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Review

# A Survey on Applications of Hybrid PV/T Panels

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**Abstract:** Photovoltaic-thermal (PV/T) collectors have gained a lot of attention in recent years due to their substantial advantages as compared to ST or PV systems alone and even to other non-solar technologies. However, PV/Ts are still not as popular in industry or construction and they are not even known to major players implementing solar energy installations. In this article, a general presentation of PV/Ts and a review of their applications are given. First, different heat extraction media (e.g., air, water, bi-fluid, etc.) and hybrid design configurations of hybrid PV/T collectors are addressed. Next, the main applications of PV/T collectors are discussed in order to highlight their feasibility and usefulness and to raise awareness for adoption in the industry and buildings sector. Applications include desalination, air-conditioning, drying, trigeneration, etc. This paper should be considered as a reference form of PV/Ts to extract key points for future research and development as well as for other applications.

**Keywords:** photovoltaic; solar thermal; photovoltaic/thermal; hybrid solar systems; applications



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## 1. Introduction

The standard of living has improved significantly, compared with a century ago and it has risen the global energy demand. However, fossil fuel energy usage is considered as the main factor for the rise in global temperature and the global average temperature has been rising at a rate of 1.7 °C per century since 1970 [1]. Warned by many researchers and scientists, many nations are adopting renewable energy technology which includes solar energy as the main component. Solar energy is clean and the most abundant energy source available around the globe. Photovoltaic-thermal (PV/T) technology uses solar energy and consists of a typical solar PV module, integrated with a solar thermal collector, which transfers the unused heat from PV module to heat transfer fluid. The PV/T system generates electricity using PV cells and thermal energy simultaneously as the sunlight is in abundance and easily accessible energy source. The solar cell converts this sunlight directly into electricity through the photoelectric effect, but the power output highly depends on the solar radiation, ambient temperature, wind speed, cell material, and age [2]. There is a wide range of solar cells available in the market such as polycrystalline/monocrystalline/amorphous-silicon, thin-film solar cells, etc. [3]. The concept of a PV/T system was first introduced by Florschuetz [4] in the early seventies of the 20th century and since then a lot of development has been made yielding to several designs of PV/T systems. Initially, the research work was carried on a flat-plate type collector where the performance of a PV/T system for a single-family residence has been analyzed over a full year [5]. Cox and Raghuraman [6] presented a mathematical model of a flat-plate collector and simulations have been performed to optimize the design. A flat-plate collector was developed by Lalovic et al. [7] and the experimental performance of a hybrid amorphous silicon PV/T system was measured. Currently, PV/T collectors convert approximately between 15–22% of absorbed solar radiations into electricity whereas remaining portion of the radiation is converted into waste heat [8]. In a PV/T system, this waste heat is transferred to the working fluid running below the PV module. The fluid can be air,

water (mixed with glycol to avoid freezing), or PCM. The material used for the production of PV cells is usually very sensitive to temperature and a rise in temperature makes PV cells less efficient [9]. This working fluid not only extracts the waste heat but also cools down the cell temperature which results in an enhanced PV performance. A glazed PV/T system that uses an additional glass cover over the PV module with an enclosed air space leads to higher thermal efficiency than an unglazed PV/T system due to lower heat loss from the collector surface but slightly reduces the PV efficiency of the module at the same time [10]. Unglazed PV/T collectors are recommended for cooling purpose, because of high heat losses as compared to glazed PV/T systems. Heat pump coupled with PV/T system has acquired much fame in the recent area of research. A merger of heat pump technology and PV/T system has characteristics of tri-generation (heating, cooling, and electricity) to fulfill the building's energy demand [11]. The integration is more efficient (with improved performance coefficient and overall efficiency) and reliable when compared to other PV/T systems [12]. Operating PV modules and heat pump system at the same time enhances electrical efficiency by absorbing the heat from PV modules as compared to operating them individually [13].

Even though PV/Ts have been studied for more than 3 decades, their popularity is still very low. As governments of many countries put the priority on electricity generation using solar power, the use of standard PV panels is still the main focus for the energy demand-response. In fact, big solar plants are mostly granted by the authorities upon a tendering procedure which generally only includes electricity components. On the other hand, in the building sector still get only offers with separated PV and ST panels. Besides, PV panel installers are generally not willing to install ST panels and vice-versa because both installations require different knowledge, expertise, and certification. Raising awareness of policymakers, energy companies and installers could yield to greater penetration of PV/Ts for solar installations.

The IEA [14] SHC (solar heating and cooling) programme has a special working group on PV/T systems (Task 60) and has published numerous reports. The aim is to raise awareness about the possibilities and benefits of the PV/T technology in order to create more confidence for solar energy industries, planners and customers. An overview of PV/T applications is provided in the report [15] 'Basic concepts of PV/T collector technologies, applications and markets'. A comparison of three different systems (PV, PV/T, and PV & ST) for three identical houses for the one-year period has been performed [16]. The results indicate that the PV/T system has better thermal and electrical yield compared to PV and ST alone. Additionally, the results showed that the electrical yield is almost the same for both PV system and PV/T system (with the similar area). Further, the existing PV/T collectors available in 2020 were summarized and the potential of PV/T technology, benefits and current barriers were also discussed in these reports. These reports presented in the SHC programme shaped the future of PV/T technology. Moreover, another report published by Keizer et al. [17] presented technological, social, economic, and political barriers and opportunities for the Dutch market.

PV/Ts have great potential for applications, for example:

- Home owners: They represent a very high potential to produce energy in order to use it for self-consumption or to share it within an energy community. In France, the average PV solar installation in homes has 3 kWp power. Adopting PV/Ts will also allow an additional 6 kWh (kW heat) which can be stored in a tank and used for sanitary or heating. The annual yield in northern France (where the sun is not so generous) is obtained by multiplying the power by the factor 1000 representing the annual radiation hours.
- Public buildings: Public buildings can be used for PV/T installations for self-consumption or sharing within the energy community for both heat and electricity. Besides reducing the energy bills and CO<sub>2</sub> emissions, they will constitute valuable demonstrators for citizen and thus enhance PV/T adoption.

- District heating: They are very popular in Europe with thousands of installations mainly in the cities. PV/Ts can be installed close to any entry point of a district heating to inject the heat used locally for the plant or be used as a complementary source generally through a heat pump to maximize efficiency. Indeed, a PV/T integrated with a heat pump is more efficient than a conventional PV/T heating system.
- Industrial applications: Drying and desalination have very intensive energy consumption. Solar plants with PV/Ts have been proven to be useful and efficient for such processes.
- Solar farms: To maximize the efficiency of land use, PV/Ts can be used when heating/cooling is needed in the vicinity. This may be the case for agroindustrial factories,

The widespread of the PV/Ts in the future will increase significantly if we understand the potential of their applications in order to raise awareness. This work presents an overview of the major applications of PV/T collectors from previously conducted research. Obviously, PV/Ts can be very profitable when simultaneous heat and electricity are needed [18]. This is the case in houses and buildings and also in some industrial processes such as desalination and drying which are intensive energy-consuming.

This paper is organised as follows: Section 2 gives a list of mediums used in order to extract heat from the PV/T collector. Section 3 provides major reported applications of PV/Ts highlighting the obtained benefits. The paper ends by conclusive remarks and perspectives.

## 2. Heat Extraction Medium

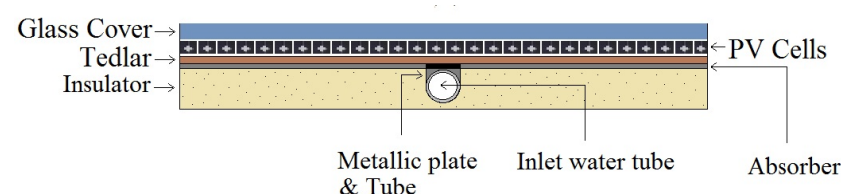
A heat transfer medium plays a vital role by extracting the unused heat from the PV module through circulation within the installation, otherwise, the temperature can go up to 80 °C. A rise of every 2 °C cell temperature can degrade the PV efficiency by 1% [19]. Liquid-based and air-based are the two common types of PV/T collectors used to extract heat from the collector. Liquid-based PV-T collectors are further subdivided into different categories which include water-based, refrigerant-based, and PCM-based PV/T collectors. Moreover, there is a bi-fluid PV/T collector that uses both air and liquid simultaneously to enhance thermal performance.

