

REVIEW

A Review of the Recent Development of Photovoltaic/Thermal (PV/T) Systems and Their Applications

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Hybrid photovoltaic/thermal systems have become an important energy technology due to their capacity of producing electrical and thermal energy simultaneously, their ease of integration into buildings and good overall performance. Conventional PV systems generate waste energy in the form of heat during the conversion of solar radiation into electricity. It has been shown that the electrical efficiency of PV panels decays with the rise in the PV cell temperature. Therefore, PV performance can be optimised if this heat is removed. Air and water are the most common media used for heat removal and the energy can then be used for heating applications in buildings. In the last five decades, researchers worldwide have carried out experimental studies, simulations and numerical modelling of different types of PV/T systems. In addition to water and air, heat removal methods such as refrigerants, PCM, heat pumps and nanofluids have been analysed. This work presents an overview and discussion of the research of the different PV/T thermal control systems of the last five years. The present study highlights key points of the different techniques that exist, such as overall efficiencies, parameters and configurations, type of system, the nature of work, country of development and applications. Based on this study, it was concluded that the PV/T systems are auspicious technology and that further work should be focused on the aesthetics of the systems to promote acceptance and improvement of the efficiency.

Keywords: photovoltaic; thermal; efficiency; air-based; water-based

1. Introduction

The reduction of global greenhouse gas (GHG) has been an important target for the last decades. This has led to an increased interest in alternative sources of energy that can meet future sustainability goals and protect our natural environment. A summary about the growth in global GHG made in 2018 by Olivier and Peters (2018), indicates that the emissions increased 1.3% in 2017 whereas the increase in 2015 and 2016 was only 0.2% and 0.6%, respectively. According to the same report, compared with 1990, today's global greenhouse gas emissions are about 55% higher. This huge emission of GHG results from the energy demand. According to the International Energy Agency, buildings are responsible for 33% of the energy consumed worldwide and 28% of the carbon dioxide (CO₂) emissions. Around 77% of the global energy demand in buildings is due to the heating and cooling, including space heating and cooling, water heating and cooking (International Energy Agency, 2019).

To contribute to the reduction of emissions, some countries have committed to decrease the use of fuels by using instead more efficient technologies and renewable sources such as solar energy. Solar power can be used to generate electricity or thermal energy through photovoltaic modules or thermal collectors. These devices can be installed in buildings to help with the reduction of energy consumption, providing electricity, Domestic Hot Water (DHW) and heating spaces.

Solar photovoltaics (PV) is a power system which comprises a sequence of interconnected components that work together to convert sunlight energy into electricity, utilise the generated energy, store it, or invert it (Shubbak, 2019). This technology has been one of the pioneering renewable technologies over the decades. The total installed capacity of solar PV reached 480 GW globally by the end of 2018, representing the second-largest renewable electricity source after wind (IRENA, 2019).

Solar thermal collectors are designed specifically to collect heat by absorbing sunlight and may be used to heat air or water for building heating. The radiation from the sun heats a liquid that goes to a hot-water tank. The liquid heats the water and flows back to the solar collector. Solar collectors are considered to be one of the renewable energy technologies with the best economics. They have

an estimated lifetime of 25 to 30 years or more and require very little maintenance except for control of antifreeze and pressure (Kubba, 2012). The literature has divided solar collectors into two types, stationary or non-concentrating and tracking or concentrating, the latter producing higher temperatures. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux (Gude, 2018).

Photovoltaic technology and thermal collectors can be combined in a single device called Photovoltaic/Thermal (PV/T), this device is formed by a PV module and a heat exchanger and it can generate both electricity and heat. Since the efficiency of a PV panel decreases when the temperature of the cell increases, removing heat from the photovoltaic module by having a fluid flowing through the collector avoids the loss of efficiency. Combining these technologies also alleviates building roof space issues that can occur with separate PV and thermal solar (Dean et al. 2015).

Even though both non-concentrated and concentrated collectors can be used to create a PV/T device, this paper is focused on providing an overview of non-concentrating PV/T systems due to their easier integration into buildings. However, recent studies made Singh and Tiwari (2017) and El-Samie et al. (2020) have been included.

Photovoltaic/thermal devices are an efficient way of utilizing the solar energy, for this reason, it has been a research topic since the late 1970s when researchers such as Kern and Russell (1978) and Florschuetz (1979) carried out investigations on flat plate PV/T collectors.

Authors such as Agrawal and Tiwari (2010), Bhattarai et al. (2012) and Adeli et al. (2012) analysed water-based and air-based PV/T systems at the beginning of the decade, being those conventional systems the most studied during the subsequent years. However, during the last five years, researchers have focused their work on several configurations of nanofluid, phase change materials (PCM) and heat pump PV/T systems.

Recent review papers written by Jia, Alva and Fang (2019), Diwania et al. (2020) and Rukman et al. (2019) include an overview of the different types of PV/T systems mentioned above, and despite some recent work is mentioned, all of them also mention experiments and simulations made on the previous decade. This review focuses on those last five years and intends to show other researchers the most recent development in this technology and what are the future contributions. In the following sections, a brief overview of the state-of-the-art of liquid-based, air-based, bi-fluid, refrigerant, heat pump, nanofluids, phase change materials and concentrated PV/T systems will be given.

2. Types of PV/T systems

Researchers have classified PV/T systems in different types throughout the years. This section reviews some of the most recent developments related to the PV/T collector with a focus on the application of building integra-

tion. The following PV/T systems are reviewed: air, water, bi-fluid, refrigerant, nanofluid, phase change materials, heat pump and concentrator type (**Figure 1**).

2.1. Liquid-based systems

A liquid can be used to remove the heat in a PV/T system. The liquid is pumped through channels in the heat-collecting plate mounted on the back of the PV module. The heat generated from the PV is conducted through the plate and absorbed by the fluid, cooling the PV module. According to researchers such as Makki et al. (2015), this cools the PV, resulting in higher efficiency yet also creates a lower temperature variation on the surface of the PV module and therefore, a higher overall efficiency. Current research focuses on PV/T collectors cooled with water, bi-fluid and refrigerant.

2.1.1. Water cooling

After reviewing the different components and configurations of a water-based PV/T, Aste, del Pero and Leonforte (2014) reported that this media has a better efficiency due to the higher heat capacity of the water, allowing stable PV temperature control.

In most of the literature, researchers have performed a theoretical and experimental analysis of water-based PV/T systems. In most cases, the final use of the heated water is to fulfil domestic needs. These studies included configurations of PV/T with glazing, without glazing, semi-transparent PV modules, partially and fully covered by PV modules, and use of different types of coatings, etc.

The performance of an uncovered PV/T collector was investigated with the aim of a mathematical model simulated in TRNSYS by Aste et al. (2016). The PV/T consisted of an uncovered mc-Si PV module, bonded with a roll-bond

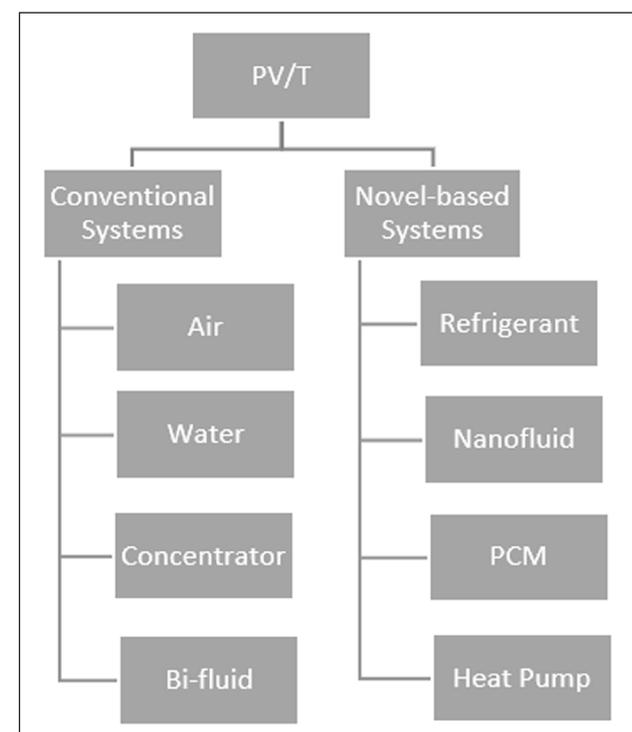


Figure 1: Conventional and Novel types of PV/T.

aluminium absorber, a cylindrical storage tank, a loop for forced water circulation and a pump (**Figure 2**). The experiment was carried out over two years in Milan, Italy. The results showed that the system can have a thermal efficiency of around 15% and an electrical efficiency of 10%, approximately.

