Chapter

Photovoltaic-Thermal Solar Collectors – A Rising Solar Technology for an Urban Sustainable Development

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Abstract

The increasing global warming awareness related to climate change due to the high emissions of carbon dioxide in recent decades linked all nations into a common cause, which requires ambitious efforts to combat climate change by adapting energy systems to its effects. This book chapter aims at investigating the potential role of Photovoltaic-Thermal (PVT) solar collector technologies for an urban sustainable development based on the current state-of-art, system components and subsidies for PVT technologies. PVT technologies are a practical solution to compete with isolated systems such as photovoltaic (PV) modules and solar thermal collectors if a significant reduction in manufacturing cost is achieved, coupled with an increased energy production performance. Therefore, its success is intensely linked to the capacity of the PVT industry/researchers to scale down its current system cost and complexity in a way that can shorten the cost/performance gap to both PV and Solar Thermal (ST) technologies. The knowledge gained presented in this book chapter has been acquired through an extensive literature review, market surveys and project development made by several PVT experts with extensive expertise in the development of PVT technologies, which establishes the foundations for more efficient and cost-effective PVT solar collectors.

Keywords: photovoltaic-thermal collector, PVT system assessment, performance evaluation, urban development, sustainable development

1. Introduction

1.1 Fundamentals of PVT collectors

The quest to decarbonize electrical and solar thermal (ST) systems has never been more urgent. While decarbonisation of the electrical system is on track, the decarbonisation of ST systems has not been tackled. ST systems typically make up about 50% of the final energy demand and [1] suggests that a large portion of the demand could potentially (i.e., while requiring significant technology developments) be supplied by renewable photovoltaic thermal (PVT) solutions. PVT solutions address another important and increasingly emerging issue—spatial and network constraints, thus requiring less space than a PV or ST collector would.

Solar energy systems are progressively increasing their installed capacity due to subsidies and incentives as well as due to their increased efficiency [2]. Higher efficiencies and economic competitiveness increase annually, which leads to more investment and a sustainable energy mix.

The active application of solar energy technologies relies mainly on the use of photovoltaic (PV) systems for electricity generation and ST systems for heat generation.

The electrical efficiency of PV cells is typically around 22% for multi-crystalline and 27% for mono-crystalline silicon wafer-based technology [3], which corresponds to a fraction of the incident solar radiation. The remaining share is converted into heat. Additionally, the highest lab efficiency for thin-film technologies, CIGS and CdTe, is 23% and 21%, respectively.

The higher combined thermal and electrical efficiencies (per unit area) of a PVT solar system have the potential to overcome the typical low surface power and energy density of PV modules, and the relatively low exergy of the ST solar collectors, as well as the limited available roof/ground area [2]. This is particularly important if the available roof area is limited, but integrated solar energy concepts are needed to achieve a climate-neutral energy supply for consumers, such as in residential and commercial buildings.

By co-generating both heat and electricity from the same gross area, PVT collectors extract the excess thermal energy generated by the PV cells by employing a heat transfer cooling fluid (HTF), increasing electrical efficiencies due to lower PV cell temperatures.

For solar energy applications, the wavelengths of importance for solar energy applications are typically from around 0.3 to approximately 2.4 μm of the solar spectrum (i.e., ultraviolet, visible and infrared region). PV cells optimally operate at a narrower range of the solar spectrum (i.e., from around 0.3 to approximately 1.1 μm), therefore the radiation that is not within this range merely warms the PV cells and can be used as thermal energy, thus limiting the maximum electrical efficiency [2].

Due to the co-generation of heat and electricity, PVT collectors utilise a broader solar irradiance spectrum, which makes them more attractive in terms of energy conversion effectiveness as can be seen in **Figure 1**.

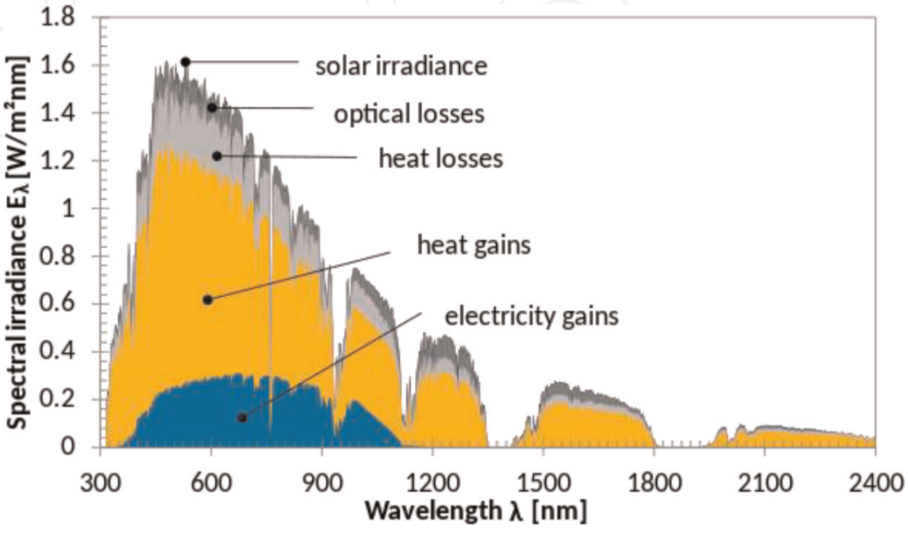

Figure 1.
Spectral distribution of solar irradiance, optical and heat losses, and heat and electricity gains. Provided by Manuel Lämmle.

Figure 1 presents the wider range of spectral irradiance operation of PVT technologies, by employing both thermal absorbers and PV cells in the same solar collector box. As previously stated, PVT solar collectors are the combination between a PV module and an ST collector into a single unit. The PV elements convert the incoming solar energy into electricity, which is typically encapsulated with ethylene-vinyl acetate (EVA) or a solar silicone gel in case of low concentration PVT solar collectors [2].

On the other hand, the thermal elements of the PVT collector convert the solar energy into heat gains typically by absorption. The absorption is done at the receiver level, in which the harvested heat from the PV cells (highest material share exposed to the solar radiation) and PVT absorber (e.g., thermally couples the PV cells to the HTF) is transferred into an HTF. A schematic cross-section of a PVT collector is presented in the following **Figure 2**.

1.1.1 Temperature dependence overview

For a solar collector to produce usable thermal energy, the HTF must be at lower temperatures than the absorber (i.e., in solar thermal collectors) and PV cells (i.e., in PVT collector) as "heat can never pass from a colder to a warmer body without some other change" (statement by Clausius from 1854). Therefore, the thermal coupling between the PV cells (hottest element in a PVT collector) and the thermal absorber (and thus the HTF) is of most importance for the overall performance of a PVT collector.

