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Configuration Designs and Recent Applications of Photovoltaic-Thermal Solar Collectors for Drying Agricultural Material: a Review

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ABSTRACT

Photovoltaic-thermal (PV-T) solar air/water collectors have received increasing attention in recent years. Efficiency is the most important parameter usually considered in PV-T technologies. The present paper expressed energy efficiency and thermal-electrical exergy of PV-T collectors, and compared the studies of researchers on the performance of these systems. The figures are provided to give an overview of how PV-T performance is improved. Changes in heat transfer fluid play a major role in electrical and thermal efficiency. A brief overview of the most promising fluids used in PV-T is reported in this article. Nowadays, improving PV- T performance by optimizing the adsorbent plate and cooling fluid and using Nano fluid has been considered by researchers. The application of these schemes in implementation, especially in agriculture, can help significantly in increasing the efficiency of solar radiation. Therefore, future work should be aimed at increasing efficiency and reducing costs to increase their competitiveness and use as a renewable and environmentally friendly energy device.

INTRODUCTION

The use of renewable energy in terms of reducing fossil fuel resources and the harmful effects of using these fuels on the environment, has received much attention in recent decades (Chandra *et al.*, 2016; Edenhofer *et al.*, 2011; Gielen *et al.*, 2019; Rezvani *et al.*, 2014; Solaymani, 2021). Role of the renewable energy in global energy is shown in Fig. 1.

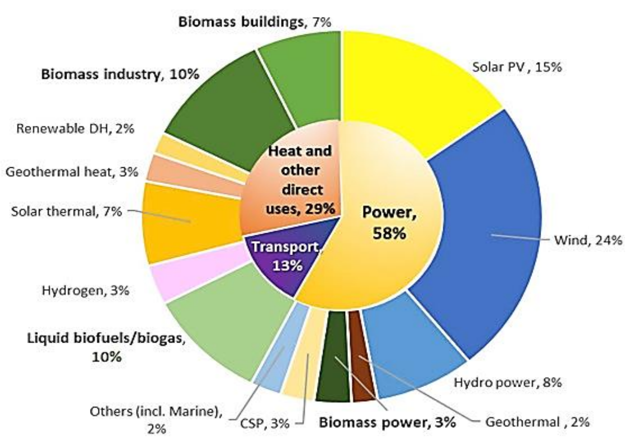

Fig 1. Role of the renewable energy in global energy (Gielen *et al.*, 2019)

Solar energy is a clean energy and can provide a significant part of the world's energy needs. Solar energy is mainly used in two types of systems: thermal and photovoltaic (PV) systems. In thermal systems, solar energy is converted into thermal energy using solar collectors. Fig. 2 shows the various types of the solar thermal collectors.

In PV systems, solar energy is directly converted into electricity. In fact, the conversion efficiency of a solar PV system is about 15 to 20%, while the remainder (82-85%) is either absorbed by the PV cell and thus heats it up (Alharbi and Kais, 2015; McCandless *et al.*, 2003). In addition, it is estimated that increasing the module temperature by one degree leads to a decrease in the PV module efficiency by between 0.4 and 0.65% (Chandra *et al.*, 2016). Both electrical efficiency and output power of PV modules depend linearly on the operating temperature .Also, electrical performance is primarily influenced by PV materials used (Dubey *et al.*, 2013). Fig. 3 shows the classification of PV cells based on PV materials.

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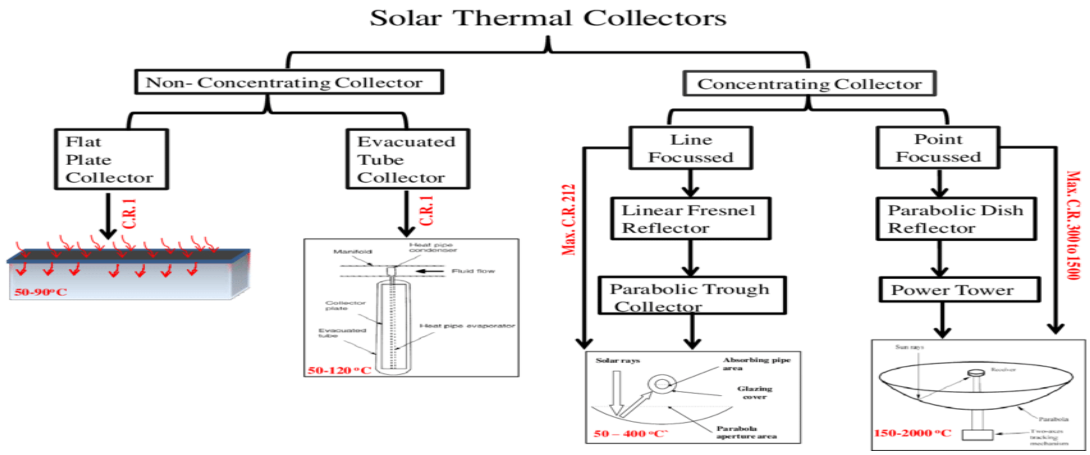

Fig 2. Various types of solar thermal collectors (Bhalla and Tyagi, 2018)

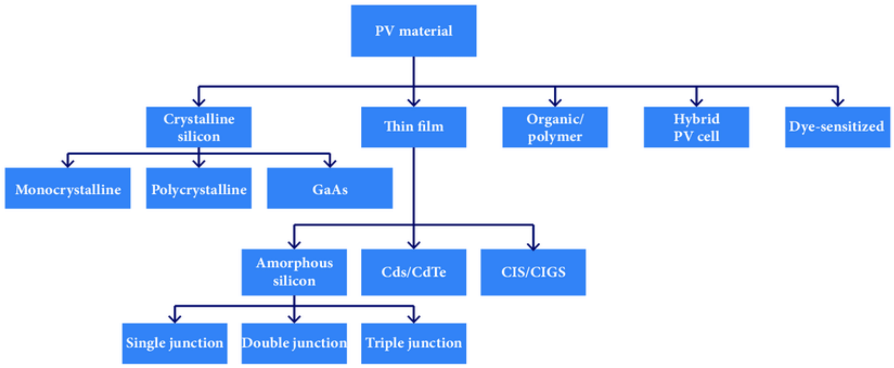

Fig 3. The classification of PV cells based on PV materials (Tyagi *et al.*, 2013)

Therefore, PV-T hybrid solar collectors were proposed as a solution to improve the efficiency of the PV modules. PV-T systems are classified in Fig. 4. Absorber panels in PV-T collectors have two main applications: first, cooling the PV modules and thus improving electrical performance, and second, collecting thermal energy and preventing its loss in the form of heat to the environment (Jakhar *et al.*, 2016; Miglioli *et al.*, 2021; Moradi *et al.*, 2013). The result of using the heating unit with the electric unit at the same time is more electrical efficiency, increasing the overall efficiency of the device, increasing the system life and longer cell life due to lowering the temperature. A research have been done since the development of these solar hybrid systems (Dwivedi *et al.*, 2020)

