Photovoltaic Thermal Technology Collectors, Systems, and Applications

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Photovoltaic thermal (PVT) technology has been drawing attention recently. Electrification of the heating sector with heat pumps run by carbon-free electricity sources like photovoltaics is setting the ground for the interest. This article gives insight into PVT technologies and collector designs according to application and operating temperatures. For most conventional designs, examples like prototypes from Research & Development projects are presented. In addition, commercial products are listed along these categories, and the influence on the gross thermal and electrical yield is depicted based on Solar Keymark certification data. The process of certification is presented in a comprehensive way, showing current limitations, giving an outlook on the most recent approach for enhanced procedures and specifications. Finally, different system layouts are presented, and examples from installations combined with a heat pump are given with their specific performances. Real performance data of several PVT installations are compared to conventional heat pump systems. The identified seasonal performance factors are in a range from 3.4 to 4.2 and in between air source and ground source heat pumps. Continuous monitoring and derived data are enablers to discover the decisive influence of the system layout and dimensioning on performance indicators like, for example, operating temperatures over the year.

1. Introduction

Photovoltaic thermal (PVT) collectors and more specifically PVT-based heating solutions are with 13% in 2022 a fast-growing innovative technology in the heating and cooling sector right now.[1] The variation of technical system solutions covers a wide range of product designs. Market development penetrates more fields of application, and a growing number of manufacturers is providing respective products and components. This article is reviewing those developments in a systematic way, by sorting along application, indicating design patterns respectively. Also, the systemlevel solutions are reviewed, showing the hybridization of renewable energy sources and conversion of multivalent heating and cooling systems based on PVT. Innovations fostering those market developments in simulation and planning tools and the relevant models and codes are a part of the analysis, too. Finally, the quite complex questions of market penetration in regard to fair competition, standardization, and certification are discussed.

PVT technology combines the conversion of solar radiation into electricity and heat using one product. The functionality is derived from basic physics and the consideration that the bandgap of photovoltaics semiconductors can absorb only a limited part of the solar radiation. In the p–n junction, this part is converted into electric energy, while the remaining part of the solar radiation spectrum is transmitted through the solar cell.[2] **Figure 1** shows the relations of the energy conversion and phenomena on a classic silicon-based photovoltaic model's average. Plotting the energy intensity of the wavelength-dependent spectral irradiance in W m^{-2} over the wavelength from 300 to 2400 nm, the orange area indicates the heat gains potential while the blue area indicates the electricity gains potential. On the covering surface there will be optical losses due to reflection caused by the change in refractive index from air to the cover material. In addition, losses result from convection losses and radiative losses of long-wave radiation summarized as heat losses.

To activate the energy potential, the design of the product must feature an electrical layout to provide a connectable electrical current as well as a hydraulic layout to connect the heat transfer fluid, too. While the design for the electrical current is with most products solved using strings and bars, as it is used in standard cell connection technics of photovoltaics modules,[2] the transport of thermal energy is often the new design aspect. The heat extraction and energy transport need to take place in perpendicular, transversal, and longitudinal dimension of the product which is the essential design focus of a PVT collector. **Figure 2** and **3** show the dimensions in an exemplary drawing in a flat plate design. The perpendicular energy transfers within the layers of materials laminated together. The transversal energy transfers from the maximum distance between two heat transfer fluid pipes (risers) into

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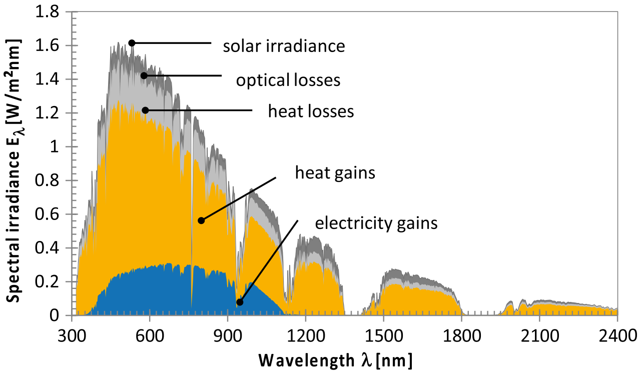

Figure 1. Spectral utilization of the solar spectrum by a PVT collector harnessing heat and electricity. Reproduced with permission.[46] Copyright 2020, Manuel Lämmle.

the heat transfer fluid (half a fin) and alongside the flow of the heat transfer fluid longitudinal. Several material heat conductivity and heat transfer resistances must be overcome. In the direction of fluid flow (longitudinal), the hydraulic layout must keep the heat extraction homogeneous and at low pressure drop (meaning frictional losses by pumping the fluid). The interaction of extracting heat from photovoltaic cell array is an important design aspect of the thermal and electrical energy management of a PVT, especially paying attention to connection boxes, microinverters and edge effects. That is why it is most relevant to bring together experiences from manufacturing and designing of photovoltaic modules and thermal collectors for an optimized PVT.

To orientate looking at the technology of PVT, application design patterns and mean operating temperature levels are of great importance. **Figure 4** shows the range of typical operating temperatures for the market-available applications of PVT solutions.

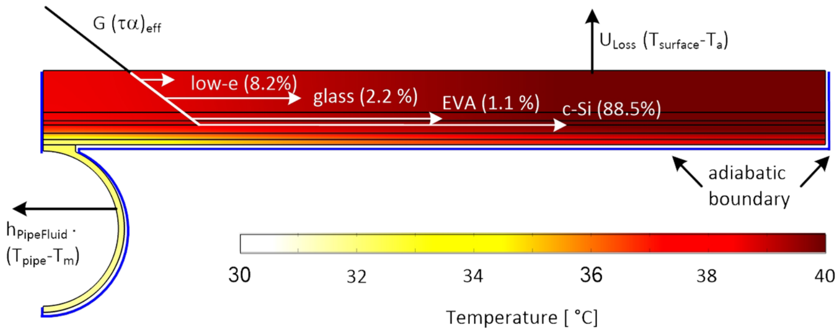

Figure 2. Cross section of direct laminated sheet and tube PVT absorber showing the optical gains and the internal temperature distribution from FEM simulations. Reproduced with permission.[16] Copyright 2018, Manuel Lämmle.

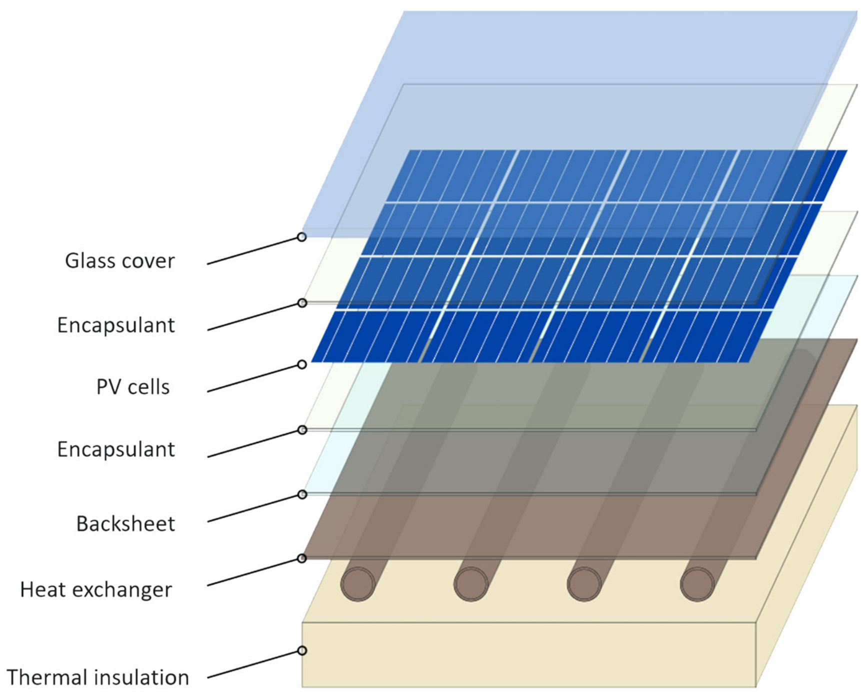

Figure 3. Schematic drawing of a PVT collector with its main components. Reproduced with permission.[8] Copyright 2020, IEA Solar Heating and Cooling Technology Collaboration Programme.

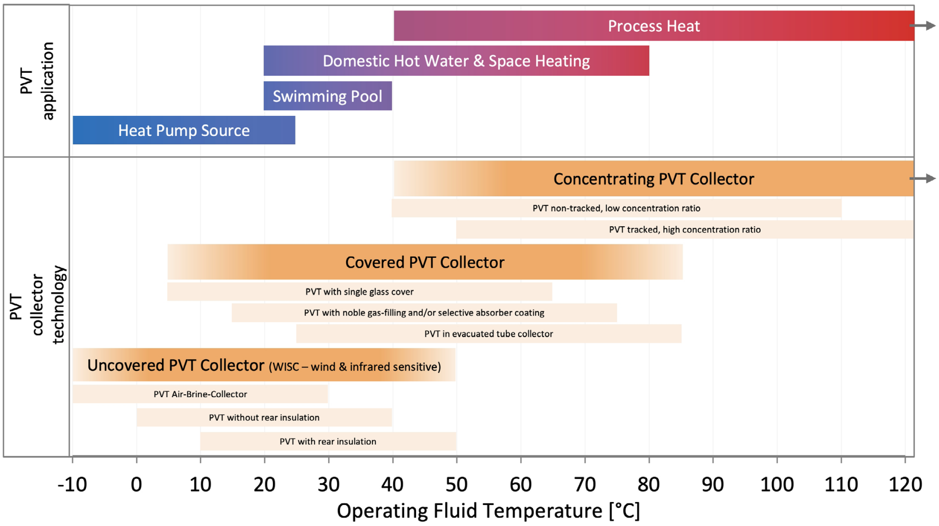

Figure 4. Applications of PVT collectors and suitable PVT technologies per corresponding temperature range as suggested by an expert survey. Adapted with permission.[16] Copyright 2018, Manuel Lämmle.