Furthermore, silicon wafer-based PV technology is typically more efficient at lower module temperatures as their average temperature coefficient is around 0.35%/°C, which leads to a lower open-circuit voltage and thus a decreased electrical efficiency [2, 5].

Just as PV modules reach higher efficiencies at lower module temperatures, the solar thermal collectors do so too as the heat losses are proportional to the receiver's surface temperature. It is important to note that the operating temperature is regulated by the overall system (i.e., the temperature required at the heat storage) and not solely by the solar collector.

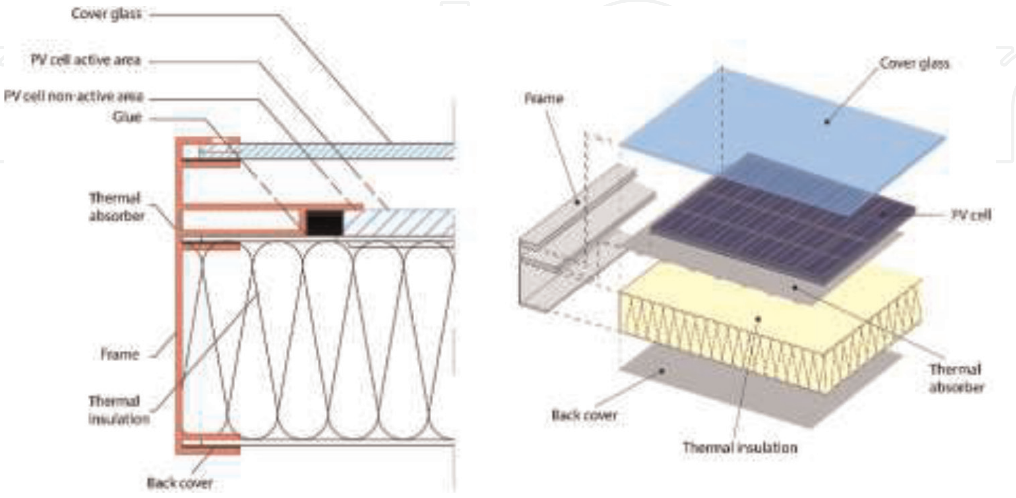

Figure 2.
Representation of an uncovered PVT collector cross-section composed by a sheet-and-tube heat exchanger and back insulation: Anti-reflective cover; front-encapsulation layer (e.g., EVA); Back-encapsulation layer (e.g., EVA); Backsheet (e.g., PVF); PV cells; thermal absorber (e.g., aluminium, copper or polymers); thermal insulation (e.g., mineral wool, polyurethane) and frame. Based on [4].

According to Lämmle [6], a solar thermal collector mean operating temperature typically ranges between 30 and 90°C. On the other hand, a PV cell typically operates at a module temperature between 30 and 60°C, which overlaps (to some extent) with a solar thermal collector mean operating temperature. This overlap in operating module and mean temperature leads to different behaviours from the PV module and the ST collector, as the ST collector has a deeper decrease in efficiency than the PV module for increasing temperatures.

Moreover, the PVT collectors do not operate at optimum efficiency for either PV or ST operation mode, which leads to a compromise between both elements. Therefore, PVT collectors operate either as *electricity* or *as heat optimum operation*, which prioritises the operating agent needs for a specific application, either giving priority to the electricity or heat generation [2]:

- *Electricity optimum operation* implies a low HTF mean temperature to lower the heat dissipation, thus enhancing the PV cell electrical efficiency.

- *Thermal optimum operation* implies higher HTF mean temperatures closer to the operation point of conventional ST collectors.

For an overall PVT collector optimum performance, it is crucial to efficiently utilise the available solar resource, therefore, it is of greatest interest to instal PVT solar collectors for better use of space.

Amongst several solar specialists, [1] consider PVT technology more complex than the available mature technologies such as PV or ST technologies. Nevertheless, PVT provides significant advantages such as the ones mentioned below.

- For the same gross are, PVT provides higher combined electrical and thermal power than a PV or ST collectors.

- The electrical production of an uncovered PVT module typically matches the electrical production of a PV module. Moreover, uncovered PVT modules can even have higher electrical outputs if operated at lower temperatures than the PV module, due to the extraction of thermal energy.

- Depending on their type, PVT collectors can produce heat for a wide range of applications.

- The ST production can be used to preheat or heat for domestic hot water (DHW). In well-designed hybrid collectors, the production can be almost as high as that of just an ST collector, 10–20% less, a reduction mainly due to the part of the irradiation that is converted to electricity.

- Thermal energy converted from either solar radiation or ambient heat can be used as a heat source for a HP. The electrical power can directly drive the circulation pumps and HP. In some cases, during summer, a fully-solar solution can be achieved when a DHW HP system can completely supply the HP consumption.

- ST energy can be stored in onsite tanks, precinct-level tanks, aquifers, ground strata and pit storage systems, which are currently much more cost-effective than electricity storage. *'This is especially true when PVT is used in combination with a*

> *HP that will make good use of the stored energy. The HP enables higher output temperatures enabling more compact storage solutions to be implemented. This is critical when space is limited. Larger thermal energy solutions can be accessed via district heating (DH) networks and enable the produced summer excess heat to be stored seasonally for the winter'.*

- The increasing demand for cooling aids the PVT technology to disseminate has it has the potential to provide direct solutions by means of heat in absorption machines or by exposition to the night radiation phenomena (e.g., for uncovered PVT solar collectors), which cools down the HTF below ambient temperatures and therefore it can be used directly and/or stored (i.e., a compact storage example is ice storage). When coupled as a source for a HP can be recharged by an unglazed PVT collector with very high efficiencies, even during the cold heating season.

- PVT solar collectors have the potential to have no social impact, as can be comparable to both PV and ST solar collectors when incorporated into a roof or façade of a building envelope (i.e., no undesirable visual impact).

- Radiative and convective cooling also can be provided directly during the night using the thermal absorber or indirectly through a machine driven by PV electricity.

The relatively small emerging solar markets and small-scale production gives higher costs in the beginning, compared to the well-developed markets for fossil fuels. This cost disadvantage has all the time been the main barrier for both Solar PV and Solar Thermal.