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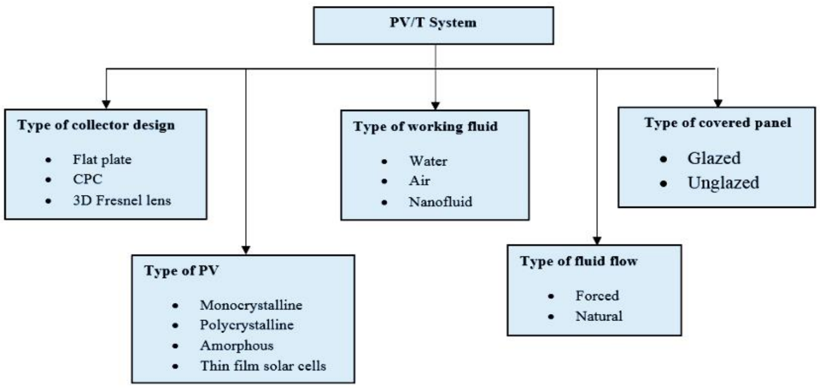

Fig 4. Classification of PV-T system (Sachit *et al.*, 2018)

However, most of the researchers use air as the working fluid because of the lower structural and maintenance costs of the collector (Bandaru *et al.*, 2021; Barone *et al.*, 2019; Beniwal *et al.*, 2020). PV-T collectors have the some advantages over conventional solar thermal collectors including: (1) use of optimal installation space due to the combination of solar collector and PV module in a single system, (2) increasing the electrical efficiency of the PV module due to the absorption of accumulated heat from its surface by the operating fluid flow in the solar collector, (3) no need for an external electrical source to move the working fluid in the solar collector, and (4) higher energy efficiency than conventional systems (Chow, 2010; Miglioli *et al.*, 2021).

In this paper, first the performance equations of the PV-T collectors are introduced, then different designs of PV-T collector are expressed, and at the end, the activities performed to optimize the PV-T collectors are described.

PERFORMANCE PARAMETERS OF PV-T COLLECTORS

Electrical Efficiency

Electrical efficiency (η_{el}) of a PV module is the ratio of the measured output power to the total amount of solar radiation hitting the surface (Duffie *et al.*, 2020; Fesharaki *et al.*, 2011) that is given by:

$$\eta_{el} = \frac{I_m V_m}{G A_p} \tag{1}$$

where G is intensity of solar radiation (W/m^2) and A_p is the surface area of the panel. I_m and V_m are the maximum output current (A) and voltage (V), respectively.

With the increase in the panel temperature, the output power and so the electrical efficiency decrease. The dependence of electrical efficiency on panel temperature is expressed by the following expression (Dubey *et al.*, 2013; Evans, 1981; Tiwari and Dubey, 2009):

$$\eta_{el} = \eta_{st}\left[1 - \beta_P(T_p - T_{st}\right] \tag{2}$$

where T_p and T_{st} are the PV cell and standard temperatures (25 °C), respectively. η_{st} stands for nominal efficiency of the PV module in standard conditions (1000 W/m^2, 25 ºC), β_P is temperature coefficients of the panel efficiency, which is usually declared by the manufacturer and is obtained by the following equation (Dubey *et al.*, 2013; Evans, 1981; Fesharaki *et al.*, 2011):

$$\beta_P = \frac{1}{T_0 - T_{st}} \tag{3}$$

where T_0 is the maximum temperature at which the electrical efficiency of the cell reaches zero (ºC) (Dubey *et al.*, 2013; Garg and Agarwal, 1995).

The temperature of solar cells is a function of ambient temperature and solar intensity. As the ambient temperature increases, the cell temperature also increases. On the other hand, as the intensity of solar radiation increases, the cells heat up and their temperature increases. The temperature of solar cells (T_c) at the different ambient temperatures (Gorawar *et al.*, 2013) and solar radiation intensities is obtained from the following approximate relationship (Dubey *et al.*, 2013; Tiwari and Dubey, 2009):

$$T_c = T_{amb} + [(NOCT - 20)/800] \times G \tag{4}$$

When the ambient temperature is 20 °C, the radiation intensity is 800 W/m^2 and the wind speed is 1 m/s, the cell temperature is called the nominal operating condition temperature (NOCT) (Dubey *et al.*, 2013; Tiwari and Dubey, 2009).

Thermal Efficiency of PV-T Systems

Thermal efficiency of a PV-T collector is the ratio of useful thermal energy gain (Q_u) to the total received solar radiation by the collector, and is defined as the following expression (Duffie *et al.*, 2020; Jahromi *et al.*, 2015):

$$\eta_{th} = \frac{Q_u}{G\,A_p} \tag{5}$$

Using the inlet (T_o) and outlet (T_i) fluid temperatures, the useful thermal energy gain of the collector can be calculated from the following equation (Duffie *et al.*, 2020):

$$Q_u = \dot{m}_f C_f (T_o - T_i) \tag{6}$$

The useful thermal energy of the collector can be also calculated using the energy balance equation as follow:

$$Q_u = A_p\left[G(\tau\alpha) - U_L\left(T_{p,m} - T_a\right)\right] \tag{7}$$

Where τα is the absorption-transmission coefficient of the glass and the cell, $T_{p,\,m}$ is the average temperature of the PV module, T_a is the average temperature of ambient.

Exergy Efficiency of PV-T Systems

Exergy efficiency is the ratio of the system output exergy to the total radiation exergy, which can be calculated from the following equation (Chow *et al.*, 2009):

$$\eta_{ex.PV-T} = \frac{\dot{E}x_{th} + \dot{E}x_{el}}{\dot{E}x_{Solar}} \tag{8}$$

where $\dot{E}x_{th}$ is the thermal exergy generated by the PV-T collector that is obtained from the following expression (Jahromi *et al.*, 2015; Kalogirou and Tripanagnostopoulos, 2006):

$$\dot{E}x_{th} = Q_u\left(1 - \frac{T_a}{T_o}\right) \tag{9}$$

$$\dot{E}x_{el} = Q_{el} \tag{10}$$

$\dot{E}x_{el}$ is electrical exergy of the PV-T collector, which is equal to its electricity energy (Q_{el}). $\dot{E}x_{solar}$ is incoming solar exergy, for which three different expressions are suggested in the literature.

$$\dot{E}x_{Solar} = \left(1 + \frac{1}{3}\left(\frac{T_a}{T_{solar}}\right)^4 - \frac{4T_a}{3T_{solar}}\right)G \quad \text{(Petela, 1964)} \tag{11}$$

$$\dot{E}x_{Solar} = \left(1 - \frac{4T_a}{3T_{solar}}\right)G \quad \text{(Spanner, 1964)} \tag{12}$$

$$\dot{E}x_{Solar} = \left(1 - \frac{T_a}{T_{solar}}\right)G \quad \text{(Jeter, 1981)} \tag{13}$$

where T_{solar}, the sun temperature, is considered to be 6000 K. The difference in results of these three equations is less than 2% (Chow *et al.*, 2009).

