Review Article

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Review of research, development and application of photovoltaic/thermal water systems

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Abstract: Among the many techniques for obtaining heat and electricity, solar thermal collectors, photovoltaic (PV) technology and PV/thermal (PV/T) technology have a very important place. The PV/T collectors enable the simultaneous conversion of solar radiation into thermal and electrical energy in a single device, with better space utilization and cost efficiency during construction. Specially designed PV/T collectors can replace the outer walls or roof covers and can be widely used in private houses, flat complexes, hospitals, schools, tourist and other objects for water heating and electrical energy generation. Due to their great application potential, hybrid collectors have been the subject of very intensive scientific research and technical development for many years. In this review article, the focus is on the research, development and application of the PV/T water systems in the last 10 years. The main task of researchers and manufacturers is to increase the efficiency of PV modules and thermal absorbers, using new materials and design types as well as their proper integration into the PV/T collector. It is also necessary to reduce the cost of these systems and make them more competitive in the market. In addition, the importance of PV/T systems is in providing energy in clean and environmentally friendly ways.

Keywords: PV/T collector, PV/T water system, thermal absorber, efficiency, cost study

1 Introduction

Hybrid PV/T collectors are a combination of PV modules and solar thermal (ST) collectors. In other words, the PV module is used as a part of a heat absorber. Most of the solar radiation absorbed by the PV module is not converted to electricity but to thermal energy, thereby increasing their temperature. The efficiency of solar cells largely depends on the temperature. As it increases, the atomic thermal vibrations of the solar cell material also increase, which negatively affects the directional movement of electrons, i.e., the flow of electric current through the solar cell is disrupted, leading to a decrease in conversion efficiency. The PV module temperature can be lowered by heat extraction using an appropriate natural or forced fluid (air or water) circulation. Different approaches are involved in integrating PV module and ST collectors in a PV/T collector as a whole [1]. The way of integration significantly affects the functioning of the hybrid system and its efficiency.

PV/T systems can be considered from several different aspects, e.g., based on the type of PV modules, the thermal absorber design, the use of protective glass, the type of the working fluid and the way it circulates, the use of a hybrid collector, etc. [2–22]. When considering the concentrated PV/thermal (CPV/T) systems, in addition to all of the above, important additional noteworthy aspects are the geometry of the reflectors, the material from which the reflector is made as well as the method of integration into the system [5,23–42].

Depending on the type of the PV module, the PV/T technologies can be divided into flat-plate, flexible and concentrated. Based on the working fluid, the flat-plate PV/T collectors are most commonly divided into PV/T air, PV/T water and combined water/air PV/T collectors.

Hybrid PV/T collectors can have a protective glass above the absorber in order to reduce heat loss. Henceforth, we distinguish between PV/T collectors with protective glass (glazed PV/T collectors) and PV/T collectors without protective glass (unglazed PV/T collectors). From the point of view of installation, hybrid systems distinguish between PV/T systems that are installed as stand-alone on buildings

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and building-integrated PV thermal (BIPV/T) systems [17,18,43–45].

A significant amount of research and development of PV/T technology has been carried out in the last 45 years. The PV/T systems have been the subject of intensive numerical and experimental investigations. The first paper in the field of hybrid conversion of solar radiation appeared in the 80s of the last century. In 1978, Kern and Russell developed the concept of the PV/T system by using water or air as the heat removal fluid with promising results [46]. The following year, Florschuetz suggested an extension of the Hottel–Whillier model for the analysis of PV/T systems [47]. Based on this model, examples of both thermal and electrical performance of a combined collector as a function of collector design parameters were presented and discussed. A number of papers soon appeared, in which various numerical methods were presented for determining the performance of hybrid collectors, and the most important of which were the numerical methods for predicting the performances of PV/T air flat-plate collectors and PV/T liquid collectors, given by Raghuraman [48].

During the 1990s, intensive testing of PV/T air collectors and PV/T water collectors of different designs was performed [49–54]. At the beginning of the 21st century, a lot of work was done to improve the design of PV/T water collectors with natural or forced water circulation [55–61] as well as to improve the design and performance of PV/T air collectors [62–67]. Simultaneously with the experimental research, work was done with the goal of finding the appropriate analytical models for predicting conversion efficiency as well as energy payback time [64,68–70]. The indoor test procedures for thermal and electrical testing of PV/T collectors connected in series are also very useful and can be used by manufacturers for testing different types of PV modules in order to optimize their products [71].

Recently, works related to BIPV/T systems are especially topical [72]. Air hybrid systems (BIPV/T-a) are much more commonly used than water hybrid systems (BIPV/T-w). Among the first, Bazillian et al. considered the possibility of applying hybrid systems in construction [73], and a numerical model has been created to simulate the performance of a residential-scale BIPV cogeneration system. In the United Kingdom, an air hybrid system was installed in 2001, together with air solar collectors integrated into the roof of a building [74]. Somewhat later, an air hybrid system integrated into the facade of a hotel was applied in Macau [75]. Most of the problems in the analysis of the BIPV/T-a systems performance are caused by the assessment of its thermal behavior, so that in the last 15 years there have been a lot of papers related to this issue [76–84].