A very important sometimes forgotten barrier is also proven long enough lifetimes for the new solar technologies. Many of the first concepts have failed in small things, as almost all new products, giving a bad reputation and extra costs for repair when introduced with too little product testing. For fossil energy supply the hardware stands for a much smaller fraction of the total cost and can be repaired at a lower cost per produced kWh when there is a problem. In this reliability respect, PV has had a great advantage, as it was first developed for Space applications, where the durability and reliability requirement is extreme. So, when "coming down to earth" that barrier was already solved. Only the cost was a barrier that could slowly be solved, by larger and larger markets and thereby mass production. Solar thermal has not had that kind of well-paying niche markets to the same extent and in almost all countries the subsidy systems have been an insufficient and too short term to develop a sustainable market.

For PV and solar thermal there were also niche markets in remote places without an electric grid, or for solar thermal replacing wood and oil during summer for hot water heating with low efficiency of the burners in these periods. Heat pumps have then become much more reliable in parallel and lower in cost and become a hard competitor for solar thermal (and can also compete with oil/fossil fuels). In a heat pump system, the PVT can find a niche market as one example, as it produces both heat for the cold side of the heat pump and electricity for the heat pump compressor operation. The cold side heat supply is sometimes forgotten when thinking about heat pump solutions. The heat pump still needs heat, its function is to increase the temperature of the available low temperature "free" heat to a useful level. This heat has to be inexpensive to make the whole system cost-effective. Here the PVT heat can make a nice contribution.

A further barrier for PV and solar thermal especially at higher latitudes is the annual distribution mismatch of demand versus energy production in many applications. This mismatch in demand and renewable supply is partly driven by the lack of solar radiation, causing lower outdoor temperatures and higher load in winter. In larger systems, seasonal storage in water pits can be used but in small systems, the heat losses in small thermal storage are too large for long-term storage. Phase change materials might be used then.

For PVT there is a further barrier that there has to be a reasonable match between supply and demand for both electricity and heat, to have full success. Oversizing gives longer payback times. Often too much heat is produced compared to electricity for the demand in a house, so efficient electric appliances can be extra cost-effective then. In systems where there is a need for heating a swimming pool or a borehole heat pump, the inclusion of PVT technologies could be a wise solution. Ideally, a total system view should be used when looking at PVT systems.

However, from these barriers can be concluded that several system types suit PVT technologies. It has been classified by the heating/cooling demand, as the electricity always can be consumed instantaneously or exported if too much power is produced.

- Hot water preheating systems for hotels.

- Swimming pool heating.

- PVT systems recharging Borehole/Ground Source heat pump systems to increase the Heat Pump COP and avoid undercooling of the borehole/ground. PVT can also be applied when changing to a larger heat pump in an existing ground source system.

- Air heating systems. For example, preheating of ventilation air or preheating of summer houses. Also drying of crops can be achieved. Many industry applications with large ventilation air use, like painting, can be interesting.

- Cooling by radiation to clear night sky conditions can also be used as a bonus with the same hybrid components.

1.2 PVT collector classification

According to Zondag [7], PVT collectors can be classified into four main categories according to their heat transfer medium, employed PV cell technology, collector design and their specific operating temperature.

Typically, PVT solar collectors either have air or liquid as an HTF, the latter being either water or a mixture between water and glycol (anti-freeze and anti-corrosion product) [8]. PVT air collectors are less sensitive to overheating as typically they are categorised as unglazed PVT collectors (i.e., glass cover, thus higher heat losses). On the other hand, PVT liquid collectors comprise the biggest installation share; however, they present overheating issues. Nevertheless, water (as a heating fluid) has a higher heat capacity and thermal conductivity than air [7].

The exponential increment in the efficiency of PV cells in recent decades tends to raise end users' expectations. Therefore, the system where this technology is employed is of most importance, since the specific suitability depends on electrical conversion efficiency, temperature and absorption coefficient [9]. c-Si PV cells have the highest share for both PVT and PV collectors. Mono-crystalline cells have enhanced electrical efficiency and solar absorption than polycrystalline PV cells. Thin-film technologies, which comprise CIGS and CdTe technologies, are typically characterised by their lower temperature coefficient than c-Si PV cells, thus more suitable to work under higher HTF and module temperatures. In applications such as

PVT collector, where cooling is needed at PV cell level, multi-junction (IIIV cells) solar cells are generally used for systems where high concentration is required. Therefore, this technology (IIIV cells) can be a contender for PVT solar collectors that require higher operating HTF temperatures.

Additionally, PVT collectors can be classified into two main clusters according to their design, such as flat plate and concentrating PVT collectors. Flat-plate PVT collectors can be sub-categorised into unglazed (e.g., similar aesthetics to PV modules, but without front glass cover) and glazed (e.g., similar in design to PV modules, with an additional front glass cover to decrease heat loss) PVT collectors.

Moreover, concentrating PVT collectors can be labelled due to their concentration ratio, such as low, medium and high concentration factors. Typically, low concentration PVT collectors are used as stationary (fixed collector tilt angle) solar systems. On the other hand, high concentration requires variable collector tilt angles and thus entails one or two-axis-tracking systems.

A balanced operating fluid temperature is critical to reach higher electrical and thermal efficiencies. Hence, the generality of the PVT water collectors and ST collectors can be allocated into three main groups for a wide range of applications [2]:

- Low-temperature applications for temperatures of around 27–35°C, which include swimming pool heating or spas. Typically found in unglazed PVT collectors (low thermal insulation);

- Medium-temperature applications for temperatures up to 80°C (e.g., glazed or evacuated tube collectors);

- High-temperature applications for temperatures higher than 80°C (e.g., high-efficiency flat-plate or concentrator collectors).

The temperatures of a specific system depend on the requirements of the heat supply system for DHW and space heating. Therefore, [9] allocated (in a schematic view, **Figure 3**) each PVT technology and applications per operating temperature.

