O1 PVT Technology Research - Best practices report

PowerUp MyHouse

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Abbreviations:

HTF= Heat Transfer Fluid

SFH = Single Family House

MFH =Multi Family House

PVT = Photovoltaic Thermal collector

Nomenclature:

G= Total solar radiation [W/m^2]

V_m= Maximum power point voltage [V]

I_m = Maximum power point current [A]

T_a= Ambient air temperature [°C]

T_{ref} = Reference PV cell temperature at standard test conditions (25°C)

T_c = Temperature of the PV cell [°C]

β = PV cell efficiency temperature dependence [C^{-1}]

T_m = mean PVT collector fluid temperature [°C]

η_{th} = Thermal efficiency of the PTV collector [-]

$\eta_{0,th}$ = Maximum thermal efficiency of the PVT collector [-]

a_1 = Heat loss coefficient [$W/m^2/K$]

a_2 = Temperature dependence of heat loss coefficient [$W/m^2/K^2$]

1. Introduction

The PVT technology combines Solar PV and Solar Thermal in the same component. The output is both heat and electricity, similar to a cogeneration steam plant.

PVT collectors extract the excess thermal energy generated by the PV cells employing a Heat Transfer cooling Fluid (HTF), which increases the PV cell overall efficiency as the temperature decreases. This is particularly important if the available roof area is limited. Integrated solar energy concepts are needed to achieve a climate-neutral energy supply for consumers, such as in residential and commercial buildings. The PVT market is gaining momentum in several European countries. In recent years, a growing number of specialized PVT technology suppliers have entered European markets.

Active solar thermal has been tried and sold since late 1800 for domestic heating purposes. Silicon PV technology was developed in the early 1950'ties. First for high value off grid use for space applications and telecommunication.

PVT was first developed and tried in the 1970'ties in USA, but for several reasons the market did not grow. The PV part was then very expensive too unlike today. Therefore concentrating PVT was tried.

Some typical PVT collector designs are given in figure 1.

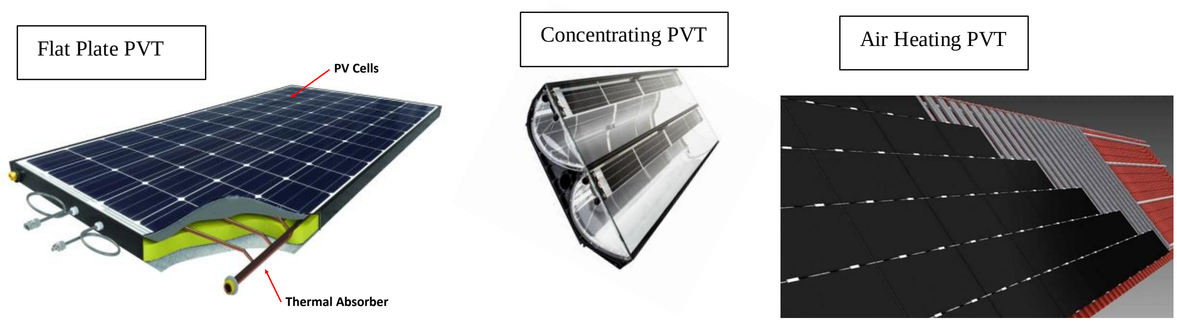

Figure 1. Some examples of different PVT collector designs for combined heat and electricity production.

When mass production of PV "suddenly" reduced the price dramatically in a few recent years from around 2010, the PVT and also solar thermal "came in the shadow" so to say. But the PVT market is still there and has potential.

The discovery around 1850 of cheap, very compact in volume per kWh, fossil fuels, that also has built in long term energy storage, almost for free, has all the time since pushed the solar technologies to the corner and to the future. The unhealthy emissions from fossil fuels were long treated as a marker for power, progress and work possibilities. Since 30-40 years back these emissions have got a price tag and have given dramatic reductions in many emissions except CO_2, as a result. This helps renewables in the competition, but only slowly until now, when a breakeven comes closer in market after market.

In this development step cheap waste biomass and heat pumps have come into use, delaying the take over of active renewables. But biomass has only a limited potential globally and has many other more valuable uses, as a material rather than as a fuel, so the cost for biomass should rise very soon, when the potential is reached.

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. The areas needed for solar are more than sufficient on roofs facades and small land areas on the country side close to the cities.

A very important sometimes forgotten barrier is also proven long enough life times for the new solar technologies. Many of the first concepts have failed in small things, as almost all new products, giving 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 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 insufficient and too short term to develop a sustainable market.

For PV and solar thermal there were also niche markets in remote places without 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 rise the temperature of the available low temperature “free” heat to a useful level. It does not produce heat from nothing. 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 a 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. Maybe adding a swimming pool or a borehole heat pump could be a wise solution. Ideally a total system view should be used when looking at PVT systems.

But after mentioning these barriers one can conclude that there are many system types really suitable for PVT to start with, already now. They are here classified after the heating/cooling demand, as the electricity always can be utilized locally and even can be exported, if too much power is produced.

1. Hot water preheating systems for hotels and other large Hot water users.

2. Swimming pool heating.
3. 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.
4. 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.
5. Cooling by radiation to clear night sky conditions, can also be used as an extra bonus with the same hybrid components.

PVT standardized testing

Also product quality and performance is checked in standard test methods, even if full PVT standardization is lagging still. A test of a PVT panel is more complicated and costly than tests of PV panels and solar collectors as both heat and power is produced. But if separate PV panels and solar collectors are installed, two tests are needed so it depends on the viewpoint too.

Also test methods for PVT systems are partly more complicated and not fully available as a complete standard yet. But basic development work has been done within IEA SHC Task 60 and within that cooperation also at DTU in Denmark, see figure 2. In such a test, a PVT collector can be fully characterized. Then there is a variant of the ScenoCalc tool that can handle PVT with the parameters derived from such a test to get standardized annual electric and thermal performance results for different locations.

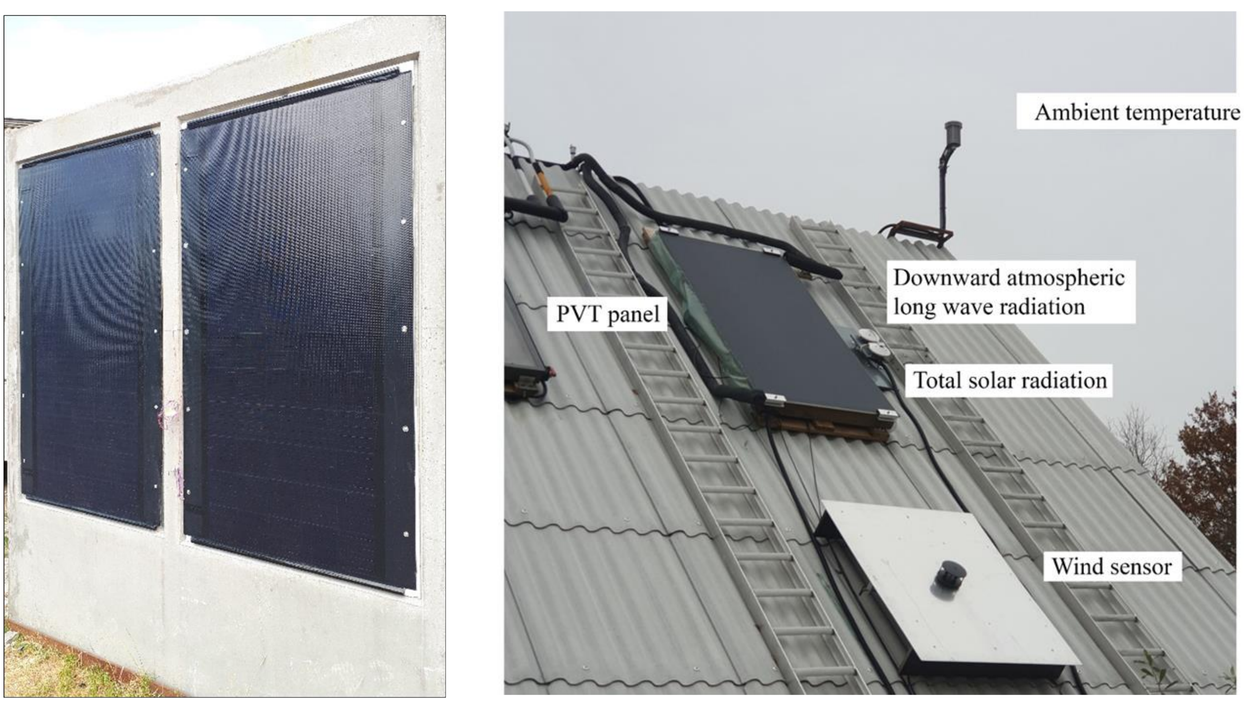

Figure 2. Racell collectors under research testing for IEA SHC Task 60 PVT test method development.

Market overview:

There are several kind of PVT designs with different advantages for different markets. The distribution at present are shown in figure 3. The total installed area of PVT was 1 million m^2 2018.

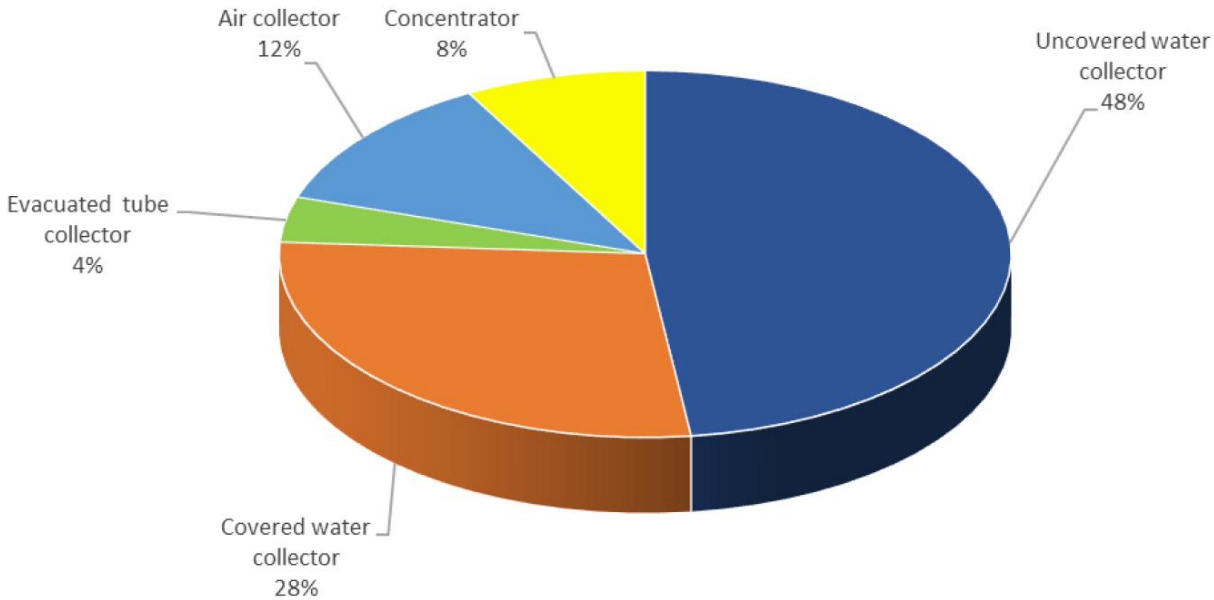

Figure 3. Different PVT collector types and how common they are at present. Uncovered PVT designs dominate. These collectors are manufactured in a wide range of countries shown in the figure 4, from IEA SHC Task 60. The Netherlands seems to be most active now.