Following the average mean operating temperatures of the PVT collectors' array of the system, it becomes obvious that there are design patterns which are suiting some applications better than others and there are even limits of providing energy with some designs to specific applications. The applications shown in the upper part of the picture cover most of the recent applications of PVT.[3]

Though in the market examples of all the design forms mentioned exist, there is a clear dominance by WISC PVT products.[3] The reasoning for that might be in the easier use of standard PV modules for low-temperature operations as some materials of standard PV have a temperature restriction already around 85 °C. An essential aspect is later described in Framework. The focus of the article is therefore on those wind- and infrared-sensitive (WISC) PVT designs, which has or does not have an extended heat exchanger surface to the ambient air. To understand the operation of those products better, **Figure 5** shows the different potential operation modes.

The graph differentiates the operating temperature conditions for the temperature of the collector fluid:1) below dew and freezing point; 2) below ambient; and 3) above ambient.

The redline in the graph describes the qualitative efficiency curve of the thermal performance of a PVT collector at an irradiance of 1000 W m^{-2}.

In condition (II) and (III), one can expect a classic performance behavior as known from a solar thermal collector.[4]

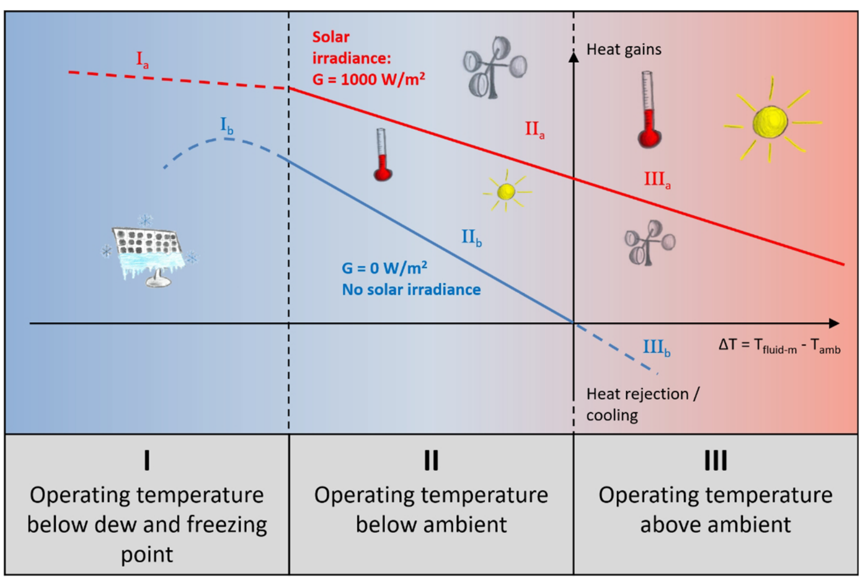

Figure 5. Presentation of different operating modes of PVT collectors. Reproduced with permission.[26] Copyright 2020, IEA Solar Heating and Cooling Technology Collaboration Programme.

Influences from ambient conditions such as wind speed, radiation, ambient temperature angular radiation, and capacity can be described by a classical model for collector efficiency curves.[5] Following the red curve, the conversion of energy from the ambient temperature is assumed to be lower in comparison to the solar energy in (II), showing that an effect in (I), respectively, is not existent in (III).

In (I), the collector temperature is lowered under dew point, leading to condensation on the surfaces. That might be in the collector box or on an outward orientated surface. If the operating temperature lowered further, lower than freezing point, the condensate starts to freeze to ice. Because of the isolating function of the ice layer, the growth of that will be limited and no further energy exchange to the surrounding is to be expected. Those effects are not covered by the recent ISO standards. Nevertheless they were content of research projects and proposals how to take them into account are available.[6] The blue curve in the graph describes the qualitative efficiency curve of the thermal performance of a PVT collector at an irradiance of 0 W m^{-2}. In condition (II), we find the explicit new functionality of such collector designs. The surfaces of those PVT collectors transfer energy from the ambient to the heat transfer fluid, to provide useful heat. This functionality is pivotal for the extra operation hours in the context of a heat pump source over a classical solar thermal collectors' application. Depending on the design, the efficiency curve for this functionality varies strongly.

In condition (III), the collectors' surface is warmer than the ambient, therefore dissipating heat energy to the ambient. This can be useful in case of a cooling need. Some products activate this functionality in their systems' configurations.

In (I) for the blue curve, the same effects as described for the red curve in section (I) apply. Condensation down to freezing will take place and intrinsically end at some under cooling temperature. Besides avoiding those operation conditions in system configurations by control strategies, there is the potential for using these operation conditions to "harvest" water from the air. This was studied for example in a complex system configuration with concentrating (CPVT) collectors.[7]

It is obvious that depending on the application a suitable design pattern must be selected. With doing so, system configuration can be designed which operates the respective PVT collector in the dedicated operation conditions.

The following section gives a specific overview of how in the collector design "form follows function". The integration of those into heating system configurations is explained in the next section.

2. Components

Different designs of PVT collectors (WISC, covered, concentrating) are discussed in this section by means of schematic drawings and typical layouts with their implications on material choice and suitable applications. In addition, for each design, a specific PVT model which has been implemented at Fraunhofer ISE is presented.

According to their structure, PVT collectors can be divided into four different categories, which is WISC, covered, evacuated, and concentrating type, compare **Figure 6**. A good survey of the types and their implications on design demands and material choice is given in ref. [8].

2.1. WISC PVT Collector

A WISC or uncovered/unglazed PVT collector is the simplest design and consists of a PV module with a heat exchanger attached (**Figure 7**).

The connection between PV panel and heat exchanger can be glued, laminated, or mechanically fixed. Good and longlasting thermal contact is essential for efficient use of solar heat. Direct lamination of the heat exchanger is a possibility, which promises a good thermal bond with high durability. PVT collectors supplying low-temperature heat for heat pumps usually come without insulation at the back side; some types rather use a surface extension, for example, metal lamella[9,10] as well as the PVT example shown in Section 2.1.1.

The operation temperature range of WISC PVT, especially if coupled with a heat pump for central Europe, is between −20 and +50 °C. As the operation temperature is in the same range as for PV installations, standard PV panels and materials, like EVA polymers for encapsulant and back sheet, can be used. For the same reason, the heat exchanger and piping can be made of polymer, and there are no requirements of withstanding fluid pressure over PN 6 and vapor, as operation is always below evaporating temperature of water-based heat transfer fluids. For further details on materials used in the PVT layers and technical requirements, see ref. [8].

Popular variants of this PVT category include collectors for air or water/glycol mixtures as heat transfer fluids, back sheets made of glass or polymer and heat exchangers made of polymer or metal, fixed mechanical or by gluing. The back side of PVT can be insulated, noninsulated, or even equipped with a surface extension by lamella or similar.

Besides the harvest of low-temperature heat, these PVT collectors can also be used for dissipating heat to the ambient

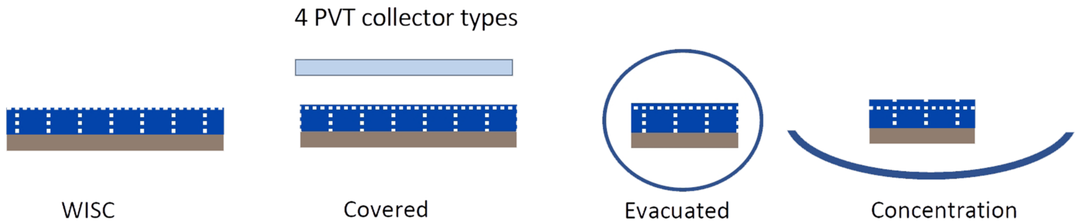

Figure 6. Scheme of categories of PVT collector types. Reproduced with permission.[8] Copyright 2020, IEA Solar Heating and Cooling Technology Collaboration Programme.

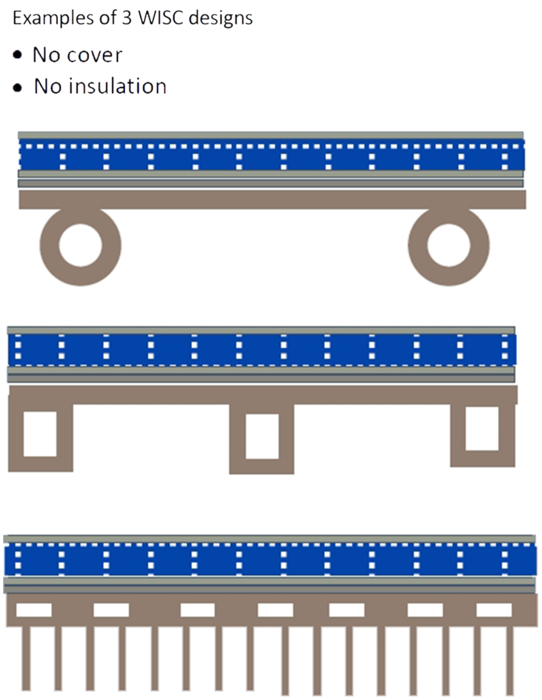

Figure 7. Examples of PVT WISC designs. Reproduced with permission.[8] Copyright 2020, IEA Solar Heating and Cooling Technology Collaboration Programme.

(convective or radiative) for cooling applications, preferably during night-time.

Uncovered ISE R&D Prototype

The following PVT collector was designed to serve as a monovalent heat source for a compression heat pump, delivering heat for space heating and domestic hot water (DHW) in a residential building. In this case of application in a configuration without heat storage, the PVT collector must provide low-temperature heat day and night, with a maximum demand during wintertime. According to these requirements, the extraction of heat from ambient air plays a crucial role in the system operation and is in the focus of the collector design. The specifications of the PVT collector comprise optimal thermal coupling between ambient air and heat exchanger, good heat transfer to the fluid even at low temperatures, and sufficient solar efficiency, setting priorities in the same order.

