.3. Low-Concentrated PV-T Collectors

Concentrated PV-T (CPV-T) collectors improve both the thermal and electrical outputs, at the same time that part of the PV cells may be replaced by low-cost reflectors [26,54,58,89]. However, CPV-T collectors are more expensive than flat-plate ones, especially when sun tracking is needed, due to the additional costs of this complex mechanism [26,54].

There are different types of CPV-T collectors, ranging from stationary and low-concentrating ratio flat-plate PV-T collectors with added reflectors, to highly concentrating ratio units that require tracking. When considering tracking collectors, there will also be significantly higher maintenance costs. Therefore, roof integration of these collectors is very difficult [54,89], so this review focuses on the former type, better suited for integration in the in-built environment.

Some authors [54,58] proposed the installation of booster diffuse reflectors (i.e., an aluminium sheet) placed between the parallel PV-T arrays. The results showed a more uniform distribution of the reflected solar radiation on the PV surface, increasing the solar input by 50% in the best case [58]. Other authors [125–127] developed a low concentration, linear, hybrid micro-concentrator collector for rooftop installation, replacing solar PV cells with inexpensive optics and tracking systems, consisting of low-cost, ultra-light-weight Fresnel mirror arrays, which allow increasing the concentrating ratio by up to 20×–30×, which is enough for the domestic market needs [125,126]. There are also examples of CPV-T collectors where a multi-port flat extruded aluminium tube in a serpentine format acts as the evaporator of a low-concentrating PV-T parabolic collector (concentration ratio of 1.6) [128].

2.2. Building-Integrated PV-T Collectors

Building-integrated collectors refer to building components able to generate electricity and/or thermal outputs by replacing conventional building components or materials, i.e., in windows, facades or roofs [129]. When using the solar resource to generate the electrical and/or thermal energy output, there are building-integrated PV (BIPV) and building-integrated PV-T (BIPV-T) collectors. Opaque building-integrated collectors were the focus of initial research, considering opaque PV technologies such as mono-crystalline and multi-crystalline silicon cells (the first PV technology strongly established in the market). In the last decade, several emerging PV technologies have also presented transparent and semi-transparent properties in the visible range of the solar spectrum, leading to transparent and semi-transparent BIPV and BIPV-T collectors [130,131]. Most of the publications found on BIPV and BIPV-T collectors consider opaque collectors. Publications on transparent and semi-transparent collectors are not extensive, and mainly all refer to semi-transparent collectors.

When designing a building-integrated solar-based collector, a compromise solution between electrical and thermal conversion efficiency and transparency must be reached. For opaque BIPV and BIPV-T collectors, low-cost state-of-the-art PV cells can be considered since these are typically non-transparent to the visible range of the solar spectrum [132–134]. On the other hand, transparent or semi-transparent PV cells usually present lower efficiencies and a wide range of costs [133,135]. Opaque BIPV-T collectors can be rooftop- or façade-integrated, while semi-transparent BIPV-T collectors replace windows or skylights. Figure 5 shows the two main types of BIPV-T collectors: (a) a roof-integrated BIPV-T collector and (b) a semi-transparent BIPV-T collector (window).

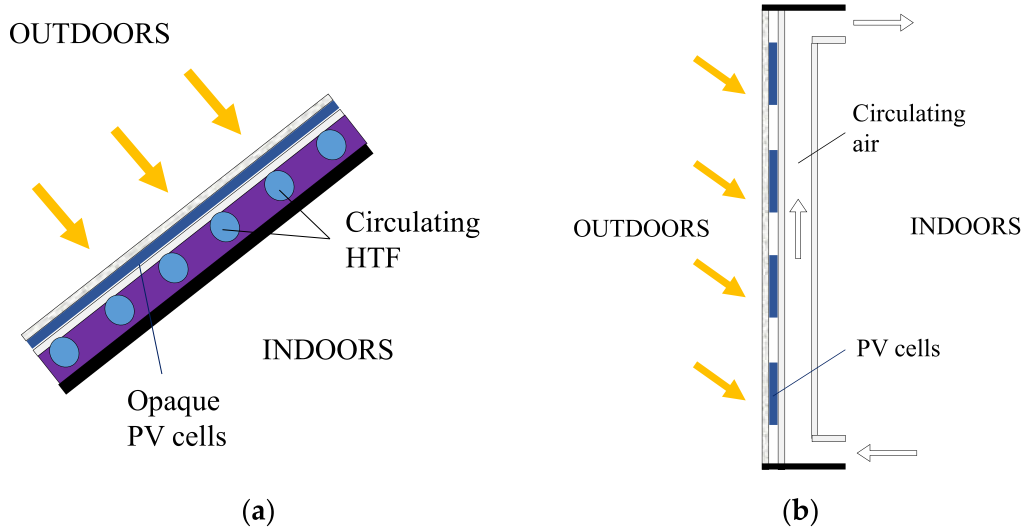

Figure 5. Two main types of BIPV-T collectors: (**a**) roof-integrated BIPV-T collector (opaque) and (**b**) semi-transparent BIPV-T collector (semi-transparent window).

There are also several operating modes in a BIPV-T collector. When there is enough solar irradiance reaching the collector surface, the HTF cools down the PV cells by removing heat. If there are space heating or DHW needs in the building at this time, the removed heat can be used for radiant floor heating, space heating or DHW provision. However, extracted heat can only be directly used for radiant floor heating in systems using water (or similar HTFs). On the other hand, the PV cells generate electricity that can cover a building's electrical needs. In the case that electricity generation is larger than the electricity demand, excess electricity might be fed to the electrical grid to be stored in batteries. Regarding the thermal energy surplus, thermal energy storage (TES) device (i.e., a water tank, but also PCM-based TES) is required to store this energy and allow its later use [136].