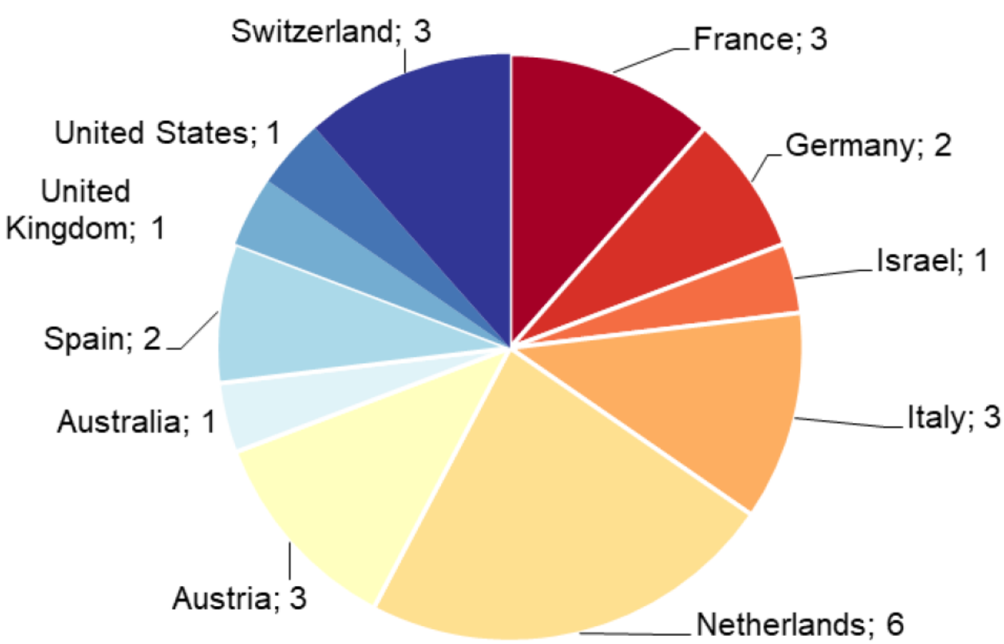

Figure 4. Countries with the number of PVT industries in each of them, from IEA SHC Task 60.

PVT can be nicely integrated into the built environment, like these examples below in figure 5. Pictures taken from IEA SHC Task 60.

Figure 5. Two Demo PVT systems. One from France for a Municipal Swimming Pool (Dual Sun PVT collectors) and one from Denmark for at Football club (Racell roof integrated PVT collectors). This shows that the PVT can look nice and be well integrated in the built environment. Pictures from IEA Task 60.

2. PVT panels. Types, efficiencies, costs

PVT collector classification

Typically, PVT solar collectors are either classified as air or liquid PVT's, characterized by its HTF (Heat Transfer Fluid). The latter being either water or water/glycol mixture [1]. PVT air collectors are known by its high heat losses and therefore less sensitive to overheating, which leads to higher electrical efficiencies. On the other hand, PVT liquid collectors have a higher installation share, yet it has overheating issues, despite water having a higher heat capacity and thermal conductivity [2]. Moreover, concentrating PVT collectors can be labelled by its concentration ratio in three different categories, such as low, medium and high concentration factors. Typically, low concentration PVT collectors are used as stationary (fixed collector tilt angle) solar energy systems, however high concentration PVT collectors require a tracking system, either one-axis or two-axis system.

As the specific suitability depends on electrical conversion efficiency, temperature and also its absorption coefficient [3], therefore a PVT system location is of most importance. Monocrystalline PV cells are commonly known to have the highest share at modular electricity production devices (e.g. both PVT and PV panels) due to their enhanced electrical efficiency and higher solar absorption compared to polycrystalline PV cells. Thin-film solar cell technologies (e.g. CIGS and CdTe), are typically characterized by their lower temperature coefficient, which makes them very attractive for higher HTF temperatures and module temperatures. In PVT applications, multi-junction PV solar cells are typically employed in high concentration solar energy systems, thus a contender for high HTF temperature PVT solar collectors.

Furthermore, the developments in heat pump technology, and the increasing interest in Building Integrated PV (BIPV) and Façade Integrated PV (FIPV) are generating more opportunities for PVT applications to enter the super competitive PV module market. Therefore, in 2018, under the management of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) programme, a task force composed by several experts (either from PVT companies or research institutes with PVT research programs) in PVT technology, has been initiated under the IEA-SHC Task 60: 'Application of PVT collectors'. To help different stakeholders to have a better understanding of what kind of PVT technologies exists and its system characteristics, Lämmle et al. (2020) [3] presented and allocated, Figure 6, each PVT collector technology according to their:

Specific operating temperature ranges;

System layout;

Design (glazed, unglazed, and concentrating);

Heat Transfer Fluid, HTF (air and water/glycol, for commercial systems).

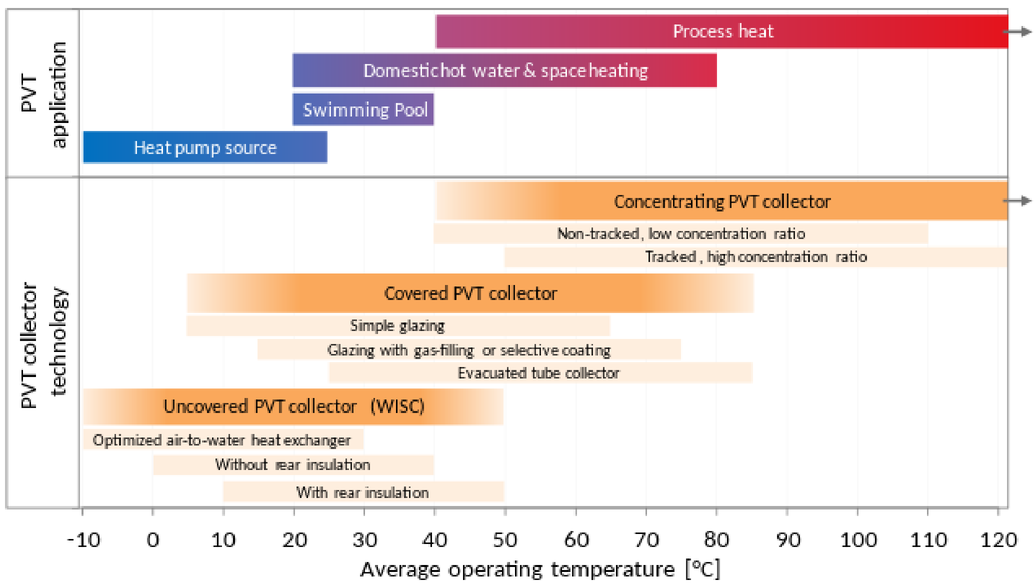

Figure 6. Map of PVT technologies and applications per operating temperature [3].

Additionally, the generality of the PVT water collectors and solar flat-plate thermal collectors can be divided into their range of applications such as:

- Low-temperature applications (~27-35°C) including swimming pool heating or spa heating.

- HTF temperatures ((~27-50 °C) are a prerequisite for space heating or integration with low-temperature heat pumps;

- Medium temperature applications for temperatures up to 80°C (e.g. unglazed collectors in high irradiance climates, or with glass cover flat-plate collectors);

- High-temperature applications for temperatures larger than 80°C, such as applications comprising high-efficiency flat-plate thermal collectors (with reduced thermal losses) or evacuated flat-plate collectors.

PVT Collector Materials

Typically, PV elements are encapsulated with Ethylene-vinyl acetate (EVA) or a solar silicone gel in case of low concentration PVT solar collectors (e.g. Solarus PC).

The thermal elements typically comprise a thermal receiver, in which the harvested heat from the PV cells is extracted and transferred into a HTF that will provide the desired heat supply for the system installation.

Overall (general form), PVT collectors are composed of an anti-reflective glass cover (in case it's a glazed collector), front-encapsulant layer (e.g. EVA or silicone gel), PV cells, a back-encapsulant layer such as EVA, a backsheet such as PVF, a heat exchanger to transfer the heat from the PV cells to the HTF such as aluminum, copper or polymers, as well as a thermal insulation such as mineral wool or polyurethane, Figure 8.

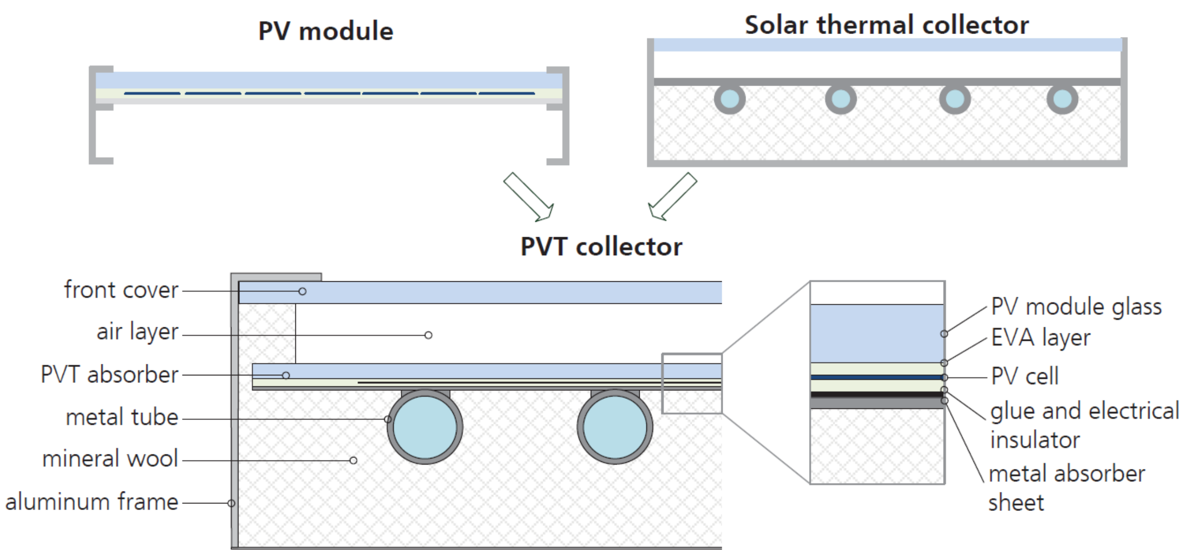

Figure 7. Schematic cross section of a sheet-and-tube type heat exchanger PVT collector with back insulation [22].