### 2.1. Liquid-Based PV/T Collector

A liquid-based PV/T collector can produce more energy than individual conventional PV and ST panels installed over the same area. One major advantage of using a liquid-based collector is high heat transfer because of high heat capacity and high thermal conductivity. A liquid-based PV/T collector can be sub-divided into the following categories.

#### 2.1.1. Water-Based Collector

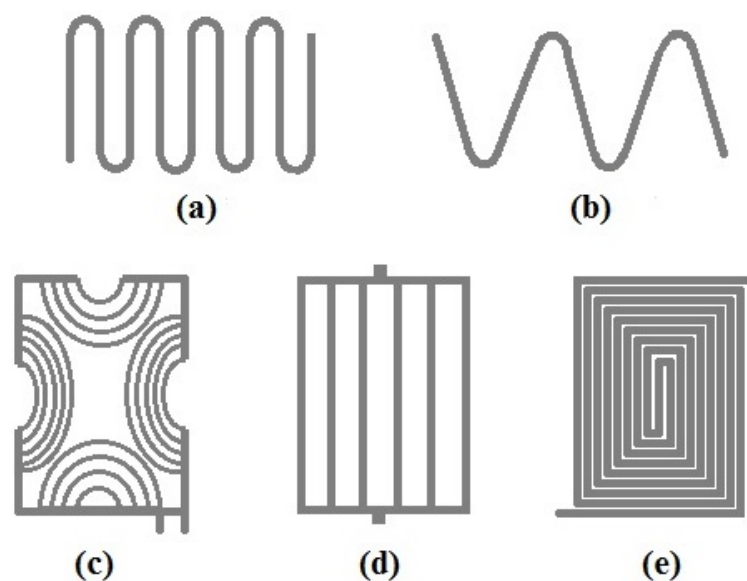
A water-based PV/T collector is the most common domestically used panel to extract heat using water as a medium which exhibits thermodynamic properties. These systems are further sub-divided into various categories [20]. In a tube PV/T collector as shown in Figure 1, a tube is fitted at the back of the panel and it can either be round or in a rectangular shape.



**Figure 1.** Sectional view of water-based photovoltaic-thermal (PV/T) collector.

The second category has a channel where it is either installed on top or under the PV module. The third category of water-based PV/T collector uses two absorbers, where a PV

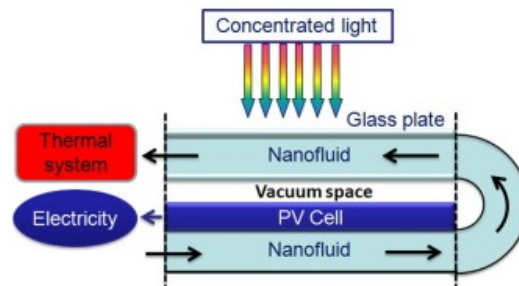
lamination acts as a primary absorber and a black colored layer on metal acts as a secondary absorber. Generally, black chrome over a nickel base or a titanium-nitride oxide layer is used on metals and is most effective [21]. These collectors have high thermal efficiency as compared to others. Roll bond is another category of water-based PV/T collector in which absorber plates are metallic, e.g., copper, aluminum or steel. In a tube PV/T collectors, there can be multiple tubes parallel to each other where water is injected from a single point and is distributed equally to all the tubes and warm water is collected from other end of the panel or it can be a single tube in a shape like moving snake (serpentine flow). The tube passage can be web-shaped, oscillatory, or spiral [22] as shown in Figure 2. To overcome freezing, water is mixed with glycol which protects metal against aging and corrosion. Glycol used in PV/T collectors is different from a typical propylene glycol. It is important to select a stable and efficient glycol otherwise the exposure to high temperature will result in degradation of the glycol and this will make fluid acidic and will create corrosion issues.



**Figure 2.** Flow passages of a liquid-based PV/T collector: (a) oscillatory flow, (b) serpentine flow, (c) web flow, (d) parallel flow and (e) parallel-serpentine flow.

### 2.1.2. Nano-Fluid Based Collector

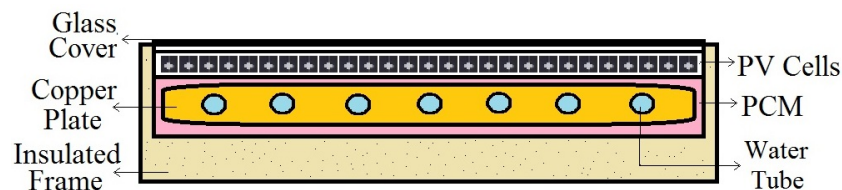
These types of collectors use nano-fluids which circulate as a working material with minimal change in the design as given in Figure 3 respectively. These fluids are composed of nano-sized solid metallic particles that are dispersed in base fluid homogeneously. In order to prepare nano-fluids, nano-sized particles must scatter and show high stability and chemical compatibility with the base fluid. There are two different processes to prepare a nano-fluid; a single step and two-step methods [23]. A two-step method is rather simple and is widely used to prepare nano-fluids but with less stability and dispersion [24]. These collectors exhibit better performance as the thermal conductivity of solid metals is superior to base fluids. However, there is also a downside of using these systems which includes; the cost of nano-particles, instability of fluid, and the increase in fluid viscosity, increases pumping power requirements [23]. Experimental investigations have been conducted on thermal conductivity and heat transfer of  $\text{Al}_2\text{O}_3$  nano-particles with water as a base fluid [25–28]. Sardarabadi et al. [29] considered metal-oxides/water as working materials to check the performance of the PV/T collector. The experimental results show that there is a significant improvement in efficiency using ZnO and  $\text{TiO}_2$ . Other than water, glycol can also be used as base fluids with oxides such as MgO,  $\text{TiO}_2$ , ZnO,  $\text{Al}_2\text{O}_3$ , and  $\text{SiO}_2$  to prepare nano-fluids [30].



**Figure 3.** Schematic diagram of a nano-fluid based PV/T collector [31].

### 2.1.3. Phase Change Material Based Collector

These collectors are in the early development stage and are similar to water-based collectors where water flows within the tubes. Additionally, it utilizes phase change material (PCM) within the PCM unit which is placed at the back of the PV module. A PCM material takes in or discharges an ample amount of energy during phase transition to provide heating or cooling. Water tubes are integrated with the PCM unit as presented in Figure 4, which absorbs and stores the heat within the material from the PV module. PCM materials have high energy storage density, high thermal conductivity, and chemical stability. During day time, these collectors operate normally when the solar radiation is available but during night time, the stored heat within the PCM material is used for heating purpose. Quantity and selection of these materials are very crucial because materials with low thermal conductivity will have a slow heat transfer and will not provide the required thermal energy. PCM materials used in PV/T collectors are divided into two categories, organic and inorganic. Organic PCM materials are derived from plants, animals, or petroleum products. These materials are safe, can be recycled but have low thermal conductivity. Inorganic PCM materials are cheaper, easily available, and have high thermal conductivity [32]. The most favorable PCM materials for heating water are myristic acid, palmitic acid, and stearic acid that keeps the high amount of heat for a longer period of time [33–35]. One of the most common and widely used PCM material is paraffin wax which is very economical, easily available as compared to other materials [36].