These specifications led to design of the heat exchanger with aluminum lamella, to maximize the interaction surface with the ambient air, a full-faced flat tube microchannel absorber to supply as much fluid contact area as possible, and a glued contact to the PV panel (**Figure 8**). All metal contacts have been soldered for optimum heat transfer from the ambient air to the fluid.

The PV panel used is an Almaden B72T double-glass module with 370 W_p electric power and size of $1980 \times 990\,mm^2$. This module type has been chosen due to its bifacial configuration with small-sized junction boxes placed near the edges of the module. As the PVT collector type was built for characterization and technical demonstration, only a facile framing consisting of extruded aluminum profiles was built for proper handling of the PVT collector (**Figure 9**).

Those products are designed for monovalent supply of heat from –20 to +25 °C. The temperature is used directly for heat pumps, regeneration of ice storage, or boreholes. Advantages of this PVT design over standard ambient air heat exchangers for heat pumps are the use of solar thermal energy surplus to the extraction of heat from ambient air and therefore sufficient thermal power with and without solar irradiation. Due to extended heat exchange areas (lamella) and availability of multi-use roof area, low-temperature gradients air/fluid are sufficient. Compared to a pure PV installation, it slightly enhances electric efficiency, if heat is extracted during times of high levels of solar irradiation. By the area-based design, no active air ventilation is needed; therefore, energy efforts and noise emittance for fans are eliminated. In addition, no energy for de-icing is necessary. In the case of installations in snow-rich areas, a melting function can even prolong the solar operation hours. By design those PVT collectors are limited to maximum temperature (≈85, 25 °C operating temperature, respectively (see also Figure 5)). The

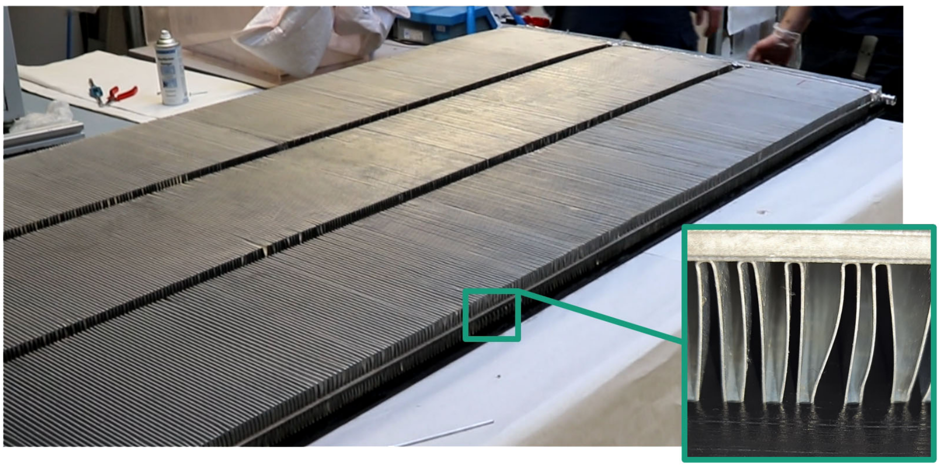

Figure 8. PVT collector prototype during the assembling: the zoomed part shows the aluminum lamella with the PV panel rear side covered with black adhesive. Reproduced with permission.[31] Copyright 2022, Fraunhofer ISE.

Figure 9. Finalized PVT collector prototype during characterization mounted on a solar test facility at the TestLab Solar Thermal Systems. Reproduced with permission.[31] Copyright 2022, Fraunhofer ISE.

supporting information shows a list of providers of collectors in this design family. For the uncovered PVT, there exist several variations of the collector design as can be found.[3,11] The variations distribute to following categories.

Photovoltaic Technology: The major share of PVT collectors is using crystalline silicon PV cells, with a bigger share of monocrystalline silicon compared to multicrystalline. Some installations are combining flexible thin-film PV stripes, like CIGS-based with customized roof-integrated heat exchangers.[12] In a research project, organic PV has been adapted to a PVT absorber for preparation of DHW in an integrated storage collector concept. Organic PV has the potential to be produced with minimized resources and carbon footprint as well as at lower costs compared to conventional silicon-based PV. The polymer absorber combined with the organic PV followed the same trend.[13,14] So far, durability and efficiency of organic PV solutions have not shown sufficient results for a successful market entrance.

Heat Transfer Fluid: The most popular version of PVT collectors and systems is operated with water/glycol brine as antifreeze liquid, especially when operated with heat pumps. For Mediterranean climate, even water without freezing protection is an option. Air as heat transfer fluid for PVT can be a good combination with roof-integrated PV systems.[15]

Rear Side of the PVT: The biggest share of commercial uncovered PVT allows for energy extraction from ambient air into the PVT absorber, which is therefore labeled as noninsulated. Insulated rear side design possibly has some advantage if operated above ambient temperature with irradiation, for example, pool heating.

2.2. Covered PVT Collector

The covered (or glazed) PVT collector comprises the components of an uncovered PVT (PV module, heat exchanger) plus additional front glazing and rear side insulation to reduce heat losses, integrated in an casing (**Figure 10**). The structure is like conventional solar flat plate collectors.[3]

The operation temperature range of covered PVT is typically from ambient temperature to 85 °C (related to Figure 3). For stagnation conditions, temperatures of 150 °C and above can be reached depending on the quality of front/rear insulation.

This implicates some thermal stability issues for the materials of the PV panel, especially for encapsulant, junction boxes, sealing compound, and cables, which usually are not validated for temperatures above 85 °C. For layouts which target good efficiencies at high operation temperatures, technical solutions for overheating protection by venting or similar have been developed and tested.[16,17]

Contrary to the uncovered PVT, a water-based heat transfer fluid will evaporate during stagnation, defining the requirements regarding draining of fluid and pressure resistance of the heat

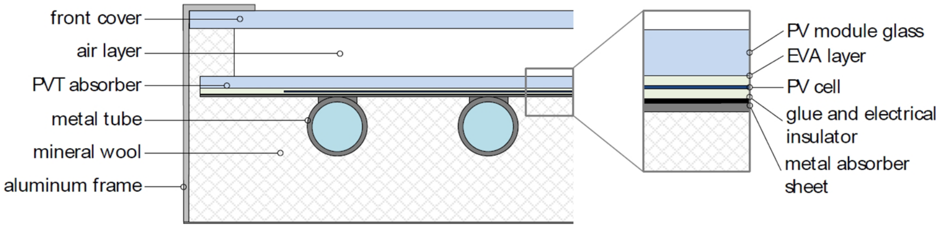

Figure 10. Schematic drawing of a covered PVT collector with layers of the module/absorber. Reproduced with permission. [16] Copyright 2018, Manuel Lämmle.

exchanger and piping, which are the same as for solar thermal collectors.

On the contrary to solar thermal collectors with selective absorber coating, the heat losses due to infrared radiation emission on the front side of the covered PVT panel limit the thermal efficiency in the upper-temperature range, if no engineering measures are taken.

Besides double glazing and inert gas filling, the use of low-emissivity (low-e)-coated glass for the front cover can reduce thermal losses arising from radiative emission significantly.

Covered ISE R & D Prototype

The following PVT prototype (**Figure 11**) was designed and assembled in the R&D project PVTmax.[18] It was built by EVA lamination of 32 (4 × 8) monocrystalline photovoltaic cells onto an aluminum absorber of 0.5 mm covered by a solar glass layer. The absorber tubes of 8 mm copper were laser welded to aluminum and designed as meander with ten bends and 77 mm fin distance. The rear side insulation was made of 40 mm glass wool; the frame of wood is covered with aluminum sheets. The outside dimensions of the collector are 1389 × 750 × 80 mm with an aperture of 0.92 m^2 and 0.77 m^2 covered with PV cells to avoid shading losses by the frame reducing the electric performance. The front glass of the collector is a commercial Centrosolar HIT 2S C+ of 3 mm thickness. The low-e coating (silver) was applied on top of the glass covering the PV cells (position three). Thus, the emissivity at 373 K was reduced to 0.13, with a good transmission value of 0.87 for the Si-PV spectrum or 0.79 for the overall solar spectrum AM1.5.

The thermal performance of the PVT collector with low-e coating compared to an identically constructed collector without coating is given in **Table 1**:

Those products are designed to be operated like a solar thermal collector. Therefore, the operation temperature range is from ca. ambient to up to 85 °C fluid temperature. Advantages of this PVT design toward a classic solar thermal collector are to provide electric energy from the same area using factor surplus to direct useable graded heat at hot water and heating support temperature levels. This enables a system level for 100% solar hot water preparation in summer and overall (e.g., in combination with an electrical back-up heating device) a solar fraction

Figure 11. Covered PVT collector with low-e glazing during performance test on the outdoor test rig of TestLab Solar Thermal Systems at Fraunhofer ISE. Reproduced with permission.[31] Copyright 2022, Fraunhofer ISE.

Table 1. PVT collector performance testing results. Reproduced with permission.[16] Copyright 2018, Manuel Lämmle.

Parameter	Symbol	Unit	Low-e	No low-e
Conversion factor MPP	$\eta_{0,\ th}$	–	0.67	0.63
Linear heat loss coefficient	c1	W/m^2K	3.98	6.37
Temperature dependence of heat losses	c2	W/m^2K^2	0.025	0.023

up to 100%. With high solar fractions of course all design aspects of decentralized solar heat supply apply (more can be found in ref. [4]). Interesting future research questions arise from the temperature control option for the PV materials and possible effects on durability because of lower- or higher-temperature exposures. The supporting information shows a list of providers of such products.

2.3. Evacuated PVT Collector

An option to reduce convective heat losses and reach higher temperatures with good thermal efficiency is applying vacuum between the absorber and ambient. Besides the enhanced insulation the vacuum has positive effects on the durability of photovoltaic cells by keeping moisture off and could save expenses for lamination. At the same time this design requires attentive choice of temperature resistant materials and components, as the stagnation temperatures will be higher than for conventional covered PVT. In principle, the vacuum setup could be applied for a flat-plate and tubular design.

