A review of thermal absorbers and their integration methods for the combined solar photovoltaic/thermal (PV/T) modules

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Abstract

Thermal absorbers and their integration methods are critical to solar photovoltaic/thermal (PV/T) modules. These two elements directly influence the cooling effort of PV layers and as a result, the related electrical/ thermal/overall efficiency. This paper conducts a critical review on the essential thermal absorbers and their integration methods for the currently-available PV modules for the purpose of producing the combined PV/T modules. A brief overview of different PV/T technologies is initially summarized, including aspects of their structure, efficiencies, thermal governing expressions and their applications. Seven different types of thermal absorbers and four corresponding integration methods are subsequently discussed and summarized in terms of their advantages/disadvantages and the associated application for various PV/T modules. Compared to traditional thermal absorbers, such as sheet-and-tube structure, rectangular tunnel with or without fins/ grooves and flat-plate tube, these four types, i.e. micro-channel heat pipe array/heat mat, extruded heat exchanger, roll-bond heat exchanger and cotton wick structure, are promising due to the significant enhancement in terms of efficiency, structure, weight, and cost etc. The appropriate or suitable integration method varies in different cases, i.e. the ethylene-vinyl acetate (EVA) based lamination method seems the best option for integration of PV layer with thermal absorber when compared with other conventional methods, such as direct contact, thermal adhesive and mechanical fixing. Finally, suggestions for further research topics are proposed from five aspects. The overall research results would provide useful information for the assistance of further development of solar PV/T modules with high feasibility for widespread application in energy supply even at district or city-level in the near future.

Keywords:
Solar, PV/T, Thermal absorber, Integration method

1. Introduction

Global current energy demand is continuously growing, therefore new solutions for energy conservation, energy supply and simultaneous environmental protection is highly desirable. The utilization of renewable energy is, without a doubt, one of the most encouraging ecological solutions towards sustainable and resilient development. Solar energy, as an inexhaustible, renewable and eco-friendly energy source is currently promising to offer potential solutions for sustainable development [1]. At present, the most widely available solar technologies are solar photovoltaic (PV) and solar thermal heat, which combined contribute towards a large share of global energy supply as illustrated in Fig. 1 [2].

According to the International Energy Agency (IEA)'s projections [3] by 2050 there will be 3000 GW of installed PV capacity worldwide, generating 4500 TW h per year and contributing 11% of expected global electricity supply (Fig. 2). China has now overtaken Germany and the US to become the world's top generator of solar PV power. During the period of the Twelfth Five-Year Plan, China's PV capacity increased 168 times, far beyond the speed of all previously observed renewable energy development. [4]. With 15 GW added in 2015, China has reached 43 GW of solar PV capacity at a mean 40% rise annually [5]. Fig. 3 shows the cumulative installed PV capacity in China from 2000 to 2015.

Currently, solar thermal only provides around 0.5% of the estimated global water and space heating demand in the buildings sector

Nomenclature

a	width of duct, m
A_c	collector aperture area, m^2
b	length of duct, m
C_b	thermal conductance of the bond between fin and tube, J/kg k
C_p	heat capacity of flowing medium, J/kg k
D_h	hydraulic diameter, m
D_i	inside diameter of flow tubes, m
D_o	outside diameter of flow tubes, m
F	fin efficiency
F'	module efficiency factor
F_R	heat-removal factor
h	heat transfer coefficient, W/m^2 k
I	incident solar radiation, W/m^2
P	power, W
Q	energy rate, W
T	temperature, °C
U	overall heat transfer coefficient, W/m^2 k
W	distance between tubes, m

Greek

α	absorptivity
δ	thickness, m
η	efficiency, %
τ	transmittance of the material

Subscripts

a	air
e	electricity
fi	fluid
in	inlet
L	loss
o	overall
p,m	mean value of plate
PV-roll bond	PV layer to roll-bond plate
th	thermal

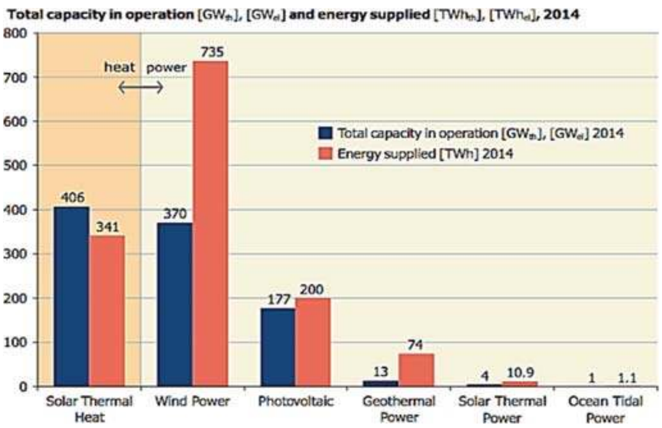


Fig. 1. Global capacity in operation and annual energy yields in 2014 [2].

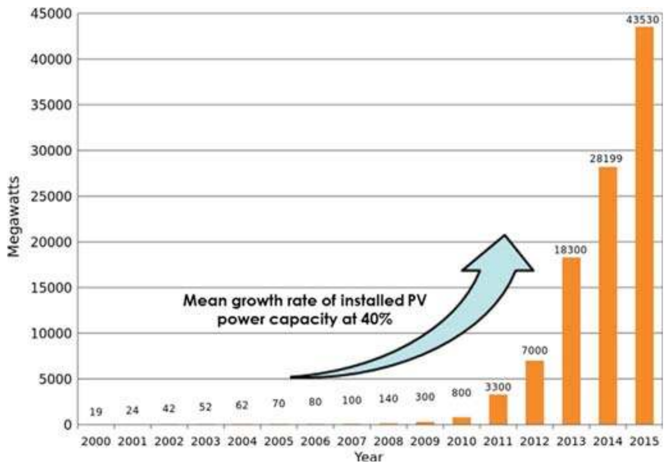


Fig. 3. Installed PV power capacity in China from 2000 to 2015 [5].

within the European area [6]. In 2005 Europe had a solar thermal system capacity of around 10 GW_{th}. This is expected to grow to 200 GW_{th} by 2030, of which up to 50% will be used for the delivery of low and medium temperature water [7]. In the UK, around 131 GW_{th} of domestic hot water has already been provided by solar systems, partly replacing conventional gas and electrical heating systems in 2011 [8]. In 2013, it was indicated that 148.2 million tonnes of oil equivalent was consumed, with 66% used for space heating and another 17% for water heating, with a total estimated cost of around £33 billion to the UK economy [9]. Meanwhile, solar driven water heating systems have been identified as having the potential to offset around 70–90% of the total energy required for water heating, thus enabling significant savings in household fossil fuel energy use [10]. Supporting the UK Government's Renewable Heat Premium Payment scheme, solar thermal is expected to offer great potential for heat source diversity and for the development of towns and cities in sustainable and affordable ways.

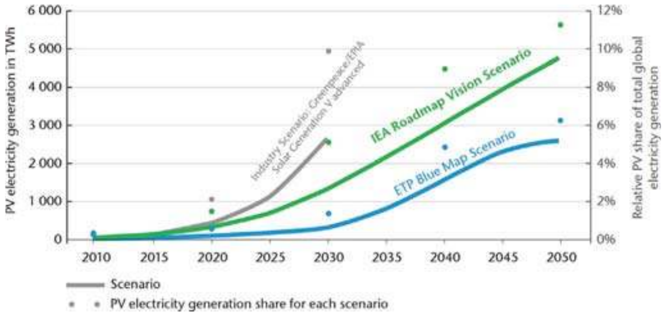


Fig. 2. Global PV power generation and relative share of total electricity generation [3].

As for China, the installed operating capacity of solar thermal in 2013 was 262.3 GW_{th}[10], far beyond the installed capacity in any other country (Fig. 4). At the beginning of 2015 the Chinese authorities released its "Renewable Energy Development Roadmap 2050" as a long-and-medium-term plan for the development of solar technologies. This plan includes the huge expansion of low-median temperature solar thermal applications to support a stronger growing Chinese economy and a low carbon future.

PV/thermal (PV/T) technologies enable dual function of solar collection within one module with an output of both electricity and heat. Such synergetic integration of PV and thermal collection results not only in improved PV efficiency [3], but also generates more energy per unit area than a stand-alone PV or solar thermal module. The market potential of PV/T technology is therefore significantly higher than for individual PV and solar thermal systems. This strategic concept will boost solar energy application in line with future development trends of both PV and solar thermal technologies as addressed above.

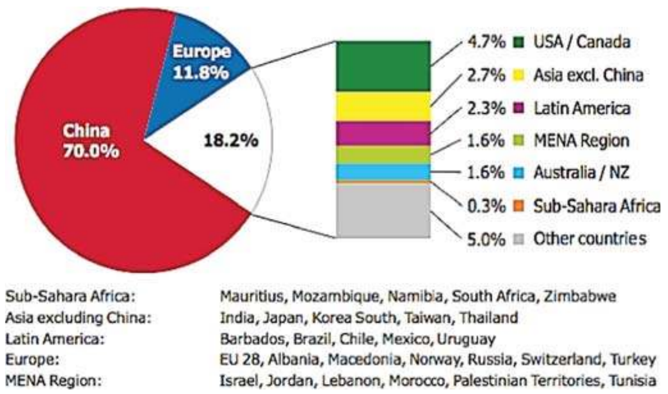


Fig. 4. Share of the total installed solar thermal capacity in operation (glazed and unglazed water and air collectors) by economic region at the end of 2013.