2.2.1. Opaque BIPV-T Collectors

As mentioned above, opaque BIPV-T collectors present the highest conversion efficiencies among BIPV-T collectors and are typically rooftop- or façade-integrated, with rooftop installations the most common [136,137]. For the same collector performance, its electrical and thermal generations depend on several factors: the solar resource at the location, orientation and tilt angle of the installation and additional layers and/or components added to the collector for its integration into the building envelope, among others. These collectors perform various functions as structural components and as energy harvesting devices. For example, a rooftop BIPV-T collector includes a transparent protective waterproofing layer to protect all the electrical collector elements as well as the underlying building materials from moisture and surface wear, among others. Apart from the above, these collectors do not present many other differences from non-integrated PV-T collectors.

2.2.2. Semi-Transparent BIPV-T Collectors

Semi-transparent BIPV-T collectors present lower conversion efficiencies than opaque collectors and are usually glazing collectors with inhomogeneous transparency, where the percentage of light that passes through is due to the separation space between encapsulated opaque PV cells. This type of collector is also called a PV cell cladding BIPV-T collector [138,139]. When semi-transparent PV cells are considered, a homogeneous semi-transparency is achieved, typically using thin-film glass-encapsulated PV cells [140,141]. Homogeneous transparency can be achieved through frame-integrated PV cells; the PV cells can be opaque while allowing the maximum possible amount of light to pass through the window glass, and a selective coating is necessary to reflect part of the incident radiation towards the PV cells. This solution also requires a thick frame for the PV cells' integration [142]. For all these types of BIPV-T collectors, the circulating fluid is typically air, as shown in Figure 5. Figure 6 shows an example of each one of the types of PV configurations of semi-transparent BIPV-T solutions.

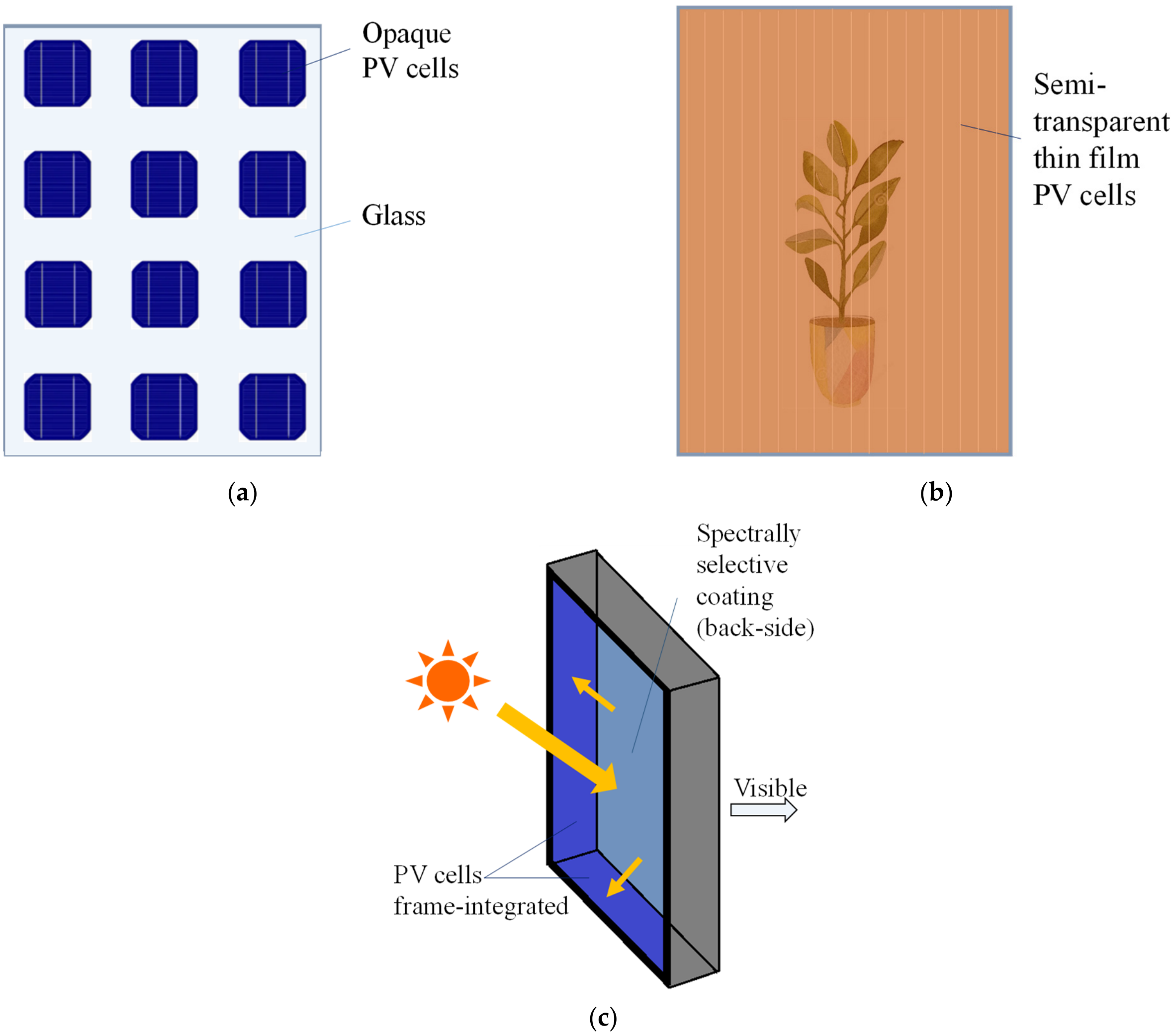

Figure 6. PV configurations in semi-transparent BIPV-T solutions: (**a**) PV cell cladding collectors [138,139], (**b**) semi-transparent thin-film PV cells [140,141] and (**c**) frame-integrated PV cells [142].