Shyam et al. (2016) carried out experiments in New Delhi, India, using a PV/T water collector consisting of three single glazed tubes partially covered by semi-transparent PV modules. Some simulations were computed with MATLAB using different sky conditions. The results showed an annual overall thermal energy of 3561.9 kWh while the storage tank water could reach 80°C in a clear sky condition.

He et al. (2017) designed four experimental PV/T solar systems with PV cell coverage of 0.4, 0.56, 0.7, and 0.82. The influence of PV cell coverage on photothermal characteristics of a PV/T system was analysed, showing thermal efficiencies of 58%, 51%, 64%, and 67%, respectively, using 250 L of water to 50°C within 5 h (meeting local demand). It was concluded that by optimizing PV cell coverage, it is feasible to improve the thermal performance of the PV/T solar system.

Sainthiya and Beniwal (2019) experimentally investigated the effect of front surface water cooling on the

performance of a PV/T module during summer and winter conditions in India. The electrical and thermal efficiencies of PV modules with and without water flow in both summer and winter seasons were calculated using energy balance equations. The required parameters were measured continuously at 1h intervals from 09:00 to 17:00 daily. It was shown that the difference between the analytical and experimental results was minor, agreeing that water flow on the front surface of the PV module significantly reduces the back-surface temperature. This improves electrical efficiency to 11–14% in winter and 9–12% in summer. The thermal efficiency was also enhanced by 22– 25% and 17–22% in winter and summer seasons, respectively.

After a CFD simulation using ANSYS, an experimental setup of a PV/T water system was analysed by Misha et al. (2019) under the weather conditions of Melaka, Malaysia. The PV/T system consisted of a PV panel connected to a dual oscillating absorber made of copper (**Figure 3**). The PV module was connected to a 100 L water tank which was connected to the inlet of the flat plate collector. The outlet from the collector was connected to the heat exchanger and the cold water sent to the storage tank. The cold water from the storage tank was then pumped into the flat plate collector. The results showed an average thermal efficiency of 59.6% and an electrical efficiency of 11.71%.

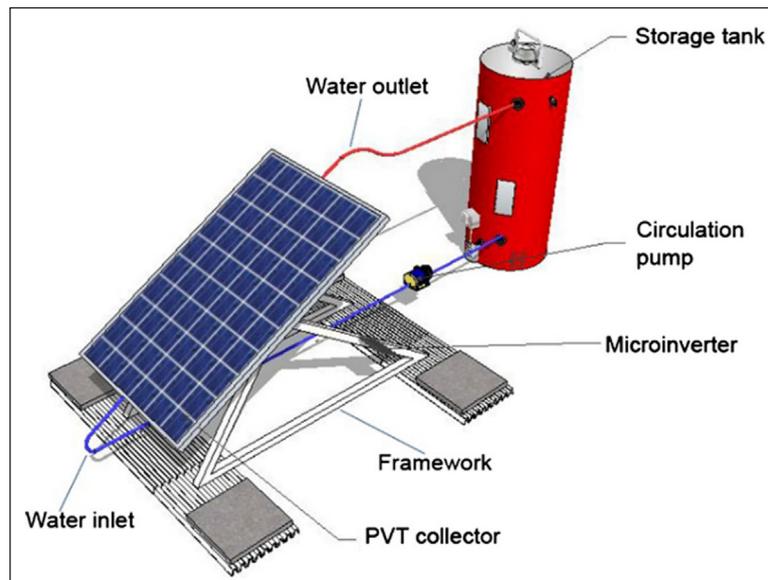


Figure 2: Uncovered PV/T collector configuration (Aste et al. 2016).

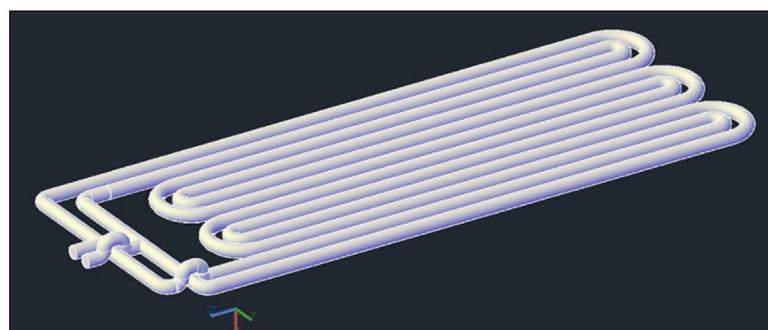


Figure 3: Dual oscillating absorber designed by Misha et al. (2019).

When the contact area of the cooling channel with the PV module is small, the heat transfer effect is affected. For that reason, an iron scrap filled tube-plate PV/T system was studied by Ma et al. (2020). By using a filling medium, the heat exchange effect of the system was enhanced due to the increase of heat exchange between the back-plane of the PV plate and the fluid inside the tube. The filling medium improves the thermal conductivity of the module and makes it useful as a building material. In this case, iron scraps were selected as a filling medium due to its cost, ability to incorporate metal resources and high thermal conductivity. For this experiment, a commercial monocrystalline module and the absorbing plate were bonded together with a layer of conductive cement. The heat collection module filled with iron scrap was placed underneath. **Figure 4** shows the structure of the PV/T system and the iron scrap bed. The average electrical efficiency and thermal efficiency of the filled tube-plate was 15.5% and 65.7%, respectively.

2.1.2. Refrigerant cooling

Various studies have shown that using a refrigerant as the cooling fluid has the greatest improvements in the PV/T's electrical efficiency. Despite this potential, recent research into the use of refrigerants has been limited due to its ozone depletion effects. The use of natural refrigerants such as CO₂ or NH₃ would be preferable as they are more environmentally sustainable.

Tsai (2015) studied a refrigerant-based photovoltaic/thermal assisted heat pump system under real conditions. The rig consisted of forty-eight solar panels arranged in two rows on a pre-coated steel support structure with of R134a refrigerant fluid in copper tubes adhered to a thermal absorber and polystyrene foam insulator, and a 200 L water tank. The experiment was conducted each day of June from 12:00 to 13:00. During this month, an average solar irradiance of almost 1 kW/m² was reached. The PV output current was between 30 A and 37 A and the output power between 800 and 900 W. The water temperature reached 50°C at the end of the experiment.

2.1.3. Nanofluid cooling

Nanofluids are fluids containing nanometre-sized particles, known as nanoparticles. These nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. They exhibit enhanced thermal conductivity and convective heat transfer coefficients compared to the base fluid. Incorporating nanofluids in PV/T systems is an advanced method that provides improved thermal management, increasing the overall energy yield.

Rejeb et al. (2016) experimentally and numerically analysed the performance of a monocrystalline silicon PV unit shown in **Figure 5**, using nanoparticles of Al₂O₃ and Cu at different concentrations (0.1, 0.2 and 0.4 wt%) and ethylene glycol and water as base fluids. The numerical model was developed using FORTRAN language with the

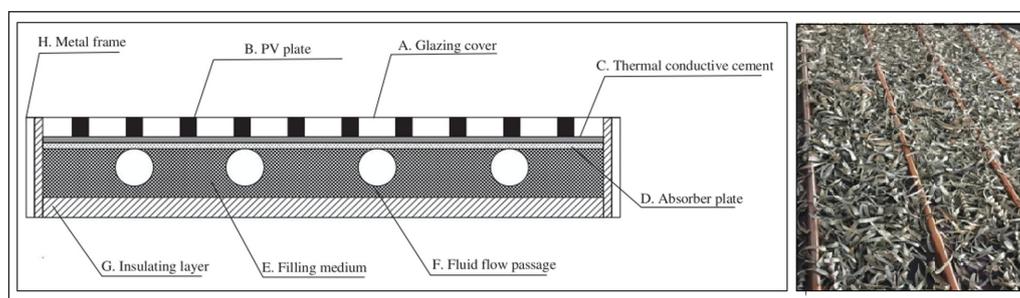


Figure 4: Cross section of the PV/T system and iron scrap filling (Ma et al. 2020).