Thermal absorbers for PV/T modules are complementary to solar cells as another way of harvesting solar energy. The overall conversion efficiency of a PV/T module increases with the efficiency of its thermal absorber according to the laws of thermodynamics. Different methods for thermal absorber design, namely sheet-and-tube structure, rectangular tunnel with or without fins/grooves, flat-plate tube, micro-channel heat pipe array/heat mat, extruded heat exchanger, roll-bond heat exchanger and cotton wick structure, are being comprehensively developed. Generally, a PV/T module is constructed by attaching a commercially available PV layer to a thermal absorber using integration methods such as mechanical or chemical adhesive bonding. This combination provides gap filler that transfers heat between the PV layer and the thermal absorber and must have a good elongation property to compensate for the different expansion of various components of the PV layer and thermal absorber. Poor thermal contact between the PV layer and the thermal absorber underneath leads to a temperature difference of about 15 °C for an unglazed PV/T module. This is due to reduced solar energy absorption, and increased heat transfer resistance in the cell to the absorber interface, resulting in poor module heat removal factor [11,12]. Moreover, the thermal resistance between the PV layer and thermal absorber may become extremely large if a small air gap or air bubbles exist within the integration layer. Therefore, both the thermal absorber and the integration method used is critical to the solar PV/T modules as they directly affect cooling of PV layers and therefore also the related electrical/thermal/overall efficiency.

This paper thus conducts a critical review on recent research and development of thermal absorbers and the integration methods required for their use within combined PV/T modules; categorised into flat-plate, flexible and concentrated thermal absorbers. The overall research provides useful information for the assistance of further development of PV/T modules with high feasibility for widespread application in energy supply even at district or city-level approaching the near future.

2. Photovoltaic/thermal (PV/T) technologies

2.1. Basic concept and theory of PV/T operation

PV modules come in a variety of forms including conventional framed flat-plate, flexible and concentrated types. However, owing to the low energy output of solar PV modules combined with the low exergy of solar thermal collectors, a solar PV/T module, combining both electrical and thermal components in a single unit area, could potentially provide a solution to the low overall (sum of electrical and thermal) efficiency. Present PV technology has a major inherent drawback in its inability to absorb solar radiation from the complete solar spectrum. In addition, PV cells suffer from a drop in efficiency with a rise in temperature. Increasing the temperature of PV cells by 1 °C causes a reduction in electrical efficiency by around 0.4–0.5% for crystalline silicon PV cells and around 0.25% for amorphous silicon (*a*-Si) PV cells [13]. This results in PV cells delivering relatively low electrical efficiencies since a major part of the incident solar energy is either lost due to convection and radiation or converted as heat. Solar PV/T can harvest these thermal energy and therefore increase overall thermal and electrical efficiency [14,15].

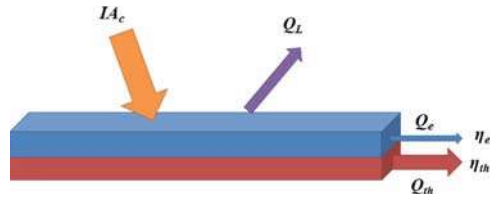


Fig. 5. : Basic operation principle of PV/T modules.

Fig. 5 shows the basic operation principle of a PV/T module. From the point of view of the first law of thermodynamics, the overall efficiency of a PV/T module is the sum of the module's thermal efficiency ηth and the module's electrical efficiency η_e, which are defined as the ratios of useful heat gain and electricity gain to the incident solar irradiation striking on the module's collecting surface, given as below:

$$\eta_{th}=\frac{Q_{th}}{IA_c}=1-\frac{U_L}{I}(T_{p,m}-T_a)-\eta_e \tag{1}$$

where Qth can alternatively be expressed by the difference in absorbed solar radiation, heat loss and the generated electricity.

$$\eta_e=\frac{Q_e}{IA_c}=\frac{P_e}{IA_c} \tag{2}$$

where Q_e is equal to the measured electrical power (P_e).

$$\eta_o=\eta_{th}+\eta_e=\frac{Q_{th}+Q_e}{IA_c}=1-\frac{Q_L}{IA_c}=1-\frac{U_L}{I}(T_{p,m}-T_a) \tag{3}$$

Apart from categorization by working fluid (i.e. air, water, refrigerant, phase change material, nano-fluid etc.) [15,16] the hybrid PV/T technologies can further be divided into flat-plate, flexible and concentrated, depending on the type of PV module, as indicated in Fig. 6. The following section will give an overview of the different PV/T technologies including aspects of their structure, efficiencies, applications etc.

2.2. Flat-plate PV/T modules

The flat-plate PV/T modules usually combine a flat-plate PV module in the front, which converts sunlight into electricity, with a solar thermal absorber at the back, which captures the remaining energy and removes excessive heat from the PV module. Such modules can be engineered to carry heat away from the PV cells thereby cooling the cells and therefore improving their efficiency by lowering resistance. The capture of both electricity and heat allow these devices to have higher exergy [17] and thus have greater overall energy efficient than solar PV or solar thermal alone [18]. A significant amount of research has gone into developing the flat-plate PV/T technology since

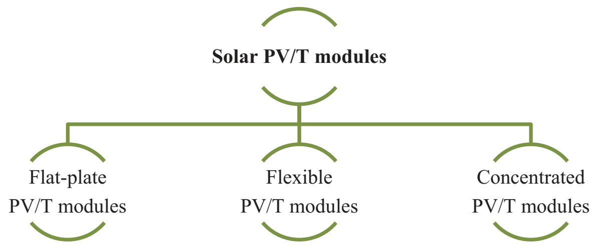
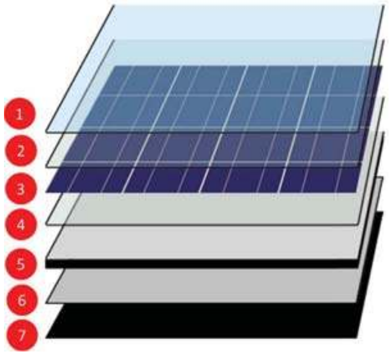


Fig. 6. : Category of solar PV/T modules according to PV types.



1: Glazing cover; 2: EVA-encapsulate; 3: Solar PV cells; 4: EVA-encapsulate;

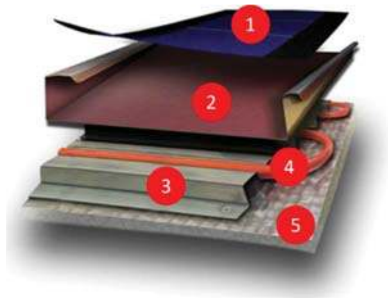
5: TPT back sheet; 6: Thermal absorber; 7: Thermal insulation

Fig. 7. Schematic of a typical flat-plat PV/T module. 1: Glazing cover; 2: EVA-encapsulate; 3: Solar PV cells; 4: EVA-encapsulate; 5: TPT back sheet; 6: Thermal absorber; 7: Thermal insulation.

the 1970s [19].

The main components of the flat-plate PV/T modules, given in Fig. 7, are the glazing cover (optional), flat-plate PV module, adhesive, thermal absorber and insulation. The adhesive often consists of ethylene-vinyl acetate (EVA) and a layer of tedlar-polyester-tellar (TPT). Glass cover is optional for flat-plate PV/T module and can either be single or double glass. PV/T devices with more than three glass covers are not recommended because their electrical efficiency is very low, due to the low transmittance of the aperture and the enhanced thermal resistance of the triple glazing cover [20]. The purpose of the thermal absorber, also called an “extracting heat device” is to reduce the temperature underneath the PV module. The fluid flowing inside the channels transport the collected thermal energy in low-temperature applications. The insulation layer prevents heat from escaping into the surrounding area. Fig. 8 shows the typical classification of flat-plate PV/T according to different working fluids [21], which have electrical, thermal and combined efficiencies in the range of 6.7–15%, 22–79%, and 40–87% respectively [22].

Flat-plate PV/T modules are produced in regular flat shapes that could be applied in both urban and rural areas, i.e. ground mounted, wall/roof mounted, etc., and for industry or building energy supply. Each module is fitted with a tubular inlet and outlet at the back or the side that allow for connection between module to module in either a serial pattern to allow the working fluid to pass through from one to another, or a parallel pattern. It is feasible to make further use of the absorbed heat through a heat pump for one or more of the following purposes, i.e. hot water supply [23–25], space heating [26,27], solar cooling [28,29], thermal storage [30], desalination [31], drying [32,33] and pool heating [34,35] etc. Electricity generation from the PV cells, either exported to the national grid or stored in batteries, will meet the



1: Thin film PV; 2: Metal roof; 3: Fin sheet; 4: Thermal pipes; 5: Insulation

Fig. 9. Schematic of a typical flexible PV/T module [37]. 1: Thin film PV; 2: Metal roof; 3: Fin sheet; 4: Thermal pipes; 5: Insulation.