Table 1 summarizes several research studies considering the different PV configurations of Figure 6, indicating the PV technology used in each study. The best research-cell efficiencies [132,143] and average visible transmittance (AVT) are also shown [133,134,144]. It is observed that silicon-based PV technologies (i.e., c-Si, m-Si and a-Si thin-films) make up the majority. Despite the promising semi-transparent and transparent properties of emerging PV technologies, transparent PV technologies are still rarely used for building-integrated applications.

Table 1. Research studies considering the different PV configurations shown in Figure 6, indicating the PV technology used in each study (c-Si—mono-crystalline; m-Si—multi-crystalline; a-Si—amorphous silicon; a-Si:H—hydrogenated amorphous silicon; CdTe—cadmium telluride; CI(G)S—cooper indium (gallium)selenide; HIT—heterojunction intrinsic thin layer; TCO—transparent conducting oxide; ZnO—zinc oxide; TiO_2—titanium oxide).

PV Configuration	PV Technology	Best Research-Cell Efficiency (%)	AVT (%)	References
Cell cladding	c-Si	26.1	Opaque	[138,139,145–148]
	m-Si	23.3	Opaque	[149–153]
	a-Si	21.2	-	[154,155]
Thin-film	CdTe/CIGS/HIT	22.1/23.4/27.6	Opaque	[156]
	a-Si:H	14.0	10–25%	[141,157–164]
	TCO (ZnO)/a:Si	24.0/14.0	<30%	[165]
	TiO_2	10.3	<30%	[166]
Frame-integrated	CIS	17.8	<90%	[142]

3. S-CCHP Systems

3.1. Non-Integrated S-CCHP Systems

PV-T collectors can be integrated with solar heating and cooling (SHC) technologies to generate electricity, heating and/or cooling. Some studies integrate concentrated PV-T collectors [167–170], air-based PV-T collectors [171] and liquid-based PV-T collectors [81,97] with cooling technologies to provide electricity, heating and cooling to buildings.

3.1.1. Flat-Plate PV-T Systems

Several authors proposed the integration of air-based PV-T collectors with heat pumps to provide water heating or space heating in buildings [29,89,172], while the integration of non-integrated air-based PV-T collectors into wider S-CCHP systems is scarcer. Most of the research focuses on BIPV-T collectors integrated with SHC technologies to provide heating, cooling and electricity (see Section 3.2).

Liquid-based PV-T collectors can be integrated with several types of SHC technologies to provide heating, cooling and electricity. In these combined S-CCHP systems, the liquid is usually water (or a mixture of glycol/water) or refrigerant.

One of the easiest configurations is the integration of the electrical output of PV-T collectors with air-to-air, air-source or water-to-water HPs [11,173,174]. Using a reversible heat pump allows the simultaneous generation of electricity, DHW and cooling, depending on the HP operation mode [174,175] (Figure 7a). The thermal output of water-based PV-T collectors can also be integrated with water-to-water heat pumps [176,177] to increase the HP COP, maintaining the source of the HP at a fairly constant temperature [11,173] (Figure 7b).

There are other more complex configurations that couple water-based PV-T collectors with water-to-water heat pumps [176] or with an adsorption chiller [178], depending on the operation mode, to supply electricity, space heating or cooling, and DHW for residential buildings [176,179], fitness centres and offices [178]. Water-based PV-T collectors can also be coupled with dual-source air-to-water HPs [180]. In this configuration, the HP evaporator can be the PV-T collector or an outdoor fan unit. For instance, on cold days, the PV-T collector acts as the HP evaporator, increasing the system COP. The air-to-water HP can also run in parallel to the PV-T collectors, using, for example, the outdoor fan unit as a condenser in cooling mode, while the PV-T collectors generate electricity and hot water (Figure 7c).