On the other hand, there are significantly fewer works related to BIPV/T-w systems. Chow and his collaborators numerically determined the annual performance of this type of a system used on residential buildings in Hong Kong and also constructed and tested experimental hybrid systems integrated into the roof of an ecological home in Hong Kong [85–88]. Intensive studies of BIPV/T-w systems have been conducted around the world, such as in India [89,90], Australia [91], Korea [92], Malaysia [93], USA [94], etc.

PV/T collectors can be combined with low-, medium- or high-concentration devices, in order to increase the solar irradiation on the collector's surface as well as to obtain more thermal and electrical energy. When it comes to CPV/T systems, the biggest challenge is to increase the energy efficiency of such a complex system, by using adequate concentrator geometry, choosing the material from which they are made of and applying it to air or water hybrid collectors, especially when it comes to high values of solar radiation concentration factors [29,95,96].

Among the first papers to consider the electrical and thermal output of PV/T water systems, with reflectors of solar radiation of low concentrating ratio, is a paper proposed by Al-Baali, as early as 1986 [97]. Research in this area continued [98], and in the first decade of the twenty-first century, a group of researchers from Greece led by Tripanagnostopoulos conducted a number of significant works in the field of hybrid conversion. These works contributed to improving the performance of air and water hybrid collectors as well as the CPV/T systems [99–103]. The use of planar reflectors for increasing the energy yield of flat-plate collectors has been widely analyzed [104–119]. Their simple geometry and low-cost implementation are primarily beneficial in the design of the CPV/T systems [109,120].

From all the above, it is obvious that PV/T technology covers a very wide area of research and application and that it is very difficult to make a serious overview of everything important in this area. In this sense, it is useful to review a specific part of PV/T technology, and hence, the authors decided to focus upon the flat-plate PV/T water systems. This article pays special attention to the choice of the PV modules and thermal absorbers, which affect the efficiency of hybrid collectors.

2 Flat-plate PV/T water collector

Apart from their construction and working fluid, PV/T air and PV/T water collectors also differ in their efficiency.

Namely, PV/T water systems are more efficient than the PV/T air systems. The PV/T air collectors are simple in construction and very economical. They are similar to solar air collectors, whereby the black thermal absorber sheet is replaced by a solar PV module, under which air as the heat transfer fluid circulates through the channels. Heated air circulation can be natural or forced. Forced circulation is much more efficient than natural because it enables better heat transfer; on the other hand, the required fan power reduces the electrical gain. The PV/T air collectors are less efficient than the PV/T water collectors due to their poor air heat transfer coefficient, lower density, lower heat capacity and lower thermal conductivity and also their efficiency decreases when the ambient air temperature is more than 20°C [121].

On the other hand, thanks to the better thermophysical properties of water than that of air, the PV/T water collectors have higher efficiency compared to PV/T air collectors. The efficiency largely depends on the choice of the PV module and thermal absorber as well as their integration into the PV/T system.

In addition, flat-plate PV/T water collectors can be connected in series or in parallel to larger solar systems. When the collectors are connected in series, the outlet water from the collector represents the inlet water for the next collector. The main disadvantage of this connection is that in case of a delay in the movement of water in one collector, the whole system stops working and also the last collectors in a row contribute a very small energy to the entire solar system due to overheating. This disadvantage can be overcome by connecting the collectors in parallel, so that each collector, independent of the others, gets the same amount of accuracy, and a possible delay in the movement of water in one or more collectors does not lead to the interruption of the entire system.

Usually flat-plate PV/T collectors are used for domestic water heating in parallel connection with natural circulation (PV/T water-heating system of thermosiphonic type), while industrial water-heating systems use a number of flat-plate PV/T collectors in series with forced circulation (active systems use a pump to circulate the water from the collector to storage). Since flat-plate PV/T collectors are in regular flat shape, they are usually used for ground or wall-/roof-mounted installation.

2.1 PV module

When designing a PV/T collector, it is very important to choose a PV module that will be integrated into the

hybrid collector. The choice of materials for the production of the solar cell will determine the absorption coefficient, the spectral sensitivity of the solar cell as well as its conversion efficiency. High electrical efficiency is very important because in most cases of application of hybrid collectors, much higher thermal energy is produced compared to electricity. Today, several different commercial PV technologies are mostly based on inorganic materials. When it comes to the type of PV modules, the solar cells from which they are made can be classified into three main groups: first-generation solar cells, second-generation solar cells and third-generation solar cells.

First-generation solar cells include single-crystalline silicon (Si) solar cells and polycrystalline Si solar cells. Commercial single-crystal Si solar modules are available with conversion efficiencies of up to 18%, whereas the best single-crystal Si solar cells obtained in the laboratory can achieve an efficiency of more than 25% [122,123]. The energy conversion efficiency can reach around 14% for a commercial and over 20% for laboratory polycrystalline Si solar cells [123,124]. Based on the latest data for 2020, the highest confirmed single-junction terrestrial cell efficiencies measured under the global AM1.5 spectrum (1,000 W/m²) at 25°C are 26.7 and 21.9% for Si single-crystalline cell (Kaneka, n-type rear IBC) and Si polycrystalline cell (FhG-ISE, n-type), respectively [123].