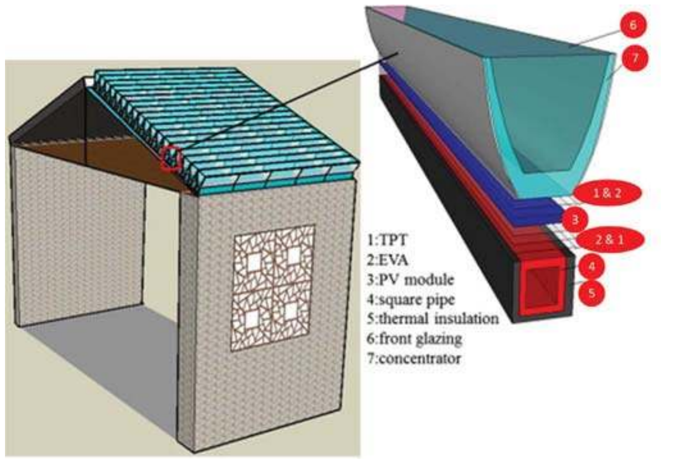


Fig. 10. Schematic of a typical concentrated PV/T module [42].

electrical load or drive the system component, i.e. water pump, heat pump compressor. The combination of these concepts could create a low (zero) carbon industry process and building driven by solar energy.

2.3. Flexible PV/T modules

Flexible PV/T modules have an almost identical structure as compared to flat-plat modules aside from the PV layers are often made of amorphous silicon (*a*-Si). The flexible PV/T modules typically include thermal pipes or air space beneath the metal sheet supporting the thin film, which may be installed above the current roof structure in the case of building retrofits. Amorphous silicon is the most popular thin film technology used at low-and-medium temperature with cell efficiencies of 5–7%, and double- and triple-junction designs raising it to 8–10% [36]. The additional thermal efficiencies of flexible PV/T modules could be in the same range as observed for flat-plate modules

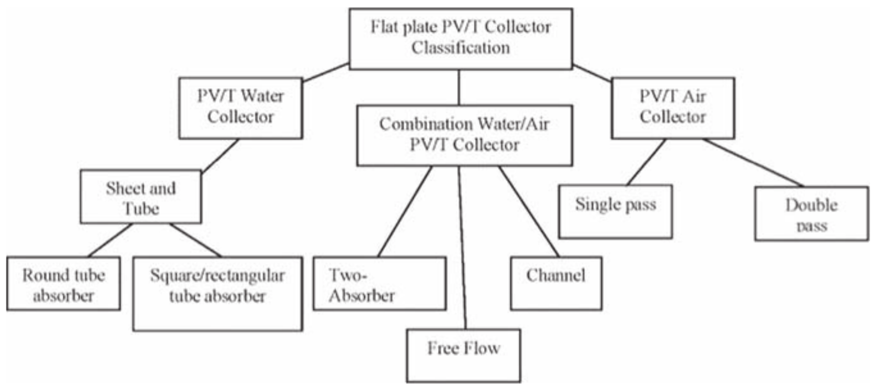


Fig. 8. Classification of flat-plate PV/T module [21].

at 22–79% [22]. A typical structure of flexible PV/T module is schematically illustrated in Fig. 9.

Due to their flexibility, flexible PV/T modules can serve as rooftop shingles/tiles, irregular building facades, and the glazing for daylights. Integration of flexible PV/T modules into the profile of the roofing sheet is the most popular design that allows for heat and power to be generated from the integrated panels and transferred to a location within the building for purposes such as hot water supply [38], space heating [39], space cooling [40], and even fresh water production etc. [41].

2.4. Concentrated PV/T modules

The structure of a concentrated PV/T module, as shown in Fig. 10, consists of upper glazing, mirror compound parabolic concentrator (CPC), high-temperature PV layer, thermal pipe and thermal insulation [42]. The PV cell is pasted on the under surface of solid CPC, consisting of crystalline silicon, cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and $SiNx/SiO_2$[43,44]. The solar transmittance varies in accordance to the changing radiation incidence angles, ranging electrical efficiency from 7% to 16% and combined efficiency from 46% to 86%, under different concentrating ratios [42–49].

The higher concentration ratios are expected in the concentrated PV/T modules in order to generate higher temperature thermal energy, mostly in case of roof or ground-mounted installation, allowing for a wide range of applications, such as solar air/water heater, solar air-condition (absorption and adsorption refrigeration) and solar dehumidification [50], greenhouse drying [45], and fresh water production

Table 1
Comparison of different PV/T technologies from aspects of application and efficiencies.

PV/T types	Temperature	Applications	Module efficiencies
Flat-plate	Low-and-medium	Flat-plate PV/T modules are in regular flat shapes that could be applied as ground mounted, wall/roof mounted: 1. *Hot water supply*[23–25] 1. *Space heating*[26,27] 1. *Solar cooling*[28,29] 1. *Thermal storage*[30] 1. *Desalination*[31] 1. *Drying*[32,33] 1. *Pool heating*[34,35]	1. Electrical efficiency of 6.7%–15%[22] 1. Thermal efficiencies of 22%–79%[22]
Flexible	Low-and-medium	Flexible PV/T modules can serve as rooftop shingles/tiles, irregular building facades, and the glazing for daylights: 1. *Hot water supply*[38] 1. *Space heating*[39] 1. *Space cooling*[40] 1. *Fresh water production*[41]	1. Electrical efficiency of 5–10%[36] 1. Thermal efficiencies of 22–79%[22]
Concentrated	High temperature	Concentrated PV/T modules are mostly in case of roof or ground-mounted installation 1. *Solar air/water heater* 1. *Solar air-condition (absorption and adsorption refrigeration) and dehumidification*[50] 1. *Greenhouse drying*[45] 1. *Fresh water production*[51]	1. Electrical efficiency of 7–16% 1. Thermal efficiency of 39–70%[42–49]

Table 2
Summary of different thermal absorbers with advantages/disadvantages, and their application for PV/T modules.

Thermal absorbers	Advantages	Disadvantages	Application
Sheet-and-tube	a. Attractive cost due to established industry b. Good heat-transfer efficiency	a. Complex structure b. Require precise welding technologies c. Heavy weight d. Limited application on buildings e. Leakage risks	a. Flat-plate PV/T b. Flexible PV/T c. Concentrated PV/T
Rectangular tunnel with or without fins/grooves	a. Simple structure b. Low weight c. Low cost	a. Relatively low efficiency b. Limited application in extreme weather conditions	a. Flat-plate PV/T b. Flexible PV/T c. Concentrated PV/T
Flat plate tube	a. Improve the contact between PV layer and absorber from line to surface (if in a round configuration)	a. Increasing fluid temperate along flow direction b. High flow resistance c. Leakage risk d. Choking risk	a. Flat-plate PV/T
Micro-channel heat pipe/heat mat	a. High heat transfer performance, high reliability, high compressive strength, low cost, and small contact thermal resistance	a. Uneven heat transfer/temperature distribution across the top and the bottom areas b. Additional thermal resistance between the condenser and the manifold	a. Flat-plate PV/T b. Flexible PV/T
Extruded heat exchanger	a. Simple structure b. Low cost	a. High volume of working fluid b. Special hydrologic design	a. Flat-plate PV/T b. Flexible PV/T
Roll-bond heat exchanger	a. Uniform temperature distribution b. Cost-effective c. High efficiency d. Low weight	a. Problem of long-term reliability b. Corrosion risk	a. Flat-plate PV/T b. Flexible PV/T
Cotton wick structure	a. Very simple structure b. Very low cost	a. Limited cooling efficiency b. Limited application	a. Flat-plate PV/T b. Flexible PV/T

etc., [51].

2.5. Comparison of three PV/T modules

Table 1 summarizes the application areas and the solar electrical/thermal efficiencies of these three different PV/T technologies. It is clear that all these PV/T modules have a wide range of applications, covering almost all domestic and industrial heat requirement. Since flat-plate PV/T modules are in regular flat shapes, they are usually applied for ground or wall/roof mounted installation. Their electrical efficiencies are relatively high since the crystal silicon cells are used in this PV/T type while their thermal efficiencies vary greatly depending on their different structures or operation conditions. Flexible PV/T modules, being able to serve as rooftop shingles/tiles, irregular building facades, and glazing for daylights, demonstrate the lowest electrical efficiency owing to the utilization of amorphous silicon cells; but their thermal efficiencies are similar to the flat-plate PV/T ones. Concentrated PV/T types are capable of connecting with complex air-conditioning systems mostly only roof or ground-mounted installations due to their high-temperature operation (high-level energy), and have slightly-less maximum thermal efficiency than the other two PV/T types (higher temperature, larger heat loss).

Table 3
Common equations applied for the estimation of the thermal efficiency of typical PV/T modules with different structures.