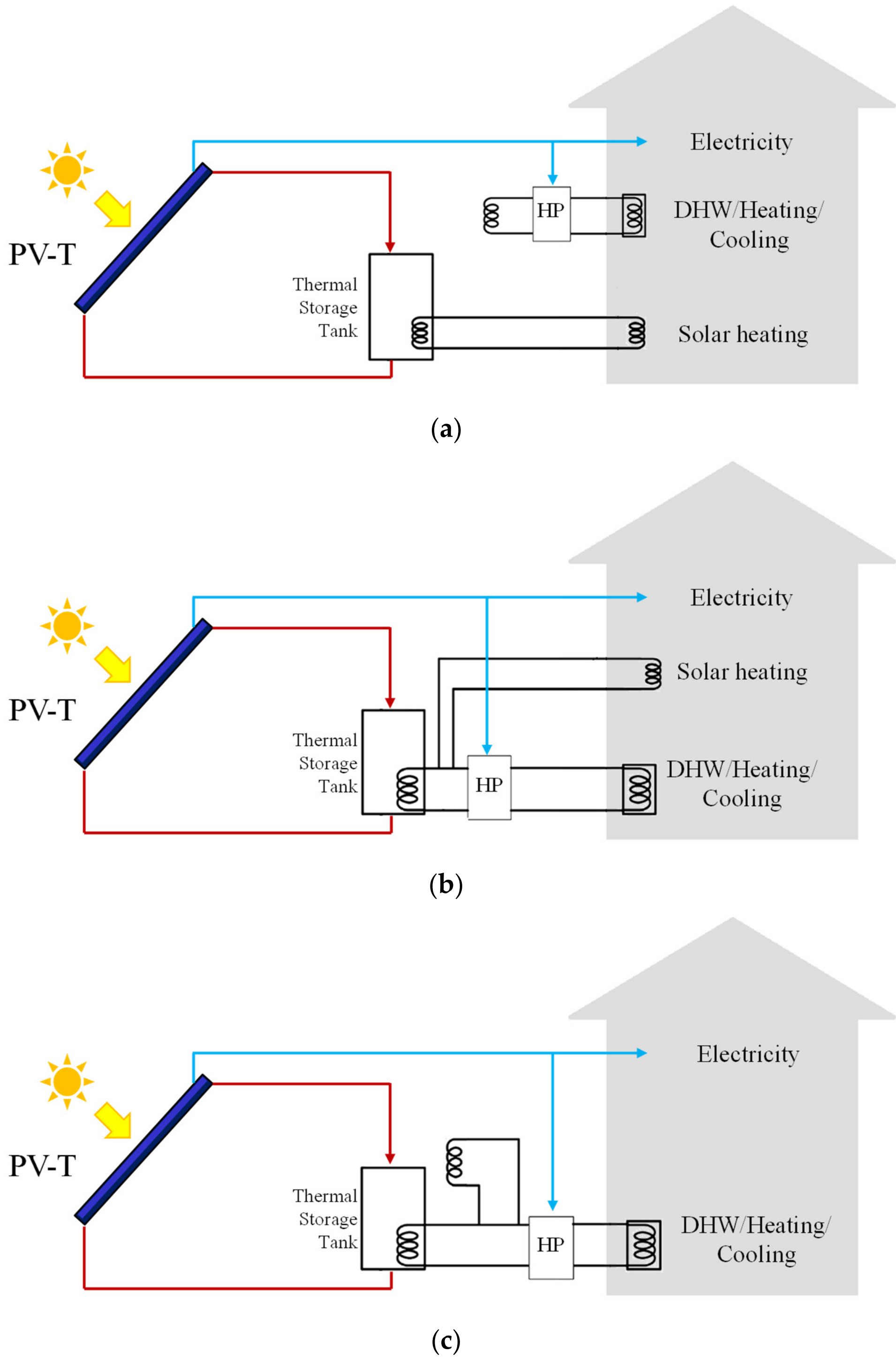

Figure 7. Schematic diagram of (**a**) a parallel air-to-water HP system, (**b**) a series water-to-water HP and system (**c**) a dual-source air-to-water HP system, all based on PV-T collectors. (Adapted with permission from [31] Copyright 2014 Elsevier B.V.)

Alternatively, some authors [181] proposed uncovered water-based PV-T collectors for direct trigeneration in residential buildings. The system provides heating, DHW, electricity and cooling with longwave radiative cooling. The annual thermal efficiency of PV-T collectors ranges between 7% and 16%, the annual heat solar fraction is 17–41% and the amount of electricity covered ranges between 29% and 47%, depending on the European city where the system is located. The radiative cooling contribution can reach up to 29% for cooling water temperature of 20 °C, while it decreases to 3–9% for 16 °C cooling water temperature.

The integration of refrigerant-based PV-T collectors with a heat pump (HP), using the PV-T collector as the HP evaporator, is more common [122,182]. These systems are also called direct-expansion solar-assisted heat pump (DX-SAHP) systems [119]. The thermal absorber of the PV-T collectors can be made of copper tubes [122,183,184] or multi-port flat extruded aluminium tubes [119]. The results show that the overall energy output is higher in the system based on PV-T collectors than in the conventional heat pump plus a *side-by-side* PV system [184]. Numerical studies [109] also concluded that DX-SAHP systems perform better with a compressor operating at a variable frequency because the mass flow rate of the refrigerant can better match the thermal load of the PV-T evaporator. The use of heat-pipe PV-T collectors is less common [185]. The theoretical results in three different climates show that the performance and economics of a DX-SAHP system based on heat-pipe PV-T collectors are very dependent on the weather conditions and economic factors, with payback times ranging from 5 to 20 years [185].

Solar cooling technologies, such as absorption [81,186,187] or adsorption chillers [5,178,188] can also be coupled with water-based PV-T collectors for the provision of heating, electricity and cooling (see Figure 8). Recent studies [189,190] have shown that a COP of up to 0.8 can be achieved by solar-driven single-stage LiBr-H_2O absorption chillers. Covered PV-T collectors are needed to reach the temperatures required to run the absorption chiller [81,97,186]. This type of S-CCHP system based on PV-T collectors and absorption chillers has been investigated in different types of buildings such as residential buildings [5,13], offices [5], universities [97,186] and factory buildings [81].

Adsorption chillers require lower water temperatures, but the COP is also lower [178,188]. Theoretical results show a maximum COP of the absorption chiller of 0.47 when coupled with covered PV-T collectors, while this value becomes 0.38 for unglazed PV-T collectors [188]. On the other hand, unglazed PV-T collectors generate more electricity than covered ones, so the selection of the type of PV-T collector also depends on the specific needs. Other authors [5] conclude that adsorption chillers are recommended in locations with scarce solar irradiance, or when coupled with low thermal performance solar collectors (such as uncovered PV-T collectors).

Finally, desiccant cooling and dehumidification systems can also be coupled with water-based or PV-T collectors [25], particularly in applications that require a temperature in the range of 50 °C to 60 °C. The review in [25] reveals that the outlet fluid temperature from existing PV-T demonstrations could almost match the low temperature required by dehumidification and cooling applications with reasonable electrical and thermal efficiencies.

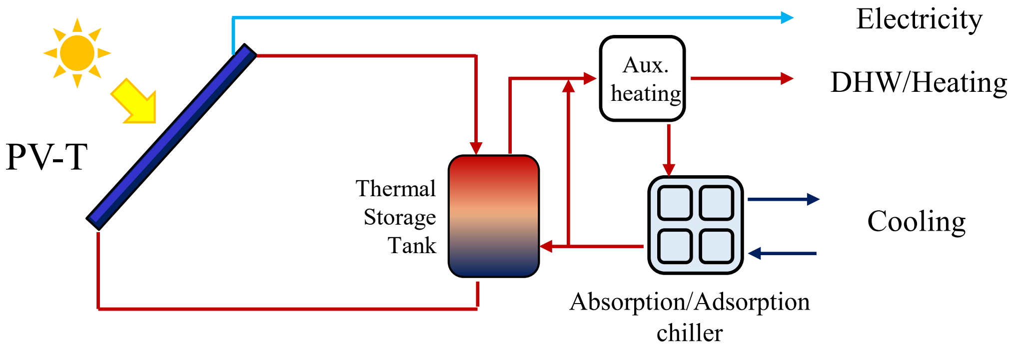

Figure 8. Schematic diagram of an S-CCHP system based on PV-T collectors and an absorption or adsorption chiller. Figure based on [81].