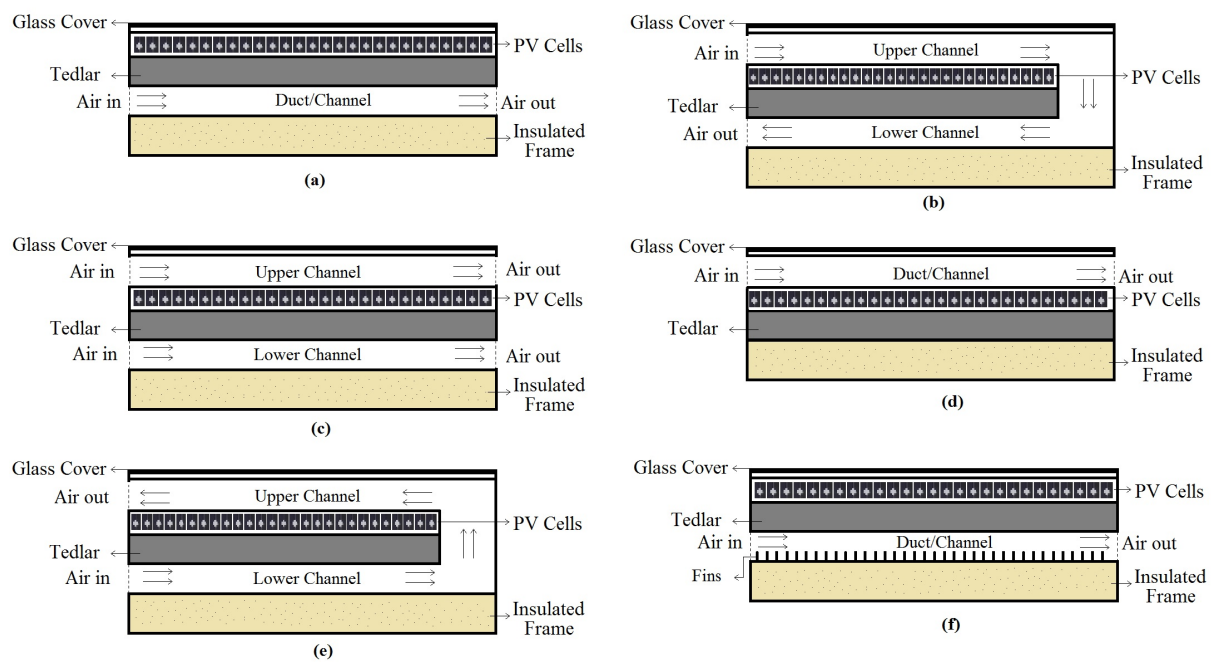


**Figure 4.** Sectional view of PCM-based PV/T collector.

### 2.2. Air-Based PV/T Collector

Air-based PV/T collectors make use of air as a heat transfer medium in order to extract heat from the PV module. Cold air is injected from one end and warm air is collected from another end of the duct. These systems are further sub-divided into various categories on the basis of air-flow pattern [37]: conventional air-based or back-pass air-based PV/T collector shown in Figure 5a is the simplest air-based flow pattern where air runs below the PV module in a single duct [38–40]. In a double-pass collector [38], the air is injected above the PV module and collected from the second channel below the PV module.





**Figure 5.** Different configurations of air-based PV/T collectors.

In this way, heat transfer fluid is kept longer due to the use of two channels as depicted in Figure 5b. Single-pass parallel PV/T collector [38] is also a dual air channel configuration where air flows parallel to each other in both channels, as shown in Figure 5c. Single-pass with a channel above a PV module [38] where fluid runs above a PV module, as shown in Figure 5d,e presents a double-pass collector where the air is injected below the PV module [40] and is opposite to double-pass collector shown in Figure 5b. To improve the heat transfer rate from the PV module to the air channel, aluminum fins were attached in the air channel, as shown in Figure 5f and these fins are placed in the lower channel in dual-pass configuration [41].

### 2.3. Bi-Fluid Based PV/T Collector

Bi-fluid-based PV/T collectors make use of air and water simultaneously, thereby enabling PV cell cooling and enhancing heat transfer. Cold air is injected from one end of the panel and warm air is received from the other side of the panel. A liquid that is mostly water mixed with glycol runs simultaneously perpendicular to the air channel. These systems extract and accommodate more heat, and provide higher output power as compared to single working fluid-based collectors. Bi-fluid based PV/T collectors can be further sub-divided into four categories: single-pass without glass cover, single-pass with glass cover, double-pass without thermal storage, and double-pass with thermal storage [37]. Figure 6 presents a layered diagram of a bi-fluid-based PV/T collector that uses air and water as heat transfer mediums. To get the maximum benefit from the PV/T collector, it is important to have some form of thermal storage that can accommodate and store all the heat extracted from the collector. For domestic purposes, PV/T systems are generally installed to preheat thermal storage for warm water or space heating. These systems have high electrical and thermal performances and provide warm air and water simultaneously. Higher cost and complex design are the major drawbacks of these PV/T collectors [20].

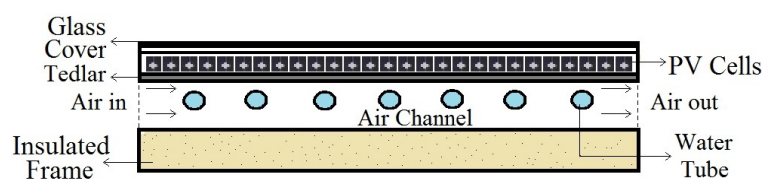


Figure 6. Sectional view of bi-fluid based PV/T collector.

### 3. Applications

PV/T collector has several applications such as building integrated photovoltaic thermal (BiPV/T) system, tri-generation, desalination, air conditioning, district heating/cooling, drying, heat storage, solar greenhouse, refrigeration, and industrial applications. In a report published in the IEA SHC programme [15], the applications of the PV/T system is divided according to their temperatures.

- Low-temperature applications take in heat pump systems and heating swimming pools or spas up to 50 °C.
- Medium-temperature applications are found in buildings for domestic hot water and space heating where the temperature of up to 80 °C is required. Further, PV/T integrated with a heat pump can be used for desiccant cooling that requires 50 to 60 °C temperature.
- High-temperature applications with a temperature above 80 °C are required for certain industrial processes, e.g., desalination and agro-industrial processes.

#### 3.1. PV/Ts versus PV + ST

In this paragraph, we compare hybrid PV/Ts with separate use of ST+PV panels in a given space area.

Let us consider a surface  $S$  in  $m^2$  with  $x\%$  PV panels and  $(1 - x)\%$  ST panels.

We denote  $C_{PV}$ ,  $P_{PV}$  (resp.  $C_{ST}$ ,  $P_{ST}$ ) the cost and the power per  $m^2$  of the PV (resp. ST) panels. Similarly, we denote  $C_{PVT}$ ,  $P_{PVT}$  the cost and the power per  $m^2$  of the PV/Ts.

Then at the surface  $S$ , the cumulative power (heat + electricity) at  $S$  is:

- for PV + ST:

$$S[xP_{PV} + (1 - x)P_{ST}] \quad (1)$$

- for PV/T:

$$SP_{PVT} \quad (2)$$

We assume that  $P_{ST} > P_{PVT}$  and  $P_{ST} > P_{PV}$  (which is generally the case). Therefore, PV/Ts provide greater power if the following condition is satisfied:

$$x > \frac{P_{ST} - P_{PVT}}{P_{ST} - P_{PV}}. \quad (3)$$

In terms of annual energy production  $E$ , if  $D$  denotes the number of radiation hours per year, then we have  $E = P * D$ . Therefore, (3) expressed in terms of produced annual energy remains the same because  $D$  simplifies so (3) is independent of  $D$ .

For numerical illustration, we consider standard conditions with radiation  $G = 1000 \text{ W/m}^2$ ,  $T_{cell} = 25 \text{ °C}$ , angle of inclination = 30°, orientation South, and we assume PV (resp. ST) panels with 15% (resp. 80%) efficiency. Therefore, we have  $P_{PV} = 150 \text{ Wp/m}^2$  and  $P_{ST} = 800 \text{ W}_{th}/m^2$ . For the PV/T, we consider 2 typical ones available in the market with the following features:

- Dualsun [42]: Unit area = 1.66  $m^2$ ,  $P_{elec} = 280 \text{ Wp}$ ,  $P_{ther} = 570 \text{ W}_{th}$ . Therefore  $P_{PVT} = (280 + 570)/1.66 = 511 \text{ W/m}^2$ . In this case, the above condition can be written  $x > 44.5\%$ .
- Solimpeks [43]: Unit area = 1.37  $m^2$ ,  $P_{elec} = 190 \text{ Wp}$ ,  $P_{ther} = 460 \text{ W}_{th}$ . Therefore  $P_{PVT} = (190 + 460)/1.37 = 474.5 \text{ W/m}^2$ . The above condition writes  $x > 50\%$ .