Polycrystalline solar cells are less energy efficient than those of single-crystalline Si PV cells, since the grain boundaries in polycrystalline Si disrupt the flow of electrons and hence reduce the power output of the cell. Compared to single-crystalline Si, polycrystalline Si material has better mechanical properties and can be cut into one third the thickness of a single-crystal material. First-generation solar cells are made of the highest quality material with the lowest concentration of defects, but their price is relatively high. The development of solar cell production technology has been aided by the rapid development of the semiconductor industry, which relies on Si as the most important material. Electronic components made of Si are stable at temperatures of up to 200°C.

Second-generation solar cells include amorphous Si (a-Si) solar cells, cadmium telluride (CdTe) solar cells, cadmium sulfide solar cells, solar cells with copper indium diselenide and its related alloys, etc. Second-generation solar cells belong to the so-called thin-film technology. In a thin-film PV cell, a thin semiconductor layer of PV materials is deposited on a low-cost supporting layer such as glass, metal or plastic foil. Thin-film technology offers significant savings in material and production process compared to crystalline Si. The conversion

efficiency is lower [123], but this would be more than balanced by the gain in power to weight ratio. Materials with a direct bandgap and a higher absorption coefficient than crystalline Si are used, so a thickness of only a few microns is sufficient for efficient absorption of solar radiation. In addition, the production and processing processes are much simpler and less demanding, thus enabling simpler production of larger surface modules.

The a-Si PV modules were the first commercially produced thin-film PV modules. The absorptivity of a-Si is about 40 times higher than that of single-crystal Si; therefore, only a thin layer of a-Si is sufficient to make PV cells of about 1 μm thick, as compared to 200 μm or more for crystalline Si cells. The big advantage is that a-Si can be deposited on various low-cost substrates, including steel, glass and plastic, and the manufacturing process requires lower temperatures, so the total material and manufacturing costs are lower per unit area as compared to those of crystalline Si cells. The highest confirmed solar cell efficiencies are 10.2% for a-Si solar cells (AIST), 21.0% for CdTe thin-film chalcogenide cells (First Solar, on glass), 23.3% for copper indium gallium selenide (CIGS) (Solar Frontier), 29.1% for gallium arsenide thin-film cells (Alta Devices), etc. [123].

Third-generation solar cells include multiple-junction solar cells, for example, indium gallium phosphide/GaAs/InGaAs with an efficiency of 37.9% (Sharp, 2-term); multiple-junction solar cells with crystalline silicon (c-Si), for example, gallium indium phosphide/GaAs/Si with an efficiency of 35.9% (NREL/CSEM/EPFL, 4-term); perovskite solar cells, for example, perovskite/CIGS cells with an efficiency of 23.3% (HZB, 2-term); dye-sensitized solar cells with an efficiency of 11.9% (Sharp); organic solar cells with an efficiency of 13.4% (Uni Potsdam), etc. [123]. The efficiencies of multiple-junction solar cells exceed the maximum theoretically calculated efficiencies for single-junction solar cells.

Perovskite solar cells are currently the fastest-advancing solar technology. They have the potential to achieve high efficiency and very low production costs, making them commercially attractive [125]. The development of efficient low-bandgap (1.2–1.3 eV) perovskite materials has enabled the production of new perovskite solar cells, i.e., all-perovskite tandem solar cells. In these cells, two perovskite compounds with different bandgaps are stacked on top of each other. The first two- and four-terminal perovskite–perovskite tandem solar cells with ideally matched bandgaps have reached efficiencies of 17 and 20.3%, respectively [126]. These solar cells are known for their excellent thermal and atmospheric stability and the lowest costs; this device architecture and

material set will enable all-perovskite thin film solar cells to reach the highest efficiencies in the long-term [127]. The latest research in 2020 showed that the energy pay-back time and greenhouse gas emission factor of the all-perovskite tandem configurations are 0.35 years and 10.7 g CO₂-eq/kW h, respectively, compared to 1.52 years and 24.6 g CO₂-eq/kW h for the Si benchmark. Thus, all-perovskite tandems have much lower carbon footprints than Si-perovskite tandems [128].

The third-generation solar cells should enable the use of the entire spectrum of solar radiation and eliminate heat losses in the solar cell. Heat dissipation has rarely been investigated in solar cells, although it has a significant impact on their performance. In recent research, an extended three-dimensional simulation of heat distribution in conventional perovskite solar cells has been performed, where electrical performance, optical absorption and heat conduction or convection have been considered [129].

PVs are a fast growing market, namely, the compound annual growth rate of cumulative PV installations including off-grid was 35% between 2010 and 2019. The Si-wafer-based PV technology accounted for about 95% of the total production in 2019. The largest share in the total production of PV modules belongs to solar cells made of single-crystalline Si. The share of single-crystalline technology is now about 65.6% (compared to 45% in 2018 and 27% in 2010) of the total production. The share of polycrystalline technology has decreased over time and now stands at 28.9% (compared to as much as 61% in 2010), while the share of thin-film technology is 5.5% (compared to 12% in 2010). When considering the share of thin-film technology today, the most represented are CdTe solar cells with a share of 4.2% followed by CIGS solar cells and a-Si solar cells with a share of 1.2% and 0.1%, respectively.