3.1.2. Low-Concentrated PV-T Systems

Low-concentrated PV-T collectors have been proposed as the evaporator of an HP water heating system [128]. Experimental results show an average COP of 4.8 for water heating while increasing the electrical efficiency of the PV cells compared to a low concentrated PV system (that is, with no heat recovery) [128].

A comprehensive comparison among different types of PV-T collectors (flat-plate vs. CPV-T collectors) and alternative cooling technologies (absorption vs. adsorption chillers) [5], concluded that in climates with high beam solar radiation, CPV-T collectors show the best performance due to the higher operating temperatures. The study also concluded that absorption chillers and high-temperature adsorption chillers perform better with CPV-T collectors than with flat-plate PV-T collectors, also due to the higher CPV-T operating temperatures.

CPV-T collectors can operate at temperatures above 100 °C, which are suitable to run single-stage LiBr-H_2O absorption chillers [167,191]. If the concentration ratio is increased, parabolic dish CPV-T collectors can operate at up to 180 °C with reasonable electric and thermal efficiencies [168], so they can be integrated with double-stage LiBr-H_2O absorption chillers, which have a higher COP than single-stage LiBr-H_2O absorption chillers [168,169]. Dynamic simulations show that this system has a significant potential for energy savings, as it can produce electricity, space heating, space cooling and DHW all year long. However, this type of system might not be profitable without public funding policies due to its high investment cost [169]. S-CCHP systems based on CPV-T and absorption chillers have been proposed for a research building [191], a university building with a fitness centre [169], and offices and dwellings [168].

3.2. Building-Integrated S-CCHP Systems

The different configurations of building-integrated S-CCHP systems to provide heating, DHW, cooling and electricity do not significantly differ from those presented in Section 3.1. The main difference between non-integrated and integrated PV-T systems relies on the orientation and internal configuration limitations of the PV-T collectors when integrated into the building envelope.

There are several research articles on BIPV-T systems, but most of them are limited to the PV-T subsystem and do not address the complete integrated S-CCHP system. For instance, recently, the energy, economic and environmental performance of a novel grid-connected BIPV-T/wind system with thermal storage for electricity and heat generation in single-family buildings was analysed [192]. The results showed that the solar energy subsystem could cover up to 65% of the building heating needs, and the PV-T/wind system showed economic competitiveness as well as the potential to reduce the annual CO_2 emissions by 54%. Other authors [193] evaluated the energy yields of a water-based BIPV-T system considering different façade orientations using a semi-transient model developed in TRNSYS [194]. The main conclusion of this work is that to maximize the rate of self-consumed energy, the most suitable exposure for the installation of solar systems does not always coincide with the one that receives the highest solar irradiation, and it should be chosen according to the hourly profile of the load. Other studies [195] analysed the performance of a BIPV-T system with the PV cells installed at optimum tilt angle and the influence of shadow. The study concluded that the reduction in insolation received by the BIPV-T system due to shading and the sky-view blocking effects are more noticeable for buildings located closer to the BIPV-T system. At the same time, it was observed that the electrical and thermal energy outputs of the BIPV-T system decreased with an increase in storey heights as well as the widths of surrounding buildings.

A novel BIPV-T system for energy efficiency in buildings was designed [136] with the main advantages being: (i) the PV module operates at lower temperatures in the summer, maximizing efficiency and PV utilization, thanks to controlled water flow through the panel, (ii) the hot water can be directly used for radiant floor or ceiling heating in winter and can decrease the cooling needs in summer dumping heat and (iii) the integration of the panel into the building skin eliminates the waterproofing concerns associated with conventionally mounted PV-T collectors. All this led to important energy benefits of the proposed BIPV-T system with a small additional investment. In this line, the techno-economic performance of a BIPV-T SAHP system in Canadian houses was evaluated [196]. The authors concluded that the majority of energy savings from the BIPV-T system are due to the HP and that the proposed system retrofit has the potential to reduce up to 18% of the annual energy use of the Canadian housing stock.

Recently, experimental research on an opaque ventilated PV-T system integrated with an HP was proposed [118]. The PV-T façade was used as the evaporator of the HP while generating electricity, and, at the same time, the cavity preheated fresh air of the building. The experimental results showed a maximum COP of 3.1 and an average electrical efficiency of 9% during the testing period. In this regard, a combined air-based BIPV-T ASHP system was modelled for the Toronto area (Canada) [197], and it was found that the preheated air generated from BIPV-T systems fed into the ASHP reduces the electricity demand to operate the HP.

Alternatively, a model for an adsorption chiller operation by recovering low-temperature heat from a BIPV-T system in an office building was developed in [198]. The authors concluded that: (i) the BIPV-T system contributes to a 24% reduction in the building space heating/cooling demands, (ii) a suitable selection of design set-point temperatures is crucial to maximize the primary energy savings associated with DHW production, (iii) the adsorption chiller can almost fulfil all the cooling demands of one floor of the building and (iv) the total primary energy savings is about 63%.

A review of heat utilisation from BIPV-T systems with low-temperature desiccant cooling and dehumidification [25] (see Figure 9) concluded that: (i) solid desiccant cooling systems offer the lowest temperature operation and high COP compared with other solar thermal cooling technologies and (ii) good cooling performance and energy-saving opportunities were found in the limited examples of existing BIPV-T desiccant cooling systems. Recently, a comprehensive review of BIPV-T systems for indoor heating [137] stated that the integration of PV into the structure of the building and the technology of thermal management have to be straightforward, and concluded that: (i) air-based BIPV-T systems are more convenient but present lower performance compared to PCM-based BIPV-T systems or other BIPV-T cooling methods; (ii) PV cells' installation on rooftops allow easier integration with other heating devices due to the broader area of installation; (iii) special attention must be paid to the stack effect that could be overcome with some openings in high-rise BIPV-T systems; (iv) improving the thermal efficiency of the buildings can also positively affect the economic criteria, so an economic assessment of these systems is important.