Beside some prototypes realized in scientific research projects,[19,20] there is a commercial product available which can be found in the Supporting Information as well.

2.4. Concentrating PVT (CPVT) Collector

In concentrating photovoltaic and thermal (CPVT) systems, direct sunlight is focused on a combined central receiver to generate heat and electricity at the same time.[21] With a global share in 2020 of nearly 100% of the installed thermal capacity, nonconcentrating PVT was the dominating technology produced. CPVT plays only a minor role in the total numbers. Nevertheless, some solar heat for industrial processes installations as well as pilot plants are realized. For detailed information, see another study.[22] Technologically, the concepts range from stationary low-concentration (e.g., Naked Energy, virtu PVT) to tracked low-concentration (e.g., SunOyster or Solarus, C-PVT[23]) and tracked high-concentration systems (e.g., ZenithSolar). A concept of a high-efficiency hybrid high-concentration photovoltaic system has been developed and investigated, see ref. [24]. Reference [25] presents a brief and complete review on the CPVT technology focusing on the fundamentals, concept, design, and test of CPVT solar collectors. The providers are also listed in the Supporting Information.

3. Framework

Currently, PVT collectors in most marketable designs are thermally characterized according to the EN ISO 9806:2017[5] procedure. The electrical key performance indicators and functional, respectively safety tests are in addition defined by a set of standards under the International Electrotechnical Commission. A more detailed overview and analysis can be found in refs. [26,27]. Under standard reporting conditions, this results in thermal characteristic values, as required for the model description of the classic solar thermal collector performance.

But there are limitations for the use on PVT collectors regarding 1) yield without irradiation (operation mode as solar–air heat exchanger), 2) correlation of cell temperature and fluid temperature, and 3) condensation enthalpy/icing at operating points below ambient temperature (for details, please see ref. [6]).

DIN EN 12 975:2022[28] specifies how the thermal and electrical yield for PVT collectors can be calculated. Therefore, it defines: Equation (1): Gross thermal yield (GTY)

$$GTY_{\Delta T}(\mathrm{Coll};\vartheta_{\mathrm{op}},\mathrm{Loc}_{\beta,\gamma},\Delta t)=\sum_{\Delta T}\dot{Q}_{+}(\mathrm{Coll};\vartheta_{\mathrm{op}},\mathrm{Loc}_{\beta,\gamma}(t_i))\Delta t \quad (1)$$

and

Equation (2): Gross electrical yield (GEY)

$$GEY_{\Delta T}(\mathrm{Coll};\vartheta_{\mathrm{op}},\mathrm{Loc}_{\beta,\gamma},\Delta t)=\sum_{\Delta T}\dot{Q}_{\mathrm{el}}(\mathrm{Coll};\vartheta_{\mathrm{op}},\mathrm{Loc}_{\beta,\gamma}(t))\Delta t \quad (2)$$

wherin

$$\dot{Q}_{\mathrm{el}}(\mathrm{Coll};\vartheta_{\mathrm{op}},\mathrm{Loc}_{\beta,\gamma}(t)) = P_{\max}(\mathrm{Coll};\mathrm{Loc}_{\beta,\gamma}(t))\times K(\theta_L,\theta_T) \times(1-\delta\times(\vartheta_{\mathrm{op}}-25\,°\mathrm{C})) \quad (3)$$

In the case of product certification, the results from the standard test are presented in a data sheet. This makes the data transparent to the public, other market participants, the trade, and the authorities. Currently, the thermal yield in defined boundary conditions is reported on page two of the Solar Keymark data sheet. It is proposed to extend this presentation to include information about electrical yield in the case of PVT collectors. Unfortunately, not all products will provide information about the design characteristics which are used in the Equation (1) and (2). Specifically, the heat transfer between cell temperature and mean fluid temperature is often not known. As the temperature of the cell is a needed input an alternative approach is necessary. In the case that this relevant input parameter for the standard equation is not known, a default value could be used which shall be defined by the basic product design category (e.g., 3 K for direct laminate, 5 K for mechanically attached, 10 K for distanced or unknown). Another alternative approach to derive those values by experimental product characterization based on the quasidynamic approach of standard EN ISO 9806:2017[5] was presented by Helmers and Kramer in 2018.[29]

Surplus, the temperature range represented in the data sheet shall be extended to match the operating conditions of PVT collectors. Result values for thermal yield and for electrical yield across the locations (Davos, Würzburg, Athens, Stockholm) should be calculated in the SKN data sheet. For this purpose, a low-temperature level of 0 °C should be added to the temperature range shown. Figure S1 and S2, Supporting Information, show more in detail the operation temperatures occurring in PVT collectors when designed for being a temperature source for the heat pump. It underlines that these low and minus temperatures occur quite frequently to be able to provide enough energy for the heat pump from ambient air.

These are relevant operating points for evaluating performance and should be identifiable in the data sheet. The electrical yields (GEY) should also be indicated at the respective temperature levels. The calculation should follow the calculation rule as defined in EN 12 975:2022,[28] in this article, Equation (2). This calculation is therefore proposed to be implemented in SCEnoCalc. This approach, as clear as it appears, is not without further need for definitions. In the following, this has been applied first time to market-available products. It is furthermore explained what limitations still exist, when interpreting those results.

In **Figure 12**, the thermal yield GTY and the electrical yield GEY are shown on the *y*-axis. They are plotted in temperature intervals represented by the mean temperature of each interval. Here, the chosen *x*-axis does not represent the absolute operating point as the reference temperature of the supplied heat (say at 20 °C outdoor temperature) but the operating point resulting from the relative over or under temperature of the fluid circuit of the collector to the ambient air temperature. Thus, if the sign is positive, there is a solar gain but thermal losses; if the sign is negative, there is a solar and ambient energy gain (which, however, cannot be correctly added as a yield contribution) and no thermal losses. The GTY and GEY are calculated using an adaptation of SCEnOCalc (version v6.2).[30] The boundary conditions of the calculation are: 1) location Würzburg (Longitude −9.95, Latidude 46,80). 2) Orientation of the PVT south, tilt angle 45°. 3) The temperature difference between mean fluid temperature and ambient temperature ($\theta_m - \vartheta\theta_a$) [*K*] has been set to 10 °C, equal to the mean ambient temperature of the location Würzburg. 4) GTY and GEY are calculated for the mean fluid temperatures −10, 0, 20, 40, 60, and 80 K for covered PVT. Where the calculation of WISC is limited to maximum 20 K to eliminate negative GTY results.

As SCEnOCalc keeps the mean fluid temperature constant while the ambient temperature is fluctuating, there are positive contributions to GTY for $\theta_m - \vartheta\theta_a < 0$ K from the ambient, even if there is no irradiation.

The results are presented in bins of 20 K, corresponding to the specified temperature differences between the collector mean temperature and the ambient temperature. Each bin shows the mean value of all GTY simulations (dot) of the products in this category at the corresponding temperature difference, as well as the variance of the simulation results (bars).

The thermal yield is calculated based on the parameter sets describing the performance of PVT collectors under standard measurement conditions. All used data sets and their origin are shown in Figure S4, Supporting Information. It is important to note that the temperature of the fluid during measurement is always higher than the ambient temperature. Therefore, there are always losses from the collector fluid to the environment. The calculated UA value (heat loss) is therefore only suitable to a limited extent for calculating operating situations in which the environment is warmer than the fluid (negative sign). Therefore, only the solar yields are represented in Figure 12. The yields generated by a power input from the ambient air cannot be considered.

This is exactly a shortcoming of the current characterization method. The heat transfer depends strongly on the ventilation of the heat exchanger surface, the radiation, and the thermal conductivity between fluid and environment. Not all collector designs allow this heat transfer path to be reversed. In heat pipes, for example, the reversibility of heat transfer and thus losses/gains depending on the sign of the temperature difference is not given. Ongoing work should improve the method at this point. How difficult it is to grasp that effect as a parameter is

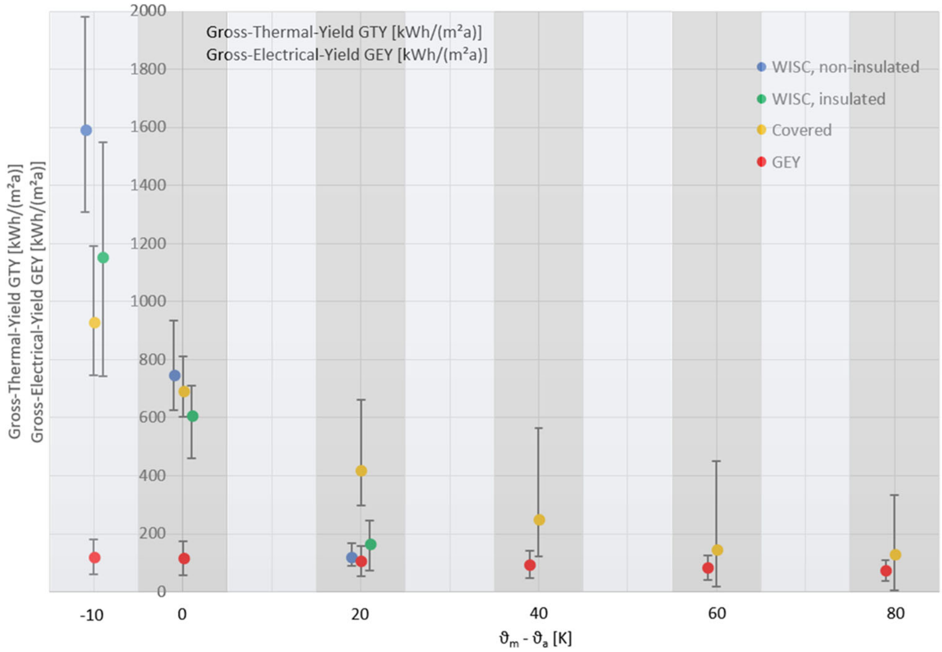

Figure 12. GTY and GEY of market-available PVT collectors as well as design studies shown for covered (glazed) PVT, noninsulated WISC PVT, and backside-insulated WISC PVT.

shown by different investigations on the same product, which show a scattering of UA values from 9.9 to 44 W K^{-1}.[31] At the same time, these collectors achieve very good yields in system monitoring (see Section 4 "PVT systems"). Here it is important to offer the market a differentiation option that represents products in a comparison across the entire application range.