In general, good electrical efficiency of solar cells is very important because in most cases of application of PV/T collectors, much higher thermal energy is produced compared to electricity.

2.2 Thermal absorber for PV/T systems

Thermal absorbers that integrate into PV/T collectors are of great importance because they directly affect the cooling of PV modules and determine the overall efficiency of the PV/T systems. Absorbers are made of materials that have good thermal conductivity (e.g., copper and aluminum). The results of recent research show

that certain types of thermal absorbers are more suited to certain types of PV/T collectors. Traditional thermal absorbers include the sheet-and-tube structure, a rectangular tunnel with or without fins/grooves and a flat-plate tube. Nowadays, the following can also be used as the thermal absorbers: micro-channel heat pipe array/heat mat, extruded heat exchanger and roll-bond heat exchanger. Compared to the traditional thermal absorbers, these three types are promising due to the significant enhancement in terms of efficiency, structure, weight, cost, etc. [18].

The most commonly used is the sheet-and-tube structure in which a flat-plate metal sheet is enwrapped in or bonded to a metal tube. The metal sheet enables the contact between the PV module and the tube and allows better heat exchange between the PV module and the working fluid. Schematic representation of different types of absorbers is given in Figure 1 in the following order: absorber obtained by drawing a copper tube into the lower part of the extruded Al profile, absorber obtained by attaching a copper tube to the Al profile, absorber obtained by pressing or rolling the Al sheet and by inserting a copper tube into the formed recess and an absorber obtained by soldering a copper tube to a profiled metal plate.

The main advantages of thermal absorbers with the sheet-and-tube structure are good heat-transfer efficiency and relatively low cost, while the main disadvantages are complex structure, demanding precision-welding technology and heavy weight that limits application in BIPV/T technology [18].

Figure 1: Schematic representation of different types of sheet-and-tube structure.

Rectangular tunnels with or without fins/grooves are made of metal sheets or polymeric materials either in separate channels or in double/multipass designs (Figure 2). They are used in all types of PV/T collectors, because the flat-plate surfaces can be easily integrated with PV modules. Additional fins, V-shaped grooves, rectangular grooves and honeycomb-shaped grooves enable increased heat transfer between the working fluid (air, water, phase-change material, thermal oil or nanofluids) and the PV modules. The advantages of this type of absorbers are simple structure, low weight and low cost, while the main disadvantage are low heat-transfer efficiency and limited application in extreme weather conditions [18].

The flat-plate tube absorber has a single unilateral channel for the fluid flow, which can be made in the form of a continuous spiral [44,93] or coil configuration. The spiral design (Figure 3) allows the highest thermal efficiency of 50.12% with a corresponding PV cell efficiency of 11.98% compared to other types of design, which is a great advantage, considering the very simple design of this type of PV/T collector [130]. Rectangular hollow tubes are made of metal (i.e. stainless steel or copper) using a special welding method for tube connection. The main advantage of this type of design is that it facilitates integration with the PV module. The disadvantages are that the efficiency of the flat-plate tube absorber is

Figure 2: Schematic representation of the rectangular tunnels as thermal absorbers for PV/T collectors [18].

Figure 3: Spiral design of flat-plate tube absorber [131].

about 2% lower compared to other types of absorbers, increasing fluid temperature in the flow direction, high flow resistance and leakage risks as well as limited application only to flat-plate PV/T water systems.

The appropriate integration method of the PV module and thermal absorber varies in different cases. Recent research shows that compared to conventional methods, such as direct contact, thermal adhesive and mechanical fixing, the ethylene-vinyl acetate (EVA)-based lamination method appears to be the best option for integrating PV modules with a thermal absorber [18].

2.3 Working principle of PV/T water collectors

It has already been said that the way of integrating the PV module and thermal absorber has a great influence on the efficiency of the PV/T water system. Their electrical efficiencies are relatively high (6.7–15%) as the crystal Si cells are most commonly used in this type of collector [45], while thermal efficiencies (22–79%) depend significantly on their different structures and operation conditions [45].

A schematic diagram of the most common types of PV/T water collectors is shown in Figure 4. The most commonly used are hybrid water collectors with the

Figure 4: Schematic cross section of a PV/T water collector with (a) tubes, (b) channels, (c) water channel above the PV module, (d) water channel under the PV module [132].

tubes and channels shown in Figure 4(a and b), respectively, which may or may not be covered with protective glass as well as collectors with a water channel above the PV module (Figure 4c) or with a water channel below the PV module (Figure 4(d), [2,132]). In addition to the main components of the flat-plate PV/T water collectors, i.e., the PV module, thermal absorber and glazing cover (optional), essential components are also the adhesive (e.g., EVA with a layer of tedlar–polyester–tellur) and insulation.

Depending on the water circulation, hybrid systems are available with natural (thermosiphon system) and forced circulation. The principle of operation of these systems is similar to that of the corresponding flat ST collectors.