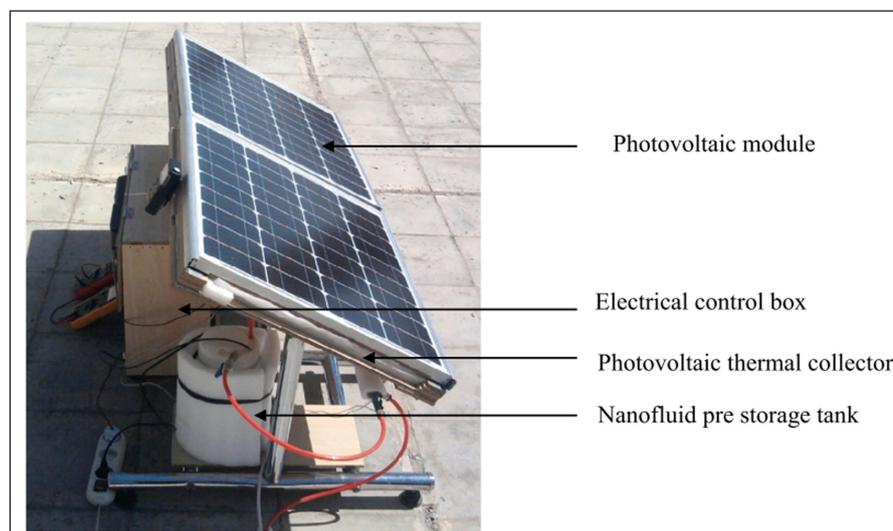


Figure 5: Experimental setup of the PV/T system studied by Rejeb et al. (2016).

experiments modelling weather conditions of Mashhad, Iran in late September from 9:30 to 15:30. It was noticed that the increase in the nanoparticles concentration leads to a degradation of the nanofluid specific heat. The results showed that CuO/H₂O at 0.4 wt% has the best thermal performance (76.88%) and electrical efficiency of 13.5%.

Hamdan et al. (2017) experimentally investigated the improvement of the PV performance using nanofluids for temperature control. Three modules were investigated, one being a baseline, the second used water cooling while the third used nanofluids. The basic idea behind the use of nanofluids is that they will provide a higher heat extraction from the PV as they have better heat transfer properties than water, therefore, the photovoltaic cell will produce higher electricity because it is cooled more efficiently. Different concentrations of Al₂O₃ and CuO were used. The optimum concentration for cooling for Al₂O₃ and CuO was 0.4% and 0.6% respectively. The increase in electrical efficiency for water Al₂O₃ and CuO cooling were shown to be 11%, 20% and 23% respectively. The results confirmed that the use of nanofluids in the thermal management of a PV module will improve its electrical performance.

Samyalingam et al. (2020) used COMSOL to numerically investigate the thermal performance of a PV/T system using MXene (Ti₃C₂) suspended in pure olein palm oil (OPO) as a heat transfer fluid. It was observed that this nanofluid improves the thermal efficiency, heat transfer performance and reduces the PV temperature. For the study, six different concentrations of MXene-OPO were used: 0.01, 0.03, 0.05, 0.08, 0.1 and 0.2 wt%. The results from the simulations showed that a concentration of 0.2 wt% with a flow rate of 0.07 kg/s has the highest thermal and electrical performance (79.13% and 13.8%, respectively) in the temperature range of 25–70°C. It was also observed that this concentration reduced the viscosity, resulting in a lower requirement of pumping power.

Rubbi et al. (2020) formulated a nanofluid from soybean oil (SO) and MXene (Ti₃C₂) particles. The numerical study was made in COMSOL using concentrations of 0.025, 0.075 and 0.125 wt%. During this study, it was observed that a concentration of 0.125 wt% of MXene-SO is better than the 0.2 wt% MXene-OPO studied by Samyalingam et al. (2020). MXene-SO showed 12.11% increment in the heat removal performance compared to MXene-OPO. This was attributed to the better thermal conductivity of

MXene nanoparticles as well as soybean oil in comparison to palm oil as a base fluid. It was concluded that thermal efficiency of 84.25% can be achieved at 0.07 kg/s mass flow rate, whereas the electrical efficiency obtained was 14.20% at the same flow rate (**Figure 6**).

2.2. Air-based systems

As its name suggests, air passes through an air-based PV/T system. This is done using the single or double pass and with an active or passive mode. Many researchers have worked with this type of collector, testing the efficiencies or optimising the design and configuration. As in the fluid-based PV/T systems, studies of air-based systems have been carried out using numerical models and simulations. Nowadays, these types of photovoltaic/thermal systems have thermal efficiencies of 32% to 34%, according to (Sathe and Dhoble, 2017).

A photovoltaic/thermal integrated greenhouse system for biogas heating was designed and evaluated by Tiwari et al. (2016) in climatic conditions of New Delhi, India in May. The system was formed by three glazed PV modules mounted on the roof of a single slope greenhouse, with two DC fans installed at the end of the duct (**Figure 7**). It was observed that the PV/T system can heat the greenhouse up to 47°C, a temperature that is good for biogas production. The thermal and overall thermal energy was 11.18 kWh and 12.76kWh, respectively, for a typical clear day. The electrical and thermal efficiencies reached 14.1% and 35.1%, respectively.

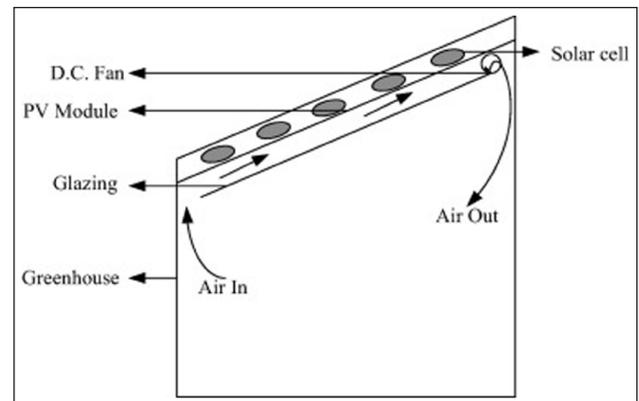


Figure 7: Cross-sectional view of PV/T system integrated in a greenhouse (Tiwari et al. 2016).

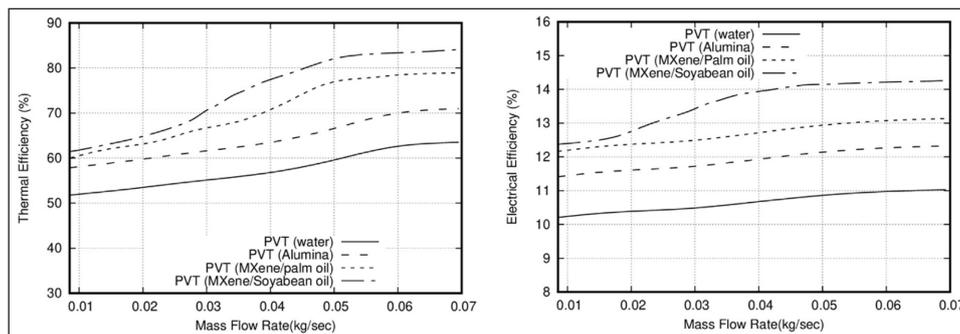


Figure 6: Performance evaluation of the thermal and electrical efficiency of a PV/T system studied by Rubbi et al. (2020).