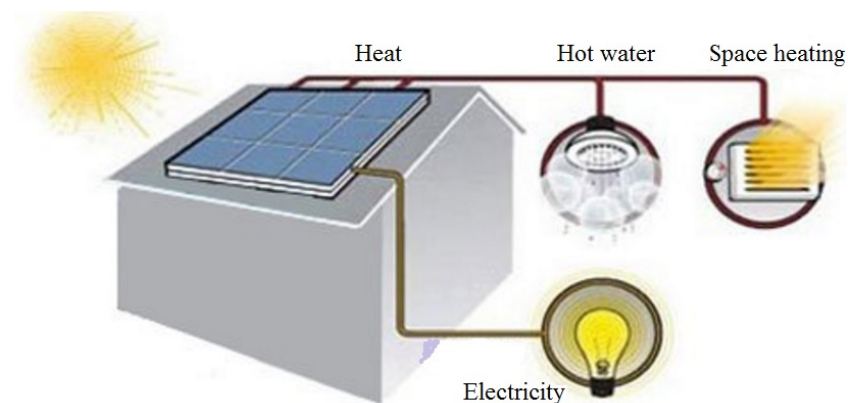
We see that both cases show that PV/Ts is better than the combination ST+PV because PVs generally cover wider areas than ST and their heat is not recovered. For instance in France, to meet energy transition requirements, new homes must use 2 m<sup>2</sup> ST panels or 5 kWp of PVs, but there is no regulation for PV/T.

### 3.2. Building

Today, one of the most common technologies of PV/T systems is building integrated photovoltaic-thermal (BiPV/T) systems that are mounted on the walls, occupies less space, and provides better efficiency. Globally, the building sector accounts for one-third of the total energy demand thus the use of PV/T systems in buildings is therefore of great importance [44]. These systems not only generate electricity but provide a comfortable temperature for domestic heating purpose and reduce the heating load by 27% [45]. In addition, building integration of air-based PV/T systems is more common than that of water-based systems. These air-based PV/T systems can be divided into two types [46]:

- naturally driven systems are those in which flow rate varies over time and it is difficult to predict the performance
- mechanically driven systems are those where the flow rate is kept constant and it is easy to estimate the performance.

The output energy obtained from these systems can be utilized for domestic water heating and space heating as depicted in Figure 7.



**Figure 7.** PV/T roof-top array supplying heating and electricity to building.

An experimental investigation has been conducted by Adnan et al. [47] where two PV/T panels with two different designs are used in order to obtain thermal and electrical power for building integrated applications. The first design which uses water as a working fluid in spiral flow configuration generates a combined efficiency of 64% with 11% electrical efficiency at a mass flow rate of 0.011 kg/s. The second collector which makes use of air as a heat transfer fluid generates a combined efficiency of 55% with 10% electrical efficiency. A comparative study has been performed experimentally by Yang and Athienitis [48] where single and multiple inlet PV/T designs were used for buildings. The simulation results showed that using a two-inlet design, the thermal efficiency is increased by 5.7% with a minor improvement in electrical efficiency. Furthermore, it is noticed that with the increase in mass flow rate, the fan power consumption increases which results in a decrease in electrical efficiency.

An air-based PV/T collector with a monocrystalline PV module was designed by Kim et al. [49] for the building and experimental results showed that the average thermal and electrical efficiencies were 22% and about 15%, respectively with an airflow rate of 240 m<sup>3</sup>/h. Another experimental study carried out by Pantic et al. [50] where he proposed three different configurations of air-based BIPV/T systems that use recovered heat for house heating. In configuration 1, the pre-heated air is used for the HVAC system preheating. In configuration 2, a high amount of heat that is stored in a rockbed heat storage

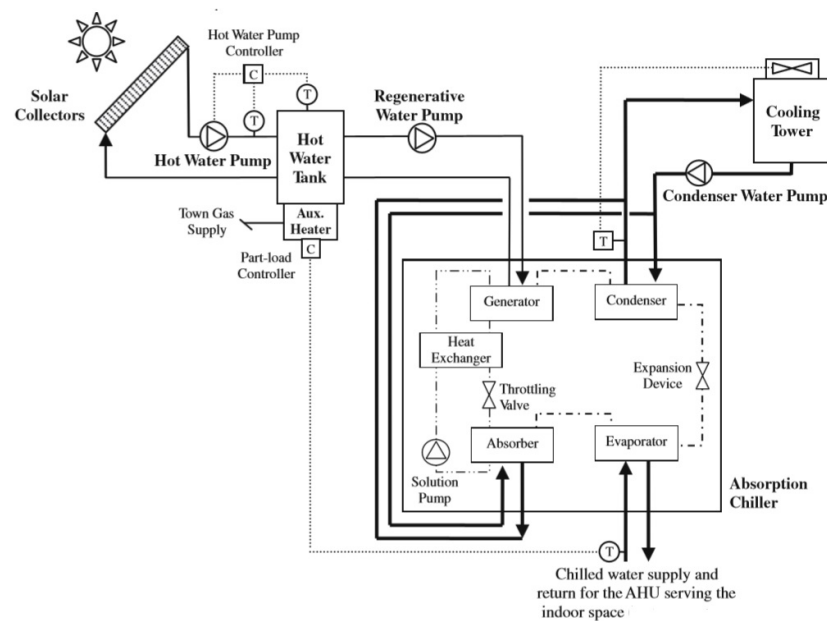
is utilized during winters with the enhanced thermal efficiency of 26.7% and with a drop in a heating load of 48.5%. In configuration 3, the recovered heat is 75% more than the first two configurations with a thermal efficiency of 42% but with an electrical power reduction of 25% with an electrical efficiency of 12.2% during winters. Lin et al. [51] analyzed the performance of a PV/T system with PCM as a part of the ceiling insulation, in which the results showed that the proposed design can raise the indoor air temperature up to 23.1 °C from the PV/T collector during winters. The proposed design can provide an average outlet air temperature from the PCM approximately 22.55 °C during winters without much fluctuation. Through night-time sky radiative cooling in summer, the ambient temperature drops with a mean temperature of 2.4 °C. The temperature change is small because of the weak radiative cooling effect. A water-based wall-mounted PV/T system has been studied by Ji et al. [52] which consists of a PV/T collector array (6 nos.), a water storage tank, connecting pipes, and a circulation pump. The proposed system not only provides thermal and electrical energy for domestic usage but also enhances the thermal insulation of the building. A similar kind of design was proposed by Chow et al. [53] where collectors are mounted at vertical facades. It was found that the thermal efficiency during the late summer of Hongkong was 38.9% at zero reduced temperature and average electrical efficiency of 8.56%. Furthermore, it was found that the space cooling load reduced by 50% in peak summer time compared with the bare wall situation.

A theoretical study conducted by Zhou et al. [54] where an analytical expression for connection of PV/T collector array was derived for a PV/T cogeneration system based on building energy demand. Further, an experimental setup comprised of 36 PV/T collectors was also established to validate the thermal model. The experimental results indicate that the total heat gain was 320 MJ with an average electrical and thermal efficiency of 10% and 23% respectively. Experiments were carried out to investigate the annual performance of PV/T collectors for residential application by Nualboonrueng et al. [55] during randomly selected day in March in Pathumthani province for medium-sized household Thai families in Bangkok using two PV/T collectors (amorphous and multi-crystalline silicon). The annual thermal production from the PV/T system was 1140 kWh/m<sup>2</sup> and electrical production was 72 kWh/m<sup>2</sup> with maximum energy output in March. The results illustrate that the thermal efficiency varies between 35% and 65% with the maximum efficiency achieved in January and the lowest in the month of June. It was also noticed that an amorphous silicon PV/T collector has better thermal efficiency but less electricity production than multi-crystalline silicon PV/T collector. The results of this study showed that the PV/T system is feasible and useful to provide thermal and electrical energy for residential applications in tropical regions.

### 3.3. Cooling (Air Conditioning)

Solar cooling using a PV/T system is in the early stage and is becoming more significant because most of the heat produced by the PV/T system gets wasted during the summer season and applying this heat for solar cooling purposes to drive the cooling cycle is a good idea. It can be achieved using various methods: absorption cycles, electric compression refrigeration, adsorption cycles, solar-mechanical processes, and desiccant cycles. A schematic diagram of the solar absorption cooling system is provided in Figure 8. A typical PV/T cooling system includes;

- Photovoltaic solar panel
- Storage tank
- Cooling unit (chiller) that operates thermally
- Control unit.