2.3.1 The PV/T system with natural water circulation

The PV/T system with natural water circulation consists of a flat PV/T collector and a solar boiler above it. The heat exchanger of the solar boiler is directly connected to the inlet and outlet pipes of the collector. After filling the closed solar system with water, the water circulation takes place naturally. Namely, the heated water from the collector as specifically lighter goes to the heat exchanger of the solar boiler, and the cold water from the heat exchanger as specifically heavier returns to the collector. The natural circulation of water in the thermosiphon system will be maintained as long as there is a temperature difference between the water in the boiler and the water in the collector, i.e., as long as solar radiation falls on the collector surface [133].

A schematic diagram of the PV/T system with natural water circulation is given in Figure 5. It consists of a flat-box aluminum-alloy PV module with single-crystalline Si cells and a water-heating system. The main parts of the water-heating system are the thermal collector and the water tank, which is fixed horizontally to an Al-alloy bracket. This design of PV/T water collectors has significant advantages compared to the sheet-and-tube metallic or flat-box plastic/rubber collectors, such as a large contact area to facilitate heat exchange between the thermal absorber plate and the fluid as well as a uniform transverse temperature distribution across the collector width. The electrical system contains a PV module, a converter, four accumulator batteries, and the associated switches and wiring. Electric thermometers are used to measure the water temperature, plate temperature and ambient temperature, while the pyranometer measures the total irradiance on the collector surface [59].

With this system a daily electrical efficiency of about 10.15% was achieved, while the daily thermal efficiency

Figure 5: Schematic diagram of PV/T system with natural water circulation [59].

exceeded 45%, with the daily total efficiency being above 52% and the daily primary energy-saving efficiency was up to 65%, and with a PV module covering factor of 0.63.

2.3.2 The PV/T system with forced water circulation

Schematic diagram of the PV/T system with forced water circulation is given in Figure 6. The main parts of the system are PV/T water collector (classic sheet-and-tube design), a solar water heater, a circulation pump, a

Figure 6: Schematic diagram of PV/T system with forced water circulation: (1) hot water storage, (2) pump, (3) valve, (4) calorimeter, (5) A/D converter, (6) pyranometer and (7) computer.

calorimeter, pyranometer, analog-to-digital (A/D) converter and corresponding connections for bringing water into the closed circuit of the solar system [109].

The circulation pump with a differential thermostat is used to maintain the forced circulation of water in the solar system and can be switched on automatically or manually. The differential thermostat is used to control the water temperature in the solar water heater and collector and to turn on the circulation pump. The circulation pump can be switched on automatically when the water temperature difference between the collector and the water heater reaches the set value ΔT (e.g., 5–15°C). With the help of the expansion vessel, the appropriate water pressure is maintained in a closed circulation circuit and in case the pressure drops in it, water from the water supply network is added to the entire solar system via the appropriate connection on the solar module. Electrical thermometers are used for the measurements of input and output temperatures from the PV/T collector and water temperature in hot water heater, whereas a calorimeter is used to measure the thermal energy obtained in the hot water heater and for the water mass flow rate.

Generated electrical energy is transmitted to the battery through a battery charge regulator and then directly submitted to the consumer through a DC/AC converter. This device is an A/D converter with a micro-controller, which enables digital measurements of the voltage, current, temperature, etc. It can be connected to a computer and can be software controlled [109].

3 PV/T water collector efficiency

In a PV/T water system, we can consider the total efficiency η_{tot} , which corresponds to the direct sum of the electrical efficiency η_e and the thermal efficiency η_{th} of the system, such as Bergene and Løvvik [50] and Fujisawa and Tani [53] proposed in their papers:

$$\eta_{\text{tot}} = \eta_e + \eta_{\text{th}}. \quad (1)$$

It is known that electric energy is of high grade since it is converted from thermal energy. Huang et al. [61] defined the primary energy-saving efficiency, which more adequately defines the energy efficiency of a PV/T collector as:

$$\eta_f = \eta_e / \eta_{\text{power}} + \eta_{\text{th}}, \quad (2)$$

where η_{power} is the electrical efficiency for a conventional power plant, and its value can be taken as 0.38.

The PV module electrical efficiency η_e can be calculated by the relation:

$$\eta_e = \frac{I_m V_m}{A_c G_{\text{tot}}}, \quad (3)$$

where I_m is the value of current and U_m is the value of voltage at maximum power point, whereas A_c is the collector surface area and G_{tot} is the total solar radiation on the PV/T collector surface. Total daily electrical efficiency η_E is defined by:

$$\eta_E = \frac{E_E}{E_S}, \quad (4)$$

where E_E (Wh) is the total electrical energy generated during the day by the PV/T collector and E_S (Wh) is the total solar radiation energy incoming during the day on the PV/T collector.

The thermal efficiency η_{th} of the flat-plate PV/T water system can be determined depending on the design of the thermal absorber.

- The classic Hottel and Willier equation systems [133] are used for the sheet-and-tube design of the thermal absorber. For flat-plate collectors at lower operating temperatures (below 90°C), it can be approximated that the collector surface is equal to the absorber surface, and radiation losses can be combined with convection and conduction losses using a unique overall heat transfer loss coefficient U_L ($\text{W m}^{-2} \text{K}^{-1}$). This coefficient is constant for a particular collector model.