PV-T DESIGN CONFIGURATIONS

Photovoltaic-thermal collectors can convert sunlight into electricity and heat at the same time, but compared to the solar thermal collectors, their heat loss is higher, so the design and construction of the PV-T absorber is important. The following is a summary of the different configurations of the PV-T collectors.

Ibrahim *et al.* (2011) provide a classification for the flat-plate PV-T collectors (Fig. 5). This review also covers the future development of flat-plate PV-T solar collectors for the application in building-integrated PV systems and building-integrated PV-T systems. From this study, it can be seen that for both PV-T air and water collectors, the most important factors that affect the efficiency of the system are the transparent cover, the number of passages, and the gap between the absorber plate and the solar panel.

He *et al.* (2011) conducted an experimental study on a PV-T system under natural water flow. In this study, a test device was developed to measure and analyze the efficiency of the PV-T system (Fig. 6), which includes a single-crystalline silicon PV-T solar collector, a conventional solar collector, and a single-crystalline silicon PV module.

The performance evaluation of a two-way hybrid PV-T solar collector was analytically and experimentally carried out by Mortezapour *et al.* (2012).

In an experiment (Fig. 7), electrical and thermal efficiencies of PV-T water collectors at the different configurations of web flow, direct flow, and spiral flow were studied by Fudholi *et al.* (2014). The results showed that the spiral flow absorber has the highest efficiency in solar radiation of 800 W/m2 and mass flow of 0.041 kg/s. The efficiency of the PV module increases with decreasing temperature and the temperature decreases nonlinearly with increasing the fluid flow rate. With increasing the flow rate, the overall efficiency of the PV-T collector increases, since the flow rate helps to cool the PV-T collector.

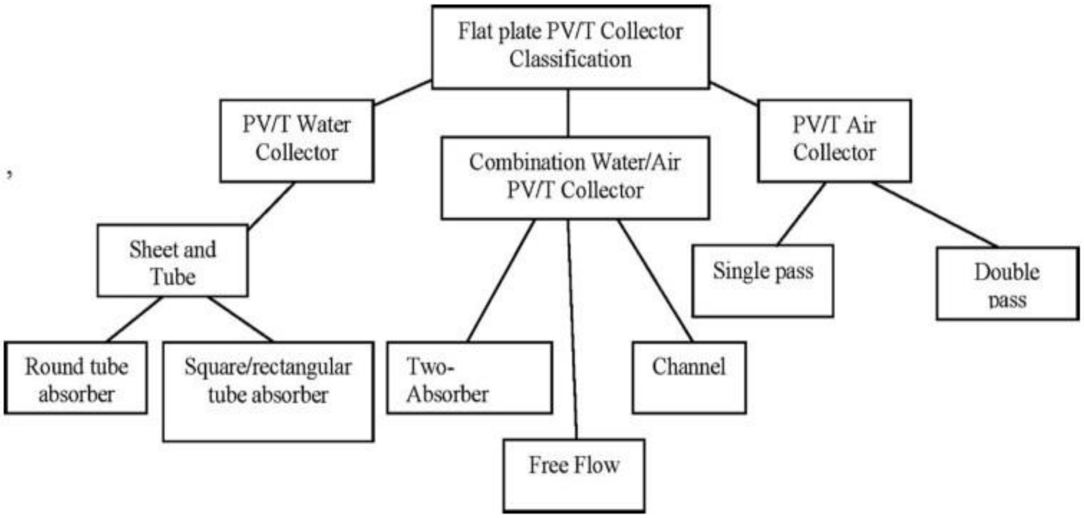

Fig 5. Flat plate PV-T collector classification (Ibrahim *et al.*, 2011)

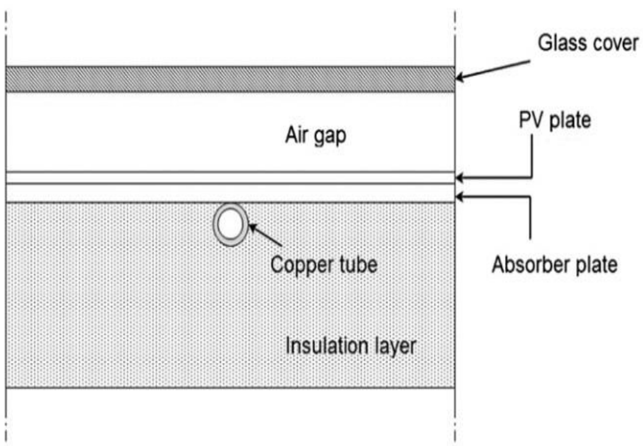

Fig. 6. Cross section of the PV-T solar collector developed by He *et al.* (2011)

Touafek *et al.* (2014) conducted a theoretical and experimental study on a PV-T collector with sheet and tube absorber. They finally suggested the form of sheets and tubes (Fig. 8). The advantages of this designed system are high heat absorption and low manufacturing cost compared to the other PV-T collectors.

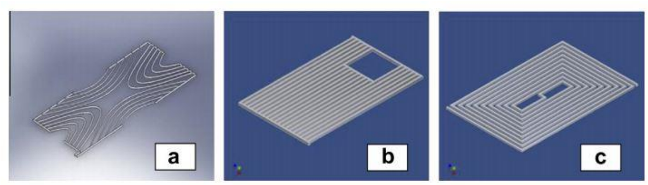

Fig 7. Three different configurations of PV-T water collectors studied by Fudholi *et al.* (2014) (a) Web flow absorber, (b) direct flow absorber, and (c) spiral flow absorber

Aste *et al.* (2015) tried to develop an accurate mathematical model for estimating electricity and thermal energy generated by a coated PV-T collector made of thin film PV technology with a flat-plate absorber (Fig. 9). Validation of the designed model is performed using measured data from experimental work. The results show that the PV-T technology offers higher overall efficiency in terms of primary energy than a simple PV module

Aste *et al.* (2016) modeled and evaluated the performance of an uncoated PV-T water collector (Fig. 10). During their research work, they presented a mathematical model for simulating the energy of PV-T systems, which includes all the factors and parameters related to the energy efficiency of an uncovered composite collector. Their mathematical model is implemented in TRNSYS software and the simulations are performed with the same configuration for three different places in Europe with different weather conditions.