Gholampour and Ameri (2016) numerically studied the heat transfer and flow of airflow of a PV/T flat transpired plate using a turbulent CFD model (in Fluent) and experimentally validated it under weather conditions of Kerman, Iran. The PV panel was mounted on a flat transpired plate with a small gap to allow air to flow (**Figure 8**). Two axial DC fans were used to draw air through the plate. The effect of different parameters such as location, suction air velocity, irradiance, ambient temperature and the PV coverage percentage was studied. The higher thermal efficiencies were achieved with a PV coverage between 45% and 55% with air velocities of 0.045 m/s and 0.06 m/s, yielding efficiencies between 75% and 80%.

A comparative study between a photovoltaic module, a conventional air-based PV/T, a glazed air PV/T and a glazed double-pass PV/T collector was presented by Slimani et al. (2017). All of them with a monocrystalline PV module attached. These were tested using numerical models and were validated with experimental results from other authors. The researchers used an airflow rate of 0.023 kg/s and weather data from the city of Algiers, Algeria. The results showed that the glazed double-pass system has the best performance with an overall efficiency of 74%.

Jha, Das and Gupta (2019) experimentally analysed and compared the energy performance of a flat plate and wavy plate PV/T air collector. The collectors consisted of two single glazed PV/T mounted with 100 W polycrystalline PV module, positioned on the top of a rectangular air channel. A mathematical model was first developed and then validated with an experiment under the weather conditions of Silchar, India. The experiment was performed from 9:00 to 16:00 during five days of June, using six different airflow rates. The results confirmed that the use of a wavy plate will enhance the heat transfer in a PV/T air collector but will require a slightly higher fan power. The thermal and electrical efficiencies of the wave plate PV/T were 34% and 13.6%, respectively, and the enhance of exergy efficiency compared with the flat PV/T was 8.4%.

Arslan, Aktaş and Can (2020) experimentally and numerically investigated the performance of a finned air-based PV/T system in Ankara weather conditions. Firstly, the fin structure was modelled and analysed using ANSYS, then the PV/T collector was designed and built. To allow air to enter the collector, two channels were opened under it. Two AC fans were placed at the air outlet to allow the incoming air to be transported upwards (**Figure 9**). The experiments were carried out at two mass flow rates,

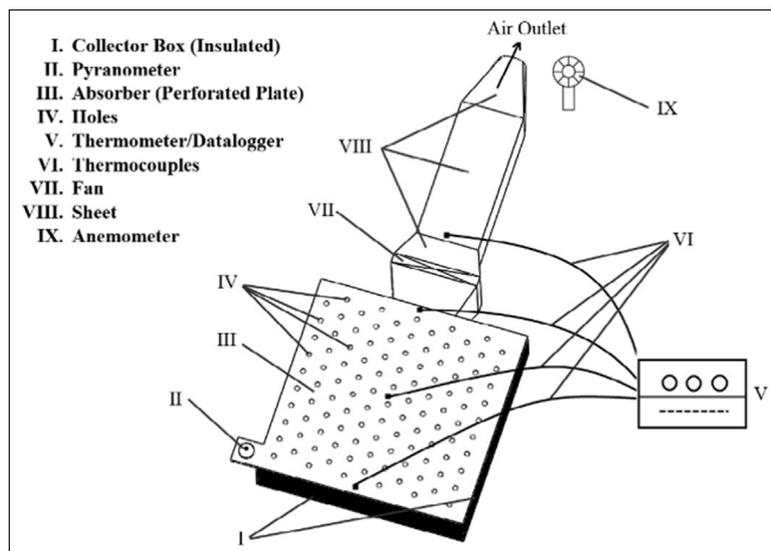


Figure 8: Schematic view of the experimental set up (Gholampour and Ameri 2016).

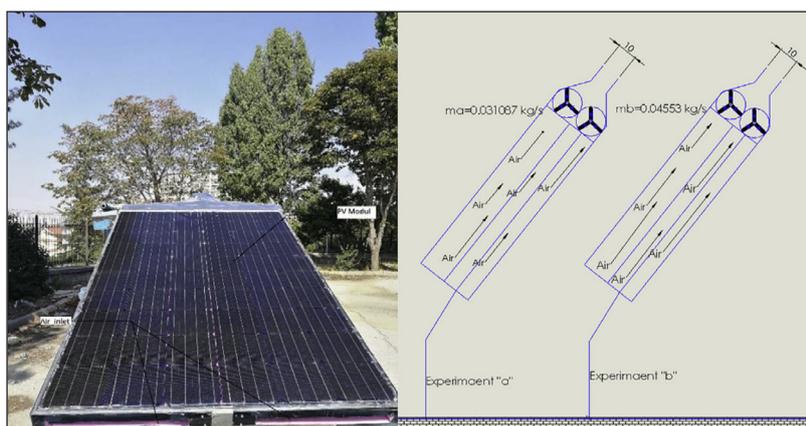


Figure 9: Experimental setup (Arslan, Aktaş and Can, 2020).

0.031 and 0.045 kg/s. The average thermal and electrical efficiencies at 0.031 kg/s were 37.10% and 13.56%, respectively and 49.5% and 13.98% at 0.045 kg/s.

D. Kong et al. (2020) studied a solar hot-air drying system, looking to propose new solutions for the agriculture. The system was formed by two types of PV cells to test the performance of two PV/T systems; amorphous silicon thin-film and polycrystalline silicon. Both systems were connected to the same inlet air and were composed of the same elements; glass cover, absorber plate, insulation layer and air channel with fins. The hot air coming from the collector was sent into the drying chamber where 12 DC fans were placed to strengthen the hot air movement and to eliminate the stagnant hot airflow zones whilst maintaining uniform humidity and temperature in the chamber (Figure 10). The average thermal efficiency of the amorphous silicon and the polycrystalline PV/T system was 48.9% and 42.9%, respectively. The average electrical efficiency achieved 10.4% on the amorphous silicon and 12% on the polycrystalline panel.

2.3. Bi-fluid systems

Only a few researchers have studied PV/T systems with two fluids. Water and air have been used in those types of systems to provide hot air, hot water and electricity at

the same time. As previously mentioned, this type of system combines water and air heat exchangers and have low operating costs and minimal use of material but have a reduced thermal to electrical conversion efficiency (Sathe and Dhoble, 2017).

Othman et al. (2016) fabricated a system formed by two transparent PV modules connected in parallel, double pass flat plate air collector, copper water tube and a storage tank (Figure 11). The experiment was conducted under solar irradiance from 350 W/m²–800 W/m² and fluid mass flow rate from 0.01 kg/s–0.10 kg/s. The numerical results showed that the electrical efficiency can reach 17% and the thermal efficiency can reach 76% with an average outlet temperature of 27.4°C when having a solar intensity of 800 W/m². Those efficiencies were achieved when having an air mass flow rate of 0.05 kg/s and 0.02 kg/s water mass flow rate.

Another 2D steady-state analysis was developed by Jarimi et al. (2016) using MATLAB and a solar simulator. As in Abu Bakar et al. (2014), three modes of operation were tested: air mode, water mode and simultaneous mode. The simultaneous mode was divided into two sub-modes: fixed air flow rate and fixed water flow rate and they were tested under average solar radiation of 700 W/m². It was observed that when one of the fluids flow rate increases,

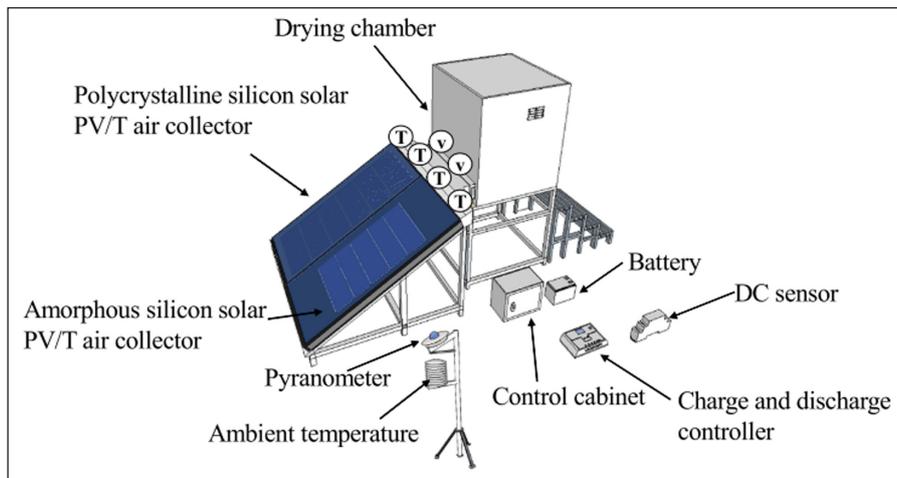


Figure 10: Schematic diagram of the drying system proposed by D. Kong et al. (2020).