The overall absorber temperature T_{abs} can be replaced by water input temperature T_{in} , and the useful power $\dot{Q}_u$ can be expressed via the heat-removal factor F_R from the

collector to the working fluid, if one uses $(T_{\text{in}} - T_a)$ instead of $(T_{\text{abs}} - T_a)$, where T_a is the ambient temperature. It should be noted that the heat-removal factor depends on the flow rate of the working fluid through the collector. The thermal efficiency can now be written in the form:

$$\eta = \frac{\dot{Q}_u}{G_{\text{tot}} A_c} = F_R \tau \alpha - F_R U_L \frac{T_{\text{in}} - T_a}{G_{\text{tot}}}, \quad (5)$$

where α is the absorptivity, τ is the transmittance of the front cover of the collector, A_c is the collector surface and G_{tot} is the intensity of solar radiation on the collector.

Thus, F_R , τ , α and U_L are constants for a given collector and the flow rate of the working fluid, which leads to the fact that the efficiency is a linear function of three parameters that define the operating conditions: the solar radiation intensity, water input temperature and the ambient temperature. Equation (5) can be rewritten in the following form:

$$\eta = \eta_0 - F_R U_L \frac{\Delta T}{G_{\text{tot}}}, \quad (6)$$

where $\eta_0 = F_R \tau \alpha$ is the optical or maximum value of the thermal collector efficiency and $\Delta T = T_{\text{in}} - T_a$.

Based on the measurement of the mass flow rate of the working fluid $\dot{m}$ through the collector, water output temperature T_o , water input temperature T_{in} , the intensity of solar radiation on the collector G_{tot} , with known heat capacity of the working fluid c_p and the collector surface A_c , the thermal efficiency of the collector can be calculated from the following expression:

$$\eta_{\text{th}} = \frac{\dot{m} c_p (T_o - T_{\text{in}})}{A_c G_{\text{tot}}}, \quad (7)$$

where the water heat capacity is $c_p = 4,180 \text{ J kg}^{-1} \text{K}^{-1}$.

The variation in thermal efficiency η_{th} relative to T_{in} , T_a and G_{tot} can be determined experimentally as a function of the ratio $\Delta T / G_{\text{tot}}$. The function $\eta_{\text{th}} = f(\Delta T / G_{\text{tot}})$ is used for performance determination of ST collectors. It can also be used for PV/T systems, as the thermal part of them corresponds approximately to a ST collector. The graph for $\eta = f(\Delta T / G)$ in the linear approximation is obtained by the method of least squares, where the intersection point of the efficiency graph with the η axis represents the optical efficiency η_0 of the collector, and its slope represents the heat loss $F_R U_L$ of the collector.

The heat-removal factor is defined via the collector efficiency factor F^* as follows:

$$F_R = \frac{\dot{m} c_p}{A_c U_L} \left[1 - \exp \left(- \frac{A_c U_L F^*}{\dot{m} c_p} \right) \right], \quad (8)$$

where

$$F^* = \frac{1/U_L}{W \left[\frac{1}{U_L[D_o + (W - D_o)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}} \right]}, \quad (9)$$

with D_o being the outside diameter of flow tubes (m), D_i the inside diameter of flow tubes (m), W is the distance between tubes (m), F the fin efficiency, C_b is the thermal conductance of the bond between the fin and tube ($W m^{-1} K^{-1}$) and h_{fi} is the heat transfer coefficient of the working fluid ($W m^{-2} K^{-1}$).

- For a rectangular tunnel with the groove design, the following expression is used [134]:

$$\eta_{th} = 0.574 - \frac{4.85(T_{in} - T_a)}{G_{tot}}. \quad (10)$$

- For flat-plate tube design, the classic Hottel and Willier equation system is used, by only changing the expression for collector efficiency factor F^* [93,133]:

$$F^* = \frac{1/U_L}{W \left[\frac{1}{U_L[D_h + (W - D_h)F]} + \frac{1}{C_b} + \frac{1}{2(a+b)h_{fi}} \right]}, \quad (11)$$

where D_h is the hydraulic diameter (m), a is the width of the duct (m) and b is the length of the duct (m).

In general, the total daily thermal efficiency η_T is calculated by the relation:

$$\eta_T = \frac{E_T}{E_s}, \quad (12)$$

where E_T (Wh) is the total thermal energy generated during the day by the PV/T collector.

4 Review of research and development of PV/T water systems

In this part of the article, an overview of research, development and application of PV/T water systems in the last 10 years is given. Research with the goal of increasing the efficiency of these systems is mainly focused on improving the design of different types of thermal absorbers and using new materials for PV modules.