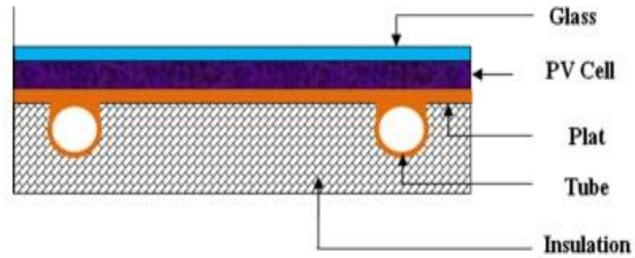

Fig 8. Model of PV-T collector suggested by Touafek *et al.* (2014)

Al-Shohani *et al.* (2016) investigated the reduction of heat accumulation in a PV module through an optical water filter to increase the electrical efficiency of the PV module (Fig. 11). In this experiment, an optical water filter was placed on top of the PV module to absorb the infrared spectra and convert them into heat. It also transmits visible spectra to the module to generate electricity at the same time. The temperature of solar cells was measured at different water thicknesses in the filter (1-5 cm) and different distances between the filter and the PV module (1-3 cm). According to the results, with increasing the thickness of the water layer, the temperature drop of the PV module increased significantly, while the distance between the filter and the PV module has less effect.

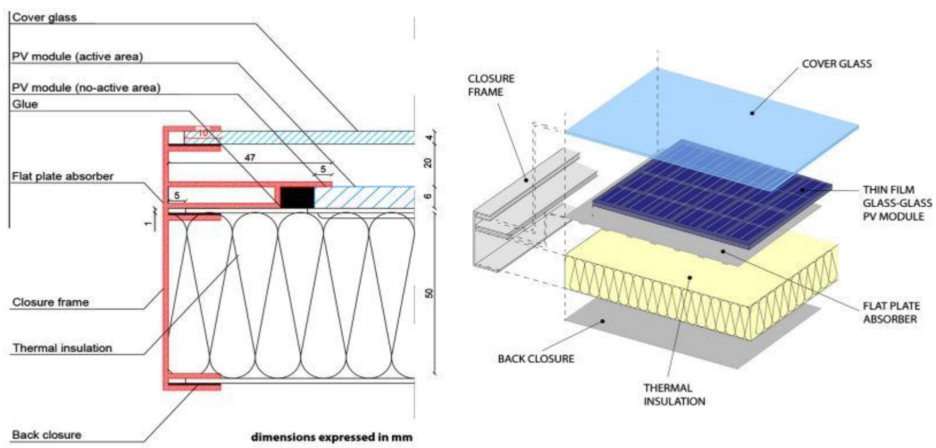

Fig 9. Section and isometric views of the PV-T collector developed by Aste *et al.* (2015)

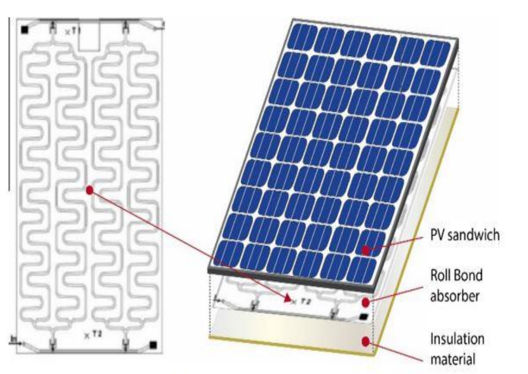

Fig 10. Absorber plate and PV-T collector configuration used by Aste *et al.* (2016)

A study was performed on three technologies of PV-T systems, solar thermal and simple PV for utilizing solar energy in buildings (Huide *et al.*, 2017). Simulation models of a PV module, a solar thermal collector and a combination of both are presented and experimentally validated in this paper. They studied all three systems in Hong Kong, Shanghai, and Beijing cities in China. Al-Waeli *et al.* (2017b) experimentally investigated silicon carbide nan fluids as the base fluid of a PV-T system (Fig. 12). In their experiment, the thermos-physical properties of Nano fluids composed of water and silicon carbide nanoparticles without the use of surfactants were investigated as the coolant for the PV-T system.

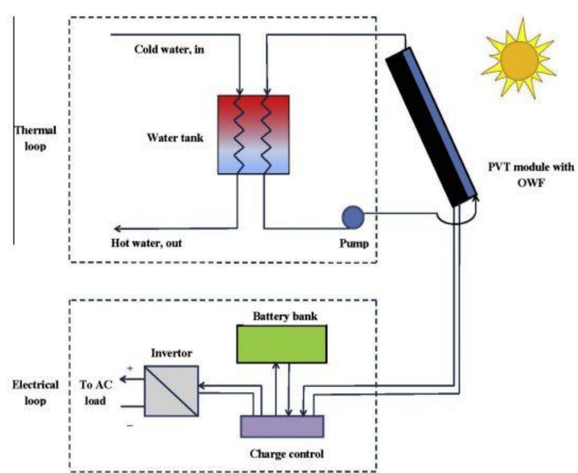

Fig 11. PV-T system with PV-T optical water filter module (Al-Shohani *et al.*, 2016)

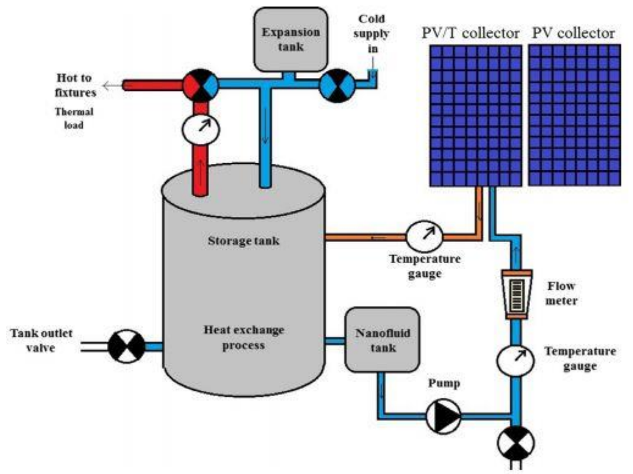

Fig 12. A schematic diagram of the experimental rig developed by Al-Waeli *et al.* (2017b)

Dimri *et al.* (2017) performed thermal modeling of a semi-transparent PV-T collector with thermoelectric cooling. In their work, the electrical efficiency of the proposed system is compared with two cases (Fig. 13): the first with a translucent PV module and the second with a translucent PV module with thermoelectric cooling.

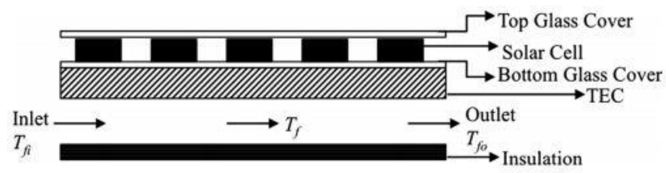

Fig 13. Cross-sectional view of proposed semitransparent PV-T thermoelectric cooler collector (Dimri *et al.*, 2017)

Al-Waeli *et al.* (2017a) conducted a comparative study on the use of aluminum oxide, copper oxide, and silicon carbide Nano fluids with water to increase the efficiency of PV modules (Fig. 14). Lari and Sahin (2017) techno-economically analyzed the use of a Nano fluid in a PV-T system for residential applications. In this work, the system with cooling Nano fluid is designed to meet the electrical needs of a residential building for the climate of Al-Dhahran, Saudi Arabia. Silver-water Nano fluid was used in this study.