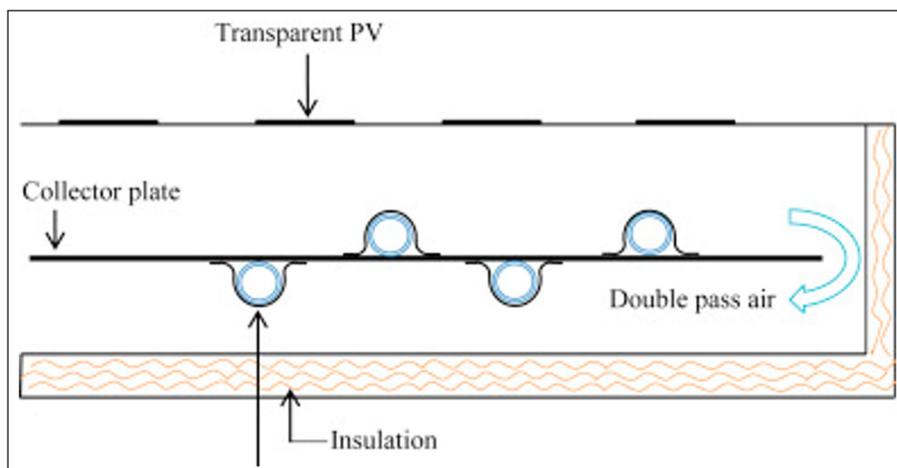


Figure 11: Structure of the combined PV/T system studied by Othman et al. (2016).

the efficiency of the other fluid decreases. It was also observed that the simultaneous use of the fluids compensates one another in extracting the unwanted heat from the collector into useful energy. When the airflow rate was fixed at 0.0262 kg/s the total thermal efficiency was around 65.70% and when the water flow rate was fixed, the thermal efficiency was around 66.12%.

Su et al. (2016) studied the performance of a PV/T solar collector with dual channels for different fluids. The configurations used were water-air, air-water, air-air and water-water and can be observed in **Figure 12**. To test the system, the weather condition of Nanjing, China on a summer day was used and the wind speed was assumed to be stable. It was observed that the cell temperature varies from 29.7°C to 46.3°C when using the water-water mode and varies from 32°C to 112°C when using the air-air mode with the conclusion that the water-water mode can

extract more heat than the air-air, where the water-water mode had a higher electrical efficiency (7.8%). Regarding the thermal efficiency, the water-water mode reached 64.4% so it was concluded that the water-water mode is the best in both electrical and thermal performance. This operation mode reached an overall efficiency of 84.2% when the mass flow rate of water is 0.15 kg/s.

A self-cleaning PV/T bi-fluid system was experimentally analysed by Lebbi et al. (2020) under the climatic conditions of Ghardaïa, Algeria. The rig was formed by an aluminium flat plate, two DC fans connected to the outlet to extract the hot air and a perforated plastic tube with 16 nozzles at the top edge of the module to ensure active cooling and self-cleaning, this can be observed in **Figure 13**. The results showed that the system can reach an electrical efficiency of 13.17% when the irradiance is 650 W/m² and average thermal efficiency of 50%.

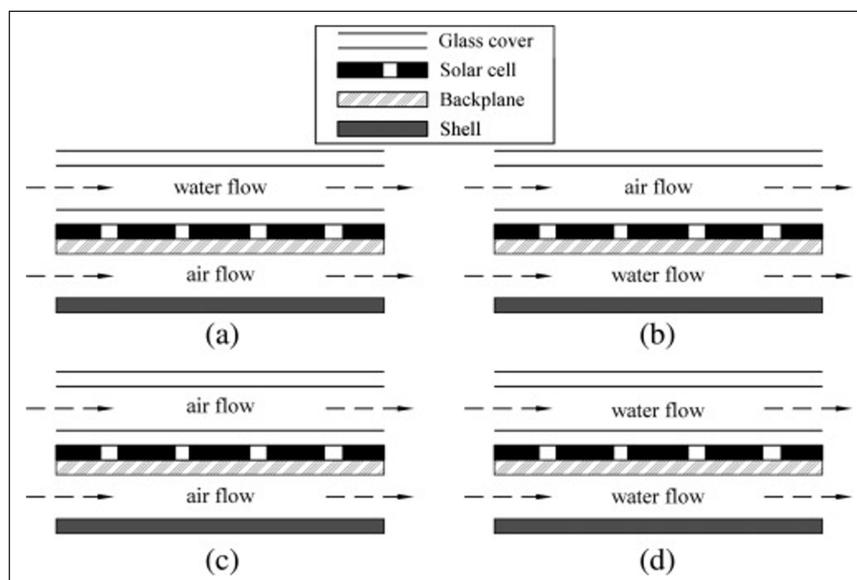


Figure 12: Configurations of a PV/T collector with dual channels (Su et al. 2016).

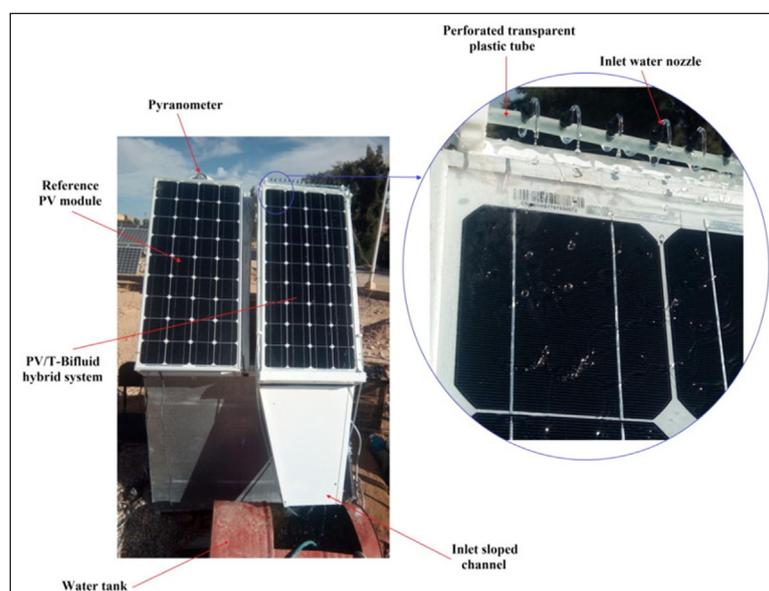


Figure 13: Setup of the PV/T system designed by Lebbi et al. (2020).

2.4. PV/T Integrated Systems

2.4.1. Heat Pump

In these systems, the heat produced from the PV/T is fed into the heat pump evaporator. The process is outlined: (1) direct expansion of the refrigerant from liquid to vapour, taking place inside the hydraulic circuit of the PV panels, (2) vapour compression for heating purposes, (3) refrigerant is condensed for heat transfer to water, (4) expansion valve (or capillary tube) used to turn high-pressure refrigerant to low-pressure liquid for reinsertion into PV/T evaporator (Riaz *et al.*, 2020). Although this system is more complex than a conventional liquid cooling system, it provides a greater heat transfer from the PV to the working fluid than the prementioned systems, allowing for greater thermal and electrical efficiencies.