**Figure 8.** Schematic diagram of solar absorption cooling [56].

The performance parameters of hybrid PV/T solar heat pump air-conditioning system are investigated and analyzed under climatic conditions (i.e., solar radiation:  $610 \text{ W/m}^2$ , ambient temperature  $24.5 \text{ }^\circ\text{C}$ , and wind speed:  $0.05 \text{ m/s}$ ) by Fang et al. [57] through experimental studies on water-heating mode. Initially, the proposed system operates steadily with variations in evaporation and condensation pressure. The COP rises to 3.35 during the initial 10 min period, it experiences a minor drop of 0.21 in the next 10 min time due to a drop in evaporation pressure, and then it remains between (2.75–2.85) for the remaining period of time. The temperature of the conventional PV panel rises to  $62 \text{ }^\circ\text{C}$  with a 0.7% decrease in PV efficiency and the temperature of the PV panel drops to  $8 \text{ }^\circ\text{C}$  in the PV/T evaporator with an increase of 1.5% in PV efficiency. Modeling of PV/T collectors for night radiative cooling of buildings was presented by Eicker and Dalibard [58] where the simulation model is then validated through experimental studies carried out in Stuttgart using two prototype PV/Twin modules. The sky is considered as a blackbody for the estimation of sky temperature. Water-based open systems operate better due to high heat capacity and achieve high cooling output because of high water emissivity. The water consumption due to evaporation is not negligible and the results showed that it can be  $3.5 \text{ kg/night}$  and because of it the closed system with PV/T collectors was chosen in this study. The cooling power measured varies between  $100$  and  $120 \text{ W/m}^2$  with the mean mass flow rate of  $23 \text{ kg/m}^2\text{h}$  during the first night and  $28 \text{ kg/m}^2\text{h}$  in the second night. Furthermore, another experimental study using 12 large PV/T modules was also carried out for the Madrid climatic conditions with  $35 \text{ }^\circ\text{C}$  ambient temperature during the day time. The average cooling power measured was between  $43.1$  and  $65.6 \text{ W/m}^2$  with an electrical coefficient of performance between 17.2 and 29.3.

An experimental study was performed by Cremers et al. [59] using two differently designed hybrid PV/T collectors where the performance of PV/T collectors using backside shielding and without using backside shielding is evaluated to know better which building integration option is suitable for cooling applications. The use of backside shielding leads to a higher zero-loss collector efficiency factor and the heat loss coefficient increases that is better for the cooling. Alobaid et al. [60] evaluated that the use of solar absorption cooling systems saved 50% of primary energy compared to vapor-compression air conditioning systems and 10–35% maximum electrical efficiency of PV/T was achieved. A simulation model governed by five keyed mathematical models was presented by Sukamongkol et al. [61] to predict the performance of a condenser heat recovery with a hybrid PV/T air heater to regenerate desiccant for reducing the energy use of an air conditioning room. Experimental

tests were also conducted under outdoor and indoor conditions for three consecutive days to validate the simulation model. A consensus was noticed between the experimental measurements and simulation results. Here, the results showed that the hybrid PV/T air heater in cooperation with the condenser saved approximately 18% of the total energy used by the air conditioning system. The average daily PV/T photovoltaic efficiencies of the experimental and simulated are 6.45% and 6.05% respectively with thermal efficiency is approximately 60%.

#### Comparison of Grid Power, PV and PV/Ts for Cooling Purpose

The PV/T collector produces heat and electricity simultaneously. The heat produced by the collector is used during the winter season but there is a need for cooling during the summer season. The heat produced during summer time by the collector is used for cooling purposes using an absorption chiller. The summer season lasts around 6 months in the southern parts with 3 peak months. These months require 12 h of cooling whereas the other 3 months require 6 h of cooling. The cooling required annually is for 1620 h approximately if 6 months demand is assumed with 3 months partial usage and 3 months full usage.

- **Case I: Direct grid power for air-conditioning**  
A central air-conditioner on average uses 1 kWh per ton per hour [62]. Consider a two-ton air conditioner that runs for 12 h a day, the usage would be 24 kWh per day. The cost of electricity is assumed to be €0.30 per kWh (this depends on the country and €0.30 per kWh is for Germany, highest in EU-27 [63]). If the air-conditioner runs partially (6 h/day) and runs completely (12 h/day) for 3 months each then the total cost of using an air-conditioner for the whole year would be €972 (complete use: €648 and partial use: €324).
- **Case II: PV power for air-conditioning**  
The yearly total energy output of a mono-crystalline silicon PV collector is 194.79 kWh/m<sup>2</sup> and daily mean electrical yield is 3.21 kWh/kW<sub>p</sub>/day, respectively [18]. Approximately three PV panels are required to cover the cooling demand for the whole year (3 months complete and 3 months partial use). The average cost assumed is €0.16 and the total cost for the whole year would be €555 which is approximately 43% less than the grid power used to operate an air-conditioner annually.
- **Case III: PV/T integrating absorption chiller for air-conditioning**  
An absorption chiller takes surplus heat from the PV/T collector and provides cooling. Consider a PV/T with 73% thermal, 10.5% electrical efficiency, and a lithium bromide absorption cooler with a COP of 0.73. A PV/T with an area of 1.65 m<sup>2</sup> produces 2096.5 kWh of heat and 298.5 kWh of electricity annually. The yearly daily average yield of the collector is 5.75 kWh of heat and 0.82 kWh electricity with a total efficiency of 83.5% [64]. The annual cooling yield is 1540 kWh by using a single PV/T collector and approximately 2 collectors are required to cover the annual cooling demand.

The payback time of using a PV system is 6.1 years whereas the payback time for a PV/T system is 16.7 years, 2.7 times higher than the PV system [65]. A PV/T based absorption cooling system saved 50% of primary energy compared to vapor-compression air-conditioning system [60].

#### 3.4. Desalination

A process of removing mineral components from saline water using solar radiation is solar desalination which can be used for human consumption or irrigation. To stay alive, it is essential to have drinking water and PV/T-based solar distillation can meet the need for it by co-generating electricity and freshwater. Thermal desalination needs high temperature and this high temperature can be achieved using concentrating PV/T collectors. It is a promising solution to obtain drinking water and it is classified into two types;

- Active solar still
- Passive solar still.

A comparative study for different types of solar still models has been conducted by Sathyamurthy et al. [66] on the basis of performance. A self-sustainable PV/T integrated-active solar still has been designed and examined under New Delhi climate by Kumar and Tiwari [67]. The proposed design can be used in remote areas and produces more than 3.5 times higher yield than the passive solar still. Additionally, it saved 43% of the power used to operate the pump. A novel thermally driven multi-effect membrane distillation concept is presented by Ong et al. [68] for isolated islands and coastal regions by developing a mathematical model under steady-state conditions to predict the performance of the system with a prediction accuracy of 95.2%. The proposed modeling approach can be used as a design tool for larger scale-up membrane distillation systems. Moreover, the approach used is feasible, economical, and has a longer lifetime due to the use of polymeric materials. Kumar and Tiwari [69] presented an experimental investigation of two PV/T solar stills (single slope active and single slope passive) for the composite climate of New Delhi. The maximum production of 224 kg is obtained for active solar still and the maximum monthly yield of 100 kg was obtained from passive solar still during the month of July. The study has shown that the production during the month of December rapidly falls to approximately 100 kg for active solar still whereas it is less than 25 kg for passive solar still.

Further, a study on the PV/T hybrid active solar still has been done by Gaur and Tiwari [70] to optimize the number of PV/T collectors, and an overall picture of hybrid active solar still is illustrated in Figure 9. The results indicate daily yield is approximately 7.9 kg and the maximum yield takes place with four PV/T collectors. Moreover, it is noticed that by increasing the number of collectors, daily yield increases and daily solar still efficiency decreases 40% with the number of collectors increasing from 2 to 10 (with 50 kg mass of water and 0.055 kg/s mass flow rate). The daily yield and solar still efficiency decrease by increasing the mass of water from 50 kg to 200 kg with a 0.055 kg/s mass flow rate for the same number of PV/T collectors. A theoretical study has been done by Sotehi et al. [71] in order to produce fresh water under the climatic conditions of Ouargla city. The numerical simulations were performed for the whole year using TRNSYS 17 software to evaluate the performance of the system.