A test sequence that specifically investigates the yields due to thermal energy absorption without irradiation at the collector and maps them with a separate parameter would be an important development step for the differentiated and realistic yield prediction of such PVT collectors. It could be implemented as an extension of test set sequences to the method proposed by Helmers and Kramer in 2018.[30]

Another assumption, which is currently also necessary to select the reference temperature (PV cell temperature) for the electrical yield, is similarly justified. Depending on the design, the heat generated during solar conversion on the cell surface is differently bonded to the heat dissipating fluid as well as the lossy surfaces. This thermal conduction determines the temperature difference of the cell and fluid at a given operating point and thus the energy conversion efficiency.

Both thermal and electrical yield for the operating points are represented by temperature ranges. The mean temperature at which the yield values are shown relates to the temperature difference between mean fluid temperature and ambient temperature. The actual cell temperature present at this fluid temperature is not determined as a numerical value for most PVT collectors. The temperature is still though needed to apply Equation (2). The following assumptions are made; the temperature of the cell is 10 K higher than the mean fluid temperature. The power dependence of the PV cell on the temperature is assumed to be constant with $\delta = 0.5\%\ K^{-1}$. This assumption allows the calculation and presentation of the GEY but again takes away the differentiation. Those assumptions were taken over from the scheme rules of the Solergy Label.[32]

Due to the described assumptions, the informative value for the electrical yield is reduced. However, the information, how much additional electrical yield can be tapped by lowered operating temperatures of the PV cell, by the designed thermal bonding of the fluid, is an important parameter. Here, methodological improvements in characterization would continue to be important (see also Helmers and Kramer in 2018[30]).

As a "state-of-the-art" method of product comparison, the simplified electrical yields are nevertheless shown in Figure 12: GTY and GEY of market-available PVT collectors as well as design studies shown for covered (glazed) PVT, noninsulated WISC PVT, and back-side-insulated WISC PVT to demonstrate that thermal conversion clearly outweighs electrical conversion in a PVT collector. Likewise, it can be shown in the tendency that the scale of the temperature dependence of the thermal yield is much larger than that of the electrical conversion coefficients. Concentrating PVT is not included due to the low availability of reliable performance parameters. The representation of PVT air collectors was also omitted due to the low availability of complete parameter sets and the limited applicability of SCEnOCalc in the case of being open to ambient collectors.

Finally, it is important to mention that at least in the European Union on the system level the Energy Label Class for heat pumps can be improved by the combination with solar thermal as a heat source. The procedure should be extended by representing the source of WISC PVT in a separate column. A respective proposal was made in an internal document toward relevant authorities. More detailed information on the existing methodology can be found in refs. [33,34]. Further improvements can be generated by taking PV self-consumption in the heat pump into account, which is represented by the smart ready test procedure. More potential herewith remains untapped for showing the benefits of thermal and/or electrical energy storage.

PVT collectors are covered by subsidy schemes in many countries as can be studied further in ref. [35].

Work is being done to ensure that the calculation rule is also consistently defined in the application guideline for the Solergy Label.[32] This will ensure a simple and logically stringent representation in the market. From 2022, there is the possibility of a collector label for thermal solar collectors, the Solergy Label. This label assigns an efficiency class to solar thermal collectors. This is highly market relevant as the products are not covered by the EU Energy Label, which ranks efficient use of energy, not energy provided by products. The application rules for this label now also include the possibility of representing PVT collectors. The Solergy Label differentiates application classes (pool heating (low temperature around ≈25 °C; DHW/area heating around ≈25/50 °C as well as heating support ≈50 °C). In addition, the yield values are presented differentiating three climate classes. Currently, this is the most suitable form of presentation in terms of marketing for PVT collectors, **Figure 13** shows an example. More information can be found at the Solar Global Certification Network.[36]

4. PVT Systems

PVT collectors offer a diverse range of applications from low-temperature applications as a heat pump source over medium applications for heat supply in buildings to high-temperature applications in process heat. The mean operating temperature of the PVT system is a good approach to cluster applications, select suitable PVT technologies, and preassess expected thermal and electrical yields. In general, with increasing system temperatures, both electrical and thermal efficiency decrease.[37] With the ongoing electrification of the heating sector, most PVT collectors are nowadays combined with heat pumps. The following table gives an overview of the different hydraulic integration schemes for solar heat pump systems based on refs. [11,38] to explain the system configurations shown in the monitoring results. Often, also a combination of different integration schemes is implemented, for example, a combination of serial and parallel integration to generate both, low- and high-temperature heat. Although the complexity of these systems might increase, it offers the possibility of making optimum use of the potential of the PVT collector (**Table 2**).

4.1. Monitoring of PVT Heat Pump Systems

In a monitoring campaign of Fraunhofer ISE, five plants with PVT collectors and heat pumps have been investigated. While all systems work in single-family homes, different collector technologies are used. The plants are very heterogeneous in their characteristics. Three buildings were renovated, two are new

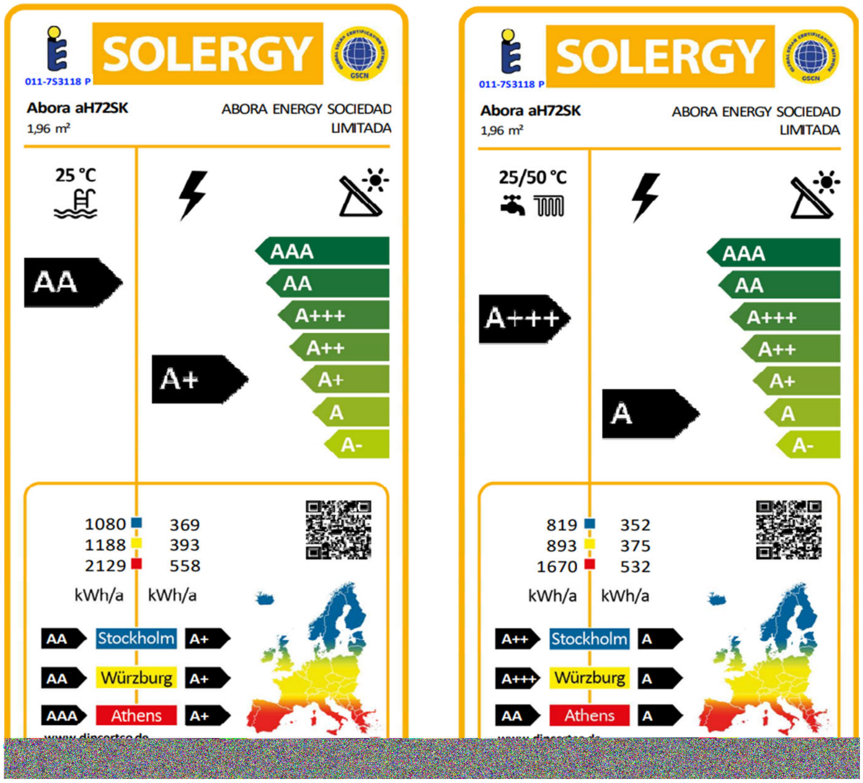

Figure 13. Solergy Label for a PVT product, showing the yearly energy output and the ranked energy efficiency, for electricity as well as for thermal energy conversion. Differentiating the temperature of the application and the climate class for an economic region (e.g., Europe). Reproduced with permission.[36] Copyright 2022, Global Solar Certification Network/GSCN.

Table 2. Hydraulic integration schemes for PVT collectors in heat pump systems.

	Serial Integration [S]	Parallel integration [P]	Regenerative integration [R]
Purpose	Supply of heat to the heat pump source (evaporator)	Direct supply of heat to the application without additional heat pump compression step	Supply of heat to regenerate the heat pump source
Examples	Heat source for heat pump with or without source storage	Domestic hot water (DWH) heating	Regeneration of boreholes or ground heat exchangers
	Direct evaporation	DHW + Space heating (Combi system)	Regeneration of ice storage
	Air pre-heating	Pool heating	Regeneration of source storage

buildings. With two systems, the PVT collector is the only source of heat for heat pump. In the other three plants, a geothermal heat source comes along additionally. In the following, a brief description of the plants is given.

Plant 1 is a renovated building with a heated area of 411 m^2 and a final energy demand of 80 kWh m^{-2}*a. The building has a swimming pool. The plant operates with a buffer tank at the source side of the heat pump. The collectors are WISC collectors. A gas boiler is used as a backup. The building is in southern Germany (**Figure 14**).

Plant 2 is a renovated building with a heated area of 240 m^2 and a final energy demand of 100 kWh m^{-2}*a. The collectors are covered PVT collectors. The plant has an additional borehole with a depth of 390 m. The building is in the Netherlands (**Figure 15**).

Plant 3 is a renovated building with a heated area of 340 m^2 and a final energy demand of 100 kWh m^{-2}*a. The collectors are WISC collectors. The plant has a borehole with a depth of 170 m. The scheme is the same as at plant 2. The building is in southern Sweden.

Plant 4 is a new building with a heated area of 190 m^2 and a final energy demand of 40 kWh m^{-2}*a. The collectors are WISC collectors with an optimized air heat exchanger. The building is in northern Germany (**Figure 16**).