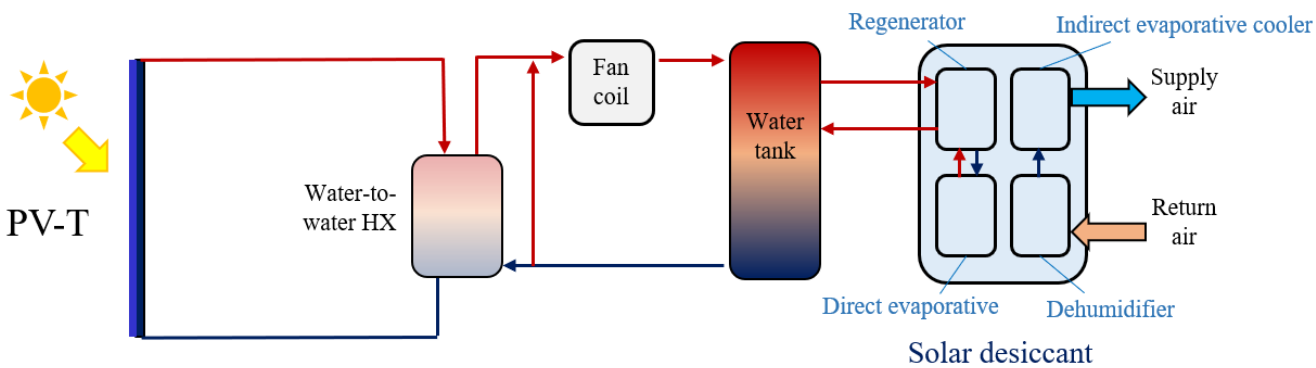

Figure 9. Schematic diagram of the BIPV-T-driven liquid desiccant cooling system presented in [25].

4. Major Advancements and Further Work on PV-T Collectors and Systems for Building Applications

In air-based PV-T collectors, major advancements in recent years involve the integration of these collectors as part of the building envelope (e.g., roof, façade or windows), the so-called building-integrated PV-T (BIPV-T) collectors [137]. There has been significant progress in the development of semi-transparent or transparent air-based BIPV-T collectors to replace windows or skylights [140]. However, despite the promising semi-transparent and transparent properties of emerging PV technologies, transparent PV technologies are still rarely used for building-integrated applications. Further work is required on transparent and semi-transparent BIPV-T systems. Detailed modelling of semi-transparent systems, considering emerging PV technologies, could provide an insight into this system's performance. Further research is also required on life cycle assessments from an economic and environmental point of view.

In liquid-based PV-T collectors, progress has been made in the last few years to improve their electrical and thermal performance [70]. Some research focused on the thermal absorber design and fabrication [28] to increase the heat transfer area and produce cost-competitive collectors, for instance, using flat-box [10] or roll-bond [121] designs. Meanwhile, major advancements include the addition of nanofluids [33] or PCMs [56] to enhance the performance of the PV-T collectors. However, more theoretical and experimental research is required for a better understanding and development of the use of nanofluids in PV-T collectors, to overcome the challenges of certain nanofluids for thermal performance improvement [39]. Further development of new feasible and energy-efficient PCM-based PV-T collectors is also proposed.

Efforts and progress in refrigerant-based PV-T collectors include the use of more environmentally friendly refrigerants, the improvement of the thermal absorber using alternative designs such as the roll-bond design and also the use of heat pipes as the thermal absorber. Heat pipes have the advantages of high heat transfer rates, no moving parts, no energy consumption and long service lifetimes, among others. However, further research is required in the design and operation of heat-pipe PV-T collectors, as well as in their integration into larger systems and in their manufacturing process.

In recent years, liquid-based BIPV-T collectors have also experienced major advancements [36], showing significant potential with the integration of nanofluids and PCMs within the PV-T collector.

In general, further work is required to study the long-term dynamic performance of PV-T collectors, as well as more economic and environmental analyses considering the long-term effects of climatic conditions. More demonstration sites of PV-T collectors in real buildings are essential for continuous field testing to promote solar PV-T technologies. All of this would allow for the definition of proper standards and regulations and, therefore, facilitate their integration into the built environment.

Regarding the S-CCHP systems, the integration of PV-T collectors with HP technologies is a promising potential alternative for different climates with modifiable configurations, for instance, for low-temperature water heating applications [40]. The integration of water-based PV-T collectors with different types of HPs has experienced major advancements, for instance, with water-to-water heat pumps [176,177] or with dual-source air-to-water HPs [180]. However, optimal control strategies are required when coupling PV-T collectors with an HP, and further research is also needed to improve system stability as well as to design and optimize the thermal energy storage system [34].

Heating, DHW, electricity and cooling can also be satisfied by uncovered water-based PV-T collectors with longwave radiative cooling. However, more research is required in this field.

Alternatively, PV-T collectors integrated with thermally-driven cooling systems have also experienced some progress [44], but there is a need for efficiency improvement of the solar thermally-operated cooling technologies. For instance, further research is required to lower the driving temperature in absorption chillers [81,97,186]. The investment costs of absorption chillers should also decrease together with the associated control and operation costs, which are even more important at a building level than in industrial applications.