Thermal absorbers	Thermal efficiency expressions
Sheet-and-tube structure	Classic Hottel and Willier equation systems[86,87] $\eta_{th}=F_R\left[(\tau\alpha)-\frac{U_L}{I}(T_{in}-T_a)-\eta_e\right]$ *where,* F_R is the heat-removal factor which is associated with the efficiency factor (F'): $\frac{F_R}{F'}=\frac{IC_p}{U_LF'}[1-\exp(-\frac{U_LF'}{IC_p})]$ *where,* F' is module efficiency factor: $F'=\frac{1/U_L}{W\left[U_L(D_o+(W-D_o)F)+\frac{1}{C_b}+\frac{1}{\pi D_i h_{fi}}\right]}$
Rectangular tunnel with or without fins/ grooves	Rectangular tunnel with grooves covered by PV cells[64]: $\eta_{th}=0.574-\frac{4.85(T_{in}-T_a)}{I}$ Polypropylene thermal absorber with honeycomb structure for PV/T module[31] $\eta_{th}=0.53-\frac{11.7(T_{in}-T_a)}{I}$ for flow rate of 200 l/h $\eta_{th}=0.51-\frac{12.6(T_{in}-T_a)}{I}$ for flow rate of 100 l/h
Flat-plate tube	Classic Hottel and Willier equation systems[86,87] by only changing the expression of module efficiency factor F',[69] $F'=\frac{1/U_L}{U_L(D_h+(W-D_h)F)+\frac{1}{C_b}+\frac{1}{2(a+b)h_{fi}}}$
Micro-channel heat pipe array/ heat mat	Experimental expression of PV/T module using micro heat pipe array[71] $\eta_{th}=0.30-\frac{0.105(T_{in}-T_a)}{I}$
Extruded heat exchanger	Experimental expression of PV/T module using extruded heat exchanger[75] $\eta_{th}=0.4687-\frac{18.828(T_{in}-T_a)}{I}$
Roll-bond heat exchanger	Classic Hottel and Willier equation systems[86,87] by only changing the expression of module efficiency factor F',[82] $F'=\frac{1/U_L}{W\left[U_L(D_o+(W-D_o)F)+\frac{1}{h_{PV-roll\ bond}}+\frac{1}{\pi D_i h_{fi}}\right]}$ Experimental expression of PV/T module using roll-bond heat exchanger[83] $\eta_{th}=0.79-\frac{5.15(T_{p,m}-T_a)}{I}$

3. Thermal absorbers for PV/T modules

Solar thermal absorbers for PV/T modules are complementary to PV cells as another method to harvest solar energy. Thermal absorbers that affect the direct cooling of PV layers are critical as they influence the electrical/thermal/overall efficiency of the PV/T modules. Recent developing research shows that different types of thermal absorbers are better suited for various PV/T modules. This part of the review will go through the thermal absorbers, summarising the advantages/disadvantages and associated application for PV/T modules are outlined in Table 2. The common equations applied for the estimation of the thermal efficiency of typical PV/T modules with different structures are also summed up in Table 3.

3.1. Sheet-and-tube structure

The sheet-and-tube structure dominates the absorbers typologies in solar thermal application. Fig. 11 shows four sheet-and-tube structures that are commonly employed as the thermal absorbers for different PV/T modules [50,52–56], in which a flat-plate metal sheet (copper, aluminium, or stainless steel) is enwrapped or bonded to a metal tube or polyethylene tube mat [57]. The metal sheet not only offers feasible contact between the PV layer and the tube, but also works in conjunction with the fin function to enhance the overall heat transfer efficiency from the PV layer to the working fluid inside the tube. The arrangement of the tubes can also differ on the basis of the sheet-and-tube structures depending on their working principles, such as parallel tube [58], heat pipe [59], fin tube [60], and coil tube [61], as illustrated in Fig. 12. Sheet-and-tube structures are common for thermal absorbers, having a high pressure bearing capacity [62] and good heat-

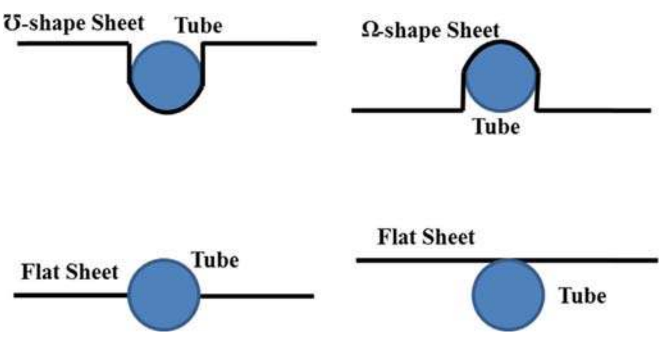


Fig. 11. Four sheet-and-tube structures as thermal absorber for PV/T modules.

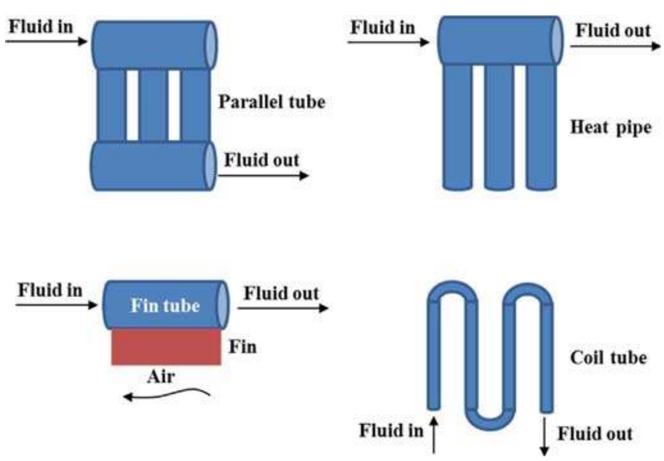


Fig. 12. Different tubes arrangements on basis of the sheet-and-tube structures.

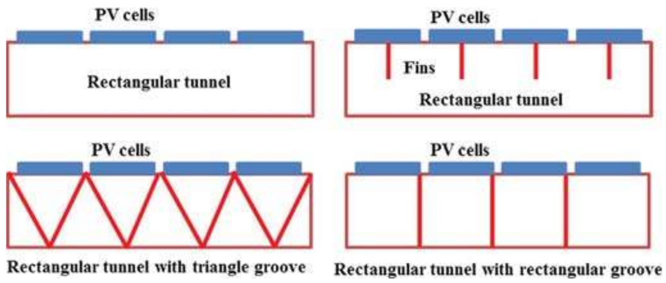


Fig. 13. Schematic of the rectangular tunnels as thermal absorbers for PV/T modules.

transfer efficiency (only 2% less efficient [52] as compared to other designs). Despite usually having complex structures, therefore requiring precise welding technologies, sheet-and-tube structures can be manufactured by well-established industry at an attractive cost. However, the groupings of metal tube arrangements often add a lot of weight to PV/T modules which limits their application on buildings in large-scale projects.

3.2. Rectangular tunnel with or without fins/grooves

Rectangular tunnels, shown in Fig. 13, are the most basic and yet promising structures as thermal absorbers for PV/T modules. They are constructed from metal sheets or polymer materials either in separate channels or double/multi-pass designs [13,63]. Rectangular tunnels can be applied in all the above mentioned PV/T modules since the flat-plate surfaces are easy to be integrated with PV cells or modules. Additional fins, V-shaped grooves, rectangular grooves and honeycomb grooves (Fig. 14) can be implemented in order to increase the heat transfer between the fluid and the PV layer [13,20,21,31,64,65]. Different fluids, such as air [20], water [64], phase change material (PCM) [66], thermal oil [67], nanofluids (i.e., dilute nanoparticle suspensions in liquids) [68] etc., can be used as the working medium that passes through the tunnel in one or both directions. These kinds of thermal absorbers are characterized by their simple structure, low weight, low cost and relatively low heat-transfer efficiency. These are normally applied in large-scale PV/T projects where an equilibrium between the investment and the amount of energy harvested is attainable.

3.3. Flat-plate tube

The flat-plate tube absorber has flattened tubes in a round tube configuration, making it easier for integration with a PV module. There are two main types of designs, i.e. spiral [21,69] and coil [70]. The flat-plate tube absorber can be made of rectangular hollow tubes of metal (i.e. stainless steel, copper) using a welding method for tube connection. It has a single unilateral channel for the fluid flow as shown in Fig. 15, which can be designed in the forms of continuous spiral or coil configuration. The flat-plate tube absorber has at least one inlet and outlet to allow the working medium to enter and to exit respectively. The inlet and the outlet of are usually arranged further away to the enter point. This allows the working medium to flow in the reversed direction across the entire PV panel. However in practice, the efficiency is about 2% lower as compared to other types of absorbers such as, channel, free flow and two-absorber [69]. These kinds of thermal absorbers improve the contact between PV layer and absorber from line to surface (if in a round configuration) but they still have problems in increasing fluid temperature along flow direction and high flow resistance as well as the risks in terms of leakage and choking etc. Most of flat-plate tube absorbers are only applied in water cooled flat-plate PV/T modules, which therefore limits its applications.