At the Centre for Energy Studies of the Indian Institute of Technology, Delhi in India, for the past 10 years, researchers have been working intensively to study hybrid systems and improve their performance. An integrated combined system of a PV/T solar water heater has been designed and tested in outdoor conditions for the

composite climate of New Delhi by Dubey and Tiwari. [68]. It is observed that the flat-plate PV/T collector partially covered with a PV module gives better thermal and average cell efficiency, which is in accordance with the results reported by earlier researchers. They also obtained an analytical expression for the characteristic equation for such a collector for different conditions, as a function of the design and climatic parameters. On the other hand, Dubey and Tiwari [135] evaluated the performance of partially covered flat-plate water collectors connected in series using theoretical modeling. Analytical expressions for N collectors connected in series were derived by using energy balance equations and computer-based thermal models. They gave a detailed analysis of thermal energy, exergy and electrical energy yield by varying the number of collectors, by considering four weather conditions of five different cities (New Delhi, Bangalore, Mumbai, Srinagar and Jodhpur) in India as well as the total carbon credit earned by the hybrid PV/T water heater investigated per the norms of the Kyoto Protocol for New Delhi climatic conditions. They found that if this type of hybrid system is installed in 10% of the total residential houses in Delhi, the total carbon credit earned by PV/T water heaters in terms of thermal energy will be US\$144.5 million per annum, and in terms of exergy is US\$14.3 million per annum.

An analytical study for determining the water temperature of an integrated PV/T solar (IPV/TS) water heater under a constant mass flow rate has been carried out by Tiwari et al. 2009 [136]. They observed that the daily overall thermal efficiency of the IPV/TS system increases with the increasing constant mass flow rate of the working fluid and that the thermal and exergy efficiency has reversed trends with respect to collection temperature, as expected. The exergy analysis of the system has also been carried out and it has been shown that the exergy and thermal efficiency of the IPV/TS system is maximal at the hot water withdrawal flow rate of 0.006 kg/s.

An experimental study of the series-connected PV/T water collector (Figures 7 and 8) performance for the climatic condition of New Delhi was performed by Shyam et al. (2016) [137], and it confirmed to a previously developed theoretical model [138]. The authors also discussed the annual energy gain, exergy gains, CO_2 mitigation, energy matrices and carbon credit of the system. The energy payback time was found to be 1.50 and 14.19 years for overall thermal energy and exergy basis, respectively.

Hybrid systems have also been intensively studied and developed in China. Based on experimental data

Figure 7: Photograph of the series-connected PV/T water collector [137].

Figure 8: Schematic diagram of the series-connected PV/T water collector [137].

and validated numerical models, a study of the appropriateness of glass cover on a thermosiphon-based PV/T water-heating system was carried out by Chow et al. [139]. In PV/T technology, the use of a glass cover on the flat-plate hybrid solar collector is favorable to the photothermic process but not to the PV process. They found that a glazed PV/T system is always suitable for the thermal or overall energy output. From the exergy analysis point of view, however, the increase in PV cell efficiency, packing factor, water mass to collector area ratio and wind velocity is found to be favorable for an unglazed system, whereas the increase in on-site solar radiation and ambient temperatures are favorable for a glazed system. Unlike the classic sheet-and-tube absorber which is generally recommended for the flat-plate PV/T collector design because of its simplicity and promising performance, Chow and Ji [140] tested the use of a

Figure 9: Cross-sectional view of an aluminum rectangular-channel PV/T water collector [140].

rectangular-channel thermal absorber (Figure 9). The authors studied the energy payback time and the greenhouse gas payback time of freestanding and BIPV/T systems in Hong Kong. This was based on two case studies of PV/T collectors with modular channel-type aluminum absorbers. The results confirmed the long-term environmental benefits of PV/T applications.

A PV/T system with natural circulation of water installed on vertical facades of high-rise residential buildings has been studied by Sun et al. (2016) [141]. They studied the influence of the connection mode of PV/T water systems and tilt angle on the energy output of the systems. It has been shown that the connection mode has more obvious influences on thermal energy than on electrical power; and compared with the parallel connection, the electric power for a series connection decreases by 2.0%, the thermal energy increases by 11.4% and the total energy increases by 5.4%. Considering only the total energy, a PV/T collector with a tilt angle of 20° can produce maximum energy benefits.

The electrical and thermal performance of a PV/T water-heating system in buildings in given climate conditions was evaluated by Shan et al. (2013) [142]. The PV/T system is constructed, so that a duct with a rectangular cross section is attached below the PV module for water flowing, where three sides of the duct are adiabatic, but the remaining one, the backplane attached to the back surface of the solar cell, has excellent thermal conductivity. The influence of the series-connected PV/T module number, the inlet temperature of water and the mass flow rate of water on the electrical and thermal performances were analyzed. The conclusion was that a lower series-connected PV modules number, lower inlet water temperature and higher water mass flow rate all result of a high electrical efficiency.

The PV/T system with a novel design of the thermal collector excluding the thermal absorber plate (Figure 10) has been proposed by Nahar et al. (2017) [143]. The PV/T

Figure 10: Cross-sectional view of PV/T water collector without a thermal absorber plate [143].

system performance has been determined analytically and validated by experimental measurements for various operating conditions under the typical climatic condition of Malaysia. Thermal performance of PV/T without an absorber plate was found to be as good as a PV/T with an absorber plate. The authors concluded that the absorber plate may be discarded from the thermal collector part of the PV/T system, which will lead to a reduction in the weight and cost of the PV/T system. The same authors have developed a three-dimensional numerical model to investigate the PV/T performance with a new pancake-shaped flow channel design, where the flow channel was attached directly to the backside of the PV module by using a thermal paste [144].