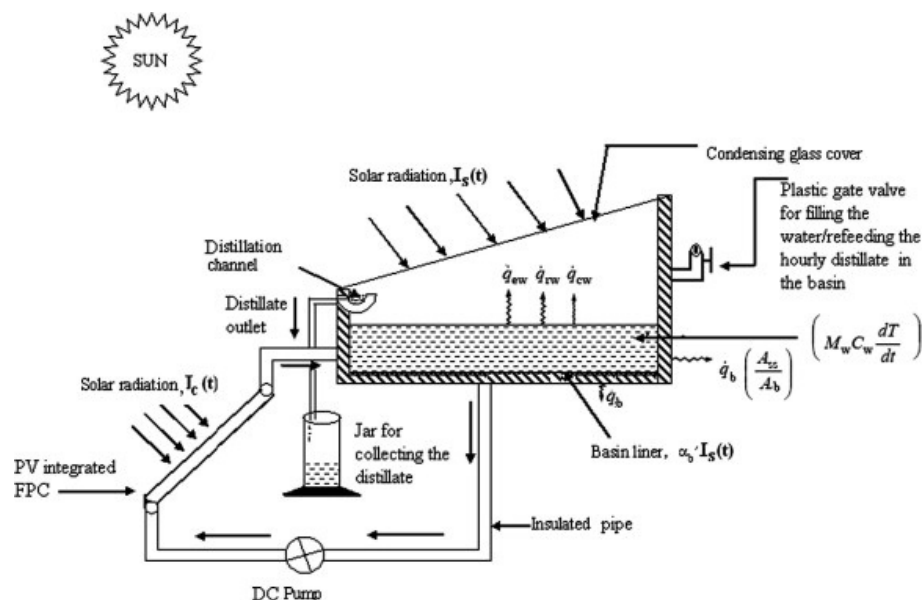


Figure 9. Schematic diagram of PV/T hybrid active solar still [70].

### 3.5. Greenhouse Drying

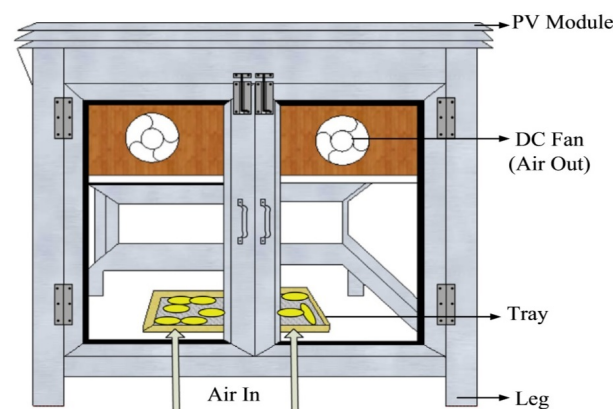
Tiwari and Tiwari [72] have developed a theoretical model for PV/T greenhouse solar dryer under forced mode to evaluate different parameters for the climatic conditions of New Dehli. The proposed theoretical model is also validated through experimental measurements. It was found that;



- The total thermal energy gain from the PV/T greenhouse dryer for January is 70 kWh and it is more than 130 kWh during the month of July.
- The total electrical energy gain is approximately 17 kWh during January and 15 kWh in the month of July.

The average overall thermal efficiency varies between 65% and 72%. It was concluded that the proposed greenhouse dryers perform well in all weather conditions.

Tiwari and Tiwari [73] conducted another study to evaluate the performance of PV/T mixed-mode greenhouse solar dryer. It was experimentally found that the overall thermal energy is 2.03 kWh and it was 1.92 kWh theoretically. Thermal mathematical modeling along with the design and fabrication of a PV/T integrating greenhouse for biogas heating is done by Tiwari et al. [74]. The proposed system incorporates 3 glazed PV/T collectors with greenhouse inclined at 30 °C from the horizontal plane and this PV/T system can be used for crop drying, improving the production of biogas, and crop cultivation along with the generation of electricity. The overall thermal energy for a clear day without load is found to be 12.76 kWh with drying chamber temperature exceeds 50 °C during the month of May for New Dehli climatic conditions. It is also noticed that regular dusting of PV/T greenhouse results in better thermal performance. The study concludes that the PV/T greenhouse is suitable for the production of biogas during both clear and cloudy conditions. Moreover, Tiwari et al. [75] then presented a detailed thermal model of an air-based PV/T integrating greenhouse drying system where mass flow rate can be varied by changing as the maximum allowable temperature for every crop is different. Overall thermal efficiency was found to be 56.30% with 11.26% photovoltaic efficiency at a mass flow rate of 0.01 kg/s. The proposed drying setup is useful during the daytime and it is recommended to use PCM-based thermal storage at night time. These systems give better performance under forced mode operation and are the most sustainable options for crop drying by integrating a DC fan as shown in Figure 10 and this fan is operated from the power generated by the PV module [76]. Koyuncu [77] explored that the overall performance of these greenhouse solar dryers can be improved using a chimney and black coated absorber. It was also concluded that the drying of products using a greenhouse dryer is 2–5 times more efficient than open sun dryers with better quality.



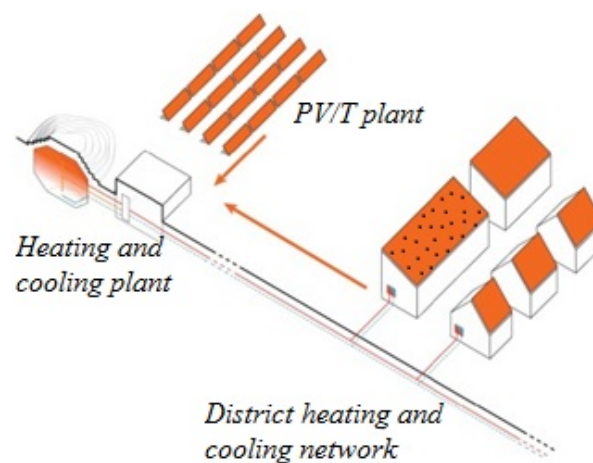
**Figure 10.** Schematic diagram of PV/T integrated greenhouse dryer [73].

### 3.6. District Heating/Cooling

Another interesting application of a hybrid PV/T system is district heating/cooling as illustrated in Figure 11. Generally, a large collector area can have a high cooling capacity and a larger collector area is linked with the storage that requires vacant space. Parabolic trough collectors are recommended for district cooling because they occupy more heat and have high thermal efficiency. This technology could be very useful for regions such as the Mediterranean, Gulf, and South Asia. The benefits of district heating/cooling include community energy management, safer operation, reduced CFC utilization via district cooling, increased reliability, reduced energy, and operation costs. A comparative case

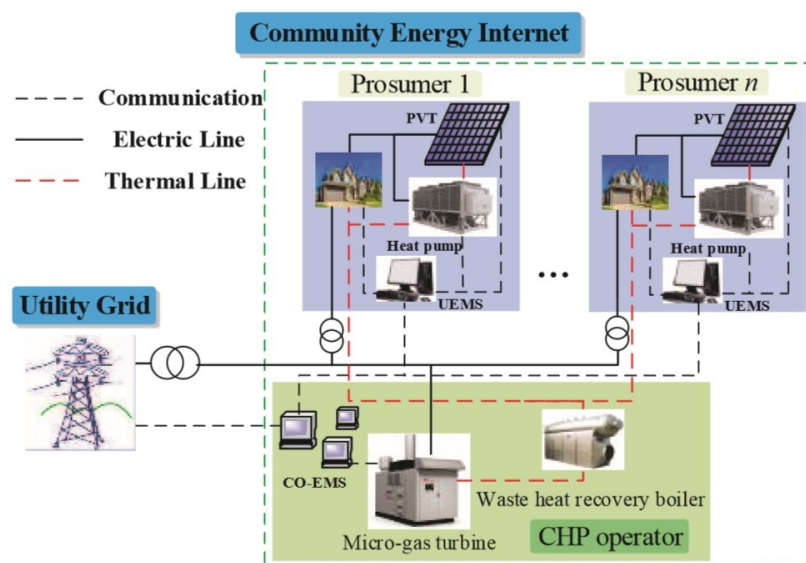


study has been done by Golla et al. [78] where a conventional cooling system is compared with the proposed absorption-based air conditioner. An absorption chiller that operates from the excessive heat produced by the PV/T plant provides cooled fluid to buildings within the district cooling network. In this study, it is assumed that the PV/T plant has an electrical efficiency of 12% with 70% thermal efficiency and a COP of 0.8 for absorption chiller. Mostly heating is required during the night and early morning time and cooling is required from 1 PM to 4 PM which goes with the peak production time from the PV/T plant. The number of hours when cooling is provided using PV plant alone is 988 h whereas the number of hours when cooling is provided using PV/T plant is 1617 h which is 62.9% more than the cooling obtained using PV plant. Optimal integration of hybrid PV/T technology in district heating systems is analyzed by Pakere et al. [79] in the Northern European climate. In this study, the assumed area is between 1000 and 3000 m<sup>2</sup> for eight different scenarios. The hourly analyses showed that the generated solar power ranges from 109 to 307 MWh per year and a higher solar fraction can be obtained with maximum PV/T installation but with higher cost.