In concentrating PVT (CPVT) collectors, an additional sheet of reflective material is added to enhance the capture of the solar radiation. In this particular case, the CPVT solar collector is composed by a low-iron solar glass, air-gap to decrease thermal losses, a thermal receiver core (e.g. aluminum core with internal elliptical channels) where the PV cells are encapsulated in a solar silicone gel with high transparency, and a reflective sheet.

PVT panels (Types, efficiencies, costs)

In order to evaluate the current state of the commercially available PVT panels and their electrical and thermal performance, eight different PVT collectors (Solarus, Abora, Dual Sun, Solimpeks, EndeF, Meyer Burger, Fototherm and Solator) are selected based on total installed area and compared in Table .

Table 1. Different PVT collectors and their principal parameters.

Company	Panel Model	Technology	Country	Size [m²]		Price [€/m² gross]	PV Specifications			Thermal Specifications		
				Gross	Aperture		Cell Type	Power Peak [W]	Eff. [%]	η_0	a_1 [W/m².k]	a_2 [W/m².k²]
Solarus [5]	Power Collector	C-PVT- Glazed	Netherlands	2.57	2.31	253	Mono	270	10	0.47	3.78	0.014
Abora [6]	aH72	PVT-Glazed-Water-airgap	Spain	1.96	1.88	204	Mono	350	17.8	0.7	5.98	0
Dual Sun [7]	Wave - 280	PVT-Unglazed-Water-N/A	France	1.66	1.58	452	Mono	280	17.2	0.578	11.4	0
Solimpeks [8]	Volter Powertherm	PVT-Glazed-Water-airgap	Turkey	1.43	1.42	243	Mono	180	16	0.486	4.028	0.067
EndeF [9]	Ecomesh	PVT-Glazed-Water-airgap	Spain	1.61	1.55	596	Mono	260	15.95	0.51	4.93	0.021

Meyer Burger [10]	3S Photovoltaics	PVT-Unglazed-Water-N/A	Switzerland	1.65	-	-	Mono	260	17.4	0.576	14.11	0
Fototherm [11]	FT250Cs	PVT-Unglazed-Water-N/A	Italy	1.61	1.59	618	Mono	250	15.5	0.559	9.123	0
Solator [12]	PVTHERMAU 300	PVT-Unglazed-Water-N/A	Austria	1.64	-	-	Mono	300	18.5	0.499	11.84	0

Performance of PVT Collectors

Solar radiation reaches the module at a solar irradiance of G where 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 and makes the entire system more efficient. The general energy equation in a simple PVT module and overall efficiency (η_{PVT}) can be defined by equation Equation 1, Equation 2 and Equation 3 [14,15].

$$\eta_{el} = \frac{Q_{el}}{GA} \quad \textbf{Equation 1}$$

$$\eta_{th} = \frac{Q_{th}}{GA} \quad \textbf{Equation 2}$$

$$\eta_{PVT} = \eta_{el} + \eta_{th} \quad \textbf{Equation 3}$$

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

Electrical Efficiency

PVT systems are two separate systems that consist of a single solar thermal collector and a PV module. They 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 [16].

For the separate PV module, electrical efficiency η_{el} is given by equation Equation 4.

$$\eta_{el} = \frac{I_m V_m}{G A_c} \quad \textbf{Equation 4}$$

I_m stands for the maximum power point current, V_m for the maximum power point voltage, *G* for total solar irradiance in W/m^2 and A_c for the collector gross area in m^2 [17]. A special maximum power point tracking controller in the system assures that the PV modules operate at the best working point (I_m, V_m)

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

$$\eta_{el} = \eta_{0,el}(1 - \beta(T_c - T_{ref})) \quad \textbf{Equation 5}$$

Where T_c is PV cell temperature, T_{ref} is reference temperature and β is the coefficient of temperature. The value of β is 0.0045 °C^{-1}. $\eta_{0,el}$ and β are normally given by the PV manufacturer. However, they can be obtained from flash tests in which the module's electrical output is measured at two different temperatures for a given solar radiation flux. The actual value of the temperature coefficient, in particular, depends not only on the PV material but on T_{ref} as well [18–20]. Figure 8 shows electrical efficiency of mentioned PVT products at reference temperature of 25°C.

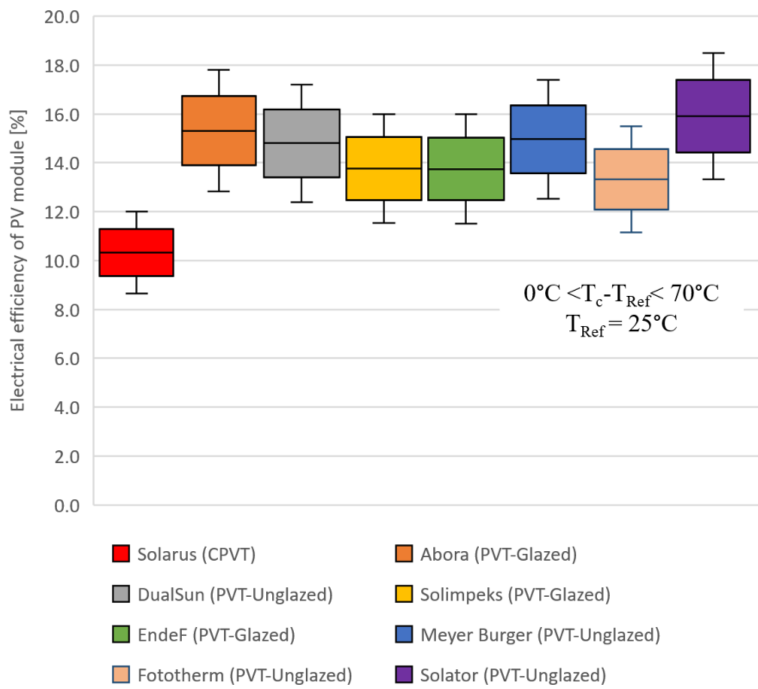

Figure 8. Comparison of the electrical efficiency of various PVT collectors.

Thermal Efficiency

Based on ISO 9806:2017 at steady-state condition 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 Equation 6.

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

where T_m is mean temperature of heat transfer fluid (°C), T_a is ambient air temperature (°C), $\eta_{0,th}$ is peak collector efficiency (η_{th} at T_m-T_a = 0), 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) [21]. Figure 9 shows thermal efficiency of mentioned PVT products at hemispherical irradiance of 800 W/m^2.

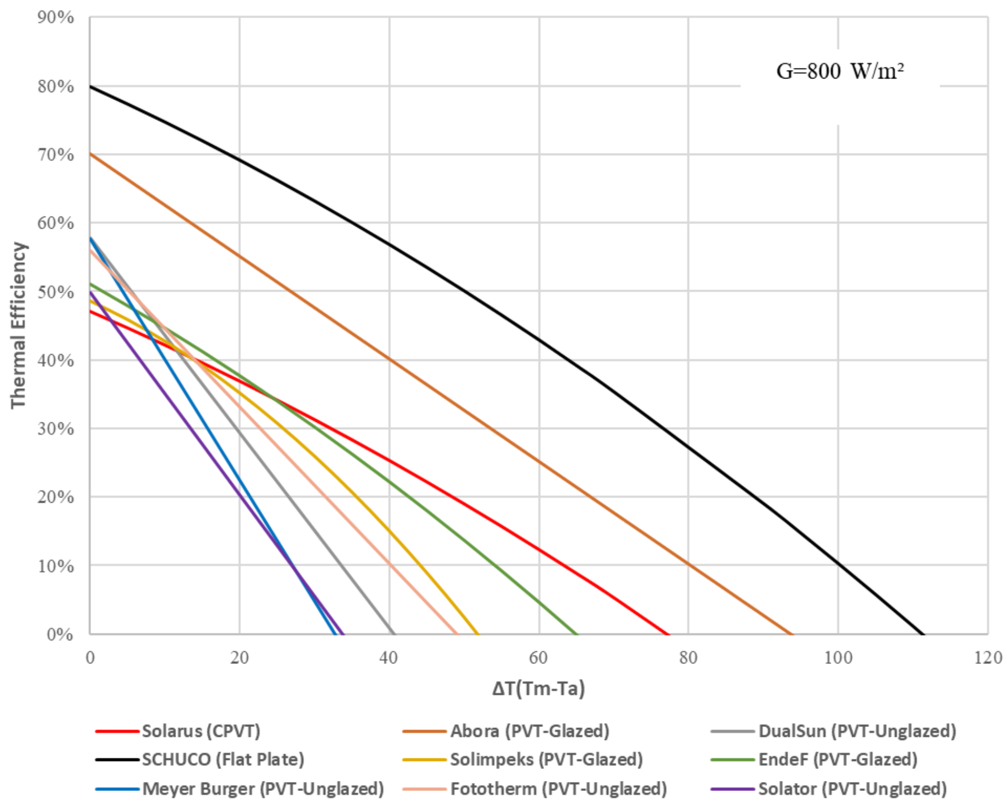

Figure 9. The thermal efficiency of various PVT collectors in comparison to the flat plate solar collector.

PV / T Hybrid (with air circulation) application in Turkey

PVT air collectors is a suitable solution for areas where direct air is used for heating (sports, theaters, movie theaters). These panels, Figure 10, are systems that operate at 20% to 40% efficiency. In these systems, the air flow rate plays a key role in lowering the cell temperature and increasing the overall energy efficiency of the system [2T]. A PVT system working with air as a heat transfer fluid, can be widely used because of its simplicity in construction, low operating cost and effective integration into buildings [3T].

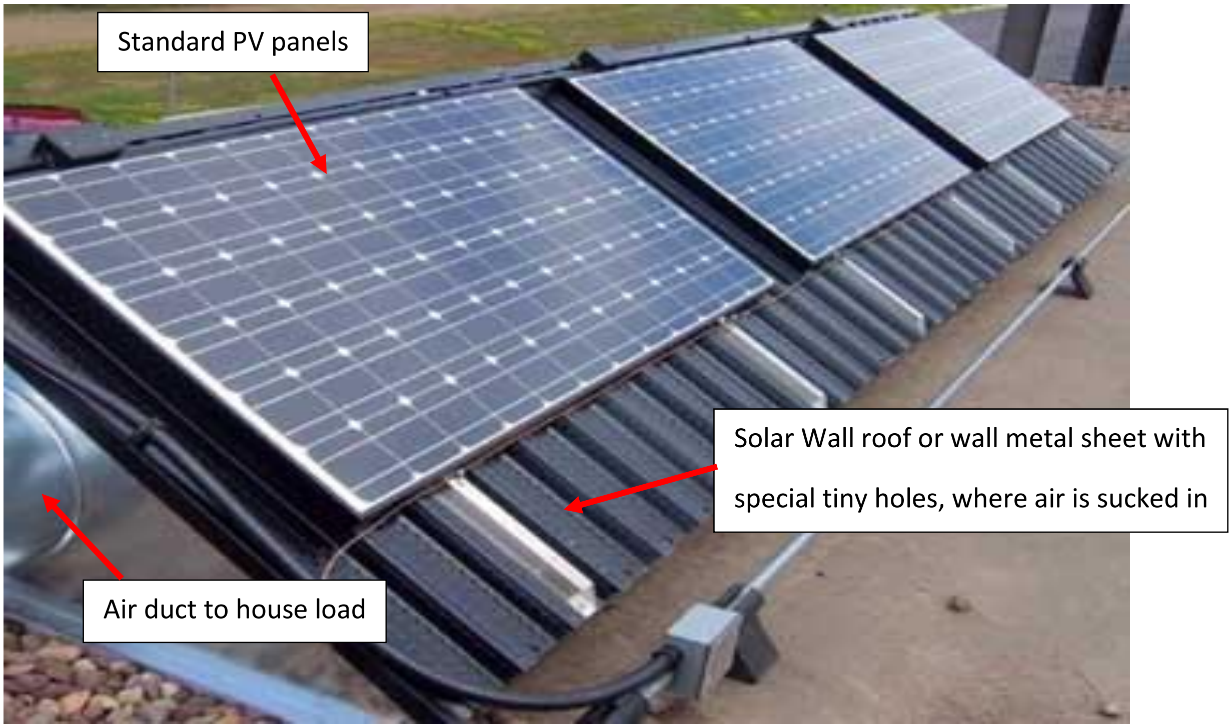

Figure 10. A small PVT Hybrid (with air circulation)

3. PVT systems. Types, components, applications, performances for different types and countries/climates, costs

PVT System Components

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' [4].