Ahmed and Radwan (2017) evaluated the performance of new modified polycrystalline PV-T systems to improve the heat dissipation process with concentrated solar radiation (Fig. 15).

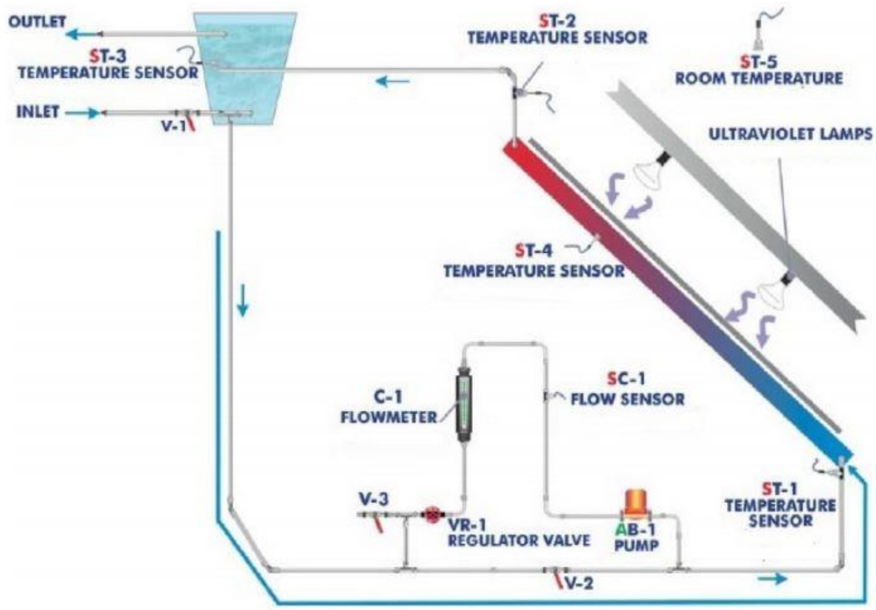

Fig 14. A schematic diagram of the indoor solar simulator used by Al-Waeli *et al.* (2017a)

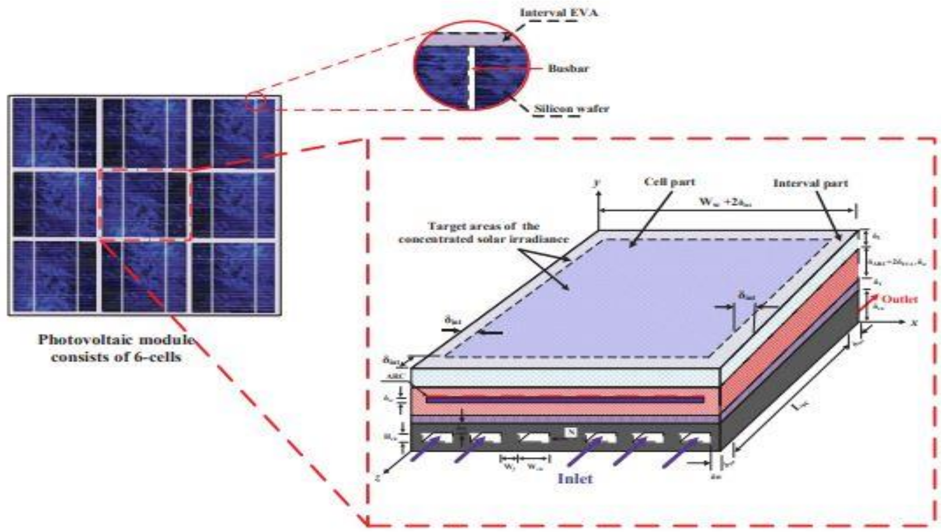

Fig 15. Schematic diagram of concentrator PV-T systems (Ahmed and Radwan, 2017)

To estimate the thermal efficiency of two opaque PV-T collectors using a solar simulator, Katiyar *et al.* (2017) presented a numerical model. The model considers the physical and spectral properties of the solar simulator and can be used to optimize the collector design. The designed model can also achieve annual system efficiencies with the help of simulation software such as TRNSYS.

Modjinou *et al.* (2017) conducted a numerical and experimental study on a solar PV-T system equipped with continuous micro-channels (Fig. 16). Acetone flows as the refrigerant inside micro-channels. Heat and mass transfer properties of the system were investigated by numerical and experimental methods using MATLAB software. They presented a linear relationship between thermal efficiency and temperature reduction parameter.

Tomar *et al.* (2017) studied the performance of four different PV-T systems including: (1) Glass-to-glass PV with integrated conduit on the cell, (2) Glass-to-glass PV without integrated conduit on the cell, (3) PV glass to polyvinyl fluoride with integrated duct on the cell, and (4) PV glass to polyvinyl fluoride without integrated duct on the cell. The glass-to-glass PV module performed better electrically and thermally. In another study numerical simulation of different PV-T water collector designs, including the box-type, round tube, and square tube was carried out using the three-dimensional computational fluid dynamics (CFD) method (Sardouei *et al.*, 2018). Nasrin *et al.* (2018) investigated the effect of high irradiation and cooling on power, energy, and performance of a PV-T system (Fig. 17). They used finite element-based COMSOL software to solve the problem numerically in a three-dimensional model and validated their modeling with existing experimental and numerical results.

Gupta and Tiwari (2018) studied the effect of water flow rate and tank storage capacity on a translucent PV-T system (Fig. 18). Analytical models were extracted for room air temperature, solar cell temperature, water tank temperature, and PV efficiency. Calculations were performed for a typical day in June in New Delhi. It was concluded that the tank capacity is not a sensitive parameter for PV cell temperature and efficiency.

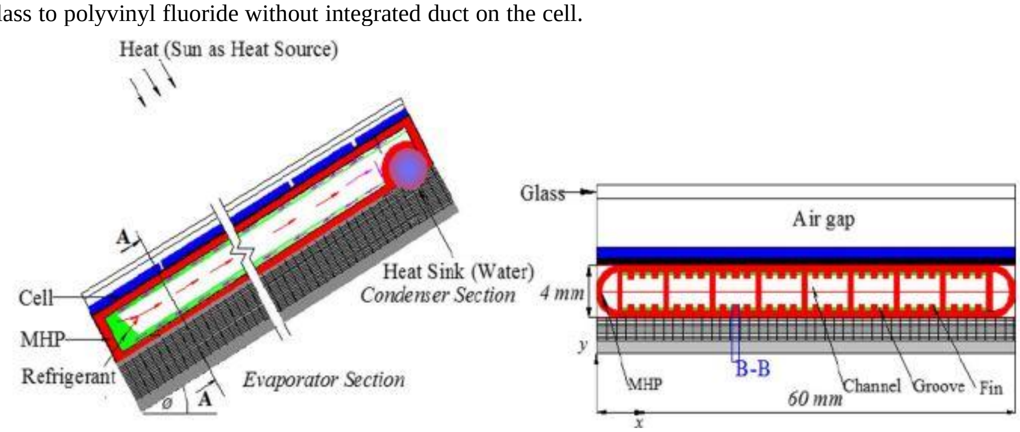

Fig 16. Detailed views of micro-channel heat pipe array incorporated with crystalline silicon solar PV-T system (Modjinou *et al.*, 2017)