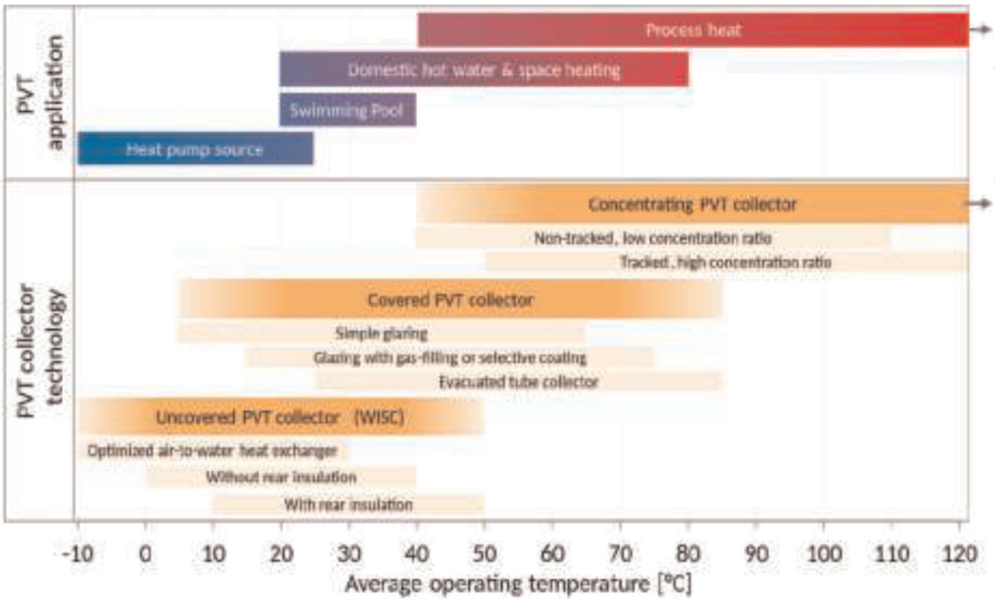

Figure 3.
Map of PVT technologies and applications per operating temperature [9].

1.3 Performance of PVT collectors

Solar radiation reaches the module at a solar irradiance, which immediately a fraction is lost to the ambient as Q_{loss} and the remaining portion empowers the PV module (Q_{el}) with a given electric efficiency (η_{el}). The accumulation of solar energy increases the temperature of the PV module and generates the thermal power of Q_{th}, depending on the fluid medium and module design, which is transferred to the thermal module through a heat transfer mechanism with a thermal efficiency of η_{th}. Finally, thermal insulation obtained by reducing and eliminating the back and sides heat losses will increase the system efficiency. The general energy equation for a simple PVT module and overall efficiency (η_{PVT}) can be defined by Eqs. (1)–(3) [10, 11].

$$\eta_{el} = \frac{Q_{el}}{G.A} \tag{1}$$

$$\eta_{th} = \frac{Q_{th}}{G.A} \tag{2}$$

$$\eta_{PVT} = \eta_{el} + \eta_{th} \tag{3}$$

Where G (W/m^2) is the solar radiation and A (m^2) is the aperture area of the module.

1.3.1 Electrical efficiency

PVT systems are two separate systems that consist of a single ST collector and a PV module, which are attached together and work simultaneously to generate electricity and thermal energy. The performance of a PVT collector is reduced when the temperature of the system rises [12]. For a separate PV module, the following Eq. (4) provides the electrical efficiency η_{el}.

$$\eta_{el} = \frac{I_{mpp}.V_{mpp}}{G.A_c} \tag{4}$$

I_{mpp} stands for the maximum power point current, V_{mpp} for the maximum power point voltage and A_c for the collector gross area in m^2 [13]. A special maximum power point tracking controller in the system assures that the PV modules operate at the best working point (I_{mpp}, V_{mpp}).

The reduction of the PV module performance with increasing temperature is given by Eq. (5), which represents the traditional linear expression for standard PV module electrical efficiency.

$$\eta_{el} = \eta_{0,el} \cdot \left[1 - \beta\left(T_c - T_{ref}\right)\right] \tag{5}$$

Where T_c is PV cell temperature, T_{ref} is reference temperature and β is the coefficient of temperature. Nevertheless, by employing flash tests in which the PV module electrical output is measured at two different temperatures for a given solar radiation flux the above mentioned-parameters can be obtained. The real temperature coefficient value depends on both PV material and T_{ref} [14–16].

1.3.2 Thermal efficiency

Based on ISO 9806: 2017 at steady-state conditions for glazed liquid heating collectors, the instantaneous efficiency η_{th} shall be calculated by statistical curve fitting, using the least-squares method, to obtain an instantaneous efficiency curve of the form presented in Eq. (6).

$$\eta_{th} = \eta_{0,th} - a_1\frac{T_m - T_a}{G} - a_2\frac{(T_m - T_a)^2}{G} \tag{6}$$

where T_m is the mean temperature of heat transfer fluid (°C), T_a is ambient air temperature (°C), η_{0_th} is peak collector efficiency (η_{th} at T_m-T_a = 0°C), G is hemispherical irradiance, a_1 is heat loss coefficient (W/m^2 K) and the temperature dependence of the heat loss coefficient comes as a_2 (W/m^2·K^2) [17].

1.4 PVT systems: Types, components and applications

Typically, a PVT collector operates in a solar thermal system, which affects the electrical and thermal yields substantially since its efficiency is temperature-dependent. *'The PVT system is amongst others characterized by its hydraulic layout, the sizing of storage and collector field, design temperatures of the heat supply system, and the system control'* [18].

It is crucial to create a context regarding the collector yield with its specific interaction between the collector, system components, weather, controller and user behaviour.

Lämmle et al. [18] selected four reference systems, which cover a wide range of promising applications and operating temperatures. A simplified hydraulic layout for each system with corresponding collector and storage dimensions is presented in **Figure 4**.

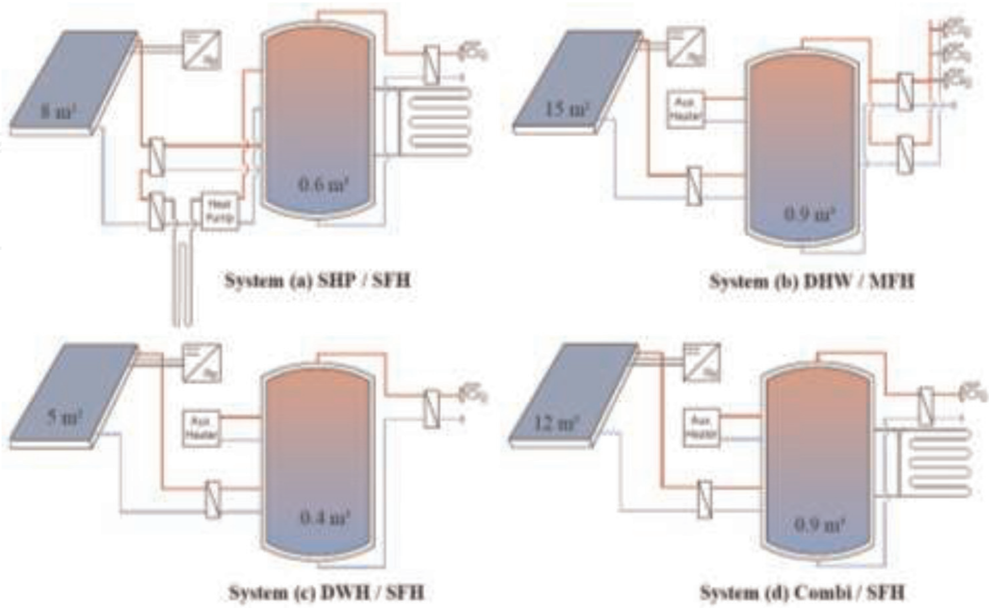

Figure 4.
System diagrams: (a) solar heat pump system in parallel/regeneration configuration in a single-family house; (b): Domestic hot water in a multi-family home; (c) domestic hot water in a single-family house, system; and (d) combi system in a single-family house [18].