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

Lämmle et al. (2017) [4] 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 are presented in Figure 11.

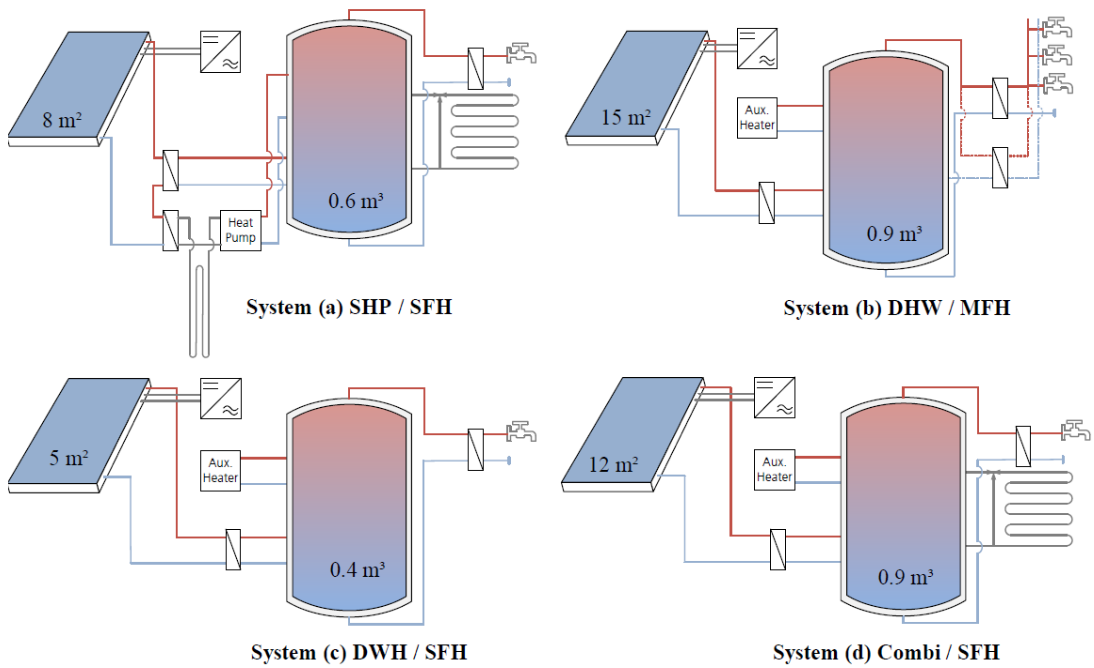

Figure 11. System diagrams: (a) solar heat pump system in parallel/regeneration configuration in a single-family house; (b): domestic hot water in a multi-family home; (c) domestic hot water in a single-family house, system; (d) combi system in a single family house [4].

System (a): Heat pump (HP) system in a single-family house (SFH) supplies space heat and domestic hot water by a ground coupled brine-water heat pump. A synergetic integration of PVT collectors can be reached when the PVT collector is coupled to the heat pump as cold side heat source or for the regeneration of a ground heat exchanger, which potentially offers lowest PVT collector temperatures.

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

System (c): Domestic hot water (DHW) system in a single-family house (SFH) is the classical system for solar thermal collectors and is therefore considered a promising application with a potentially big market for PVT collectors [2]. 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 single-family house (SFH) is a challenging application with high requirements for the thermal efficiency of the PVT collector, since the heat demand occurs mostly in winter, with low levels of irradiance and low 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 optimizing the interplay with the electricity grid. In table 2 a detailed list of system components is given for both the thermal and electrical part.

Table 2. PVT systems: Detailed component list.

Electrical components	PVT collector
	Solar cabling
	Energy meter
	Inverter; power optimizers (optional)
	Global and diffuse radiation sensors (for both electrical and thermal operation analysis)
	Grid analyser
	Support structure (for both electrical and thermal operation)
	Monitoring system
	Electrical cabinet and its components
	Battery storage (optional)
Thermal components	PVT collector
	Piping
	Hydraulic components (valves, flowmeters, temperature sensors, pumps etc)
	Heat exchanger
	Storage tank (auxiliary heater)
	Antifreeze product
	Expansion vessel

Moreover, under the SHC-IEA Task 60 supervision, 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 like final purchased energy, useful energy used for instance in space heating, or environmental energy sources, as well as different system components such as heat pump, PVT collectors or a storage, are shown and highlighted with specific colors if they exist in the system concept.

For the system components, the following given elements are defined and can be highlighted if they exist in the concept:

(1) Solar energy converters (e.g. PVT and solar thermal collectors);

(2) Thermal storages (i.e. source side of the heat pump);

(3) Heat pump;

(4) Backup heater (e.g. boiler or heating rod);

(5) Thermal storages (i.e. sink side of the heat pump);

(6) Electrical storages (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;

Right boundary: 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.

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

Within the system boundaries, different elements are highlighted (via placeholders) if they take part of the system layout/schematic. In case a specific component is not used, it will also be shown in the schematic but without any highlight (i.e. no 'connection line styles', Figure 12).

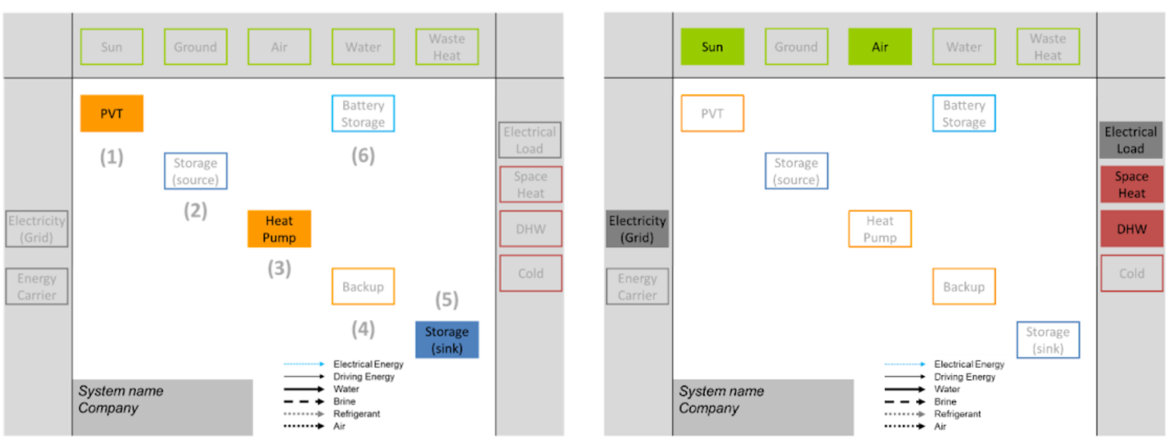

Figure 12. System "square view" components (highlighted left) and boundaries (highlighted right).

To differentiate system components and boundaries, the following colors are used:

- Energy Converters: Orange
- Thermal storages: Blue
- Electrical storages: Light Blue (color also used for electrical energy flows)
- Final Energy: Grey
- Environmental Energy: Green
- Useful Energy: Red

The system components are connected among themselves and with the boundaries via lines to depict the energy flows in the system. As shown in Figure 13, 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).

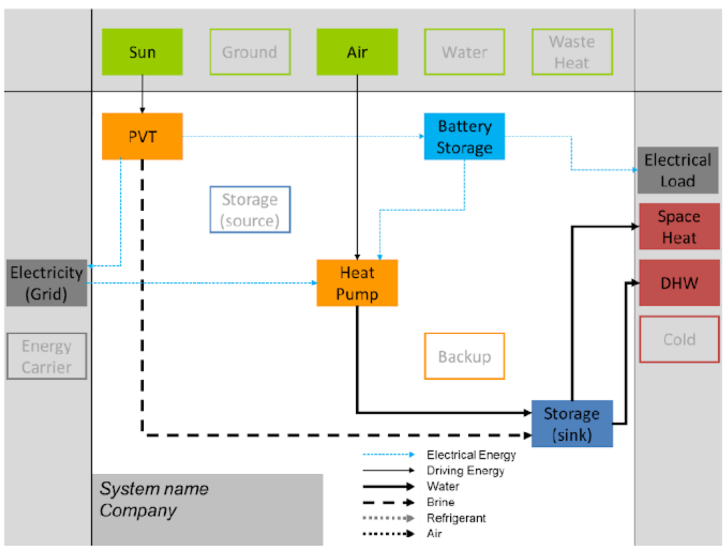

Figure 13. System "square view" connections.

PVT System Applications **(Solar Heat Worldwide report 2020)**

In 2019, suppliers of PVT technology commissioned at least 2800 new PVT systems worldwide. The cumulated number of PVT systems in operation at the end of 2019 reached its highest number at 25823 systems. The breakdown *in number of systems* is 86 % for solar air(pre)heating and cooling of buildings followed by 7 % for domestic hot water preparation for single family houses and 4 % for solar combi-systems that supply both domestic hot water and space heating. Around 1 % of the total installed capacity provided heat and electricity to large domestic hot water (DHW) systems such as multifamily houses, hotels, hospitals and schools. The remaining systems account for around 2 % and deliver heat and electricity to other applications, including swimming pool heating, district heating applications and solar heat for industrial applications,

Table 3.

Table 3. PVT systems by application. (Source: IEA SHC Task 60 survey, AEE INTEC).

PVT Applications	Number of installations [#]	Total collector area [m²]
Swimming pool heating	102	9,449
Domestic hot water systems SFH	1,767	60,588
Large domestic hot water systems	214	133,831
Solar combi systems for SFH	1,087	26,903
Large solar combi systems	265	57,024
Solar air systems	22,317	485,510
Solar district heating systems	20	11,082
Solar heat for industrial applications	51	21,624
Not classifiable		360,877
TOTAL		1,166,888

In a global context, the distribution of solar air systems (that dominate the PVT market, see Figure 14, is mainly driven by the dominance of the French market, where almost all of the manufactured PVT collectors are air collectors. Nevertheless, uncovered PVT collectors are the most common technology.