3.4. Micro-channel heat pipe array/heat mat

Micro-channel heat pipe array (MHPA) [71–73], also termed as heat mat [39], is a flat-plate heat pipe based thermal absorber suitable for flat-plate and flexible PV/T modules. Fig. 16 shows a flat aluminium plate with multiple parallel micro heat pipes operating independently [71]. The entire MHPA/heat mat based PV/T module setup is shown in Fig. 17. Each micro heat pipe has many inner microgrooves (or micro-fins) that allow efficient heat transfer from upper surface facing solar irradiation to the heat pipe working fluid. This fluid boils and flows up to the condenser section of the heat pipe cooled itself using a manifold. The MHPA/heat mat bears the advantages of high heat transfer performance, high reliability, high compressive strength, low cost, and small contact thermal resistance because of its flat-plate structure [39,71–73]. It can also be applied in cold regions when ammonium hydroxide is used as the working fluid. However, it may still have the limitation such as uneven heat transfer/temperature distribution across the top and the bottom areas of a PV layer as well as having additional thermal resistance between the condenser and the manifold.

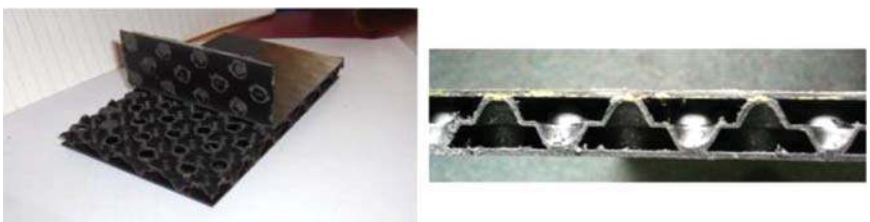


Fig. 14. Polypropylene thermal absorber with honeycomb structure for PV/T module [31].

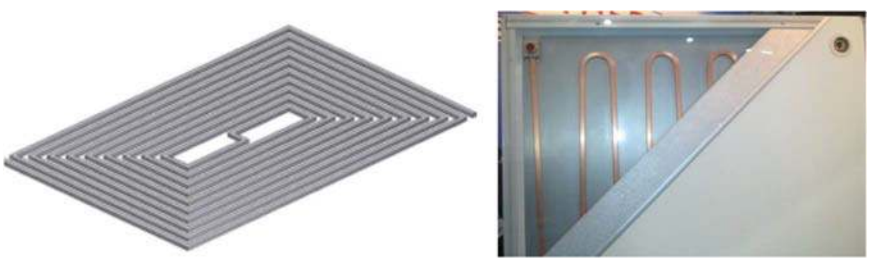


Fig. 15. Thermal absorber with flat-plate tube for PV/T modules [69,70].

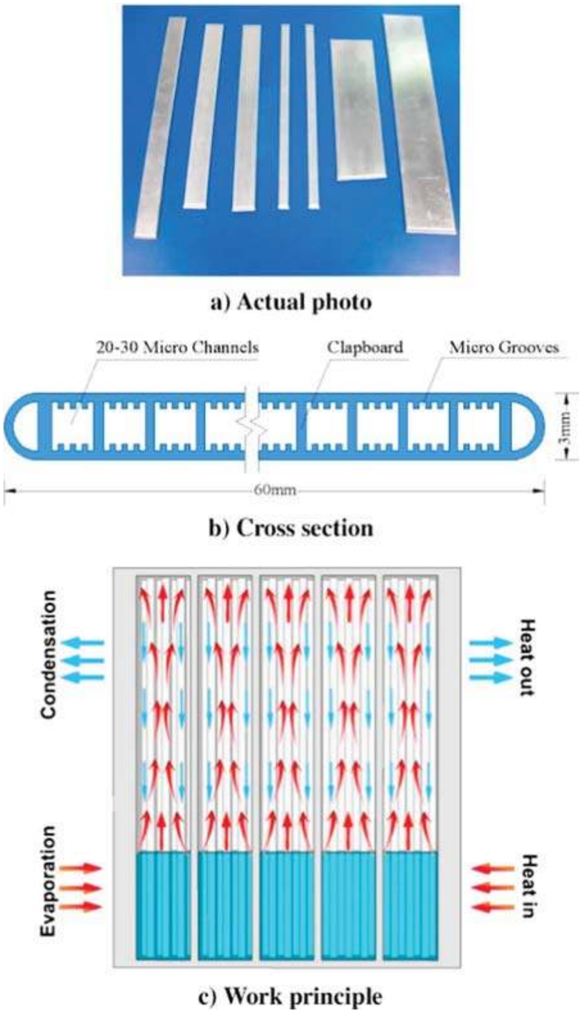


Fig. 16. Micro-channel heat pipe for PV/T module [71].

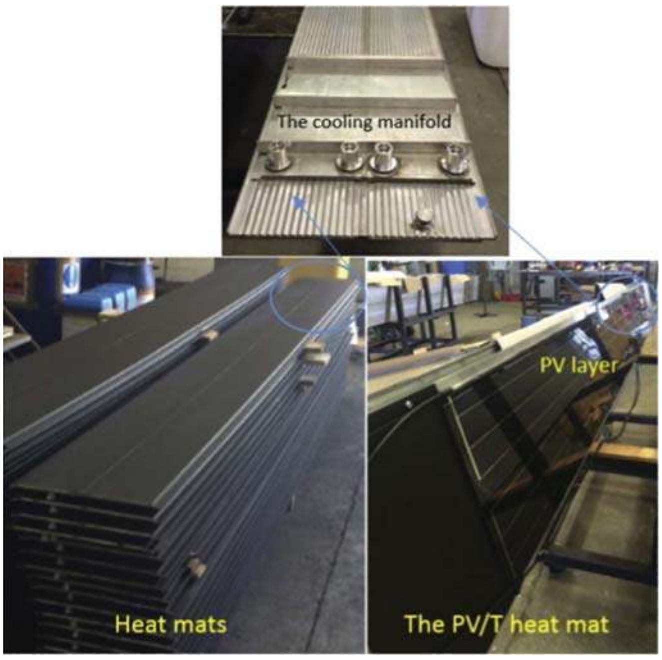


Fig. 17. Heat mats for PV/T module [39].

3.5. Extruded heat exchanger

Fig. 18 illustrates an extruded metal heat exchanger as the thermal absorber for PV/T modules. A single layer of steel sheet is extruded into corrugations and then attached beneath the TPT back sheet of the PV layer consequently, forming up the internal parallel flow channels. Fig. 19 displays another extruded metal heat exchanger as the thermal absorber for PV/T modules. This thermal absorber is made up of two parallel thin flat-plate metal sheets, one of which is extruded by machinery mould to form arrays of pin-fin banks, while another sheet remains smooth in order to fit beneath the PV layer. A laser-welding technology is applied to join them together, forming up the built-in turbulent flow channels.

The extruded heat exchanger can also be constructed using non-metal materials. Fig. 20 indicates an extruded heat exchanger comprised of a polycarbonate box that is located above the PV panel. It has a thin layer of fluid flow through it that absorbs infrared radiation without modifying the visible part of spectrum. The polycarbonate heat exchanger is extruded into a particular flow pattern that allows the working fluid to pass through in a serpentine way.

Such extruded heat exchangers have now become a promising potential solution as solar thermal absorbers for flat-plate and flexible PV/T modules in a wide range of applications, particularly feasible for use in simple robust constructions and industrialization processes. As a result, these types of thermal absorbers could be produced at low cost since with significant cost reductions achieved due to the increased flexibility of application in industrial mass production. In addition, different arrangement and combination of the extruded corrugations can form up various flow channels by eliminating complex tubing system. So the channel structures can feature a high complexity without any additional costs. However, these thermal absorbers usually require a high volume of fluid flow due to the relatively low heat transfer coefficient. Therefore, it needs to be pay careful attention to the hydrologic design when they are applied in large-sale projects.

3.6. Roll-bond heat exchanger

Roll-bond technology is widely employed for the manufacturing of heat exchangers, such as evaporators for refrigeration, radiant panels, cytostatic circuits, and so on. It is now also popular in cooling the flat-plate and flexible PV modules [77–84]. Roll-Bond heat exchangers are manufactured using a well-established production process that foresees the construction of panels with various channel configurations by a sandwich bonding technique, using two 99.5% pure aluminium sheets, based on a rolling process and a consequent inflation process [77]. Fig. 21 displays a roll-bond heat exchanger for PV/T modules with two aluminium sheets. Before bonding the two aluminium sheets together, the inner surface of one dedicated aluminium sheet has the desired pattern of flow channels printed onto it via a serigraphic process. A special graphite ink is used which prevents welding of the inner surfaces where it has been applied. Finally, the un-bonded pattern of channels is elevated by inflating them with air at high pressure. It is also possible to replace the non-roll-bond aluminium sheet with an expanded graphite sheet, whose plasticity and the stability over time assure a very good interface between the roll-bond sheet and the TPT back sheet of PV layer as indicated in Fig. 22[78]. The exchangers are completed by inlet and outlet connections. The thermal absorbers with roll-bond technology enable the customization and optimization of the fluid channels to achieve higher efficiency in a cost-effective way. These main features allow for a more uniform temperature distribution across the absorber with respect to the standard sheet-and-tube structures typically made of a metal sheet welded to metal tubes. However, there is little research addressing the long-term reliability and corrosion risk of pure aluminium sheets within these roll-bond heat exchangers based PV/T modules.