Zhou, Ma, et al. (2020) developed a numerical simulation and experimental validation for a microchannel PV/T module integrated with a direct-expansion solar heat pump system. The schematic for the solar-driven heat pump system shown in **Figure 14** comprises of 11 micro-channel PV/T modules (evaporator), a compressor, a heat storage tank (condenser) and an electric expansion valve. The heat storage tank was connected to the heat exchanger located inside the building, providing space heating. The numerical simulation model contains individual energy balance calculations of each of these components and was carried out using real weather information. The experimental average electrical, thermal and overall efficiencies of the PV/T module were 13.1%, 56.6% and 69.7% respectively which were validated by the simulation results. It was further shown that the solar heat pump system could provide adequate space heating for a 150 m² space in real-world conditions.

Zhou, Zhu, et al. (2020) experimentally and theoretically investigated novel solar-assisted indirect-expansion heat pump system integrated with a novel channel PV/T collector intended for space heating under typical conditions for winter in Lvliang, China. The PV/T collector consisted of a glass cover, PV cell layer, absorber, mini-channel heat exchanger, air vent, insulation layer and frame. An air gap between the glass cover and the absorber was added to remove the need for an air vent behind the heat exchanger. The experimental testing was carried out for

more than seven days and one typical day's data was used as input parameters. The results showed a discrepancy between simulated and experimental data ranged from 4.0% to 9.1%. **Table 1** shows the results obtained from both studies.

The simulation model is verified by the experimental result – is a reasonable method for predicting the seasonal performance of the system in future.

Koşan et al. (2020) designed and tested a PV/T assisted heat pump drying system and compared it with a PV panel. To set up the experiment, two 100W PV panels were used. The rear surface of one of them was equipped with copper pipes to create the PV/T system, using refrigerant R134a as a cooling medium. This system was then connected to a heat pump unit and a drying chamber. The experiments to test the cooling of the PV were carried out under summer weather conditions to enhance electrical performance. The testing of the drying chamber was carried out in the autumn to evaluate the heat obtained from the heat pump. The average electrical efficiency and the average thermal efficiency were 12.27% and 53.66%, respectively. It was also observed that the thermal efficiency of PV panels cooled by refrigerant is higher than other fluids.

A PV/T cascade heat pump was numerically studied under the tropical weather conditions of Chiang Mai, Thailand by R. Kong et al. (2020). The cascade heat pump is a combination of low-temperature cycle and high-temperature cycle, having R134a and R245fa refrigerants as working fluids. During the PV/T heat pump operation, part of the cool water is used to cool down the module temperature. This can enhance the electrical performance of the system. The researchers used Microsoft Excel and

Table 1: Efficiencies obtained by Zhou, Zhu et al. 2020.

	Experimental	Simulation
Electrical efficiency	14.6%	15.8%
Thermal efficiency	39.3%	42.2%
Overall efficiency	53.9%	58%
COPHP	4.9	4.6

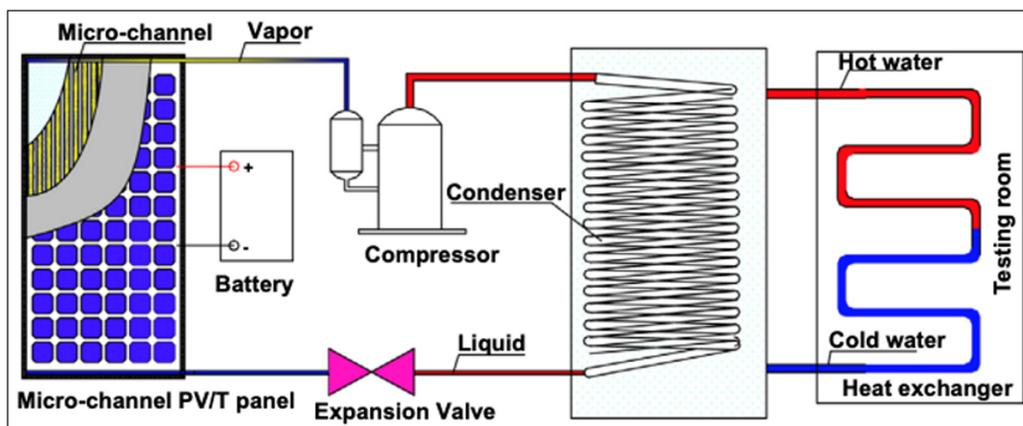


Figure 14: Solar assisted direct-expansion heat pump system employing the novel PV/mini-channels -evaporator modules (Zhou, Ma, et al. 2020).

MATLAB to carry out the simulations. The total operation time of the heat pump was 10 hours per day throughout a year. The results showed that the system is capable of producing hot water up to 90°C and cold water between 12 and 18°C.

The performance of a heat pump water system coupled with an air-based PV/T system was experimentally investigated by Choi et al. (2020). The collector was formed by two important parts: the PV module and the air channel composed of an aluminium duct, insulator and transverse triangular obstacle to improving the heat transfer performance from the PV module to flowing air (Figure 15). A heat pump with a single-stage compression cycle was added to the rig. The evaporator was a fin and tube heat exchanger, capable of retrieving thermal energy from an air source, and the condenser was a plate type heat exchanger, which produced hot water. The experiments were carried out on a clear day of October in Busan, South Korea. The results showed that the average values of power generation and electrical efficiency in the PV/T system were 144.23 W/m² and 16.61%. The thermal efficiency varied from 26.04% to 33.23%, with an average value of 30.28%.

2.4.2. Phase Change Materials

Phase Change Materials (PCM) are those which change the phase from solid to liquid within the design temperature range, absorbing or releasing heat/energy. During this heat absorption, phase change materials temperature remains constant (Hall, 2010). Researchers have used PCM in solar cells, preserving its temperature close to the ambient temperature and so, improving efficiency.

Gaur et al. (2017) developed a mathematical model for a water-based un-glazed PV/T collector with and without PCM under the absorber channel (Figure 16). They carried out the investigations using PCM OM37 for a typical winter and summer day in Lyon, France. It was observed that during the night, PCM heats the collector water, providing hot water in the next morning. The results of the study showed that the electrical efficiency for a typical summer day is 16.3% and 26.87% on a winter day. The overall thermal energy for a summer day is 14.14 kWh and 13.18 kWh for a winter day. These results were compared with the performance of the system without PCM and it was concluded that the performance is better when using phase change materials.

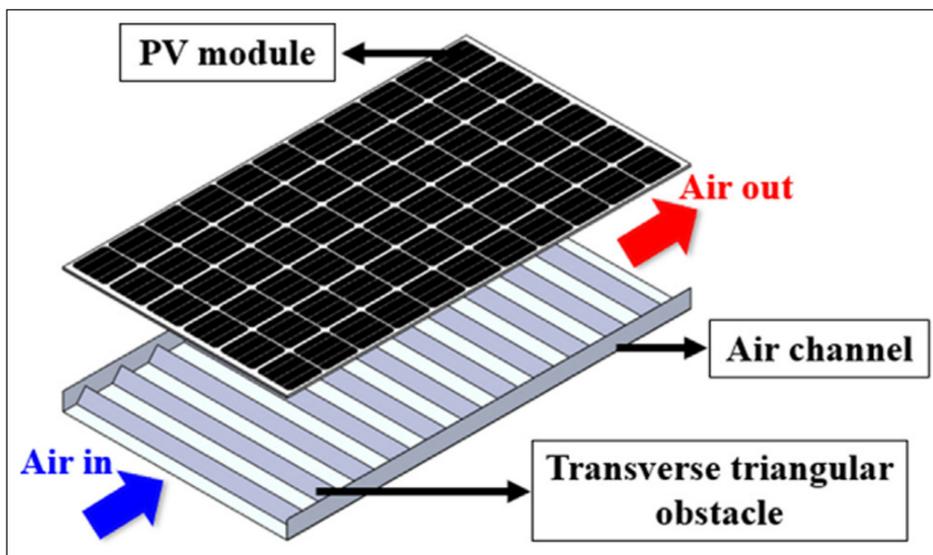


Figure 15: Schematic view of the air-based PV/T analysed by Choi et al. (2020).