By the end of 2019, 3296 systems with uncovered PVT collectors were in operation, corresponding to a gross area of 667178 m^2. Out of these systems, 54 % were used for domestic hot water preparation in single and multifamily houses, hotels, and hospitals. Around 33 % of the systems supplied heat and electricity to households and to electric heating elements for domestic hot water and space heating (combi-systems).

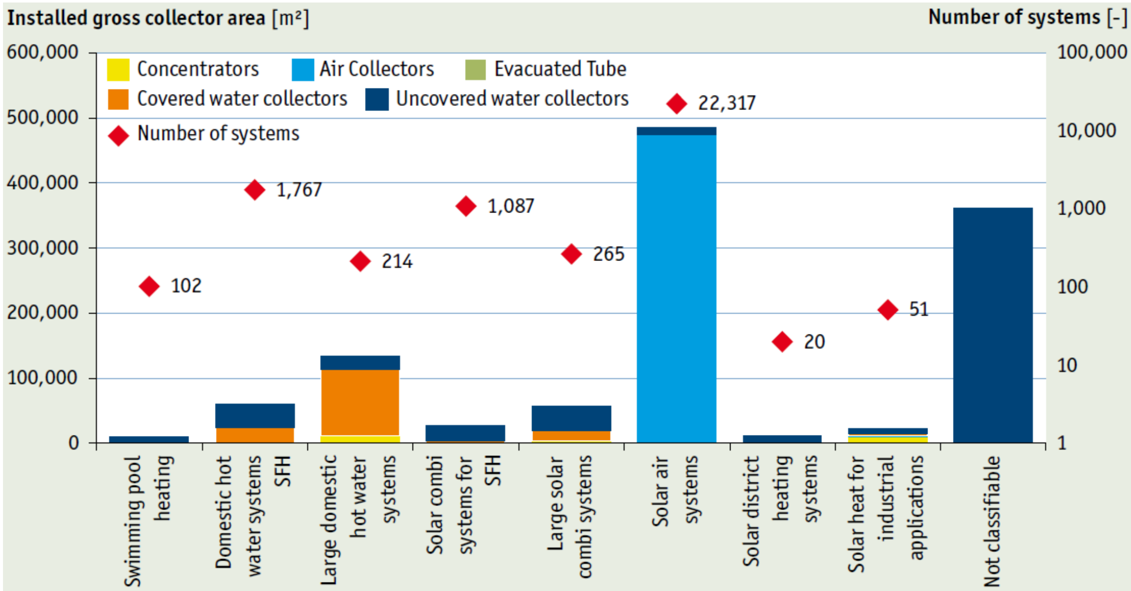

Figure 14. PVT systems in operation worldwide by application, collector type and collector area at the end of 2019. (Source: IEA SHC Task 60 survey, AEE INTEC)

General market overview (Solar Heat Worldwide report 2020)

In 2018, a market survey carried out by IEA SHC Task 60-PVT Systems, in which more than 1 million m^2 of PVT collectors were installed in over 25 countries, was included for the first time in the Solar Heat Worldwide report in 2019. SHC Task 60 PVT Systems carried out this survey again in 2019, which was also included in the Solar Heat Worldwide report in 2019, with responses from 31 PVT collector manufactures and PVT system suppliers in 12 different countries, Table 4. The total installed PVT collector area, in 2019, was of 1166888 m^2 (606 MW_{th}, 208 MW_{peak}). The main part has been installed in Europe (675427 m^2), followed by Asia (excluding South Korea (281104 m^2) and China (133942 m^2), which accounted for 567 MW_{th}, 194 MW_{peak} of the total installed capacity. The remaining installed collector area was shared between the MENA countries Egypt and Israel (57509 m^2), Sub-Sahara African countries (8767 m^2), USA (5400 m^2), Australia (547 m^2) and Latin America (408 m^2).

In the European market, France leads with an overall installed PVT collector area of 484587 m^2 followed by Germany with 112326 m^2 and the Netherlands with 32127 m^2. In Italy, Spain and Switzerland, PVT collector areas range between 10000 m^2 and 15000 m^2. In the remaining European countries, PVT collector areas of less than 10000 m^2 were reported.

Table 4. Cumulated installed collector area by PVT collector type and country, at the end of 2019. (Source: IEA SHC Task 60 survey, AEE INTEC)

Country	Water Collectors [m²]			Air Collectors [m²]	Concentators [m²]	TOTAL [m²]
	uncovered	covered	evacuated tube			
Australia	523	0	0	24	0	547
Austria	595	922	0	0	0	1,517
Belgium	712	0	16	290	15	1,033
Brazil	26	0	0	0	0	26
Chile	213	101	0	0	10	325
China	133,721	50	0	0	171	133,942
Denmark	85	0	0	0	0	85
Ecuador	0	4	0	0	0	4
Egypt	0	0	0	0	21	21
France	12,619	68	0	471,900	0	484,587
Germany	110,622	1,452	0	87	165	112,326
Ghana	8,000	0	0	0	0	8,000
Hungary	525	53	0	0	0	578
India	0	7	0	0	255	262
Israel	57,488	0	0	0	0	57,488
Italy	13,331	2,170	0	0	0	15,501
Korea, South	280,814	0	0	0	0	280,814
Luxembourg	635	0	0	145	0	780
Macedonia	260	74	0	0	0	334
Maldives	0	0	0	0	21	21
Netherlands	30,353	0	0	0	1,773	32,127
Norway	267	0	0	0	0	267
Pakistan	0	7	0	0	0	7
Paraguey	0	0	0	0	51	51
Portugal	335	0	0	0	0	335
South Africa	0	0	16	0	751	767
Spain	1,552	11,350	0	0	0	12,902
Sweden	0	0	0	0	31	31
Switzerland	7,720	36	0	3,530	0	11,286
United Kingdom	851	312	229	348	0	1,740
United States	5,400	0	0	0	0	5,400
Uruguay	0	2	0	0	0	2
Other	529	3,240	16	0	0	3,785
TOTAL	667,178	19,846	277	476,324	3,263	1,166,888

Market development of PVT collectors between 2017 and 2019 **(Solar Heat Worldwide report 2020)**

The PVT collectors market, in 2018 and 2019, was characterized by a significant global growth on an average of +9 %. The European market registered a slightly higher growth rate of +14%, which corresponds to an increase of 40.8 MW_{th} and 13.3 MW_{peak} of the yearly new thermal and electrical installed capacity, respectively, see Figure 15.

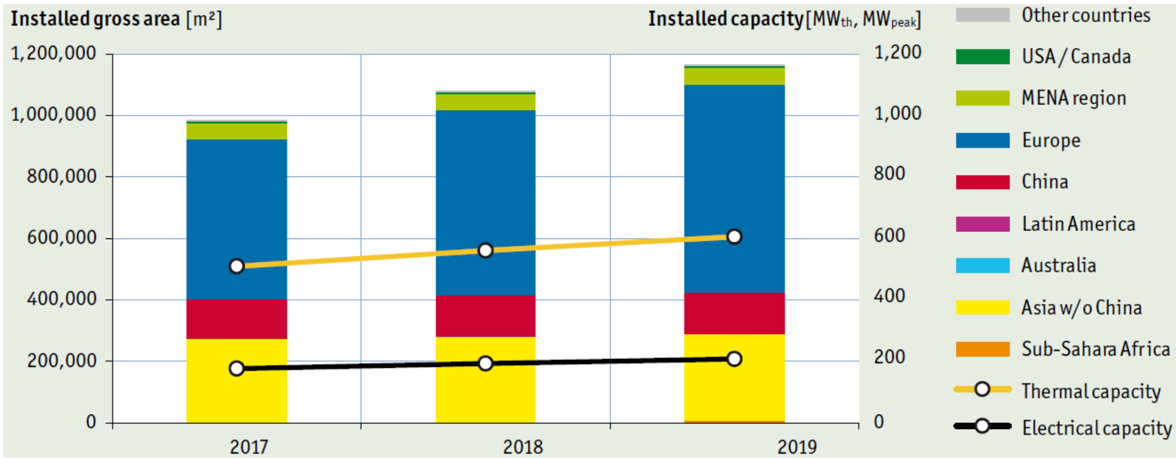

Figure 15. Global market development of PVT collectors from 2017 to 2019 (Source: IEA SHC Task 60 survey, AEE INTEC)

By the end of 2019, 606 MW_{th} and 208 MW_{peak} of total cumulative thermal capacity and PV power of PVT collectors was installed worldwide, respectively. Uncovered PVT water/glycol collectors are the dominating PVT technology produced with a global share that reached 55 % of installed thermal capacity, followed by PVT air collectors (43 %) and covered PVT water/glycol collectors (2 %). Evacuated tube collectors and concentrators (a niche market, with only one company operating at the time being) play only a minor role in the total numbers see

Table 5.

Table 5. Total installed thermal and electrical PVT collector capacity in 2019. (Source: IEA SHC Task 60 survey, AEE INTEC)

Country	Water Collectors						Air Collectors		Concentrators		TOTAL	
	uncovered		covered		evacuated tube							
	[kW_{th}]	[kW_{peak}]	[kW_{th}]	[kW_{peak}]	[kW_{th}]	[kW_{peak}]	[kW_{th}]	[kW_{peak}]	[kW_{th}]	[kW_{peak}]	[kW_{th}]	[kW_{peak}]
Australia	262	97	0	0	0	0	13	4	0	0	275	101
Austria	298	110	484	143	0	0	0	0	0	0	782	253
Belgium	357	132	0	0	7	2	158	49	8	2	529	184
Brazil	13	5	0	0	0	0	0	0	0	0	13	5
Chile	107	39	53	16	0	0	0	0	5	1	165	56
China	66,964	24,700	26	8	0	0	0	0	88	18	67,079	24,726
Denmark	43	16	0	0	0	0	0	0	0	0	43	16
Ecuador	0	0	2	1	0	0	0	0	0	0	2	1
Egypt	0	0	0	0	0	0	0	0	11	2	11	2
France	6,319	2,331	36	10	0	0	257,159	80,223	0	0	263,514	82,564
Germany	55,397	20,434	763	225	0	0	47	15	85	17	56,292	20,690
Ghana	4,006	1,478	0	0	0	0	0	0	0	0	4,006	1,478
Hungary	263	97	28	8	0	0	0	0	0	0	291	105
India	0	0	4	1	0	0	0	0	132	27	136	28
Israel	28,789	10,619	0	0	0	0	0	0	0	0	28,789	10,619
Italy	6,676	2,462	1,140	336	0	0	0	0	0	0	7,816	2,798
Korea, South	140,625	51,871	0	0	0	0	0	0	0	0	140,625	51,871
Luxembourg	318	117	0	0	0	0	79	25	0	0	397	142
Macedonia	130	48	39	11	0	0	0	0	0	0	169	59
Maldives	0	0	0	0	0	0	0	0	11	2	11	2
Netherlands	15,200	5,607	0	0	0	0	0	0	919	185	16,119	5,792
Norway	134	49	0	0	0	0	0	0	0	0	134	49
Pakistan	0	0	4	1	0	0	0	0	0	0	4	1
Paraguey	0	0	0	0	0	0	0	0	27	5	27	5
Portugal	168	62	0	0	0	0	0	0	0	0	168	62
South Africa	0	0	0	0	7	2	0	0	389	78	396	80
Spain	777	287	5,962	1,756	0	0	0	0	0	0	6,739	2,043
Sweden	0	0	0	0	0	0	0	0	16	3	16	3
Switzerland	3,866	1,426	19	6	0	0	1,924	600	0	0	5,809	2,032
UK	426	157	164	48	97	25	190	59	0	0	877	290
USA	2,704	997	0	0	0	0	0	0	0	0	2,704	997
Uruguay	0	0	1	0	0	0	0	0	0	0	1	0
Other	265	98	1,702	501	7	2	0	0	0	0	1,974	601
Total	334,107	123,238	10,425	3,071	118	30	259,570	80,975	1,691	341	605,910	207,655

In table 6, a large number of systems within IEA SHC Task 60 are presented with manufacturer, area and application. The majority is low temperature systems, most suitable for a PVT collector.