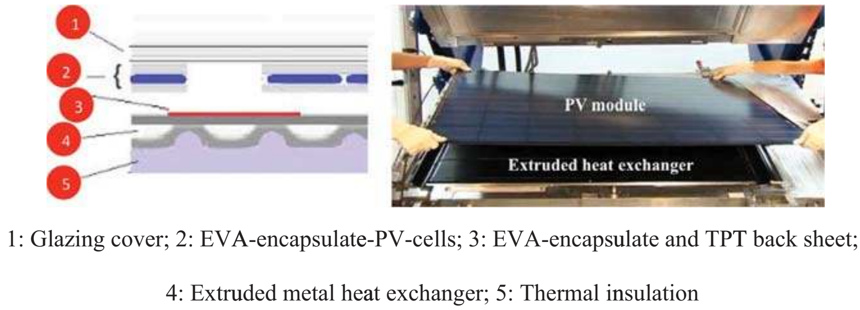


Fig. 18. An extruded metal heat exchanger with corrugations for PV/T module [74]. 1: Glazing cover; 2: EVA-encapsulate-PV-cells; 3: EVA-encapsulate and TPT back sheet; 4: Extruded metal heat exchanger; 5: Thermal insulation.

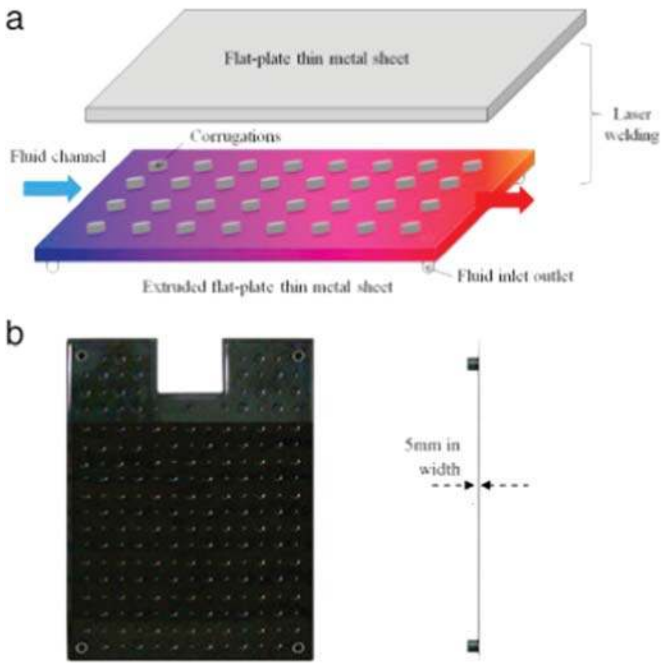


Fig. 19. An extruded metal heat exchanger with internal pin-fin banks for PV/T module [75].

3.7. Cotton wick structure

A passive thermal absorber with aluminium heat spreaders used in conjunction with cotton wicks have recently been developed for controlling the temperature during operation of flat-plate PV module, as shown in Fig. 23 [85]. Three aluminium heat spreaders are fabricated in-house and screwed to the PV modules. Flat-plate cotton wicks commonly used for lamps and lanterns are positioned at the heat spreaders with their ends free for dipping in water stored in the headers. Aluminium spikes were used as stiffeners to ensure proper contact of the wick structure with the heat spreader and to avoid the sagging of cotton wicks. PVC pipes were used as headers, in which a rectangular slot was cut longitudinally on its surface for the insertion of the ends of the PV panel and the wicks. Such passive thermal absorbers have very simple structures and are very low cost; however, cooling efficiency is very limited and therefore these absorbers are only applicable to certain application scenarios.

4. Integration methods for PV/T modules

Generally, a PV/T module is constructed by attaching a commercially available PV module to a thermal absorber using various techniques such as mechanical or chemical bonding. The integration is another critical element that directly influences a PV/T module's thermal efficiency due to thermal resistance between PV layer and

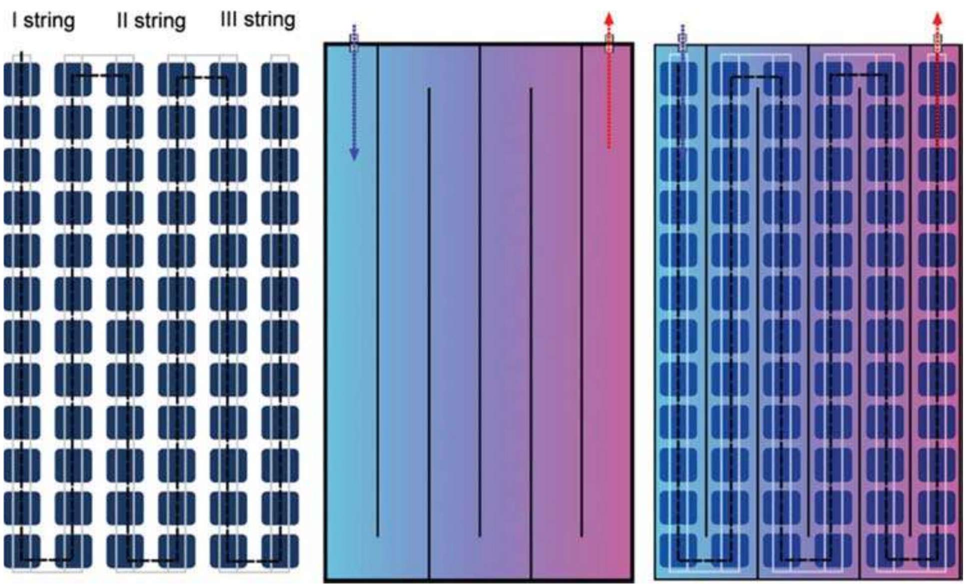


Fig. 20. An extruded polycarbonate heat exchanger for PV/T module [76].

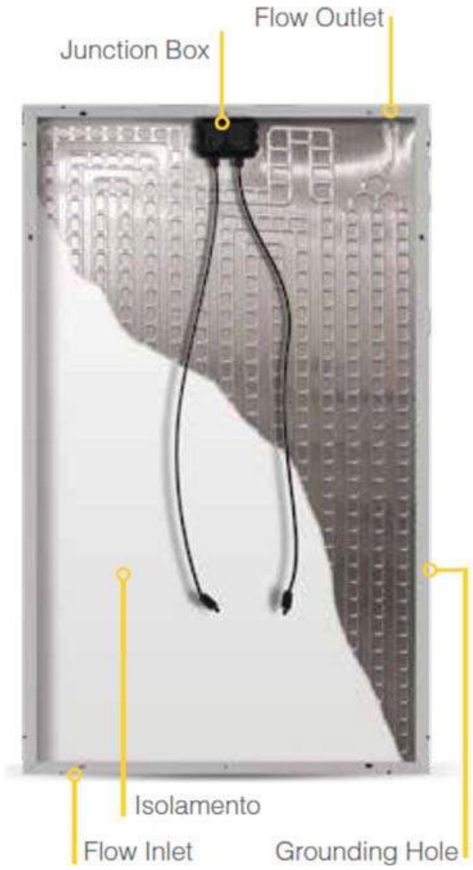


Fig. 21. Roll-bond heat exchanger for PV/T modules - two aluminium sheets [77].

Fig. 22. Roll-bond heat exchanger for PV/T modules – single aluminium sheet [78].

thermal absorber. As a result, a critical review of the currently available integration methods is discussed in this section in terms of their advantages and limitations for application as summarized in Table 4.

4.1. Direct contact

Some air or water based flat-plate or flexible PV/T modules have the integration features of direct contact between the PV layer and the working fluid [88–90]. Figs. 24 and 25 demonstrate the direct ventilation based and direct water spray based PV/T concepts respectively. Fig. 24 presents the novel ceiling ventilation system integrated with solar PVT modules and PCM [66]. The two PCM layers with an air channel are integrated beneath a PV layer and mounted onto the building ceiling as a part of the ceiling insulation to increase the local thermal mass. The air flows upwards in direct contact with the PV layer therefore cooling it down. In Fig. 25, a feeding tube with groups of small holes on it is placed on the top of the PV module that is to produce the water film flow downwards over the PV module. Direct-contact integration method is the simplest way to combine the cooling effort of thermal absorbers with dedicated PV layers. No additional thermal resistance is observed, however direct-contact integration has several limitations including low pressure bearing capacity, poor thermal-removal efficiency, freezing risk etc. Therefore, these modules can are most suitable for passive building design or water-based cooling strategies when the PV modules are also implemented.

4.2. Thermal adhesive

Thermally conductive adhesives, in either film or mucilage status, are the most widely used method in terms of the integration of PV layer with their thermal absorbers for all kinds of PV/T modules, which include epoxies, silicones and elastomeric solutions with the thermal conductivity ranging from 0.8 to 11.4 W/m-K [91,92] depending on the materials and the geometry. Thermal characteristics of the adhesive include having high thermal conductivity, low electrical conductivity, extreme operating temperature range, good elongation properties, which influence the overall efficiency of the PV/T modules greatly [22]. Figs. 26 and 27 show two examples of different thermal adhesives used to combine PV layers and absorbers, i.e., silicone gel [93] and mucilage glue [94]. The thermal adhesive integration method is simple and cost effective. However, there is uncertainty as to its long-term performance in cases of high solar intensity as well as the risk of mini air gaps/bubbles forming. Imprecise adhesive thickness between the PV layer and thermal absorber can also be an issue.