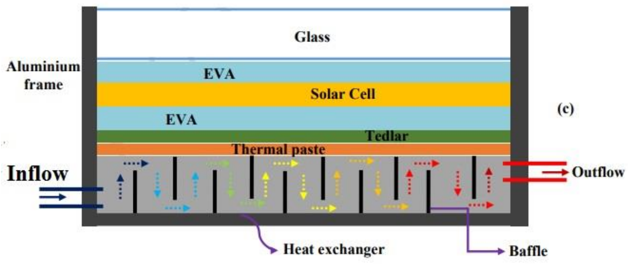

Fig 17. A schematic diagram of the PV-T collector used by Nasrin *et al.* (2018)

Gupta and Tiwari (2018) studied the effect of water flow rate and tank storage capacity on a translucent PV-T system (Fig. 18). Analytical models were extracted for room air temperature, solar cell temperature, water tank temperature, and PV efficiency. Calculations were performed for a typical day in June in New Delhi. It was concluded that the tank capacity is not a sensitive parameter for PV cell temperature and efficiency.

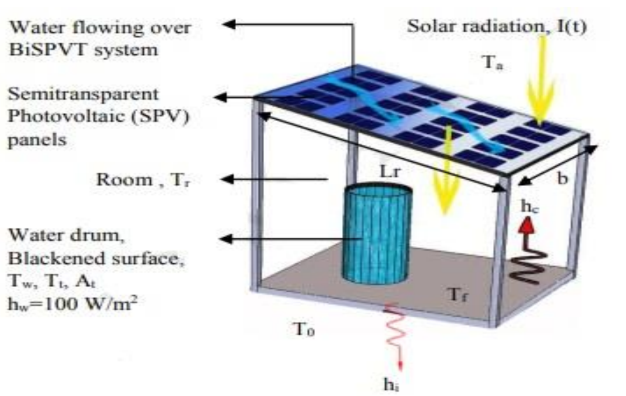

Fig 18. Schematic view of building integrated semitransparent PV-T system of Gupta and Tiwari (2018)

Bigorajski and Chwieduk (2019) analytically studied a simple PV-T system with glass cover. Results of the system simulation for home applications in countries with high latitudes showed that for December and January, more electrical energy is generated by PV-T systems than thermal energy. Choi *et al.* (2020) investigated the performance of a PV-T air collector with a heat pump.

Wu *et al.* (2021) numerically evaluated the performance of a PV-T collector based on silica aerogel (Fig. 19). Aerogel is very transparent in sunlight and opaque in infrared light. The results showed that heat loss at operating temperature of 70 °C was reduced by about 70% compared to the conventional PV-T collectors.

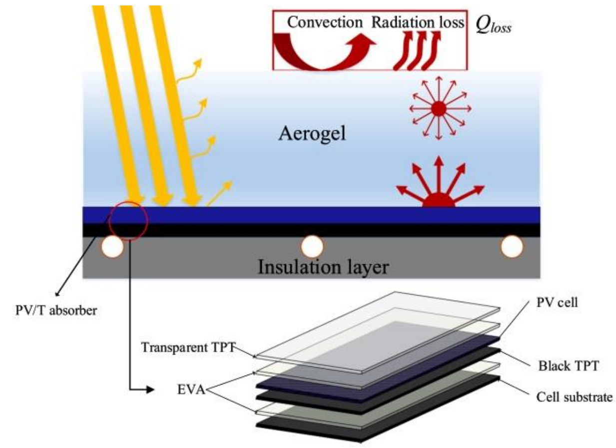

Fig 19. Schematic of the aerogel-based PV-T collector (Wu *et al.*, 2021)

Venkatesh *et al.* (2022) experimentally improved the energy efficiency of a PV-T water collector with different concentrations of graphene Nano fluids (Fig. 20). They also investigated the effect of the Nano fluid on the temperature of PV and PV-T panels. In this work, graphene Nano fluids were dispersed in ultrasonic vibrating water with sodium deoxy cholate as a surfactant for 1 hour.

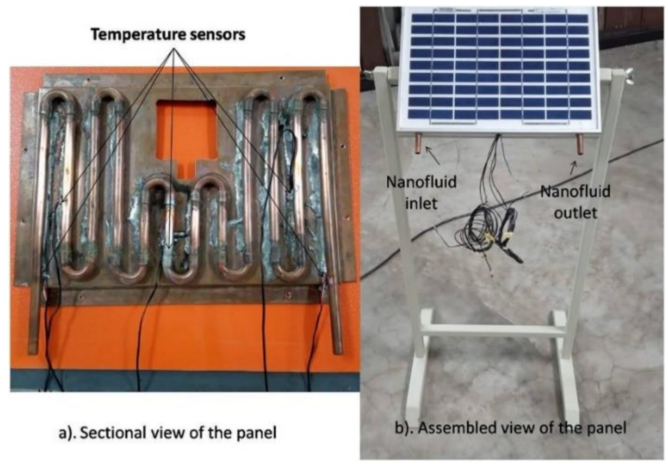

Fig 20. Photographic view of the solar PV-T panel with pipe lines (Venkatesh *et al.*, 2022)

A Nano fluid and Nano-enhanced phase change material (NEPCM) based spectral splitting PV-T system was parametric investigated by Yazdanifard *et al.* (2021). In this work, using a layer design containing an optical fluid and a phase change material as a new alternative adsorbent filter was investigated (Fig. 21).

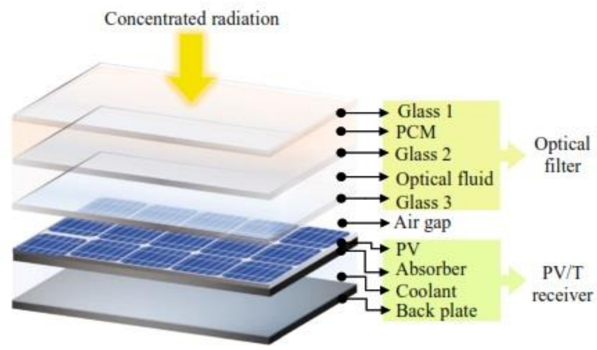

Fig 21. Schematic of the proposed spectral filtering concentrated PV-T system (Yazdanifard *et al.*, 2021)

Yazdanifard *et al.* (2020) numerical modeled a concentrated PV-T system which utilizes a phase change material and Nano fluid spectral splitting (Fig. 22). In this work, all the steps required to achieve the optical properties of phase change material are described in detail to facilitate further investigation.