System (a): A ground-coupled brine-water heat pump (HP) system incorporated into a single-family house (SFH) supplies space heat and DHW. By coupling a PVT collector to the cold side heat source of a HP or regeneration of a ground heat exchanger can potentially provide lower PVT collector temperatures and thus higher efficiencies.

System (b): A Domestic hot water (DHW) system in a multi-family house (MFH) is typically dimensioned to reach relatively low solar fraction. Therefore, the HTF is typically preheating and the overall operating collector loop temperatures are lower.

System (c): DHW system in a SFH is the classical system for solar thermal collectors and is therefore considered a promising application with a potentially big market for PVT collectors [7]. If the PVT system is not oversized compared to the load the operating temperatures can be quite low.

System (d): Combined DHW and space heating (combi) system in a SFH represent a challenge for PVT collectors due to the challenging thermal requirement efficiencies during winter, as the heat demand typically occurs with low levels of irradiance and ambient temperatures. Here avoiding oversizing is very important.

The electrical system can also be coupled with an electrical power meter, power optimizers in each PVT collector, battery storage systems and smart controllers optimising the interplay with the electricity grid.

Moreover, under the SHC-IEA Task 60 framework, a detailed representation scheme has been developed for combined electrical and thermal energy flows in PVT systems, which can be seen as an enhancement of the work developed at SHC-IEA Task 44.

In general, the system boundaries such as the final purchased energy, useful energy used in space heating, as well as system components (i.e., PVT collectors, heat pump and thermal storage) are represented and highlighted with explicit colours.

The system components are defined and highlighted as follows:

- Solar energy collectors (e.g., PV, ST and PVT collectors);
- Thermal storage (i.e., source side of the heat pump);
- Heat pump;
- Backup heater (e.g., boiler or heating rod);
- Thermal storages (i.e., sink side of the heat pump);
- Electrical storage (e.g., batteries).

Furthermore, three different system boundaries were defined as ‘left’, ‘right’ and ‘upper boundary’:

- *Left boundary*: Final purchased energy (e.g., gas or grid electricity);
- *Right boundary*: Useful energy such as DHW preparation or space heating; and final electrical energy consumption/load (e.g., residential electricity load for lighting, cooking);
- *Upper boundary*: Environmental energy sources such as the sun, ambient air or ground.

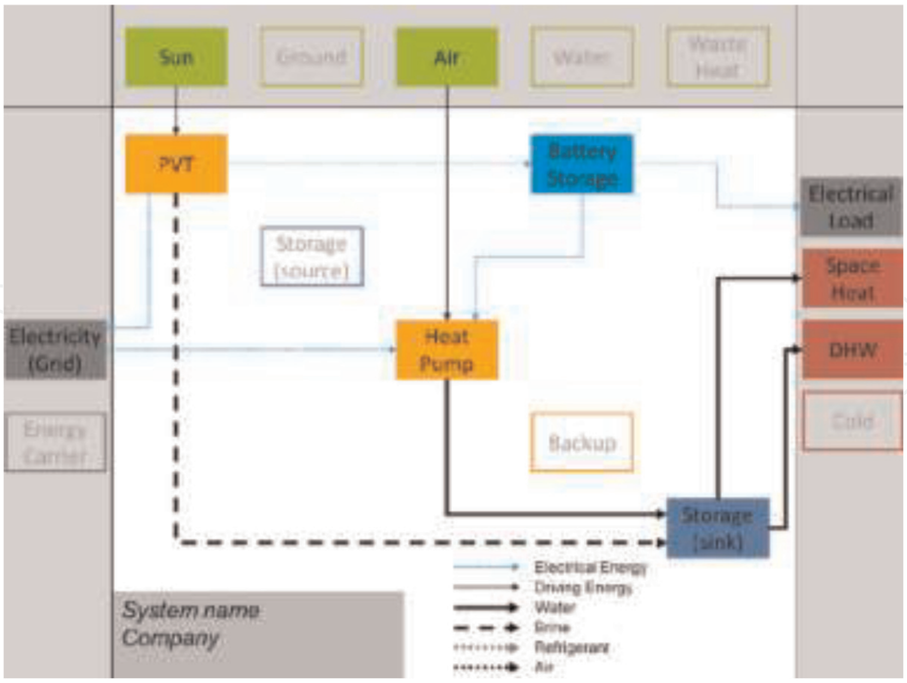

Figure 5.
System "square view" connection diagram, which comprises the system components (highlighted left) and boundaries (highlighted right) [19].

The scheme visualisation is very similar to other energy flow charts, yet it differentiates from previous ones as it has fixed boundaries, positions and colours, which are well defined by 'connection line styles'.

Within the system boundaries, different elements are highlighted (via placeholders) if they take part in the system layout/schematic. In case a specific component is not used, it is also shown in **Figure 5** without any highlight (i.e., no 'connection line styles').

The system components and boundaries have been differentiated by colours, such as Orange for Energy Converters, Blue for Thermal storages, Light Blue (colour also used for electrical energy flows) for Electrical storages, Grey for Final Energy, Green for Environmental Energy and Red for Useful Energy.

The system components are connected by arrows/lines, which represent the system energy flow. As shown in **Figure 5**, six different line styles are used for the indication of:

- Different energy carrier mediums (water, brine, refrigerant or air);
- Electrical energy or other driving energies (e.g., solar irradiation or gas).

1.5 Current state of PVT technology[1]

The past years showed that the PVT market is gaining momentum, especially in European countries, where the highest share of installed capacity of PVT collectors is located. Recently, the exponentially growing number of specialised PVT

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[1] The data presented in this chapter has been acquired from the Solar Heat Worldwide report (2018, 2019 and 2020).

manufacturers that entered the European market, increased the awareness and interest in this technology, which led it to be included in the market survey developed by the Solar Heat Worldwide consortium. The report presented in both 2018 and 2019 included data from the work developed by experts in both PV and ST technologies, who are enthusiastic and share a common passion for this emerging solar technology. A market survey has been carried out under the works made by the IEA SHC Task 60 participants on "Application of PVT collectors."