Plant 5 is a new building with a heated area of 310 m^2 and a final energy demand of 50 kWh m^{-2}*a. The plant has an

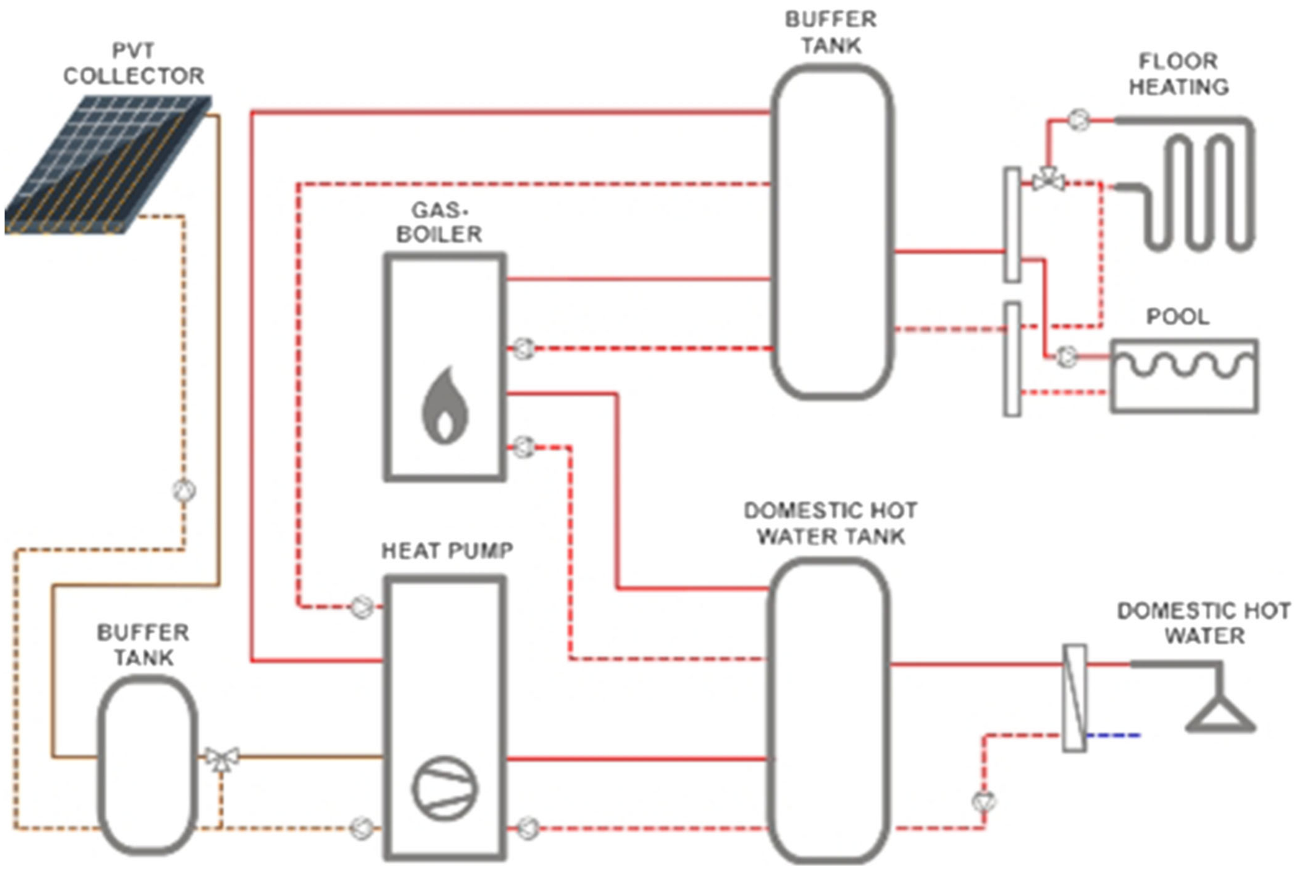

Figure 14. Plant 1. Reproduced with permission.[12] Copyright 2022, Fraunhofer ISE.

additional Earth collector. The PVT collectors are WISC collectors. The building is in central Germany (**Figure 17**).

5. Definition of the Balance Boundary and the System Seasonal Performance Factor

In the following, the balance boundary and the system seasonal performance factor is defined. Subsequently the KPIs of the five plants are discussed.

The plants are evaluated based on the system performance factor SPF (seasonal performance factor before storage = SPF_bST). The following figure shows the energy flows which are considered in the SPF (**Figure 18**).

On the thermal side, the energy which is provided to the buffer tank(s) for DHW and space heating is considered. This energy can either be provided by the heat pump, by the heating rod, or by the PVT collector. The electric energy which is considered for the calculation of the SPF is for the heat pump (compressor and controller), backup heater, and the brine pump(s).

The five plants are equipped with heat meters and electricity meters to measure the energy flows and the temperatures mentioned above. Ambient conditions such as temperature, humidity, and global irradiation are measured additionally. The systems are evaluated regarding the efficiency of the heat pump heating system. For this purpose, the SPF as defined in the following is used. **Figure 19** shows the seasonal performance factor of the five examined plants sorted in descending order of the SPF. The period under review runs from January to December 2022.

The SPF_bST is indicated as a green column referencing the left side y-axis. It reaches from 4.2 at plant 5 to 3.4 at plant 3 for the period under consideration. Next to the green column there is a stacked column. This column shows the share of the electrical energy demand of the compressor (yellow), the primary pump(s) (grey), and the backup heater (black) in relation to the total electric energy consumption of the heat pump (compressor, controller, primary pumps, and backup heater) referencing to unity on the left-side y-axis. The energy demand of the secondary pumps is not considered in this investigation.

At plant 5 the share of the compressor is at 89%, while the brine pump and the controller of the heat pump consume 11% of the electrical energy. At plant 4 the compressors' energy demand is at 79% and the brine pump and controller at 13%. Plant 4 is the only plant where the electrical backup heater was in operation. The share of the electrical energy demand is at 8% during the period considered.

At plant 3 there is a high share of the brine pump and controller with 25%. At this plant in summertime the PVT collector is used to recharge the borehole. For this reason, there is a high-energy demand for the brine pump without the compressor being in operation.

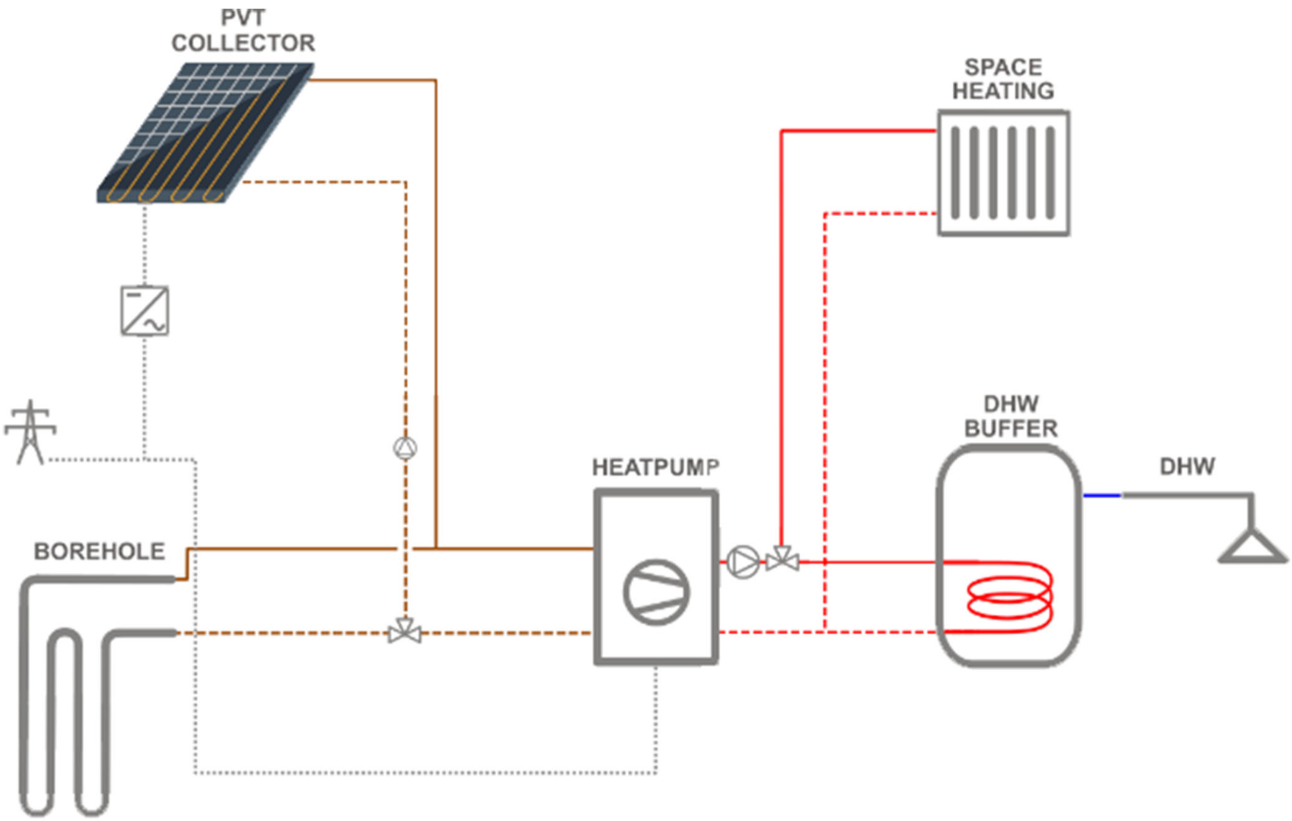

Figure 15. Plant 2 and 3. Reproduced with permission.[12] Copyright 2022, Fraunhofer ISE.