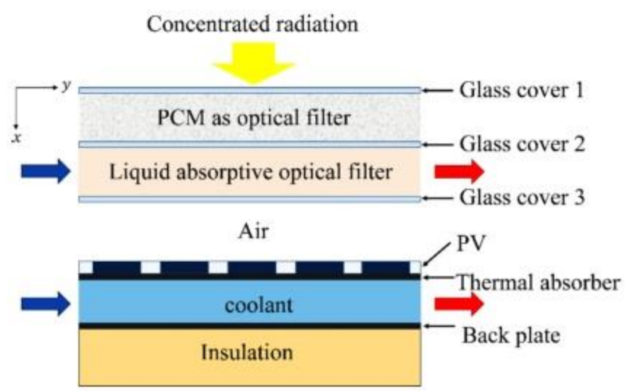

Fig 22. The Nano fluid-phase change material spectral splitting concentrated PV-T system (Yazdanifard *et al.*, 2020)

Khajepour and Ameri (2020) analyzed a hybrid solar PV-T power plant. They stated that by combining the photovoltaic system with solar thermal power plant, the optimal size of the solar thermal field is reduced, as, hybrid concentrated solar power-PV increases the possibility of more storage of solar heat.

A summary of investigation results of the different PV-T designs described in this work is given in Table 1.

APPLICATIONS OF PV-T COLLECTORS FOR DRYING AGRICULTURE PRODUCTS

Technology on farms is changing and improving rapidly. These improvements will change farm machinery and equipment as well as farm facilities and buildings. As we all know, solar energy is the largest and cheapest source of energy on Earth. Solar energy can easily supply energy to farms. Various solar energy capturing devices and systems have been developed and are in operation for agricultural applications, including solar thermal and electric devices such as solar sprays, solar greenhouse heating systems, solar dryers, solar water pumps, and ventilation for livestock, solar aeration pumps, solar power and so on. The following are some of the applications of the PV-T solar collectors in agriculture, then the application of PV-T collectors in drying agricultural products is discussed.

Tiwari *et al.* (2009) studied an integrated PV-T water heater in farm buildings (Fig. 23). Exergy analysis and thermal efficiency of the system were investigated. With increasing the water flow rate and collection temperature, the total daily thermal and exergy efficiencies increased and decreased, respectively. It was also observed that the thermal and exergy efficiencies were reversed due to the collection temperature.

Corbin and Zhai (2010) experimentally and numerically investigated the thermal and electrical performance of a building-integrated PV-T collector system. They studied the effect of the known heat recovery on cell efficiency as well as the application of the device as a solar water heater. Ramos *et al.* (2017) investigated hybrid PV-T solar systems for heating and cooling energy supply in greenhouse environments (Fig. 24). To optimize the overall energy of the systems designed to meet heating and cooling needs, these systems can be connected to heat pumps. This addresses the technical and economic challenges of some systems when considering the lowest cost per kWh of energy production in the housing sector. The first technical reliability and pricing of the proposed system has been studied in 10 European locations with local climatic profiles.

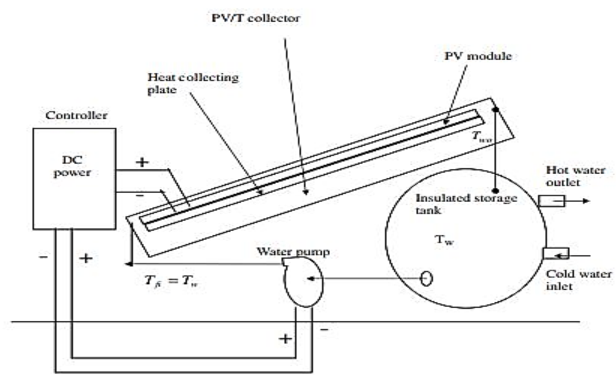

Fig 23. Schematic diagram of the integrated PV-T system (Tiwari *et al.*, 2009)

A new solar-assisted heat pump driven by PV-T collectors was proposed by Calise et al., (2016). This paper presents a dynamic simulation model and a thermos-economic analysis of the new multi-generation system based on the solar-assisted heat pump and an absorption chiller, both driven by PV-T collectors. Poonia et al. (2018) designed a PV-T hybrid solar dryer for drying of ber (Zizyphus mauritiana). This research paper describes the drying kinetics of Zizyphus mauritiana and the economic evaluation of a PV-T hybrid solar dryer made using locally available materials. Four mathematical models were evaluated to predict drying behavior of Zizyphus mauritiana in PV-T hybrid solar dryers. The economic evaluation of the PV-T hybrid solar dryer showed that the dryer unit is cost-effective and its economic durability is guaranteed.

Table 1. Investigation results of different PV-T designs

PV-T design	Electrical Efficiency	Thermal efficiency	Exergy efficiency	Additional information	Reference
PV-T system under natural water flow	10%	40%	-	About 75% of thermal efficiency was for a traditional solar thermosiphon system	(He *et al.*, 2011)
PV-T with webs, direct and spiral flow absorbers	13.8%	54.6%	-	The spiral flow absorber exhibited the highest performance	(Fudholi *et al.*, 2014)
Sheet and tubes hybrid PV-T collector	-	70%	-	Theoretical and experimental review of hybrid PV-T	(Touafek *et al.*, 2014)
Semitransparent PV-T with thermoelectric cooler collector	17%	19%	≈14%	A thermal model has been derived.	(Dimri *et al.*, 2017)
Comparison of several types of Nano fluid-based PV-T	18%	50%	-	Silicon carbide has better thermal conductivity	(Al-Waeli *et al.*, 2017a)
Silver-water Nano fluid-based PV-T	14%	60.8%	82%	Optimum design is selected through CFD, and reduced emission of CO_2 by 16,974.57 tons/year	(Lari and Sahin, 2017)
Low-concentrator polycrystalline silicon PV-T	17.5%	70.8%	-	The modified solar cell produces the highest net power of 45 W, while a normal cell produces 34 W	(Ahmed and Radwan, 2017)
PV-T water collector	1.5-28%	23-75%	6.8-14%	Absorbents have tubes	(Fudholi *et al.*, 2018)
PV-T air collector coupled heat pump water heaying	16.61%	33.23%	-	The maximum increase in COP of heat pump using PV-T compared to air heat pump was 8.57%.	(Choi *et al.*, 2020)
Aerogel-based PV-T collector	17.31%	60%	20.4%	PV type was Poly-crystalline silicon, and thermal exergy efficiency increased by 46%.	(Wu *et al.*, 2021)

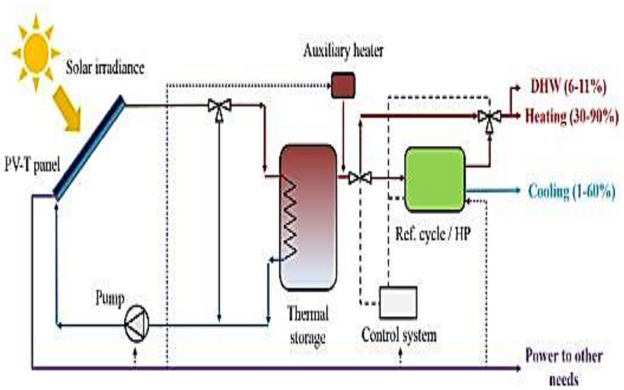

Fig 24. Schematic diagram of the proposed PV-T system for solar heating and cooling provision (Ramos *et al.*, 2017)

Tiwari *et al.* (2018a) reviewed the greenhouse dryers equipped with PV-T air collectors. They stated that the forced drying is better than the natural drying in term of controlling drying parameters. The average thermal efficiency, electrical efficiency and overall thermal efficiency for PV-T air collectors are 26.68%, 11.26%, and 56.30% at a mass flow rate of 0.01 kg/s, respectively.