By the beginning of 2019 (relative to 2018), a cornerstone had been reached of more than 1 million square meters of PVT collectors installed, in more than 25 countries.

The report developed by Weiss and Spörk-Dür [20] presents the global market developments and trends in 2019 of PVT solar collectors, in which the total area installed is around 1.167×10^6 m^2 (e.g., 675×10^3 m^2 in Europe, 281×10^3 m^2 in Asia, 134×10^3 m^2 in China and 70×10^3 m^2 for the rest of the world). Overall, it accounted for 606 MW$_{th}$, 208 MW$_{peak}$ of the total installed capacity, which was provided by 31 PVT collector manufacturers and PVT system suppliers from 12 different countries.

Within the countries with the highest capacity installed, France has to date around 42%, South Korea 24%, China around 11% and Germany with roughly 10%. The market for PVT collectors registered a significant global growth of +9% on average in 2018 and 2019. This trend was also observed in the European market with a slightly higher growth rate of +14%, which corresponds to an increase of the annually new installed thermal and electrical capacity of 41 MW$_{th}$ and 13 MW$_{peak}$, respectively [2].

Unglazed (also known as uncovered) water collectors are the most disseminated PVT technology with its largest market share of around 55% followed by air collectors (43%) and covered water collectors (2%). Evacuated tube collectors and low concentrator PVT play only a minor role in the total number of PVT installed capacity.

PVT technology suppliers commissioned at least 2800 new PVT systems worldwide in 2019. The number of PVT systems in operation at the end of 2019 was 25,823, of which 3296 uncovered PVT collectors were in operation, corresponding to a gross area of 667×10^3 m^2. Out of these systems, solar air (pre)heating and cooling for buildings has almost 86% of the PVT installations, trailed by DHW for single-family households with 7% and finally followed by solar combi-systems (e.g., for DHW, space heating, multifamily houses, hotels, hospitals, swimming pools, and district heating) with just 7%.

In a global context, solar air systems (i.e., including PVT air collectors) have the highest share of the PVT market, with the majority of the installations being located in the French market.

1.6 PVT collectors state of art

Previously, PVT collectors have been classified according to their design, either as flat or concentrating PVT collectors, therefore, the literature overview in the following chapter is strongly focused on the current PVT solar collector state of art.

Glazed liquid-based HTF PVT collectors aim at replacing conventional solar thermal collectors given the similarity between systems and operating temperature range. Zondag [7] expects these types of PVT collectors to overcome the challenge of temperature stability reaching higher shares of the solar market. Moreover, Zondag [7] expected that researchers would focus on temperature-protected PVT collectors with overheating protection, which was the aim of the work developed by Lämmle [6].

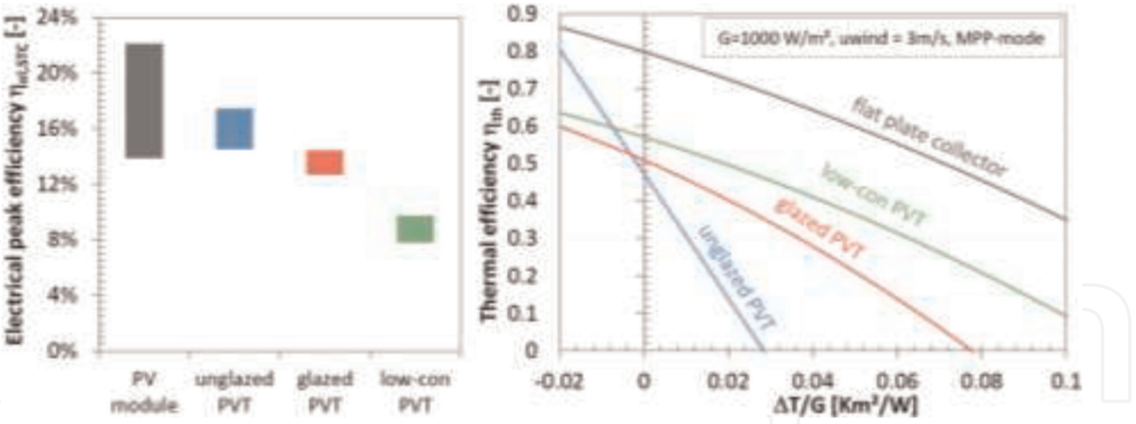

Figure 6.
Comparison of the electrical and thermal efficiency of best of market unglazed, glazed, and low-concentrating PVT collectors. Efficiency related to aperture area (provided by Manuel Lämmle and presented in [6]).

There are several commercially available concentrating PVT collectors, such as the stationary low concentrating PVT from Solarus and the line focusing PVT that was introduced by Absolicon AB and SunOyster Systems GmbH.

The motivation behind liquid-based concentrating PVT collectors is to replace the conventional thermal absorbers and at the same time decrease the amount of active PV area by applying cheaper reflectors. The reduced active PV cell area decreases the overall radiative heat losses due to the reduced hot surfaces. Stationary low concentration factor solar collectors (typically below 10 suns) do not reach temperatures higher than 120°C [9], as they do not need the use of tracking systems due to their relatively high acceptance angles [21].

Lämmle [6] made a direct comparison between ("the best PVT collectors in the market") unglazed (from MeyerBurger) and glazed (from EndeF) flat-plate PVT, low concentration (from Solarus) PVT, and a standard PV and ST module, to assess the current state of both thermal and electrical performance of the available PVT collectors. The results have been presented in the following **Figure 6**.

The thermal peak efficiencies range from 48% (for unglazed PVT) up to 53% (for the CPVT). These values fall below the 80% for standard flat plate solar thermal collectors due to simultaneous electrical generation (i.e., the fraction of incident solar radiation is directly converted into electricity), lower absorptance and higher emittance of the receivers (i.e., higher reflection losses), in most cases, a higher thermal resistance between the PV cells and the HTF.

On the other hand, both unglazed and glazed PVT collectors can compete with thin-film PV modules, but not with the high-efficiency mono-Si modules that reach around 22%.

Overall and as stated previously, a higher electrical efficiency leads to a lower thermal efficiency, which reinforces the educated "rule of thumb" that PVT collectors can either be optimised for high electrical or thermal performance.