**Figure 11.** PV/T district heating and cooling.

Community energy is the participation and ownership of defined community members in a renewable project to supply and share energy within the community and reduced the peak demand. In this, a thermal producer can be an electric consumer and a thermal consumer can also act as an electric producer depending on the energy usage. A consensus approach is used by Liu et al. [80] for distributed energy sharing in community energy internet (CEI) and the structure of it is depicted in Figure 12. A social welfare maximization model was built and a consensus-based fully distributed algorithm is designed to solve the problem. Additionally, the proposed model is validated by selecting six residential buildings. Solar radiation is available during the daytime only and as a result, electricity is in excess, the number of prosumer roles acted as an electric consumer is much high than the number of electric producers. It was concluded that if the heat pumps make full use of the waste heat from the PV/T collectors, the prosumers can make full use of solar energy. Further, an energy storage unit is recommended as a useful tool for solving the problem. A linear programming model for optimizing the structure and operation of a distributed energy resource system with district energy networks is presented by Luo et al. [81] on a virtual island with four buildings in the South China Sea. The results showed that the cooling consumption of building 4 is much lower than other sites despite the fact that PV/T collectors, water tank, and absorption chillers space are the same for all the buildings. The cost borne by building 4 is decreased by 16.11% when energy networks are applied. The surplus energy is transported to other sites to balance the energy system via the energy networks. The results indicate that this energy network reduced the cost of the entire system. It is also noticed that distance and imbalance between the energy supply and demand can influence the network layout to a large extent.



**Figure 12.** Structure of Community Energy Internet (CEI) with photovoltaic-thermal and heat pump (PV/T-HP) prosumers [80].

### 3.7. Trigeneration

In recent years tri-generation application is being intensively researched. A novel polygeneration system case study was presented by Calise et al. [82] producing electricity, space heating, and cooling and domestic hot water. The system includes PV/T collectors, an absorption chiller, storage tanks, auxiliary heaters, heat exchangers, pumps, controllers, and a cooling tower. The thermal energy obtained from the panels is used to run the absorption chiller whereas the electrical energy generated from the collectors is used for system loads and building lights. The supplementary electricity is transferred to the grid. The simulation results showed that it is technically feasible to produce electricity, space cooling, space heating, and domestic hot water all year long. In the study conducted by Zhou et al. [83], a roll-bond PV/T heat pump system was used to investigate tri-generation performance theoretically and experimentally during the summer season. The system goes to a co-generation mode in the winter time and has heating and electrical power generation. The mathematical model is validated and the simulation results are consistent with the experimental results. Here, the results showed that the proposed model has the potential to achieve tri-generation (hot water, space cooling, and electricity) for buildings with high efficiency and long-term stable working conditions. The daily cumulative electrical power generation was around 2 kWh with thermal energy of 6.13 kWh and cooling power of 18.5 kWh during the whole refrigeration process.

Another heat pump based trigeneration PV/T system is modeled by Joyce et al. [84] to meet the typical demand of an urban single-family. The system is designed to produce electricity, domestic hot water as well as heating, ventilation, and air conditioning (HVAC). The proposed tri-generation model is provided in Figure 13 with the simplest and reliable configuration. The simulations were performed for the Lisbon climate and it was estimated that 6188 kWh of annual energy is required to meet the comfort levels of the building (i.e., heating, cooling, domestic hot water, and home appliances). The results indicate that the system can generate electrical energy of 6795 kWh (PV: 5493 kWh and PV/T: 1302 kWh) at an average efficiency of 13.45% and 1618 kWh of thermal energy through PV/T collectors.

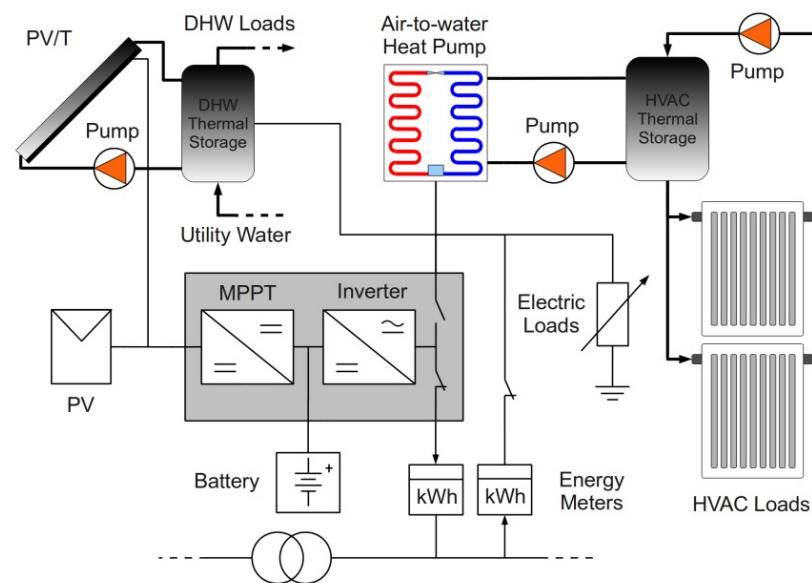


Figure 13. Schematic diagram of PV/T tri-generation system setup [84].

### 3.8. Refrigeration

Refrigeration is another possible application of photovoltaic-thermal systems and can be used in medical laboratories, malls, and slaughterhouses especially for isolated islands and coastal regions. Lu et al. [85] proposed a novel hybrid heat dissipation photovoltaic-thermal heat pump for refrigeration during a summer night. The steady-state simulation model of the system presented in this study has been established and is then validated through experimental measurements. The PV/T modules can make good use of night sky radiation and convection with the surrounding air with an average hybrid heat dissipation flux of approximately  $420 \text{ W/m}^2$ . The change in ambient temperature and wind velocity can have a significant influence on the PV/T module heat dissipation performance and system refrigeration performance. The experimental results also showed that the average  $\text{COP}_{ref}$  varies between 1.8 and 2.1 under various ambient conditions and is not much affected by the relative humidity of the air. The refrigeration performance of a photovoltaic-thermal heat pump system is investigated experimentally by Liang et al. [11] using 4 roll-bond photovoltaic-thermal modules in northern China on a summer night. A schematic diagram of the proposed PV/T heat pump system on the refrigeration mode is given in Figure 14. The refrigeration COP during the chilled water process under overcast conditions fluctuates between 2.4 and 3.0 with an average value of 2.66 and under the clear condition, it varies between 2.6 and 3.4 with an average value of 2.99, an increase of 12.4% than overcast condition. The results show that the proposed system is practically feasible and can achieve refrigeration with high-performance.

### 3.9. Heat Pump Integrated with a PV/T Collector

The priority is to save energy and lower the cost for the purpose of heating and cooling. The heat pump integrated with a PV/T system is more efficient than a standard PV/T heating/cooling system. These devices take heat from a low-temperature medium and transfer heat to a high-temperature medium. They can also work in places like Ottawa, Canada where the temperature gets extra chilly. The heat pump integrated with the PV/T system becomes less efficient when the ambient temperature drops because there is not enough heat produced by the PV/T system. The major advantage of using a PV/T system is the combined production of both electricity and heat. The electricity generated by the collector can be used to raise the temperature in order to get the desired temperature. According to natural resources Canada [86], an approximately 3.3 kWh of heat is obtained for every 1 kWh of electricity used to power the heat pump at  $10^\circ\text{C}$ . A PV/T collector

assisted with a heat pump can be used for cooling the PV module. Noro and Lazzarin [87] evaluated the economic performance of the hybrid PV/T heat pump system using eight PV/T collectors for a two-stage Italian house with a volume of 364 m<sup>3</sup>. In order to obtain domestic hot water, the inlet water temperature is set around 12 °C and the water delivered to the user is 45 °C. A control system is proposed to drive the system:

- For space heating, a three-way valve is supposed to bypass the storage if the temperature of the storage tank is lower than the water temperature from the radiant floor plant.
- Pump turns on if the solar radiation is >300 W/m<sup>2</sup> and the temperature from PV/T collector is >7 °C than storage temperature.
- Pump turns off if the temperature from PV/T collector is <3 °C and not taking solar radiation into account.