Alizadeh *et al.* (2019) proposed a novel solar juice concentration system (SJCS) with a liquid desiccant bed and closed-loop air circulation system (Fig. 25). Thermal energy was supplied by solar collectors and electrical energy of the system designed by PV module. The SJCS was recommended for fruit juice processing industries due to the low energy consumption and acceptable and competitive product color quality. A liquid desiccant-assisted solar dryer equipped with a PV-T regeneration system was developed by Dorouzi *et al.* (2018). They experimentally studied the dryer at the different drying temperatures and activation RHs of the regeneration system (Fig. 26).

Fig 25. A photograph of the liquid desiccant-assisted SJCS: 1- solar air heater, 2- concentration chamber, 3- unglazed solar collector, 4- desiccant bed, 5- blower, 6- PV module (Alizadeh *et al.*, 2019)

Fig 26. A photograph of the liquid desiccant-assisted solar dryer: 1- solar collector, 2- air entrance to the collector, 3- drying chamber, 4- liquid desiccant bed, 5- connecting tube, 6- PV panel, 7- regeneration system's pump, 8- distribution pipe (Dorouzi *et al.*, 2018).

Pourafshar *et al.* (2020) developed a photovoltaic-thermal solar humidifier for the humidification-dehumidification (HDH) desalination system coupled with heat pump. The designed PV-T solar humidifier is a double-pass dual-fluid solar collector (Fig. 27).

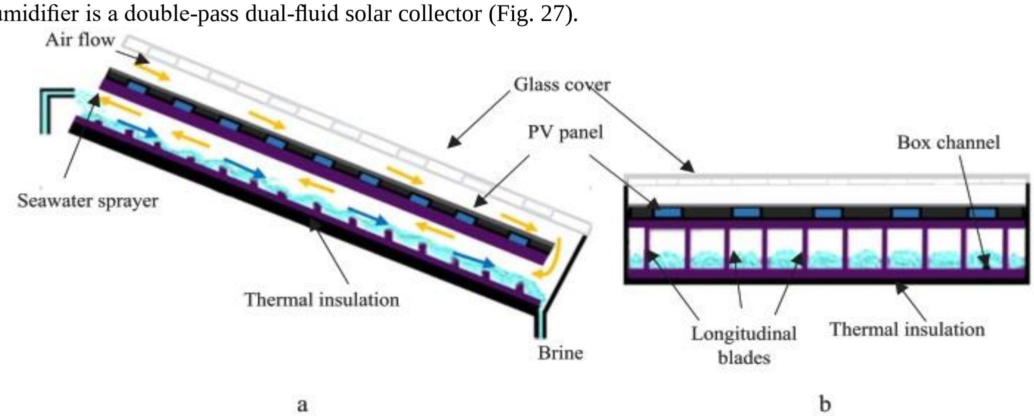

Fig 27. Longitudinal (a) and cross sections (b) of the PV-T solar humidifier (Pourafshar *et al.*, 2020).

Mirzaei *et al.* (2021) investigated an infrared dryer equipped with a photovoltaic-thermal collector in glazed and unglazed modes (Fig. 28). In this study, all of energy needed for the drying process is provided by solar energy.
Table 2 summarizes the PV-T applications described in this review.

CONCLUSIONS

According to research studies, in recent years all industrialized countries and most developing countries have conducted extensive research on renewable energy, especially solar energy. Although much attention has been paid to PV-T collectors so far, there is still a chance that this technology will be further developed in the future. Efficiency is the most important parameter to be considered in PV-T technologies. Changes in heat carrier fluid play a major role in electrical and thermal efficiency. A brief overview of the most promising fluids used in PV-T is reported in this article. The structure of these collectors can be further examined in terms of geometry, shape, and heat transfer medium. Also, these systems must be able to be used in real buildings so that their practical use can be displayed. Therefore, future work should be aimed at increasing efficiency and reducing costs to increase their competitiveness and use as a renewable and environmentally friendly energy device.

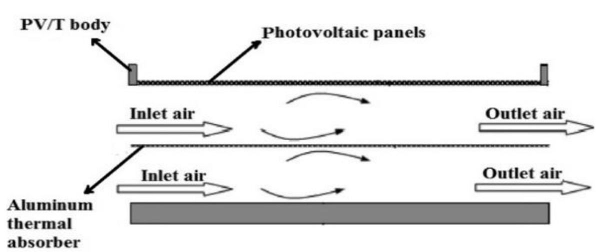

Fig 28. Schematic of the studied PV-T air system developed by (Mirzaei *et al.*, 2021)

Table 2. Summary of different PV-T applications

PV-T applications	Electrical Efficiency	Thermal efficiency	Exergy efficiency	Additional information	Reference
Integrated photovoltaic thermal solar water heater	-	45-55%	49-65%	Increasing water flow rate increased thermal efficiency	(Tiwari *et al.*, 2009)
Building-integrated PV-T collector	15.9%	19%	-	Efficiency of PV cells can be increased up to 5.3%	(Corbin and Zhai, 2010)
PV-T for heating, cooling and energy supply	15-20%	50%	-	Total energy cost of the systems was in the range of 0.06 -0.12 €/kWh	(Ramos *et al.*, 2017)
PV-T air integrated greenhouse dryer	26.68%	56.3%	26.9%	Thermal modelling of PV-T air collector integrated greenhouse drying system	(Tiwari *et al.*, 2018b)
Drying with PV-T regeneration	-	38.5-63.4%.	-	Maximum specific moisture extraction rate was around 0.275 kg/kW h	(Dorouzi *et al.*, 2018)
PV-T humidifier desalination with heat pump	11.3%	Maximum 75.6%	-	The highest evaporation rate was 1.06 kg/h/m^2 humidifier surface	(Pourafshar *et al.*, 2020)
Infrared dryer equipped with a PV-T collector	9%	-	0.5%	Using the forced hot air flow	(Mirzaei *et al.*, 2021)

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