4.3. EVA based lamination

Ethylene vinyl acetate (EVA) is the copolymer of ethylene and vinyl acetate. It is processed as a thermoplastic material with thermal conductivity ranging from 0.31 to 5.56 W/m-K [95] depending on the vinyl acetate content and the way the material are used. Recent researches demonstrate that the transparent EVA sealant can be applied to combine the PV layer and the thermal absorbers through the PV vacuum lamination chamber in most flat-plate PV/T modules. Fig. 28 depicts a section of the heat pipe-PV/T module [96]. In total, there are six component layers i.e., glass cover, transparent TPT, EVA, PV cells, black TPT, and aluminium-sheet-and-tube thermal absorber, being placed in sequence for lamination together.

To further reduce the thermal resistance between the PV cells and the fluid, researchers replaced the TPT back sheet (at low thermal conductivity) of PV cells with the metal sheet (with high thermal conductivity) [97,98]. Fig. 29 displays a copper sheet being laminated in direct contact with the PV cells [97]. This PV/T module comprises the glass cover, EVA, PV cells, EVA and copper, which are placed in a lamination chamber at high temperature and pressure conditions in order to remove any air that is present and to allow the polymerization reaction of EVA. The high electrical resistivity and high elongation property of the EVA layer acts as a buffer layer between the PV cells and the copper sheet. The electrical terminals of the PV/T module are on the side of the PV/T module with sufficient electrical insulation from the copper sheet [97]. This modification eliminates the need for a TPT back sheet and the additional thermal conductive adhesive required for combination of a PV layer and a thermal absorber.,

Although, the EVA layer has slightly lower thermal conductivity than the thermal adhesive, the difference in thermal resistance between the two can be ignored on consideration of their thicknesses. In addition, the EVA based lamination method can eliminate risks, such as imprecise adhesive thickness, formation of mini air-gaps/bubbles etc., between the PV layer and the thermal absorber. Moreover, it is possible to replace the TPT back sheet of the PV layer with an EVA attached thermal absorber, which leads to a significant reduction in the overall thermal resistance from the PV cells to working fluid. This method is also cost-effective, ideal for integration of the PV layer with their absorbers based on established industrial PV manufacturing lines. However, careful attention needs to be made at temperatures over 140 °C after the lamination process. The laminated PV/T module needs to be cooled down by the quenching method, a rapid cooling process

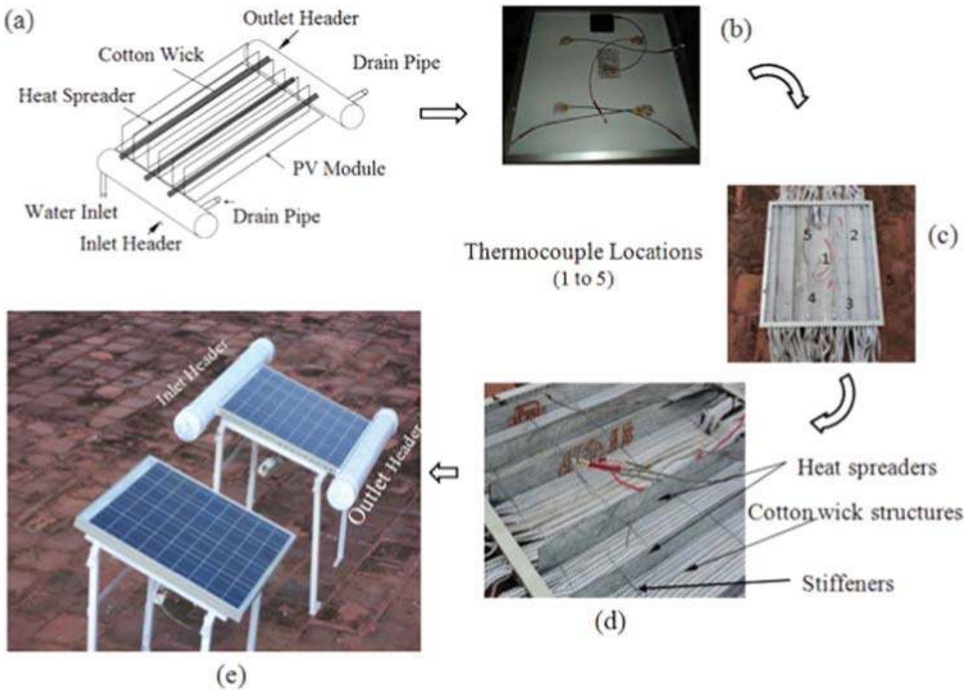


Fig. 23. Cotton wick structure as thermal absorber for PV/T modules [85].

Table 4
Summary of different integration methods with advantages/disadvantages, and their application for PV/T modules.

Integration method	Advantages	Disadvantages	Application
Direct contact	a. Simplest way b. No additional thermal resistance	a. limitations in low pressure bearing capacity b. Poor thermal-removal efficiency c. Freezing risk d. Limited application	a. Flat-plate PV/T b. Flexible PV/T
Thermal adhesive	a. Simple structure b. Low cost	a. Loose risk b. Mini air-gap/bubble c. Imprecise adhesive thickness	a. Flat-plate PV/T b. Flexible PV/T c. Concentrated PV/T
EVA based lamination	a. Secured firm combination b. Possible to eliminate TPT back sheet for reduction in the overall thermal resistance c. Cost-effective due to established PV manufacturing industry lines	a. Careful attention needs to be paid to the cooling of lamination piece b. Slightly low thermal conductivity	a. Flat-plate PV/T
Mechanical fixing	a. Mature technology b. Secured firm combination	a. Increase overall cost b. Increase overall weight c. Small air gap exists between PV layer and thermal absorber d. Weak the overall performance	a. Flat-plate PV/T b. Concentrated PV/T

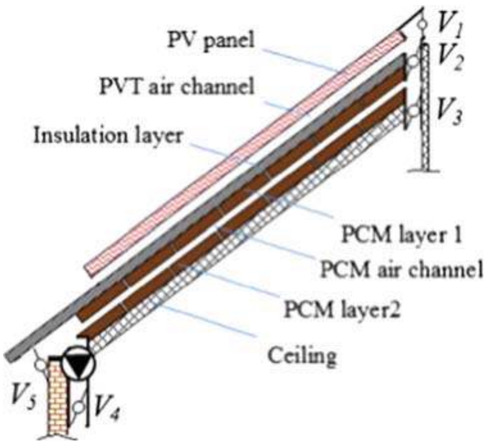


Fig. 24. Direct water spray based PV/T module [66].

using air [98]. The reason for such a specialised cooling technique is that metal sheet usually has a much higher thermal expansion coefficient than any of the other components within the PV layer, which may bend into an arc geometry (rather than the flat-plate) if under free cooling [98].

4.4. Mechanical fixing

Integration of the PV layer with thermal absorber through mechanical fixing is also very common in most of flat-plate and concentrated PV/T modules. Fig. 30 shows the integration of a thermal absorber with the PV layer by the fixing of rods with springs [31]. The polypropylene absorber is pressed against the back of the PV module by a construction consisting of five aluminium rods, springs, and aluminium strips. Similarly in Fig. 31, the thermal absorber is fixed on the PV layer by several specially designed mounting brackets. One of

Fig. 25. Direct water spray based PV/T module [38].

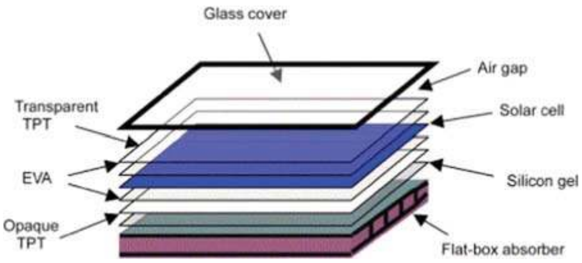


Fig. 26. Combine PV layer with thermal absorber by silicone gel [93].

the bracket ends is fixed onto the PV frame with a grounding bolt and screw whilst the other bracket end clamps the PV frame by tightening the wingnut. The whole bracket is further reinforced with the thermal absorber by two bottom bolt holes and screws. The thermal insulation layer can finally be fixed onto the absorber using a similar approach [99]. Xu et al. [75] also mentioned that attaching the thermal absorber beneath the PV layer through a series of U-shaped resilient metal clips could lead to a rapid PV/T formation.

Mechanical fixing firmly secures the combination of PV layer and thermal absorber, but it adds additional consolidation elements i.e. screws, springs, strips, brackets, clips etc., which increase the overall cost and weight of the PV/T module. More importantly, mechanical fixing cannot eliminate the small air gap that exists between the PV layer and the thermal absorber, which may result in large thermal

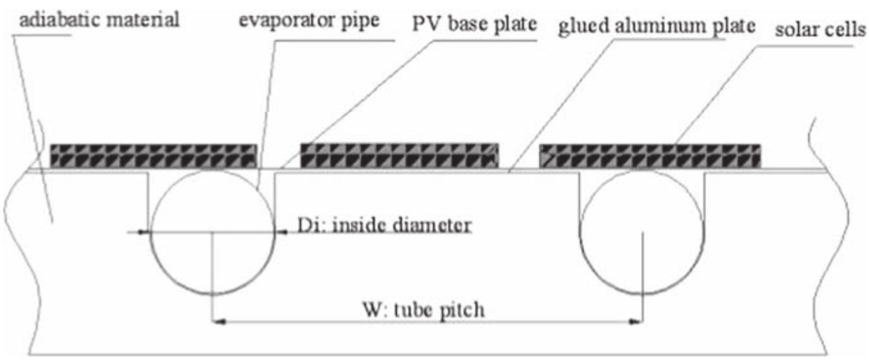


Fig. 27. Combine PV layer with thermal absorber by mucilage glue [94].