1.7 Needs for different key actors

To establish a sustainable PVT system market there are needs for improvements on all levels. A market survey has been conducted to address the most relevant key factors for PVT technologies, where the following general needs can be pinned down as:

- Design tools for PVT systems;
- Decreased costs for PVT systems compared to separate PV and ST systems;
- Development of simple and easy to instal PVT systems;
- A complete test standard for PVT like for PV and ST;
- Teaching on all levels, also architects and installers;
- Demo systems with proven performance and reliability;
- Proven building integration designs.

Moreover, different needs for Key Actors are required from a different set of intervenients such as:

Researchers: Development of standards and planning/optimization tools for PVT systems.

Manufacturers: Development of improved PVT system types and prefabricated components for PVT systems, such as PVT panels, heat pumps, storage, etc.

Project planners, consultants, decision-makers, energy planners, property/real-state owners and construction/building contractors: Education on PVT systems and different PVT demonstration systems in different locations followed for many years to document high reliability, high performance and long lifetime of PVT systems.

Installers: Installer education on PVT systems.

1.8 The legal face of PVT solar collectors—European incentives

The PowerUp MyHouse project aims to increase the knowledge and awareness about solar energy applications and in particular about PVT technologies. The project aims to investigate the best technological applications, manufacturing, installation, measures, calculations, legislation, incentives, supports, qualifications, experiments and vocational education related to PVT.

The project has been divided into *PVT Technologies Research*, which aims to present the latest researches done in and out of the European Union (EU) related to PVT technologies. *The legal face of PVT* aims to present legal arrangements on PVT done in well-developed countries such as legislation and incentives. A *Guidebook* in which the project will test a PVT system. Finally, the *learning module on PVT* is focused on vocational training for students in RES.

The PVT technology is still very recent in commercial terms, so the existing legislation is not suitable or does not explicitly contemplate all these types of solar systems. Furthermore, there are not many references about legislation applicable to PVT technology. Thus, given the scarce information on the legal framework for PVT systems, this document addresses this issue at the level of renewable energy system (RES) systems for the production of both electricity and heating, which are widely disseminated.

For PVT systems to have a fair chance compared to PV systems, special high subsidy levels for PVT systems are suggested for the following years. It is estimated that these subsidies might generate a sustainable market for PVT and PV systems.

The O1 output from the EU project PowerUp MyHouse on PVT Technology Research—Best practices report [22] suggests several subsidy scheme principles, such as:

- The subsidy is only paid as long as the system is working and according to how high the energy production is, in €/kWh. This also promotes a sustainable aftermarket for repair and upgrade systems.
- The subsidy level is lowered year by year for new customers, according to the system cost development on the market.
- Early PVT adopters/investors get a contract with a high enough fixed subsidy (in €/kWh), stable over 10 years, to create a more predictable payback time, even when the reduction in system costs and subsidy reductions is fast for later customers.
- The energy meter should be located directly after the PVT inverter, to avoid economic uncertainties, due to local differences in self-consumption.
- If possible, add another energy meter on the thermal side, which can be used with a different lower subsidy level.
- These meter results can also be used to assure and compare system performance and assist companies.

The existing support and incentives, both for $RES_{electricity}$ and RES_{heat}, in the different countries, addressed in this document, are significantly different both in terms of amounts and in terms of the diversity of financial mechanisms. On the other hand, in some cases, there is the possibility that PVT systems are covered by the same supports as one or even both $RES_{electricity}$ and RES_{heat} systems.

In the countries of the EU, the next developments and opportunities in the renewable energy sector depend heavily on renewable energy development plans linked to the objective of reducing greenhouse gas emissions and the fulfilment of the commitments assumed under the Paris Agreement [23]. These renewable energy development plans are governed by two main regulations:

1. The EU Winter Package is a mechanism that aims at smoother the energy transition to clean energy. It defines the main goals for the EU-members for 2030, which tackle the decrease of greenhouse gas emissions, as well as energy efficiency and RES incorporation objectives. The binding goals set for the EU (directly) associated with RES are:
    a. To cut greenhouse gas emissions by 40% in relation to 1990 levels;
    b. 32% of final energy consumption to come from renewable sources;
    c. An increase in the energy efficiency of 33%.
2. The Integrated National Energy and Climate Change Plan. Following the guidelines defined in the Governance Regulation, each European country

government included specific objectives in its respective document. It appears that in some of them they seem significantly more ambitious than those defined by the EU.

In this sense and according to the Solar Thermal World most recent publication [24], the main challenges facing the PVT industrial sector are:

- Policy setting opportunities presented with the New Green Deal in the EU, in which the PVT sector has to be heard with a strong voice to be able to ensure that is not excluded from the debate, as it has been in the past, where, unfortunately, Australia still has no subsidies for RES until 2020;

- In 2020, the Renovation Wave Strategy published by the European Commission aims at improving the energy performance of buildings. It states that significant renovations can lead to noteworthy energy performance improvements up to 60%. Therefore, an opportunity to bring PVT technologies to the front and centre of this initiative by being engaged as a body in this process [25];

- Promising and emerging opportunities have been presented in the 4th Generation District Heating (4GDH) program where lower temperatures (i.e., below 100°C) are being trialled and promoted as the future choice for expanding the decarbonisation of heating and cooling. This significantly enables PVT, when coupled with HP, to play a noteworthy role in distributed and centralised solar solutions [26];

- Seasonal storage provides an opportunity for PVT based systems with the ability to monetize more of the heat generated that may otherwise be lost due to truncated thermal production (i.e., when the customers' summer PVT production exceeds thermal demand);

- The increasing interest in solar cooling can lead the PVT technologies to contribute to these low carbon solutions, by means of heating features during daytime and cooling features during night-time.

Decisively, the Recovery and Resilience Facility aims at supporting reforms and investments undertaken by the Member States, which aids the economic and social impact mitigation of the Covid-19 pandemic. Moreover, these programs tend to strengthen the European economies and societies by means of a more sustainable, resilient and better prepared economic and social structure to combat the challenges and take the opportunities of the green and digital transition.

However, for the PVT technology to grow significantly outside its market niche, amongst other necessary actions, it is recommended to take the following measures [27]:

- Players must develop clever and fair support schemes for PVT collectors and systems, present them to governments around the world, and request their implementation. After all, the PVT sector does not receive nearly as much support as the PV or solar thermal industry.

- Enlarging the knowledge of architects, planners and installers about PVT solutions. This should be helped by the fact that PVT is more efficient than just PV and is an attractive alternative to air and ground heat pumps.

Moreover, and following the previously stated incentives for solar systems, the European Union's Horizon 2020 research and innovation program leads the incentives for funding these types of solar technologies, such as the RES4BUILD, which develops RES-based solutions for decarbonising the energy use in buildings (e.g., new or renovated, tailored to their size, type and the climatic zones).