Table 6. PVT Systems in operation and their installed area[13].

Company	Project Name	Installed Collector area [m²]	Application	Total Installed area [m²]
Solarus	Henri Willig cheese factory, nl	226	Cheese Production Process	732
	University of Gävle, Sweden	51	DH supply	
	Anco lifestyle centre, nl	123	DHW & Swimming Pool	
	Ipragaz, Tu	179	-	
	Vineyard hotel, SA	153	DHW	
Abora	SYTA Truck Washing	264	Heat Water for Process	783
	Hotel Resort Iberostar Buganvilles	200	DHW & Swimming Pool	
	Sant Cugat's Sports Center	264	DHW & Swimming Pool	
	Multi Dwelling Azud	55	DHW	
Dual Sun	Ambérieu-en-Bugey	6.4	DHW	619
	Saint-Genis-les-Ollières	9.6	DHW	
	Sète	300	DHW & Pool preheating	
	Perpignan	300	DHW & Pool preheating	
	Pilot PVT plant - University of Catania	3.3	DHW	
EndeF	ECOMESH 1	30	DHW	234
	ECOMESH 2	10	Solar Combi system	
	ECOMESH 3	148	DHW for hotel	
	ECOMESH 4	46	DHW & Water pool supply	
Solvis	NVZ-Freiburg	48	DHW for administrative center	48
Meyer Burger	Lintharea	292	Preheating of groundwater before used in heat pump	1658
	P&D plant "Oberfeld"	1320	Combi System for Multi Family House (MFH)	
	Single Family House	46	Borehole regeneration & pool heating	

Fototherm	ATLAS O.C. s.r.o.	188	DHW, regeneration of boreholes	188
Caotec	Multi Family House SOTCHA	130	Combi System for MFH	130
Solator	Multi Family House SENTMATT	423	Combi System for MFH	423

4. Best practices for PVT systems. Marketed systems.

PVT system real data example: District heating CPVT solar energy system in Sweden

The inlet and outlet temperature of the system have been selected by the average inlet and outlet temperature values for the given year, where the working temperatures varied between 43ºC and 62ºC. The system is placed at the wall facade of a laboratory building at Gävle University (Sweden) back in 2014. It is divided into three main rows with 8, 4 and 8 collector prototypes, as can be seen in Figure 1.

Figure 1. Wall facade installation of asymmetric C-PVT solar collector prototypes at Gävle University, Sweden.

The thermal system, see Figure 2 is composed of five simple parallel loops with four asymmetric Solarus CPVT solar collectors per loop, where each loop has one sensor installed, Figure 2, from sensor 1 to 5. The system is connected to a heat exchanger, which is connected to the district heating network, providing heat to the University buildings.

The thermal system is composed of several temperature and pressure sensors in order to monitor the different sections of the system. Figure 2 shows the layout of the thermal system with the respective components.

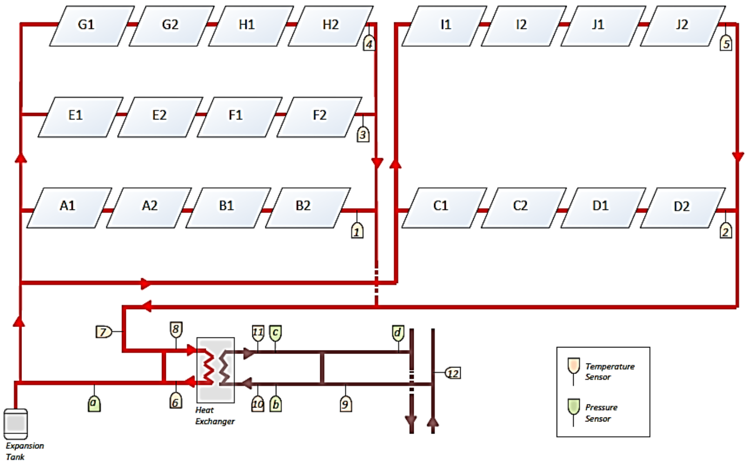

Figure 2. System thermal layout, connected to the district heating network.

On the other hand, the electrical system presented in Figure 3, is composed of two systems connected directly to the grid. System 1 is composed by four groups of two collectors (for a total peak power of 1.8 kW_p) and system 2 by six groups of two units (for a total peak power of 3 kW_p). For each loop, an inverter is connected, and per two collectors a power optimizer is used.

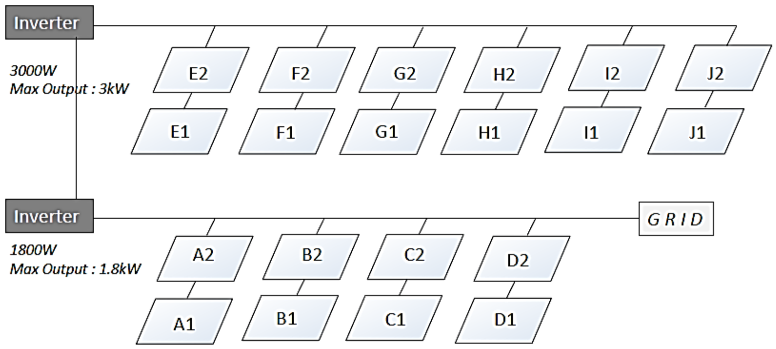

Figure 3. Electrical layout, divided into two systems. System 1 with 1.8 kW_p and system 2 with 3 kW_p.

Thermal performance coefficients

The thermal collector coefficients such as heat loss coefficient (c_1 = 3.5 $W/m^2.K$), temperature dependent heat loss coefficient (c_2 = 0.013 $W/m^2.K^2$), and the collector optical efficiency for beam radiation ($\eta_{0,b}$ = 0.44) characterize the thermal side of the CPVT.

Electrical performance coefficients

The temperature coefficient of electrical power β and the standard panel electrical peak efficiency $\eta_{el,STC}$ are 0.43 %/K and 8 %, respectively.

The system is located in Gävle, Sweden (Lat. 60.67°N; Long. 17.17°E) and on the year 2018 is characterized by an average global irradiation in the horizontal plane of 996 kWh/m^2/year which led to a system electrical and thermal annual efficiency of 4.2 % and 7.2 %, respectively. The relatively high operating temperatures for this system, connected to district heating, reduced the efficiencies a lot, but this was within expectations. The best performances for PTV systems are achieved within low temperature applications.

The use of SolarWall systems in Turkey

Another use that has become widespread for industrial applications in Turkey is SolarWall systems, Figure 19 and 20 [4]. In SolarWall systems, air heating technology is combined with photovoltaics. Through these systems, it is an integrated solution that reduces the overheating in PV panels.

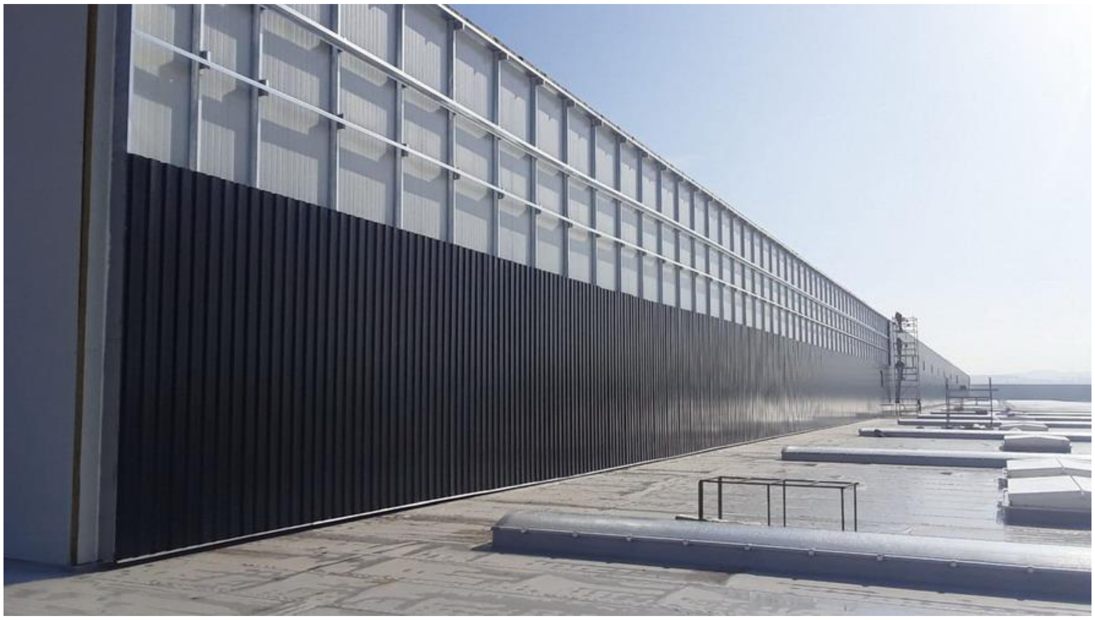

Figure 19. SolarWall PVT air heating systems

Figure 20. SolarWall PVT air heating systems

These systems are also called SolarDuct. These systems are an integrated solution that eliminates the overheating problem. The heat of these systems is directed to the building's HVAC system. The efficiency change for a 100% PV coated SolarWall is given in Figure 21.