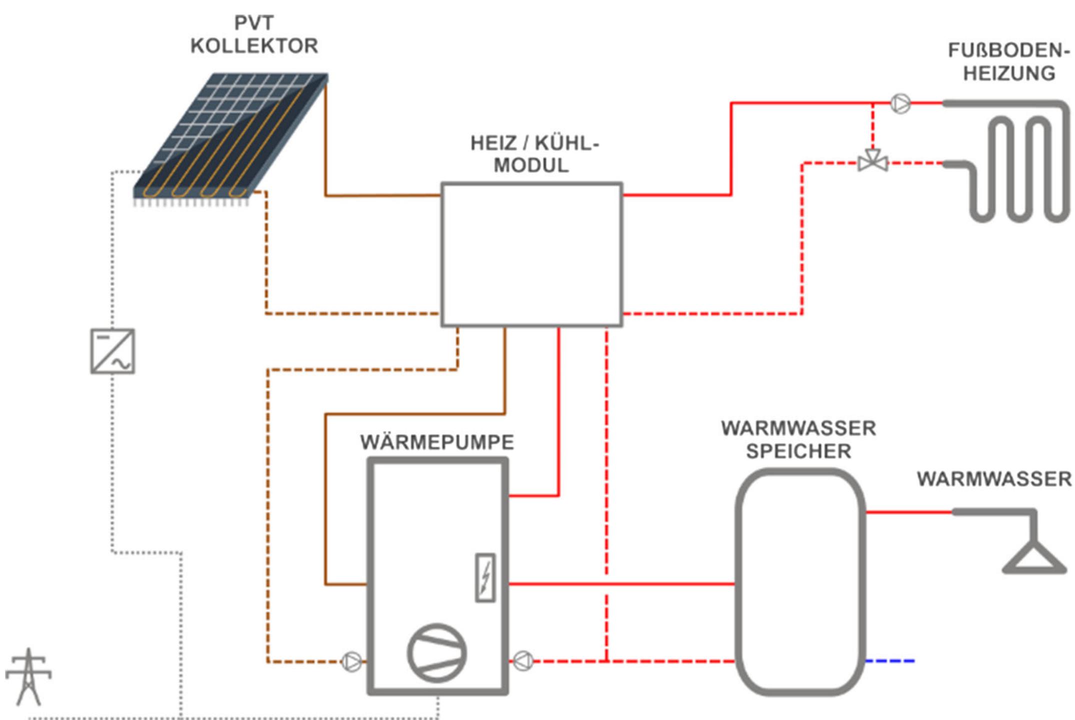

Figure 16. Plant 4. Reproduced with permission.[12] Copyright 2022, Fraunhofer ISE.

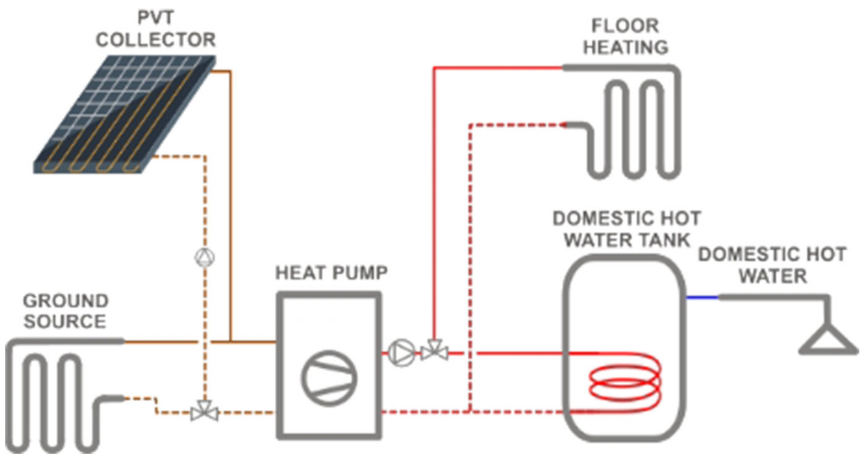

Figure 17. Plant 5. Reproduced with permission.[12] Copyright 2022, Fraunhofer ISE.

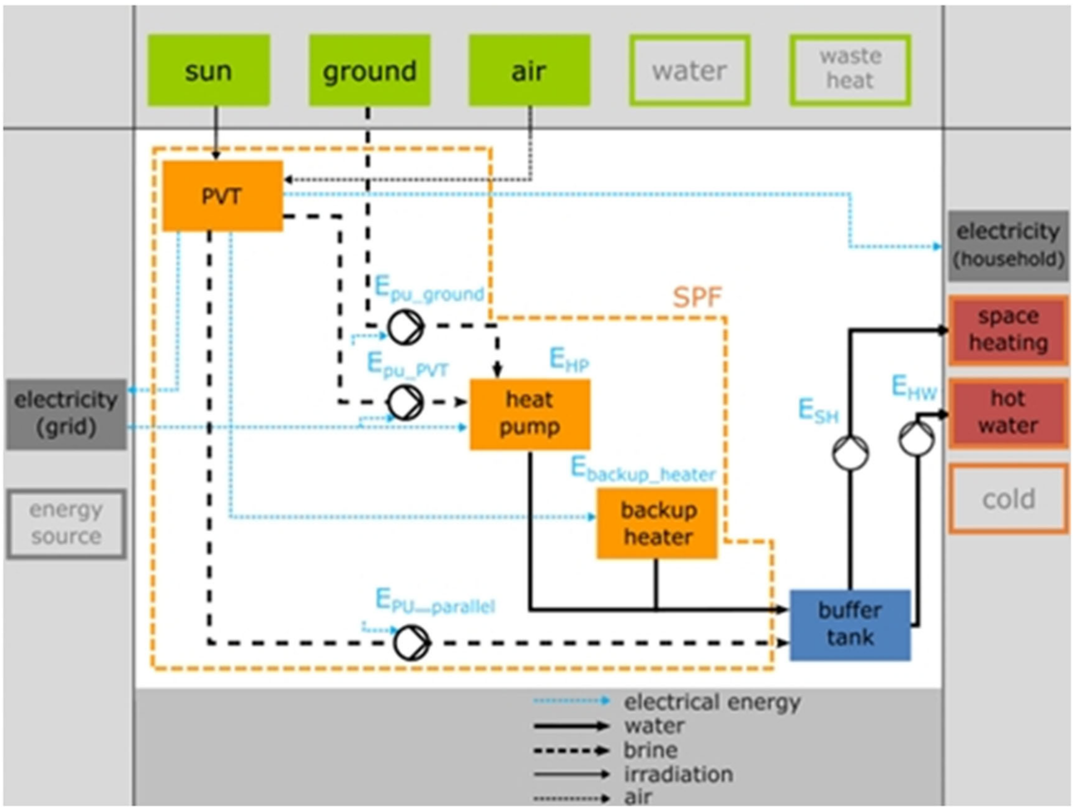

Figure 18. Square view of combined heat pump and PVT system visualizing the energy fluxes and indicating the boundaries for the seasonal performance factor (Fraunhofer ISE based on. Reproduced with permission.[47] Copyright 2019, IEA Solar Heating and Cooling Technology Collaboration Programme.

The next stacked column shows the share of thermal energy provided by the heat pump for DHW in blue and the share of energy provided for space heating in red. Except for plant 3 the share of DHW ranges between 15% and 20%. At plant 3 the share is with 5% very little.

Figure 15 furthermore shows the energetically weighted temperatures of the heat source, DHW production, and space heating. The graph shows the middle temperature of the respective circuit. It is calculated by the arithmetic mean temperature between supply and return line. The spread between flow and return line is shown by the error bars.

The middle temperature of the heat source is the temperature which is provided to the heat pump by either the PVT circuit (plant 4 and plant 1) or the PVT and borehole (plant 5, 2, and 3). The temperature ranges between 2.4 and 4.5 °C. At plant 2, the temperature is 9.1 °C. The middle temperature of the DHW

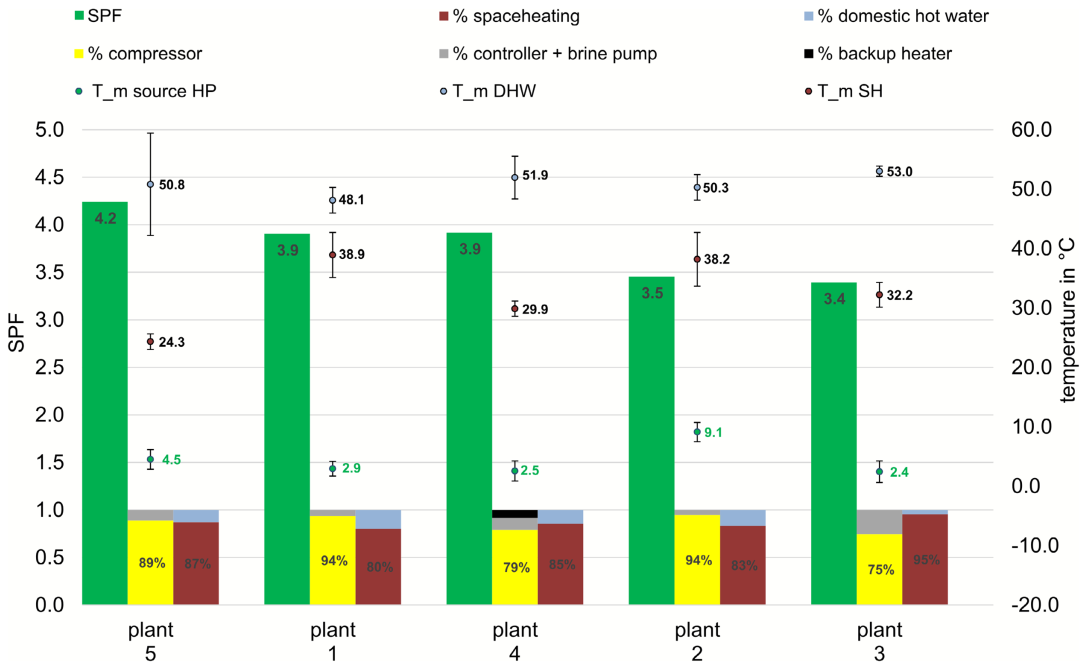

Figure 19. SPF of five PVT: heat pump plants in single-family houses in 2022.

production of the heat pump ranges between 48.1 °C at plant 1 and 53.0 °C at plant 3. The middle temperature of the HP while in space heating mode ranges from 24.3 °C at plant 5 and 38.9 °C at plant 1. The SPF of the plants is strongly influenced by the temperatures of the heat sink and heat source. Plant 5 has a temperature of the heat source of 4.5 K. The middle temperature of the space heating is at very low 24.3 °C. Furthermore, most of the heat (89%) has been provided in the space heating mode. Plant 1 runs on a high temperature in the heating mode but has still SPF of 3.9. At this plant a large amount of heat in the heating mode is produced in summertime for heating the indoor swimming pool.