The project adopted a co-development approach, in which all the intervenients are involved in a dynamic process. Moreover, and in parallel, a full life cycle assessment (LCA) and life cycle economics (LCE) analysis are carried out, which aims at presenting the real impact of each proposed design. The diverse consortium and the dedicated exploitation tasks will connect the project with the market, paving the way for a wide application of the developed solutions.

Furthermore, the European Union's Horizon 2020 research and innovation program also provided financing for the development of PVT systems like the one presented by the RES4LIVE consortium, which adapts RES technologies, machinery and their demonstration at a large-scale on farm level. It requires supporting measures concerning spatial planning, infrastructure, different business models and market organisation, trends that are not all under control from a farmers' perspective.

The RES4LIVE project aims at fitting livestock farming with attractive costs, operational flexibility and low maintenance. The key technologies include integrated heat pumps, PVT solar collectors, PV panels, geothermal energy, electrification of on-farm machinery and biogas to be replaced by biomethane to fuel the retrofitted tractors.

Moreover, the PVT technology will be preferably installed on rooftops without occupying agricultural land. Focus on the collector mounting, piping and installation procedures to reach standardised solutions for livestock farming through (1) reducing the PVT system installations costs by more than 40%, and (2) by simplifying the installation process, to be handled by non-specialised technicians.

2. Conclusions

Due to the combination of both PV and ST technologies in the same gross area, PVT technologies employ the benefits of cooling the PV cells, thus increasing their overall efficiency, and thus using this excess heat to increase the HTF temperature of a solar thermal system.

Cabral [2] showed that PVT technologies have the potential to be a viable solution to compete with isolated systems such as PV and ST solar collectors if a significant reduction in manufacturing cost is achieved, coupled with an increased energy production performance. Therefore, its success is intensely linked to the capacity of the PVT industry/researchers to scale down its current system cost and complexity in a way that can shorten the cost/performance gap between both PV and ST technologies. PV and ST technologies have several decades of constant development; especially the PV industry with an exponential performance increment and constant decrease in material costs has been registered in the past decades.

Additionally, a bifacial PVT receiver comprising PV cells, which are high emitters, could potentially be equipped with a selective surface (i.e., between the PV cells) to increase the thermal energy yield through higher thermal efficiency.

The global production of silicon-crystalline-based PV modules typically entails a significant consumption of fossil fuels, which increases the dependence on non-RES sources. Conversely, the production of PVT collectors requires less energy. Other ways to increase useful thermal power at higher temperatures might rely on low-emissivity coatings either on top/bottom of solar glass covers or on top of the receiver core.

However, further studies are required to reduce reflectance and absorptance losses in the coatings. On the other hand, limited suitable highly transparent low-emissivity coatings are commercially available, which might limit a wider deployment of low-emissivity coatings in PVT collectors.

Furthermore, PVT technologies, in theory, allow the end-user to benefit from both feed-in tariffs and renewable heat incentives (RHI), due to the simultaneous production of electricity and heat. For DHW systems, in the UK, PVT technologies only benefit from the feed-in tariffs. However, for non-DHW systems, PVT technologies benefit from both incentives, which decreases the payback time.

In addition, the financial attractiveness concerning manufacturing and indirect costs can be improved by providing complete solar solutions with pre-configured packages of PVT collectors and auxiliary heating systems that facilitate the end user's decision. Moreover, the architectonic integration of PVT technologies into the building envelope offers a combined solution for both electricity and heat production while requiring less installation area.

An operational PVT system falls short in heat production when compared with a separate PV + ST system, which produces the majority of heat for DHW in the summer months. Whereas, in the winter months, when the required amount of DHW is not met, a backup system is required such as a heating component (i.e., boiler). This issue is also seen in ST systems, thus PVT technologies by also supplying electricity are on the verge of potentially being competitive, as PVTs are, at the core, ST collectors that can produce electricity from the same gross area. Therefore, it makes the future of PVT technology strictly reliant on the future of ST technologies, which rely on energy efficiency, durability and reliability aspects of a collector development.

The current global transformation of energy systems based on fossil fuels to RE systems lies predominantly on a high share of electrical power generation. The aim of reaching the required share of heating and cooling via power generation by the end of this century seems unrealistic with today's progress, which will require sustainable solutions such as ST and therefore PVT collectors.

The electrical storage trend is already ongoing through electrical batteries; nonetheless, heat tends to be easier, cheaper and environmentally friendlier to store than electricity, as it already gave real proof of its maturity and efficient reliability. In this way, PVT technologies have an opportunity to increase their market share, not neglecting permanent developments, both in terms of performance and in terms of cost reduction.

The high share of greenhouse gas emissions in the heat sector requires severe and methodical decarbonisation by a balanced technology mix, in which ST and PVT technologies must be considered, as it is crucial to achieve the already proposed goals in several environmental agreements.

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Acronyms and abbreviations

BTES	Borehole thermal energy storage
BTES	Building thermal energy storage
CdTe	Cadmium telluride
CPVT	Concentrating Photovoltaic-Thermal
CIGS	Copper indium gallium selenide
c-Si	Crystalline silicon
DHW	Domestic hot water
EU	European Union
EVA	Ethylene-vinyl acetate
HP	Heat pump
HTF	Heat Transfer Cooling Fluid
LCA	Life cycle assessment
LCE	Life cycle economics
MFH	Multi-family house
PV	Photovoltaic
PVT	Photovoltaic-thermal
PV + ST	Photovoltaic and solar thermal system combination
RE	Renewable energy
RES	Renewable energy systems
RHI	Renewable heat incentives
SFH	Single-family house
SDH	Solar district heating
ST	Solar thermal

Appendices and nomenclature

t_c	Cell temperature [°C]
β	Coefficient of temperature [°C/%]
A_c	Collector gross area [m^2]
I_{mpp}	Current maximum power point [A]
η_{el}	Electrical efficiency [%]
a_1	First-order heat loss coefficient at (tm—ta) = 0 [W/m^2 K]
η_{opt}	Optical efficiency [%]

η_{PVT}	PVT overall efficiency
T_{ref}	Reference temperature [°C]
G	Solar irradiance (global) [W/m^2]
a_2	Temperature dependence of heat loss coefficient [W/m^2 K^2]
$\eta_{opt,theo.}$	Theoretical optical efficiency [%]
η_{th}	Thermal efficiency [%]
Q_{th}	Thermal power [W]
V_{mpp}	Voltage maximum power point [V]

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