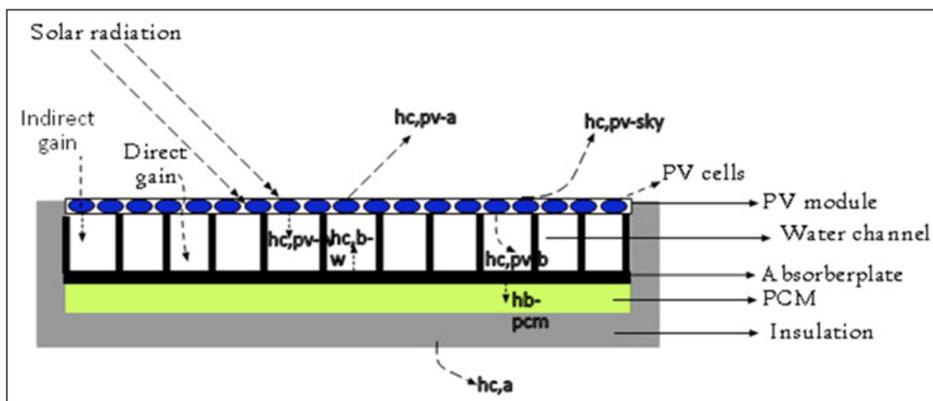


Figure 16: Schematic diagram of the unglazed PV/T system with PCM (Gaur et al. 2017).

A water-based photovoltaic/thermal system with paraffin wax RT-30 as phase change material was studied by Preet et al. (2017) in Gurdaspur, India. To increase the heat storage capacity of the PCM, copper pipes were inserted within it and water flowed through them to extract heat of the phase change material, nine fins were also integrated to increase the heat transfer rate (Figure 17). It was observed that, when using a mass flow rate of 0.013 kg/s, the system has a reduction of 49.8% in the temperature compared with the average solar radiation and a reduction of 51.4% with a mass flow rate of 0.023 kg/s. It was also observed that the electrical efficiency of a PV/T – PCM system is around 190% higher compared with a conventional PV panel. Regarding the thermal efficiency, the PV/T-PCM system showed a lower performance compared with a conventional PV/T, 15.96% and 33.81%, respectively. This is due to the rise in temperature of water in the PV/T system is higher as compared to PV/T-PCM system at the same solar intensity.

Li et al. (2019) experimentally investigated the performance of a PV/T module with phase change material and compared it with a PV-only and a PV-PCM system. The collector consisted of a 100Wp crystalline PV panel attached to a PCM container without using the typical contact layer and then attached to a 40L water tank. Technical grade paraffin wax was selected as the PCM for this study, this due to its excellent energy storage capacity. The experiment was run under the weather conditions of Shanghai, China during July. The results showed that the PV/T-PCM system could produce output water of 41.6°C during the

day. The exergy improvement compared with the PV-PCM was 30.4% and the overall exergetic energy increased by 8.32%.

Das et al. (2020) developed a transparent multi-crystalline PV module with rectangular spiral absorber tubes directly glued to the PV backside. A 10mm layer of PCM (OM35) and biochar derived from water hyacinth was used as cooling media (Figure 18). The PCM-biochar composite material was manufactured by impregnation. Six different mass ratios of PCM and biochar were selected to optimise, which would give better results in terms of stability, leakage test and conductivity. The performance parameters of the PV/T module were calculated under a constant flow rate of 0.015 kg/s. The experiment was performed from 10:00 to 16:00 h, and data were recorded every 30 minutes. The calculated average thermal efficiency was 73.5% and the electrical efficiency varied between 11.3% and 13.47%, being 13.1% the average value.

Akshayveer et al. (2020) developed and validated a PV/T-PCM system using the weather conditions of Varanasi, India. Two numerical models were created to study the performance of the PV panel when the airflow channel is attached above it and PCM adhered beneath the panel. A PV panel, PV-PCM and PV/T-PCM system were compared and it was observed that PCM reduces the PV temperature up to 73.97°C and attaching a natural air-flow channel on top reduced the temperature up to 63.24°C. This helped to increase the electrical efficiency from 8.85% (PV panel) to 10.6% (PV/T-PCM). The outlet temperature of air reached 42.52°C with a mass flux of 8.25 kg/s.

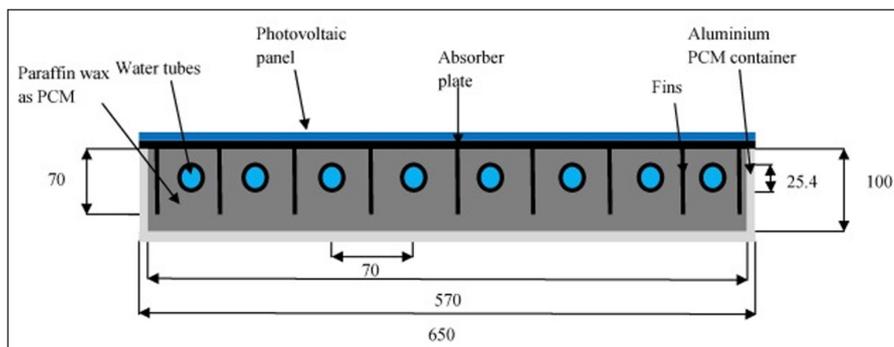


Figure 17: Diagram of PV/T – PCM system studied by (Preet et al. 2017).

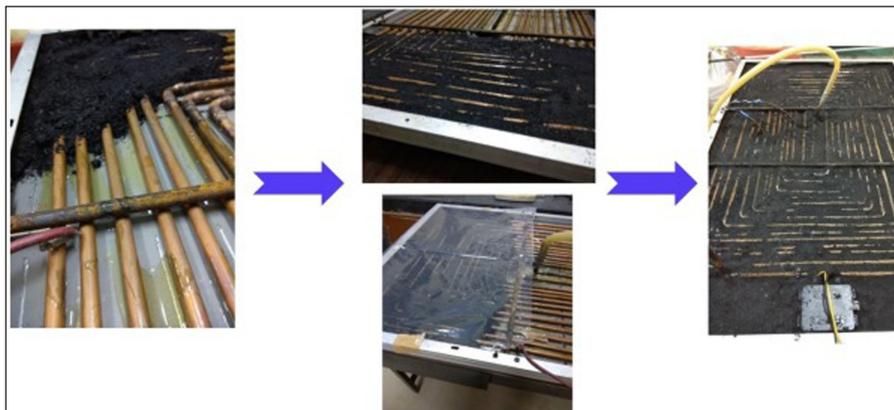


Figure 18: Rectangular spiral absorber and PCM-hyacinth biochar composite, Das et al. (2020).

2.5. Concentrated PV/T Systems

These systems concentrate solar radiation onto a PV receiver using reflectors. CPV/Ts can often reach solar concentrations equivalent to 100 suns and require more complex components which include dual-axis tracking and multi-junction PV cells. A cooling fluid is generally circulated between the PV receivers and a heat exchanger in a closed loop. Providing there is a high demand for heat overall CPV/T efficiencies can operate up to 80%, gathered as electricity and heat. PV/T collectors are advantageous due to the use of a reflector material, which is less expensive than PV panels, hence expensive PV panels can be replaced by less expensive reflector material reducing the overall cost of the system. The drawbacks are that stable cooling is necessary because of the high temperatures which can damage PV cells. Some CPV/T designs include an additional power generation cycle, such as Rankine, utilising the additional thermal energy.

Singh and Tiwari (2017) studied the performance of basin type solar stills integrated with N identical partially covered CPV/T system depending on the effect of water depth. Solar distillation is the process of getting potable water from saline water using thermal energy. **Figure 19** shows the schematic diagram of the system. It can be observed that the N identical CPC water collectors are partially covered (25%) with PV/T. The single slope active solar still had a basin area of $2\text{ m} \times 1\text{ m}$ made of glass-reinforced plastic with a transparent glass cover. The inner surfaces were painted in black to maximise the absorption of solar flux. It was concluded that the optimum mass flow rate is 0.04 m/s and the optimum water depth of the single-slope basin is 0.70 m and 0.31 m for a double slope basin.