The average thermal and electrical energy produced by the PV/T collectors was 3315 and 2636 kWh/year for three different cities (Venice, Rome, and Crotona). Moreover, the results indicate that the primary energy saved is between 35% and 65%, and discounted payback of the investment can be around 10 years in mild climates. A study conducted by Kong et al. [88] where payback period of the unit was 7.87 years with an annual grid energy saving of 23.76 MWh using PV/T-cascade heat pump design. Koşan et al. [89] analyzed the performance of the PV/T assisted heat pump drying system. It was found that thermal efficiency varies between 38.51 and 70.56% with an average efficiency of 56.37% depending on ambient conditions. The average electrical efficiency obtained was 12.25% with a maximum efficiency of 14.02%. A numerical and experimental study conducted by Zhou et al. [90] to investigate the performance of a solar-driven heat pump system employing micro-channel PV/T modules for the room of 150 m<sup>2</sup> with room temperature remains at 18.5 °C. Figure 15 provides a schematic diagram of a solar-driven direct-expansion heat pump system. The average electrical efficiency of the PV/T system was 13.7% and the average thermal efficiency was 55.0%. The obtained simulation results are consistent with the experimental results, with a maximum error of 7.2%. Further, it was concluded that the use of a microchannel tube can improve the efficiency of the PV/T collector.

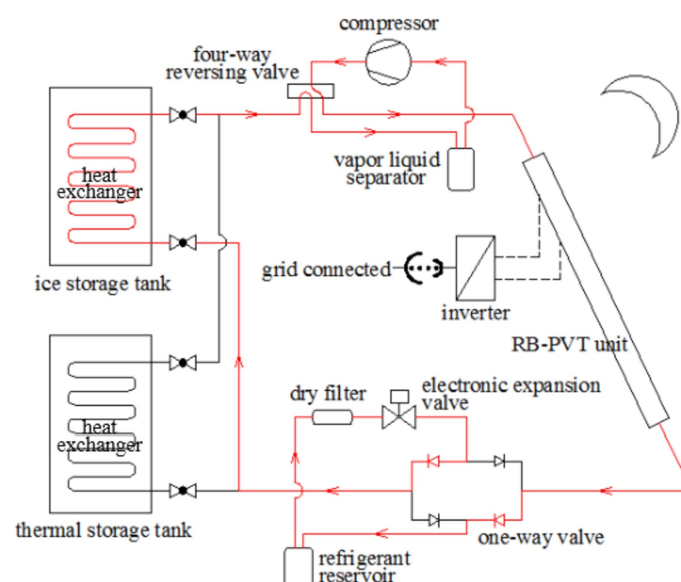
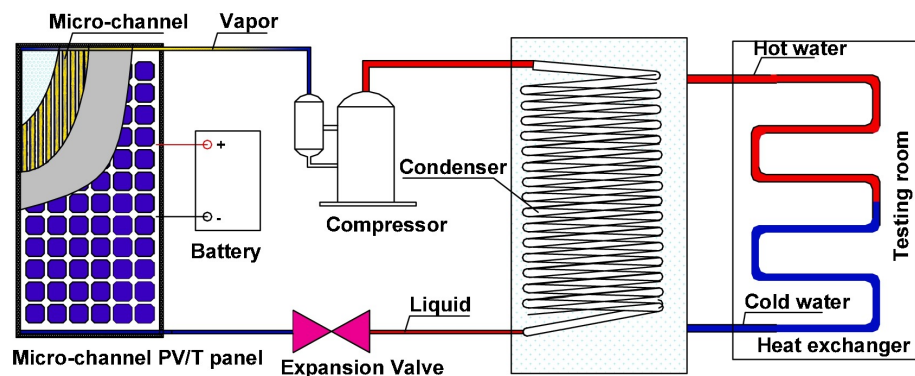


Figure 14. Schematic diagram of the proposed PV/T heat pump system on refrigeration mode [11].



**Figure 15.** Solar driven direct-expansion heat pump system employing the novel PV/minichannels-evaporator modules [90].

### 3.10. Software Tools

The feasibility study of a solar installation needs design and simulation tools to optimize the energy production taking into account different characteristics such as solar radiation in the considered location, panels technology, orientation, inclination, shadow, storage, etc. To this end, various software have been developed. Engineers and researchers use these simulation tools for the sizing of the power plant, pre-feasibility analysis and optimization, technical and economic analysis in order to avoid system over-size, poor reliability, and high installation and maintenance costs.

In [91], a review of 19 software tools for hybrid energy systems is presented: HOMER, Hybrid2, RETScreen, iHOGA, INSEL, TRNSYS, iGRHYSO, HYBRIDS, RAPSIM, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, SOLSIM and HYBRID DESIGNER. It should be mentioned that these software are general platform for an entire system (building, process, etc.) analysis, design and management and not only for solar. In addition to this list, there are many other specific solar software applications to be mentioned such as HelioScope, Aurora, BlueSol, Solarius, PVWatts Calculator, SolarEdge, Polysun, PVGIS, Candela3D, PVCASE, KACO, SMA Sunny Design, FRONIUS, PV Designer, PV-DesignPro, PV F-Chart, PV\*SOL, PVsyst, PVWatts, RetScreen, Solar Advisor Model (SAM), PV Planner, SOLARGIS, Solar Pro...

A number of these software tools are suitable for solar thermal plants to simulate hot water needs, definition of the hydraulic circuit of the installation, tank storage, collectors, etc. Besides, many photovoltaic inverters and solar thermal components manufacturers provide their one free software in order to size and design a solar system generally with their products (for instance inverters from MASTERVOLT Syscalc, INGECON SUN PLANNER, ABB Solar PVSize, etc.).

As far as solar energy is concerned, solar radiation and meteorological data are necessary. Related data is often embedded in the software tool or can be found using available databases such as Solcast, OpenSolarDB, World Radiation Data Centre (WRDC), SoDa HelioClim3, NASA SSE, Global Solar Atlas, Global solar Atlas, Worldclimate, etc. Note that in the software tools SOLARGIS, PVGIS, one can already find TMY data (typical meteorological year data).

Despite a wide choice of software tools for designing solar installations, they all have limitations. In [92], 23 solar PV design and management software tools are analyzed and their disadvantages are highlighted. This means that tools are needed but expertise is needed to enable the designer to achieve a good design. This is true for PV/T systems where electrical and thermal skills are required and no specific and dedicated tools are available.

## 4. Conclusions and Perspectives

This work provides a comprehensive review of heat extraction mediums and the application of the PV/T collectors. These systems have many potential advantages over conventional PV systems or conventional thermal collectors separately. They usually

provide more electricity and heat with limited roof space and will become more useful in the future. These systems integrate both the PV module and the conventional ST module into one unit and reduce the installation cost compared to two systems alone.

The combined efficiency (electrical and thermal) of the PV/T collector is higher than that of the PV module and solar thermal collector alone. The use of new materials, e.g., PCM, nanofluids and accurate dynamic models that provides a pragmatic and practicable performance of the system are needed to improve PV/T technology. The material used for the making of solar cells plays an important role in the performance of the PV/T system.

For the liquid-based PV/T collectors, it is recommended to optimize contact surfaces between the PV module and the tubes to enhance the overall efficiency of the system. The thermal efficiency of a water-based PV/T collector can be improved by adding a PCM or nano-fluid whereas for air-based PV/T collectors the efficiency can be enhanced by adding fins in the air-channel. The use of liquid is more efficient and recent developments showed that there is a shift from an air-based PV/T system to liquid-based PV/T systems integrated with a heat pump.

The use of PV/T systems in industries is still marginal despite they can contribute to cover both electrical and thermal energy demand. Applications such as solar cooling are still in the early stages and need a good deal of attention for large scale applications.

These systems offer numerous benefits but the drawbacks cannot be ignored.

- The initial installation cost of these systems is higher and additional space is required for their applications.
- A possible drawback of these systems is that they highly depend on weather conditions and additional energy input is required to fulfill the supply of energy, especially during the winter season. In summer, there may be a waste of excess energy during depending on the location but this can be solved through storage.

Despite an early introduction of these systems, the market is still very small compared to conventional PV systems or conventional thermal collectors.

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## Abbreviations

The following abbreviations are used in this manuscript:

BIPV/T	Building integrated photovoltaic-thermal
CFC	Chlorofluorocarbons
COP	Coefficient of performance
CPV/T	Concentrating photovoltaic-thermal
HVAC	Heating, ventilation, and air conditioning
IEA	International energy agency
PV	Photovoltaic
PV/T	Photovoltaic-thermal
PCM	Phase change material
SHC	Solar heating and cooling
ST	Solar thermal



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