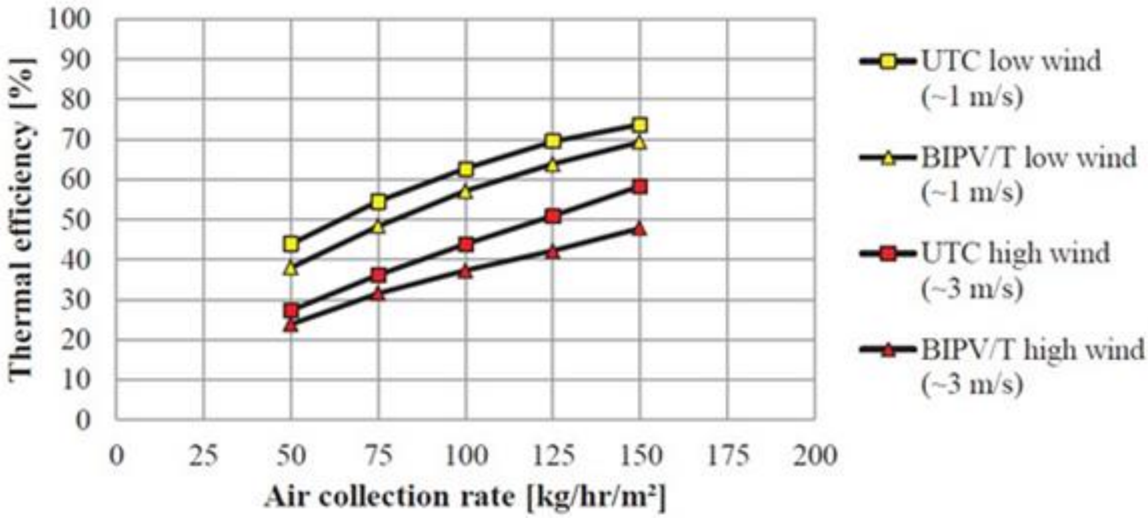

Figure 21. Comparison between UTC and adjusted BIPV/T thermal efficiency under low and high wind conditions [5T].

Best practices for PVT systems. Marketed systems in Turkey

Thanks to the incentives for electricity generation in Turkey, the PV market is constantly developing. In addition, hot water supply via solar collector is widely used in houses in Turkey, especially in the Mediterranean and Aegean regions. Moreover, it is common to use PV panels imported from China by small-scale companies in Turkey. On the other hand, applications for PVT technology in Turkey are limited. For this reason, the market for PVT applications is at the development stage. PVT panels are produced by Solimpeks, a firm established in Konya city in Turkey [1T]. In addition, PVT panels produced by the relevant company are also exported. The thermal parts of the PVT panels produced by the Solimpeks company change as water or air. In Turkey, currently, PVT panels produced by Solimpeks are predominantly used. In addition, industrial applications of PVT panels are carried out by the SolarWall company established in Istanbul, Turkey [4T]. Through these applications, the ventilation or process air required in commercial and industrial buildings is heated. Thanks to this application, the outside air is heated before entering the ventilation or process units, thereby reducing the heating load.

Best practices for PVT systems. Marketed systems in Potugal

The Hybrid Panel, as it contains the components of the two systems, photovoltaic and thermal, has a maintenance like that of the solar thermal system. Therefore, it is necessary to clean and check all components regularly to keep the system in good working condition. The normal maintenance procedures for these systems involve cleaning the accumulated dirt on the panels (mainly at the top), checking and, if necessary, correcting the state of the electrical connections, cracks, leaks, pumps and valves [3P] [4P].

Even though hybrid solar systems have been the subject of study for some decades, there are not many technologies in the market today. Listed below are the most successful technologies and brands currently on the market [3P] [4P]:

- Dual Sun, DualSun is a hybrid solar panel developed in France, and the company already has 800 installations and 15 awards.

- Solar Angel, Solar Angel is a hybrid technology with 250 W electrical and 650 W peak thermal developed in England. When installed correctly, they can produce 20% more than conventional photovoltaics.

- FotothermAl and Fototherm CS They were built in 2006 by the Italian company Fototherm. Both models are certified and are already on the market.

- PowerTherm and PowerVolt (Volther), these are two hybrid panels developed by the Turkish company Solimpeks, in which the first features a design to optimize thermal performance while the second is built to obtain better performance at the photovoltaic level.

- Abora is a Spanish company that operates in the design, development and manufacture of hybrid solar panels since 2017. This brand announces having the PVT market's most efficient panel taking advantage of 89% of solar irradiation.

- Solarus AB is a Swedish company founded in 2006. In 2020 was created the company Solarus Smart Energy Solutions B.V. that sell and develop high temperature PVT collectors - concentrating photovoltaic-thermal (CPVT) collectors.

Reference is also made to an English company that has been developing a promising hybrid technology known under the name Virtu, Naked energy (Virtu). This technology uses vacuum tubes with photovoltaic cells inside. In 2020, Virtu was not yet available on the market, but it already had several facilities for research purposes.

This section briefly presents the economic analysis carried out by Barbosa in his master internship [4P]. This work presents a comparative study among four hybrid panels, two photovoltaic panels and two thermal panels to meet the needs of a 1-bedroom apartment, a 5-bedroom villa and a bakery with its own manufacture in two different Portuguese cities (Lisbon and Covilhã).

The Hybrid panels under analysis are: Dual Sun; Fototherm AL; Fototherm CS; and PowerTerm.

As a comparison of the electric efficiency, the following photovoltaic panels were selected: Jinko250 and Rec250. To compare thermal performance, the following thermal collectors were selected: BaxiSol250; and Kaplan2.0 due to being the most common models in the country.

The simulations were considered for the climatic zones of Lisbon and Covilhã, with the panels oriented to the south with an inclination of 34°.

The choice of water tanks was based on those that best adapted to the needs of each case, for example a single tank of 100 L for the 1-bedroom apartment (as daily consumption would be 80 L) and a tank of 300 L for the 5-bedroom villa (adapted to a consumption of 240 L daily).

In this work, the economic study was carried out only for 1-bedroom apartment. Three different options were considered to satisfy its energy needs: a standard panel kit (Thermal Collector and Photovoltaic Panel), PVTs and lastly combined Heat Pump plus PV panels. The author concluded that the hybrid panel is not the best economic solution due to its high payback period compared to other systems [4P]:

- In the PVT panel with initial cost of €700 is obtained a return period around of 10 years. The accumulated savings after the lifetime (25 years) of the hybrid panel is €697.

- Standard kit, with initial cost of €900, has around 7 years return period and the accumulated savings after its lifetime (25 years) is € 1571.

- Heat pump plus PV panel, with initial cost of €1730 and a return period of around 7 years, reaches an accumulated (25 years) savings of €2700.

The longer payback period of PVT is due to the low thermal production in this application that is insufficient to cover the high initial cost. On the other hand, the combination of the Heat Pump system with PV panel, despite being a system with a higher initial investment, is the best solution. A combination of PVT and Heat pump cold though be interesting in the future if a whole system is developed.

Best practices Lithuania in very early stage

PVT modules are still a novelty in Lithuania and there are very few companies selling it on the market. PVT modules can be found in several manufacturers advertisements, but due to their price level compared to other alternatives today, they are not interesting for the consumer yet. No evidence was found that PVT modules are installed by at least a few households. In figure 22 an interesting flow pattern is shown for the absorber. Table 7 show typical costs in Lithuania.

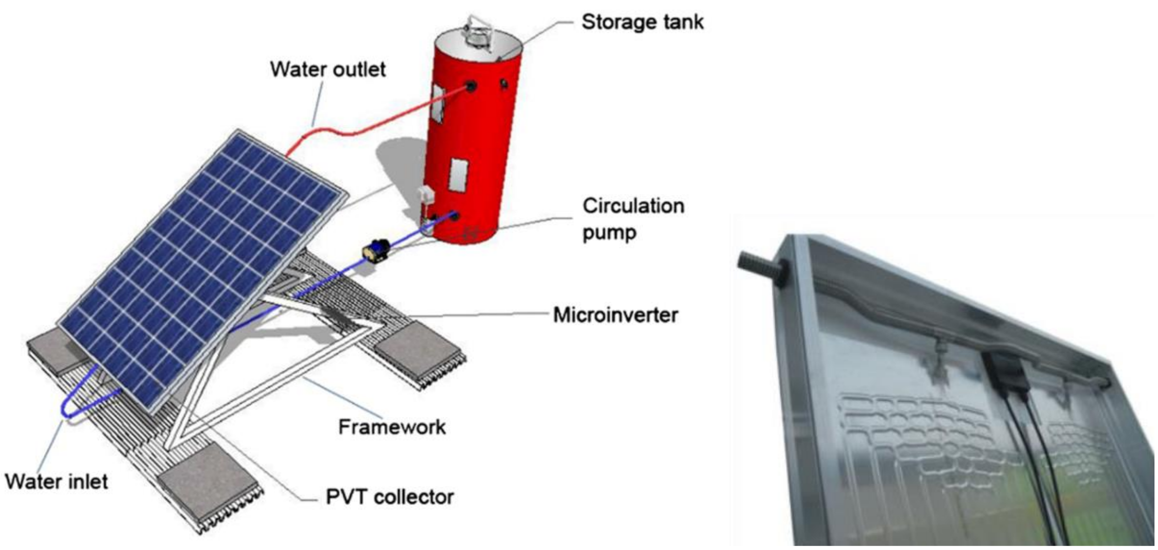

Figure 22. A simple PVT system in Lithuania. Note the absorber flow pattern to the right.

Table 7. Typical prices in Lithuania

Type	Collector Ensol E-PVT 2,0	Solitek PV	Flat Collector EM1V/2,0B	Vacuum collector SP S58-22
Price	753,01 Eur	163,35 Eur	419,95 Eur	492,25 Eur

Best practices for PVT systems in Denmark

Marketed systems by Racell are mostly building integrated and will replace wall and roofing materials, see figure 23. This requires extra care. Large modules are used, to reduce the number of connections and make the installation easier.

Figure 23. Roof integrated PVT panels in Denmark.

Another example is a demo system at a football clubhouse in Stenlöse in Denmark, with Racell roof integrated PVT collectors, see figure 24. The PVT system supports both hot water production and heating and reduce purchased electricity.

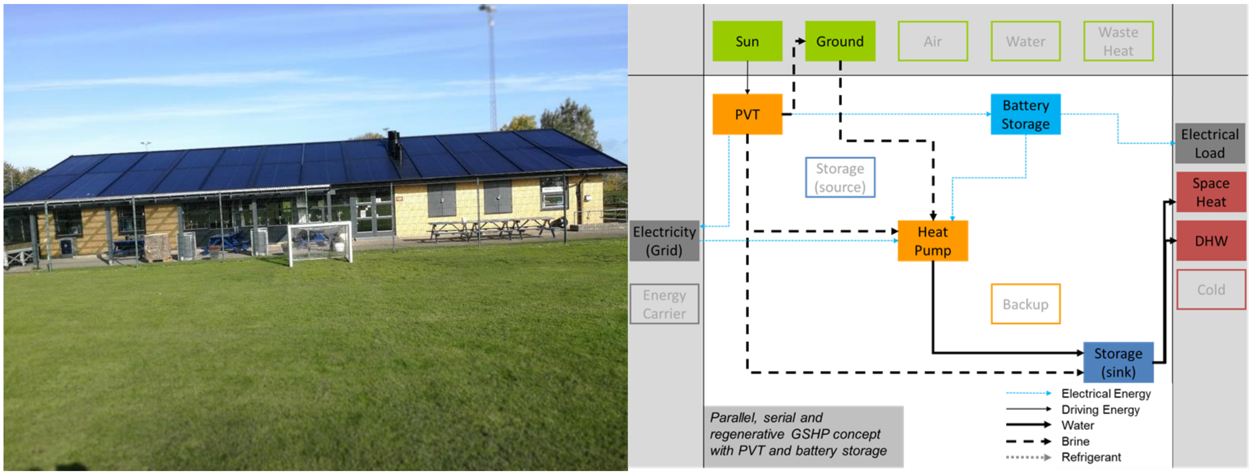

Figure 24. PVT roof integrated system in Stenløse, Denmark.