El-Samie et al. (2020) modelled the optical, thermal and electrical performance of the low CPV/T collector using finite volume CFD and was validated by the Monte Carlo ray-tracing method. The authors investigated different heat sink designs (U-type & Z-type) & coolants (water,

ethylene glycol, and Therminol VP-1). It was found that variations of irradiance greatly influence the electric performance, while high thermal efficiency of about 48 to 51% can be achieved throughout the day. Z type heat sink found to reduce the PV cell temperature more than U-type. The water-cooling system achieved the highest efficiencies with an average thermal efficiency of 48.8% and an average electrical efficiency of 7.1%.

3. Conclusions

According to the literature cited in this work, the following summary has been provided. It is likely for the researchers to carry out studies on water-based and air-based PV/T systems due to their performance and easier integration into buildings. It was also observed that most of the studies have been developed using flat-plate PV/T collectors. However, during the last years, several researchers have focused their work on novelty technologies such as PCM and nanofluids. Air-based PV/T systems have a better performance when they have more than one entry and they are suitable for space heating in cold climates. Partially covered systems have higher thermal performance but lower electrical performance. Most of the simulations were made using software like MATLAB, ANSYS and TRNSYS and using 2D steady-state heat transfer models. In bi-fluid systems, when the mass flow rate of a fluid increases and the other parameters remain stable, one of the thermal or electrical efficiency decreases. It was also observed that these systems can reach thermal efficiencies up to 76% and electrical efficiencies up to 17%, which is the case of the experiments carried out by Jarimi et al. (2016). The experiment carried out by Choi et al. (2020) showed that the use of a heat pump can significantly enhance the electrical performance of a PV/T system, however, the thermal performance is one of the lowest. The same was observed in some of the PCM based systems. The highest thermal efficiencies were achieved when using nanofluids as cooling media, confirming that this novelty technology

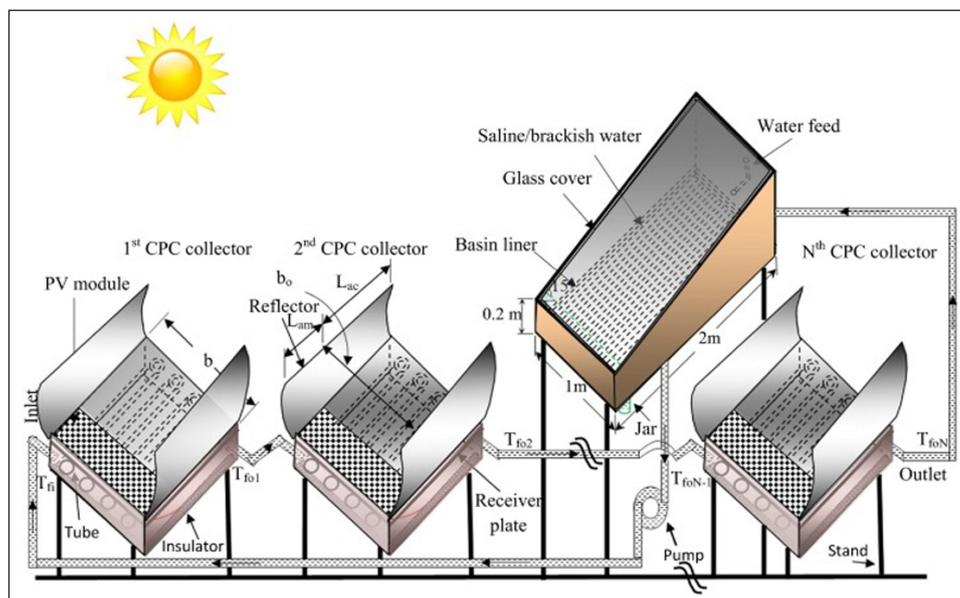


Figure 19: Diagram of a single slope active solar still partially covered by CPV/T (Singh and Tiwari 2017).

is worth studying and applying. The electrical and thermal efficiencies of concentrated PV/T systems are high (between 7.1% and 10.02% and 48%–60%, respectively), but the installation requires a lot of space and so they are difficult to integrate into small buildings such as residences but can be suitable for other applications such as solar distillation. **Table 2** below shows a summary of all the review papers quoted in this work. The type of system and its electrical efficiency, thermal efficiency, origin, author and year are specified.

4. Gaps and challenges

Finally, it is important to notice that there is room for improvement regarding the Building Integrated PV/T systems. Several authors have studied PV/T integrated into buildings, but these systems keep being inaeesthetic and hence, not attractive to the users. Those systems also stay as experimental rigs or can only be roof-mounted, so, without a proper design, it is difficult to expand the PV/T market. For this reason, it is recommended to carry out more studies on these systems and not only to improve

Table 2: Summary of the recent work on PV/T systems.

Author	Type	Year	Electrical efficiency	Thermal efficiency	Origin
Aste <i>et al.</i> (2016)	Water-based	2016	10	15	Italy
Shyam <i>et al.</i> (2016)	Water-based	2016	5 to 6	–	India
He, Xiao and Li (2017)	Water-based	2017	–	51 to 67	China
Sainthiya and Beniwal (2019)	Water-based	2019	11 to 14	22 to 25	India
Misha <i>et al.</i> (2019)	Water-based	2020	11.71	59.6	Malaysia
Ma <i>et al.</i> (2020)	Water-based	2020	15.5	65.7	China
Tsai (2015)	Refrigerant	2015	–	–	Taiwan
Rejeb <i>et al.</i> (2016)	Nanofluid	2016	13.5	76.88	Iran
Hamdan and Kardasi (2017)	Nanofluid	2017	12.06	–	Jordan
Samylingam <i>et al.</i> (2020)	Nanofluid	2020	13.8	79.13	Malaysia
Rubbi <i>et al.</i> (2020)	Nanofluid	2020	14.20	84.25	Malaysia
Tiwari <i>et al.</i> (2016)	Air-based	2016	–	–	India
Gholampour and Ameri (2016)	Air-based	2016	–	45 to 55	Iran
Slimani <i>et al.</i> (2017)	Air-based	2017	10.65	44	Algeria
Jha, Das and Gupta (2019)	Air-based	2019	13.6	34	India
Arslan, Aktaş and Can (2020)	Air-based	2020	13.98	49.5	Turkey
D. Kong <i>et al.</i> (2020)	Air-based	2020	12	48.9	China
Othman <i>et al.</i> (2016)	Bi-fluid	2016	17	76	Malaysia
Jarimi <i>et al.</i> (2016)	Bi-fluid	2016	–	66.12	Malaysia
Su <i>et al.</i> (2016)	Bi-fluid	2016	7.8	–	China
Lebbi <i>et al.</i> (2020)	Bi-fluid	2020	13.17	50	Algeria
Zhou, Ma, <i>et al.</i> (2020)	Heat Pump	2020	13.1	56.6	China
Zhou, Zhu, <i>et al.</i> (2020)	Heat Pump	2020	14.6 to 15.8	39.3 to 42.2	China
Koşan <i>et al.</i> (2020)	Heat Pump	2020	12.27	53.66	Turkey
R. Kong <i>et al.</i> (2020)	Heat Pump	2020	–	–	Thailand
Choi <i>et al.</i> (2020)	Heat Pump	2020	16.61	30.28	South Korea
Gaur <i>et al.</i> (2017)	PCM	2017	16.3	26.87	France
Preet <i>et al.</i> (2017)	PCM	2017	15.96	33.81	India
Li <i>et al.</i> (2019)	PCM	2019	–	–	China
Das <i>et al.</i> (2020)	PCM	2020	13.1	73.5	India
Akshayveer <i>et al.</i> (2020)	PCM	2020	10.6	–	India
Singh and Tiwari (2017)	CPV/T	2017	–	60	India
El-Samie <i>et al.</i> (2020)	CPV/T	2020	7.1	48.8	China

the aesthetic but to optimise the configuration and then increase the efficiencies. Also, the next phase of research should investigate the changes to heat transfer through the external envelope and how this will affect the building space heating and cooling loads. Another gap in this research area is the economic evaluation, it is difficult to find information about the cost of a PV/T system so it is suggested to provide such information soon and make it accessible not only to other researchers but to designers, architects and engineers.

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Competing Interests

Saffa Riffat is the Editor in Chief of the journal and was completely removed from all editorial processing for this paper.

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