5. PV-T-Based S-CCHP Systems' Potential and Discussion

As mentioned in the introduction, H/C are responsible for 51% of the total final energy use in Europe [1,2]. Solar thermal systems have the potential to cover a large fraction of the demand for heating, DHW and possibly cooling, as these systems can provide hot water at temperatures up to 150 °C. In winter, the heating demand is high but the solar resource is less abundant, while in summer the diurnal profile of the solar irradiance follows closely that of the cooling demand, which in most cases is currently covered by conventional refrigeration systems [199]. The use of conventional refrigeration systems (normally electrically driven) can give rise to high electricity consumption, which can be covered by PV panels or PV-T collectors. Therefore, there is an important potential for primary energy savings and energy bills reduction by integrating PV or PV-T systems into buildings for the provision of power, heating and cooling.

A systematic review of ASHP systems assisted by ST, PV and PV-T collectors was presented in 2020 [43], which concluded that the ST-ASHP system is the most studied alternative; it has the lowest COP (mean value of 2.90) but requires a lower investment than the PV-ASHP or PVT-ASHP systems. Instead, the PV-ASHP and PVT-ASHP systems have a mean COP of 3.75 and 3.03, respectively, but need larger investments and require more complex control strategies. In this regard, another study [200] performed a techno-economic assessment of four alternative SAHP systems: PV panels integrated with an ASHP, and FPC, PV-T or FPC plus PV panels integrated with a water-source HP. The results show that the most sustainable solution financially depends on the electricity costs; with electricity costs up to 0.23 EUR/kW, the PV-ASHP seems the best alternative, while for higher electricity costs, the PV-T system integrated with a water-source HP seems the best choice.

The current HP market sector is experiencing significant growth. Appliance sales for all H/C market technologies increased by 20% in 2015 [201] and by 3.4% between 2019 and 2020 [202], showing great potential for the near future. The emerging trend over the last few years is that: (i) air-source HP units are gaining in market share to the detriment of the ground-source HP market, (ii) the reversible HPs using air as their vector are taking advantage of record temperatures that have given a boost to the cooling market, (iii) the energy independence and the growth of the self-consumption market are driving another market trend that HPs can turn to their advantage, (iv) HPs must reduce associated GHG with low GWP refrigerant selection, refrigerant load reductions and efficiency improvements, and (v) there is an important performance enhancement potential by combining HPs with solar-based solutions.

However, despite their market uptake, current HP technologies are still far from operating synergistically with solar inputs and their use is constrained in cold weather due to frosting and in hot weather due to poor heat rejection, in both cases penalizing performance. Oil-free compressor technology is not used in heating solutions yet because of the medium evaporation temperatures that the first compressor generation (dedicated to cooling) needs [203,204]. They cover only high capacity because of their expensive technology, but the power range has been increased in last years. Here, anti-frost and selective emissivity control, as well as water flow control and selective evaporation should be developed to overcome these problems. Current HP hybridization approaches involve simple connections to solar thermal collectors or PV panels: (i) In ST collectors integrated with HPs, the best performance is obtained with traditional parallel systems [205], while the higher potential of heat source side solutions requires a sophisticated, robust and well-tuned control to achieve high annual solar fractions [206]. (ii) In PV panels integrated with HPs, the PV generation and HP consumption profiles are rarely managed integrally. PV-T and reversible HP coupling efforts to date are scarce and have faced several challenges [207].

A recent study [186] compared the techno-economic and environmental performance of an S-CCHP system based on PV-T collectors integrated with an absorption chiller, with a system based on ETCs and an absorption chiller and with a conventional PV-only system. The result shows that the lack of electricity generation by the ETC-based system limits its profitability, leading to 2.3 times longer payback time than the S-CCHP system. Meanwhile, the PV-only system has almost 3 times shorter payback time than the S-CCHP system, mainly due to the considerably lower investment cost. However, the S-CCHP system has the potential to displace 16% and 1.4 times more CO_2 emissions than the PV-only system and the ETC-based system, respectively. A similar study [81] compared S-CCHP systems based on absorption chillers vs. conventional HPs, and with PV-T collectors vs. ETC, for the energy provision in the food-processing industry. The two main challenges found were the overlapping of the cooling and hot water demands of the food-processing industry, and the high hot water temperatures required [81]. These, together with the larger investment cost of the S-CCHP system based on an absorption chiller, lead to a longer payback time than a system with uncovered PV-T collectors and conventional HPs. The results also showed that when the potential environmental benefit is quantified (through carbon pricing), all the proposed solar systems become economically attractive, i.e., with positive total cost savings at the end of the system lifetime. Alternatively, PV-T collectors can also be integrated with PV panels or ST collectors to adjust the ratio of heating and electricity supply to meet specific demands [95].

The solar-driven cooling market via thermally-driven (absorption/adsorption) technologies is at an early stage of maturity, with approximately 1350 systems installed worldwide (as of the end of 2015). More than 75% of the installations worldwide are located in Europe, led by Spain, Italy and Germany. However, the vast majority of the installed solar air conditioning systems are coupled with either FPCs or ETCs. There are also a few examples of installations of concentrated collectors (Fresnel or parabolic-trough) in India, Turkey and Australia. At present, there are only a small number of companies that offer packaged, ready-to-install solar air conditioning systems. The majority of currently available systems involve separate components that have been installed together onsite to meet the specific needs of different projects [208].

Driving heat in absorption chillers generally needs temperatures above 75 °C, sometimes up to 85 °C or higher. Heat rejection for available absorption chillers needs wet cooling towers, as the units available in the market are limited to operating temperatures for the heat rejection of 35–38 °C [209]. In standard absorption chillers, the heat rejection system is responsible for 60–95% of the electricity consumption [210], so there is still room for improvement to reduce this consumption, for instance, through modern control strategies [211]. In the previous literature, separated controllers are used for the absorption chiller and the heat rejection devices, and pumps run at a fixed speed because absorption chillers do not allow flexible flow rates. Hence, an enhanced control unit of the absorption chiller is of significant importance. It is estimated that if a master controller controlling all actuators such as pumps or heat rejection devices is used, it is possible to save up to 80% of the parasitic electrical effort.