PVT/heat pump system installed in Ølstykke Denmark

Measurements for a PVT/heat pump system installed in Ølstykke in 2018 consisting of 35 m² roof integrated PVT panels, a modulating 3-12 kW Danfoss Varius Pro+ heat pump and a 7.5 kWh Fronius battery have been analysed. Figure 25 shows a photo and a principle sketch of the system. The system, which supplies all space heating and domestic hot water to the house, also included 60 m² PV panels on the north-facing roof. The heat pump is located in the depository attached to the northern wall of the house.

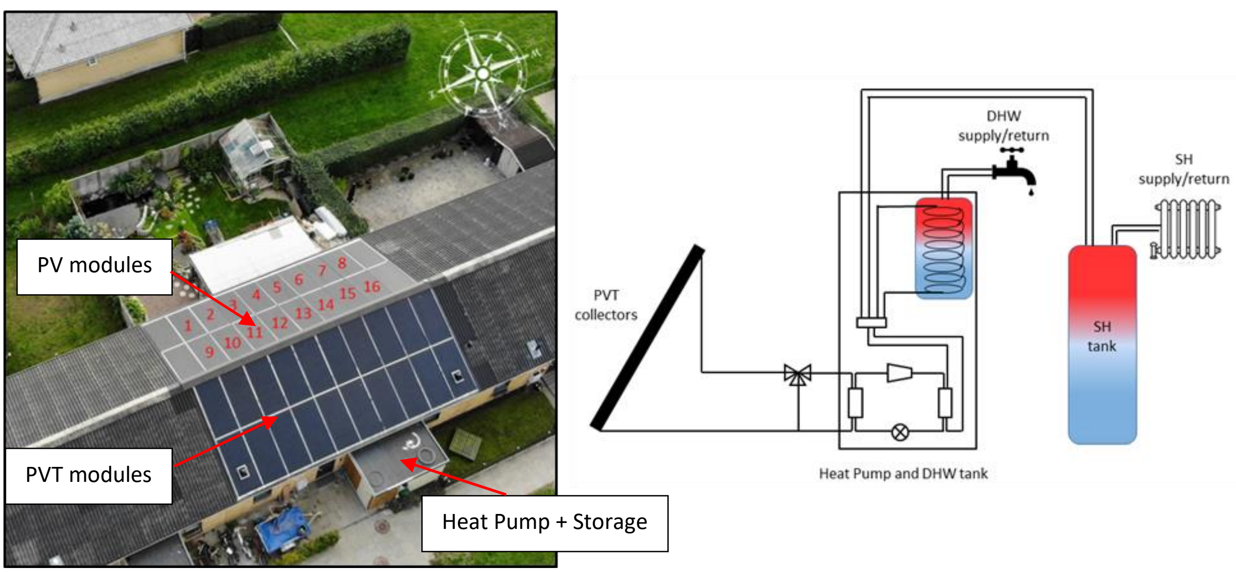

Figure 25. Aerial photo of the roof integrated PVT panels and schematic sketch of the system.

The PVT panels produces both heat and electricity and the heat is both produced by solar radiation and by the ambient air.

Measurements of the space heating demand and the hot water consumption of the house were carried out. The electricity consumption of the heat pump, the heat production of the PVT panels, the electricity production of the PVT and PV panels and weather data such as solar radiation on the PVT panels and the outdoor temperature were measured. The system was then simulated and validated to be able to generalize the results for future optimization of the concept.

PVT plus Heat pump test/demo system at DTU:

A PVT plus heat pump test system was built and monitored at DTU. The system was then carefully modelled by simulation and the system model was validated for later optimizations of the concept.

The main components in the test system are shown in table 8.

Table 8. Components overview in the DTY PVT heat pump test system.

Component	**Description**
PVT collector	3.1 m^2 PVT panel (WISC) from Racell Technologies
DHW storage	160 litres with two 0.75 m^2spiral heat exchangers
Cold storage	200 litres with two inlets/outlets in the upper part of the tank and two in the bottom part of the tank
Heat pump	Vølund F1155-6.
Controller	Technische Alternative UVR 63
Solar collector loop pump	Grundfos Alpha2 25-80

By adding a cold storage of 200 liter, the heat pump operation can be more flexible in time.

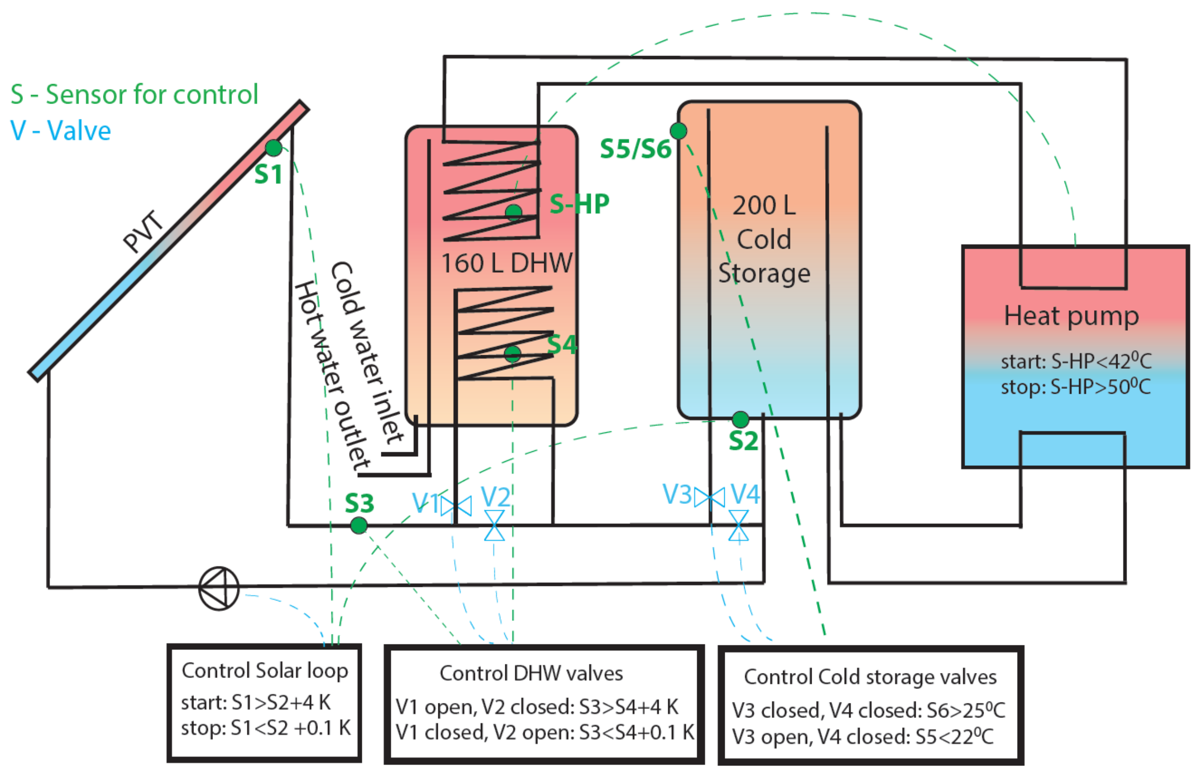

Figure 26. Illustration of the PVT test system at DTU and the control strategy and sensor locations.

5. Needs for different key actors

In order to establish a sustainable PVT system market there are needs for improvements on all levels. The following needs can be mentioned:

General needs:

a) Design Tools for PVT systems

b) Decreased costs for PVT systems compared to separate PV and solar heating systems

c) Development of simple and easy to install PVT systems

d) A complete test standard for PVT like for PV and Solar Thermal

e) Teaching on all levels, also architects and installers

f) Demo systems with proven performance and reliability. ”Bankability” = Banks/Investors rely on the technology to lend money.

g) Proven building integration designs.

Needs for Key Actors:

Researchers:

Development of standards for PVT panels

Development of standards for PVT systems

Development of planning/optimization tools for PVT systems

Manufacturers:

Development of improved PVT system types

Development of prefabricated components for PVT systems: PVT panels, heat pumps, storages etc.

Project planners, consultants, decision makers, energy planners:

Education on PVT systems

Different PVT demonstration systems in different locations followed during many years with the aim to document high reliability, high performance and long life time of PVT systems

Installers:

Installer education on PVT systems

6. Conclusions

The total installed PVT area has passed 1 million m^2 already in 2018 .

Many different PVT designs are available mainly differing on the thermal side for air or fluid heating and covered or uncovered or concentrating or non-concentrating.

The installed cost is still quite high per m^2 in the range from 500-1400 Euro per m^2 in 2018-2019 prices .

In small first demo systems the costs gets higher.

The combined heat and electricity output requires extra care when designing a system to get the best use of the energy and best economy. Two to four times more heat than electricity is produced. But the heat output varies strongly with the temperature produced.

Low temperature heat is produced with the highest efficiency in a PVT collector and therefore preheating of hot water, swimming pool heating, air heating or heat pump cold side loads are best suited.

Well proven tested products are available from a quite large number of manufacturers.

IEA SHC Task 60 has recently (Finished December 2020) published very useful material for deeper studies.

Checklist:

- The demand should match with production for both electricity and heat
- Try to match demand both in annual sum and monthly distribution level
- Do not oversize for the best economy.
- A heat pump needs both electricity and a cold side heat source. A PVT panel could be very suitable to deliver both energy needs.
- An outdoor swimming pool heat and operating electricity demand could match very well.
- In a large multifamily housing area with ground source heat pump, the PVT heat may be stored to winter in the ground and reduce electricity consumption for the heat pump by higher heat source temperatures in winter.
- Electricity efficient appliances in the house/system may match the PVT heat/electricity balance better.
- Reliability and durability should be addressed carefully. It is a long term investment with payment in advance for energy maybe 20-30 years. Then low operating and repair costs are crucial.
- There are many types of PVT that match different system types and locations best.

7. Links to materials used for this report.

Air heating PVT: https://www.optisolarpvt.eu/technology/ https://www.gseintegration.com/en/AirSystem.html

Fluid heating PVT: https://abora-solar.com/en/ https://dualsun.com/en/ https://racell.dk/ https://solarus.com/en/

IEA 60 systems overview: https://task60.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task60-A1-Existing-PVT-Systems-and-Solutions.pdf

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