The SPF of plant 3 is negatively influenced by the high-energy demand of the brine pump in summertime. On the other hand, recharging the borehole in summertime results in a better performance of the PV in summertime and a higher temperature of the borehole and consequently of the heat pumps heat source in wintertime.

To orientate those performance values in the exiting market surrounding the following, **Figure 20** shows the SPF of heat pump heating systems in existing single-family houses with different degrees of renovation in Germany on the *y*-Axis derived from another monitoring campaign of Fraunhofer ISE.[39] To compare the boundary conditions with regard to the

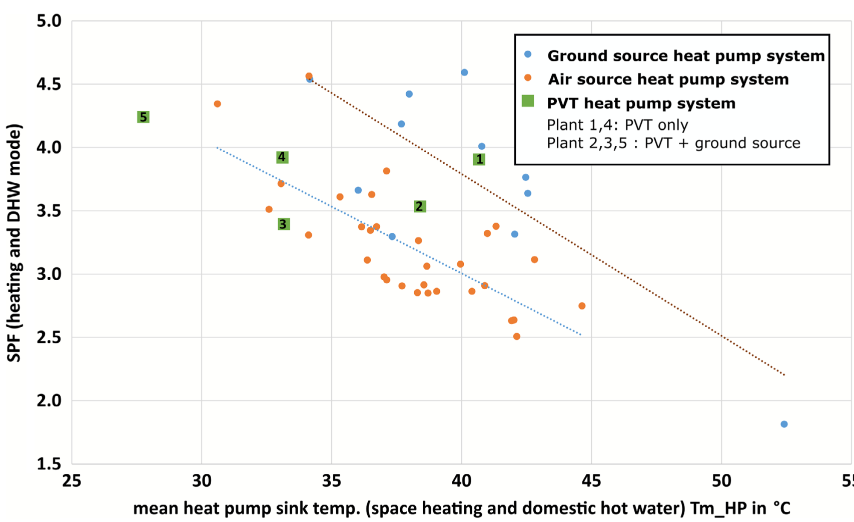

Figure 20. SPF of air source (blue dots and trend line) and ground source (brown dots and trend line) heat pump systems in comparison with the five plants (green).

mean temperature levels, the SPF is recalculated with respect to the mean heat pump sink temperature (space heating and DHW).

Figure 20 shows the annual SPF of air source heat pumps in blue and ground source heat pumps in brown. Additionally, the trendlines of the two data series are shown. Over the course of the year, the average heat source temperature is higher for ground systems than for air source heat pump systems. For this reason, these heat pumps with a ground source achieve a higher SPF at the same heat sink temperatures.

Plant 2, 4, and 5 reach a performance which ranges between the performance of air and ground source heat pumps. It must be considered that the ground geothermal source has been sized to work in combination with a PVT collector. Plant 3 reaches a SPF which is comparable to a an air source heat pump. Plant 1 reaches a SPF which is in the range of ground source heat pumps. This plant uses PVT as the only heat source for the heat pump but comes along with an additional gas boiler. For all the plants 1 to 5, it must be considered that those plans are prototypes for the manufacturers and installers. There is optimization potential in the products, control strategies, and system configurations for the coming years.

5.1. Simulation of PVT Heat Pump Systems

Model-based simulations are an effective tool to design and optimize PVT systems.[40] This includes the selection and evaluation of PVT products, dimensioning the collector field, and sizing the thermal storages and components. With system simulations, the electrical and thermal performance of the PVT system can be predicted, such as the seasonal performance factor or degree of electrical self-sufficiency. For this purpose, design software packages such as Polysun[41] or Tsol[42] are used by system designers that offer templates and easy-to use functionality. TRNSYS[40] or Dymola/Modelica[43] are frequently used for more complex system simulations in research and development. Lämmle and Munz (2022)[44] simulate PVT heat pump systems with different types of PVT collectors. The PVT design from Section 2.1.1 is also analyzed. Chhugani and Pärisch et al. (2023)[45] compared simulations of different heat supply systems for a single-family house, focusing on PVT and heat pump systems, and put the results into relation with monitoring data from a heat pump and PVT installation in a real single-family house.

The system performance varies with increasing areas of PVT collectors: with larger size of the PVT collector, the absorber and heat transfer area increases, so the SPF of the heat pump system increases. To quantify this effect, the area of the PVT collector array is varied, with specific values of 1–5 m^2 of collector area per kWth of the nominal capacity of the heat pump. For deeper understanding the variability is shown in Table S8, Supporting Information. The PVT collectors with microchannel and finned heat exchanger achieve seasonal performance factors in the order of magnitude between air and brine heat pumps. PVT collectors without air-to-brine heat exchangers perform less efficiently. Because of the passive air coupling, large PVT heat exchanger areas are required to achieve the efficiency of air-source heat pumps.

6. Conclusion

PVT collector technology is a market-available technology of solar energy converters. The variation of product designs is wide, and many fields of application are tried out. Comparing the energy output for both electricity and thermal energy in a standardized way already on the collector level, as suggested in the article, helps transparency. Limitations of the methodologies available up today were shown. Also, it was shown that the relevant mean operating temperature is shifted to lower temperatures. As the application of PVT together with heat pumps, grows recently the most, the performance is represented in the proposed form. Nonresidential applications like hotels, fire stations, sports clubs, etc. play an increasing role in market numbers, as well. The product design strongly correlates to the applications mean operation temperature, which is an appropriate mean to select sufficient system configurations of components. Therewith, specific designs find suitable process temperatures of application. The increased land use factor is a basic advantage of the PVT technology. Comparing PVT solutions to specific established solutions leads to specific advantages and shortcomings. Heat sources' advantages over heat pumps are no moving parts, no noise, no extra area needs, solar radiation as an added energy source, and no drilling at similar performance figures. Disadvantages are that roof area must be available and the technology is still new to the market. And at least for this early generation of systems, the performance is rather at the level of air source heat pumps, not yet at the level of ground source heat pumps. The toolbox to design, configure systems, rank, compare, and monitor is getting more enhanced. Even smaller effects can be described and are understood, still leaving room for further research and development and thus optimization of the performance. This includes new fields of application, like district heating networks, night cooling using the atmospheric window, water condensation in arid climates for drinking water, AgroPVT, and more. The status the early generation of systems is nevertheless promising and it is assumed that the PVT technology will develop more into a significant market share as one renewable energy technology, harvesting and providing carbon-free energy.

Appendix

Nomenclature 3. Symbols in order of appearance.

Symbol	Definition	Unit
λ	Wavelength (of irradiation)	nm
E_λ	Spectral irradiance	$W\,m^{-2} \cdot nm^{-1}$
G_{eff}	Effective hemispherical solar irradiance	$W\,m^{-2}$
α	Absorptance	–
τ	Transmittance	–
U_{loss}	Heat transfer coefficient (for thermal losses)	$W\,m^{-2} \cdot K^{-1}$
$T_{surface}$	Surface temperature (of collector/absorber)	°C
T_a	Ambient temperature	°C
T_{pipe}	Temperature of the pipe wall	°
T_m	Average fluid temperature	°C
$h_{PipeFluid}$	Heat transfer coefficient (from pipe to fluid)	$W\,m^{-2}\,K^{-1}$

G	Hemispherical solar irradiance	$W\,m^{-2}$
ΔT	Temperature gradient/difference	°C
$T_{fluid-m}$	Average fluid temperature	°C
T_{amb}	Ambient temperature	°C
$\eta_{0,th}$	Thermal efficiency; conversion factor of PVT collector in MPP operation	–
ϑ_{op}	Fluid operating temperature	°C
$Loc_{\beta,\gamma}$	Location defined by azimuth and latitude	
$\dot{Q}$	Thermal energy	Wh
$\dot{Q}_{el}$	Electrical energy	Wh
P_{max}	Maximum Power	W
t	Time	–
K	Incident angle modifier	–
θ_L	Solar angle in longitudinal direction	°
θ_T	Solar angle in transversal direction	°
δ	Temperature coefficient of PV cell material	$\%\ K^{-1}$
c_1	Linear heat loss coefficient of thermal efficiency	$\frac{W}{(m^2 \times K)}$
c_2	Quadratic heat loss coefficient of thermal efficiency; temperature dependence of heat losses	$\frac{W}{(m^2 \times K^2)}$
GTY	Gross thermal yield	$kWh\,m^{-2} \cdot a^{-1}$
GEY	Gross electrical yield	$kWh\,m^{-2} \cdot a^{-1}$
ϑ_a	Ambient temperature	°C
ϑ_m	Average collector/fluid temperature	°C
GSY	Gross solar yield	$kWh\,m^{-2} \cdot a^{-1}$
E_{HP}	Electric consumption of heat pump; analog for other consumers	kWh
SPF	Seasonal performance factor; efficiency of heat pump	–
T_m source HP	Average temperature of heat pump source; analog for other hydraulic circuits	°C
$T_{m,HP}$	Average supply temperature of heat pump	°C
SPF_bst	Seasonal performance factor "before storage"; balanced at the entrance of storage/without storage losses	–

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

hybrid collector technology, photovoltaic thermal collectors, photovoltaic technology, photovoltaic thermal heat pump systems

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