Absorption chillers for domestic applications have prices much larger than 1 EUR/W [212] and are therefore out of broad market usage. Overall system investment costs (without solar thermal collector costs) easily reach values above 3.5 EUR/W [213], while these values should be below 1.5 EUR/W to reach market demands and a sustainable market entry. Hence, the investment costs of absorption chillers should decrease together with the associated control and operation costs, which are even more important at a small scale than in industrial applications.

In S-CCHP systems, usually, several conventional thermal energy storages are used to store the solar thermal output and the hot/chilled water for H/C purposes. The three main drawbacks of the use of multiple tanks are the space constraints, investment costs and cost of operation (maintenance and heat losses), so research is needed to develop cost-competitive and compact TES units optimised for the different temperatures that can also be integrated into a single overall unit. For instance, integrating a PCM-based TES between the PV-T closed-loop circuit and the H/C unit (e.g., HP or absorption/adsorption chiller) could ensure a constant temperature is supplied to the H/C unit, enhancing the performance of both PV-T collectors and the H/C unit. This would also have the advantage of load-shifting: energy generation by PV-T collectors can be partially or wholly decoupled from the heat demand by the H/C unit. Integrating a PCM-based TES to the H/C unit outputs could also increase its performance by ensuring a constant temperature is supplied to H/C appliances.

Again, there would be the advantage of load-shifting and decoupling the supply from the demand for H/C. Furthermore, the reduced size and high capacity of the stores as compared to available water tanks, and their modular design allow different temperatures of the store to be combined into a single unit, with minimal external connections.

6. Conclusions

This work aims to review the state-of-the-art PV-T collectors for building applications, as well as the corresponding PV-T systems for combined cooling, heating and power provision in the built environment. Based on this review, the following conclusions are drawn:

1. Air-based PV-T collectors are the simplest design and typically cheaper, although the thermal performance is lower compared to liquid-based PV-T collectors. Different thermal absorber designs have been proposed to improve heat transfer, including the addition of several fin configurations. The main applications include space heating and solar drying (particularly in the agriculture sector). These PV-T collectors are particularly suitable for building applications in medium and high latitude countries. Usually, these collectors are integrated with an air-source HP for space heating provision.
2. Liquid-based PV-T collectors have a more complex design compared to air-based PV-T collectors and their cost is generally higher, but they have larger thermal efficiency and the thermal output has more applications, including space heating, water heating and solar cooling.
3. The most common design for water-based PV-T collectors comprises a metallic sheet-and-tube absorber and parallel pipes, while in refrigerant-based PV-T collectors, a serpentine sheet-and-tube is typically used.
4. Major advancements in liquid-based PV-T collectors include the addition of nanofluids or PCMs to enhance their performance. However, more theoretical and experimental research is required for a better understanding and development of the integration of nanofluids and PCMs in PV-T collectors.
5. Refrigerant-based PV-T collectors usually have higher electrical efficiencies than air- or water-based PV-T collectors due to the lower operating temperature of the PV cells, but they have some disadvantages such as the high risk of refrigerant leakage, uneven refrigerant distribution in evaporation tubes, the potential induced degradation, delamination and UV degradation, or the need of a perfect seal in the refrigerant cycle to prevent air entering the system during operation. Heat-pipe PV-T collectors may have the potential to overcome some of these problems, but further research is required in their design and operation.
6. Single-covered PV-T collectors appear like an interesting option when a significant thermal output is needed, while the best exergy gain is found for uncovered PV-T collectors.
7. The thermal absorber design (including the fluid flow pattern) has a considerable impact on the cooling of the PV cells and the temperature of the thermal output of the collector. Recent research focused on the thermal absorber design and fabrication, to increase the heat transfer area and produce cost-competitive collectors, for instance, using flat-box or roll-bond designs.
8. To cater to the demands of applications where high temperatures are required, achieving low emissivity is critical, which can be attained by applying suitable coatings, and PV-T collector evacuation then also becomes a critical factor for reducing convective thermal losses.
9. The most suitable PV-T collector type to satisfy the space heating demand depends on the weather conditions and the space heating system, if available, among others.
10. DHW provision appears to be the most common PV-T application at present.
11. The larger complexity and risks of BIPV-T collectors compared to stand-alone PV-T collectors have acted to hinder their potential and uptake, so more research is required in the detailed modelling, analysis of any impacts on the building structure and

integration methods for installation as well as more experimental assessments and long-term performance analyses.

12. The most suitable combination of PV-T collector and H/C technology depends on the specific location (solar irradiance, ambient temperatures) and the specific application, among others.

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Nomenclature

ASHP	air-source heat pump
a-Si	amorphous silicon
a-Si:H	hydrogenated amorphous silicon
AVT	average visible transmittance
BIPV	building-integrated PV
BIPV-T	building-integrated PV-T
CdTe	cadmium telluride
CFD	computational fluid dynamics
CI(G)S	cooper indium (gallium) selenide
COP	coefficient of performance
CPV-T	concentrated PV-T
c-Si	mono-crystalline silicon
DHW	domestic hot water
DX	direct-expansion
ETC	evacuated tube collectors
H/C	heating and cooling
HIT	heterojunction intrinsic thin layer
HP	heat pump
HTF	heat transfer fluids
IDX	indirect-expansion
FPC	Flat-plate collectors
GHG	greenhouse gas
PCM	phase change material
m-Si	multi-crystalline silicon
PV	photovoltaic
PV-T	photovoltaic-thermal
PTC	parabolic through collectors
RES	renewable energy sources
SAHP	Solar-assisted heat pump
S-CCHP	solar combined cooling, heating and power
SH	space heating
SHC	solar heating and cooling
ST	solar thermal
TCO	transparent conducting oxide
TES	thermal energy storage
TiO_2	titanium oxide
ZnO	zinc oxide

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