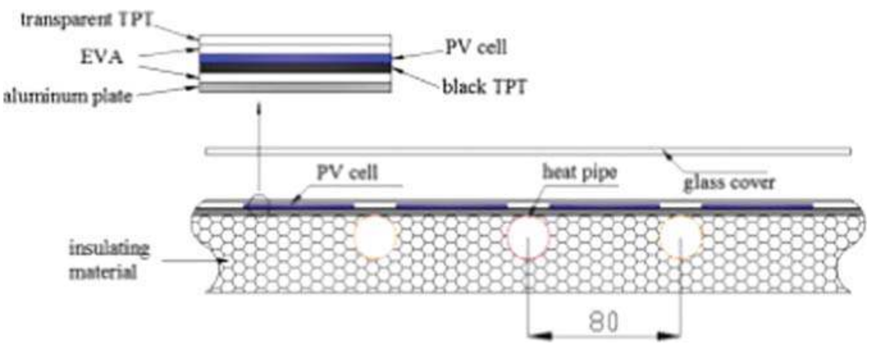


Fig. 28. Combine PV layer with thermal absorber by EVA lamination with TPT back sheet [96].

Fig. 29. Combine PV layer with thermal absorber by EVA lamination without TPT back sheet [97].

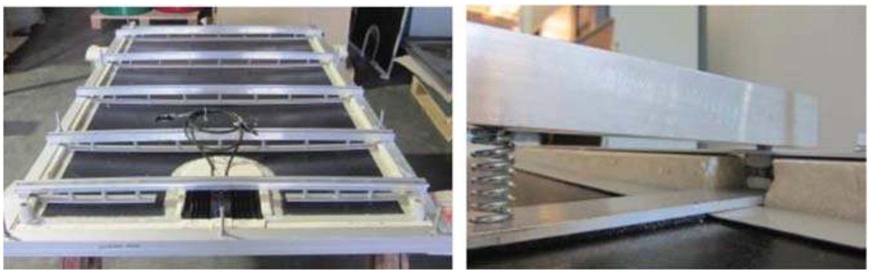


Fig. 30. Integrating thermal absorber with PV layer by the fixing rods with springs [31].

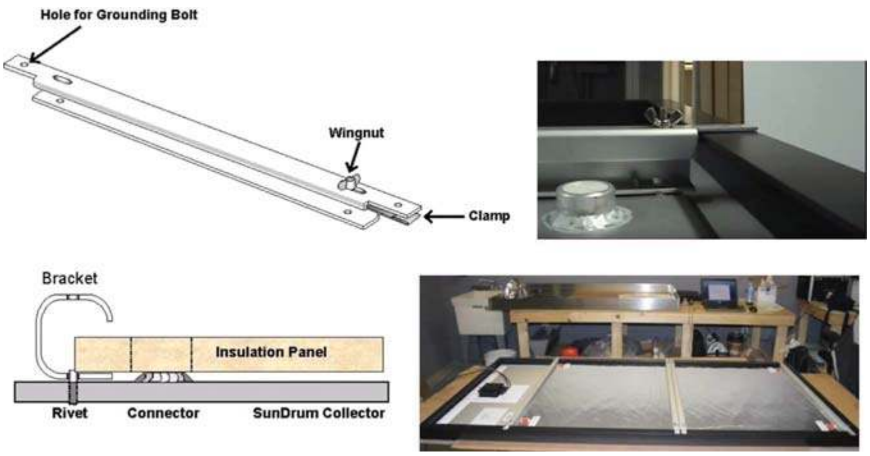


Fig. 31. Mechanical integration for PV/T module: mounting brackets (upper) and combination with thermal insulation (bottom) [99].

resistance and weaken the overall performance of the PV/T module for long-term operation.

5. Suggestions for further research

5.1. Thermal absorbers for concentrated PV/T modules

Most of the existing researches on concentrated PV/T modules focus on the study of concentrators and solar tracking systems etc., so as to ensure effective collection of solar radiation. These concentrated PV/T modules usually incorporate rectangular duct or thermal oil pipe thermal absorbers. New research topics on appropriate high-efficient thermal absorbers may need to be investigated further. In addition, most of the concentrated PV/T modules are designed for power generation while further research may focus on wider applications like industrial heating load, or distributed district/city-level power/heating network, which also require the development of new thermal absorbers for dedicated concentrated PV/T systems.

5.2. Research on EVA based lamination method

Although the appropriate integration method for combining thermal absorbers with PV layers varies with different cases, the EVA based lamination method seems to be the best option for integration of PV layer and thermal absorber on the basis of the research reviewed in this paper. It is therefore suggested that further research on this integration method should be undertaken including concept design, prototype fabrication process, theoretical analysis, experimental evaluation and socio-economic assessment, especially for flexible and concentrated PV/T modules. Furthermore, comparison of different integration methods for different PV/T modules is also desirable to provide further design guidance and optimization strategies for the integration methods applied in various conditions.

5.3. Building integrated PV/T module (BIPV/T)

Building integrated PV/T (BIPV/T) is another interesting topic with BIPV/T serving as the building envelops in addition to generating electricity and heat. BIPV/T can make supplementary heat available to the building with less loss (distributed energy supply mode) and can be used either directly for low-temperature applications or through the mediation of a heat pump for higher temperatures. BIPV/T creates a symbiotic relationship between energy and building. Despite the potential of BIPV/T it currently has serious deficiencies due to the introduction of greater complexity and risk relative to a pure PV/T module. There are also many other unresolved issues with BIPV/T with respect to its modelling, detailing, impact on building physics and systems, integration method for installation and long-term performance.

5.4. Fundamental research on thermal expansion coefficient of PV/T module

Potential bending of a laminated PV/T module, owing to the differing thermal expansion coefficients of the constituent components, requires fundamental research to be undertaken to explore feasible solutions. This may include theoretical analyses, derived from the governing equations of mass, energy and momentum, on the basis of heat transfer and flow characteristics as well as CFD based numerical modelling. Validation experiments are also important to modelling by delivering detailed discussion on various impact factors.

5.5. Field research on long-term reliability of PV/T module

Aside from fundamental theory and experimental laboratory research, studies into the field application of PV/T modules for long-term operation should also be considered in future work. Although short-term evaluation of PV/T modules in real climates have been carried out by a number of researchers, a long-term (seasonal or annual) scheme is essential to resolve different practical uncertainties, especially for the BIPV/T modules. On the whole, comprehensive evaluation of BIPV/T can be made from the perspectives of construction, hydraulic and hygiene characteristics. This work has certain challenges including BIPV/T module installation, distributed power/heat demand/supply, proper testing venue selection, detailed assessment categories and any possible unpredicted operational problems.

6. Conclusion

This paper conducts a critical review on thermal absorbers and their integration methods into currently-available PV modules for the purpose of developing combined PV/T modules. Depending on the type of PV module, PV/T technologies are categorized into flat-plate, flexible and concentrated. Flat-plate PV/T modules are regular flat shapes with combined efficiencies ranging between 40–87% and can be applied in urban and rural areas, be ground mounted, wall/roof mounted, etc. and used for both industry and building energy supply. Flexible PV/T modules with overall efficiencies ranging from 27–89% can serve as rooftop shingles and tiles, irregular building facades or as glazing for daylights. The higher concentration ratio in concentrated PV/T modules enables them to generate higher temperature heat with the combined efficiency varying from 46% to 86%, making them suitable for a wider range of applications.

Recent research development shows that there are different types of thermal absorbers suiting for the PV/T modules, i.e. sheet-and-tube structure, rectangular tunnel with or without fins/grooves, flat-plate tube, micro-channel heat pipe array/heat mat, extruded heat exchanger, roll-bond heat exchanger and cotton wick structure, with the latter four types are showing promising potential due to the significant enhancement in efficiency, their structure, weight, and cost etc. Although suitable integration methods for combining thermal absorbers and PV layers vary in different cases, EVA based lamination seems to be the best option when compared to other traditional methods such as direct contact, thermal adhesive and mechanical fixing.

Suggestions for further research topics have been proposed in five particular areas: (1) developing more appropriate thermal absorbers for concentrated PV/T modules; (2) conducting research on the EVA based lamination method; (3) investigating building integrated PV/T modules (BIPV/T); (4) fundamental research on the thermal expansion coefficient of PV/T modules; (5) carrying out field research on the long-term reliability of PV/T modules in operation. This combined research would provide much useful information for the further development of solar PV/T modules with high feasibility for use in a wide variety of energy supply applications even at district or city-level.

Acknowledgement

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