For the PV/T water collector without a thermal absorber plate, Nahar et al. (2019) examined the effect of different flow parameters on heat transfer and PV/T performance as well as the effect of irradiation level and depth of the flow channel on the thermal and electrical performance of the system [145]. The obtained results showed that the electrical and thermal efficiencies increase with higher values of both the Reynolds and Prandtl number, and the heat transfer rate increases as high as 25.5% with increasing Reynolds number. A maximum reduction of 10°C in PV cell temperature was achieved by increasing the channel depth.

The electrical efficiency of a PV/T system under outdoor operating conditions in Malaysia has been studied by Rahman et al. (2017) [146]. A finned tube was attached under the PV module for cooling. The results showed that the PV cell temperature, solar irradiation intensity, mass flow rate of water, humidity and dust significantly affect the PV module performance. The electrical efficiency decreases by approximately 0.22% as the temperature of the PV module increases by 1°C.

The effect of different high irradiation levels and cooling fluid flow rate on power, energy and performance

of a PV/T system has been studied by Nasrin et al. (2018) [147]. Their analytical model has been validated with experimental measurements. It is observed that the PV/T system's overall performance increases with the increasing fluid flow rate, with an optimum flow rate of about 180 L/h. An increase in irradiation from 1,000–5,000 W/m² corresponds to an increase in the electrical and thermal energy output of 197–983 W and 1,165–5,387 W, respectively.

A group of researchers from Greece in the last 15 years has had a number of significant works in the field of hybrid conversion that have contributed to improving the performance of PV/T water collectors [100,101,121]. They also showed that PV cooling could increase the electrical efficiency of PV modules, increasing the total efficiency of the system. The system performance can be improved by using an additional glazing to increase the thermal output. Sakellariou and Axaopoulos (2017) [148] have studied a retrofitted PV/T collector and a conventional PV module, which were installed together. The thermal absorber type was serpentine flat water based, and it was made of copper sheet and tubes. Outdoor experiments were conducted to study the PV/T and PV performances during the autumn to winter period. The results showed that the PVT system can slightly increase its average electrical efficiency by 0.32% during this period and obtain additional thermal energy, with a daily average efficiency of 20.33%.

A detailed thermal model for calculating the thermal parameters of a PV/T collector with sheet-and-tube configuration, where galvanized steel is used, was developed by Hocine et al. (2015) in Algeria [149]. The advantages of this type of collector are simple implementation, better heat absorption and lower production cost compared to other configurations of hybrid collectors [150]. A computer simulation program was developed in order to calculate the thermal (solar cell temperature, outlet water temperature, thermal efficiency and useful thermal energy) and electrical parameters of a PV/T collector. The results of the numerical simulation are in good agreement with the experimental measurements noted in the previous literature, and the thermal simulation results are more precise. The thermal efficiency of this type of PV/T water collector is about 54.51% and the electrical efficiency is 11.12%, for sample climatic, operating and design parameters.

Another mathematical model for the PV/T water collector with sheet-and-tube design has been proposed by Khelifa et al. (2016) [151]. This collector consists of a PV module and a cooling system within the various system layers: a cover of glass, the PV cell, a layer of tedlar, a flat-plate thermal absorber with tubes for the circulation

Figure 11: Cross-sectional view of PV/T water collector with sheet-and-tube design [151].

of water and the insulation (Figure 11). The temperatures of the various layers of the solar PV/T collector and the coolant temperature were predicted in this model. The water flow and heat transfer in the collector were studied using the ANSYS14 Software, while the heat transfer phenomenon conjugate between the PV cells and the coolant was modeled using the FLUENT Software. The heat transfer by solar radiation was not modeled; however, the effects of radiation were taken into consideration when calculating the conditions for heat flux limit for the collector layers.

A 3D dynamic numerical model of a high-efficiency PV/T water collector integrated into a domestic hot water (DHW) system has been developed by Pierrick et al. (2015) [152]. The thermal absorber was constructed using a roll-bond manufacturing process. A film of electrical insulator was added to the heat exchanger, upon which are laminated 32 interconnected single-crystalline Si PV cells encapsulated by the EVA films. The cells are protected by a polymer film and a layer of thermal insulation, with a low thermal conductivity, which is added to the rear of the panel (Figure 12). The experimentally obtained electrical and thermal performance of the PV/T collector indicated an overall efficiency of more than 87%, which is a significant improvement upon the thermal and electrical efficiencies of previously developed PV/T systems reported by Chow et al. (2010) [2]. The authors introduced a high-accuracy model and its validation in steady state and dynamic regimes using monitoring data recovered from BEST Lab's Solar Domestic Hot Water System facility. This model was satisfactory as the discrepancy in the fluid temperature is at the maximum of 2°C in the dynamic state, where the electrical power generation is slightly underestimated.

A new mathematical model for PV/T water system's performance simulation was proposed by Aste et al.

Figure 12: Exploded view of a PV/T water collector component [152].

(2015) [153]. Their simulation model was developed to evaluate the performance of a covered PV/T water collector made with thin-film PV technology and a roll-bond flat-plate absorber. They also considered the daily and annual yield of the proposed PV/T collector, compared to a standard PV module. Subsequently, Aste et al. (2016) [154] presented a mathematical model for energy simulation of an uncovered PV/T water system. Their model can be easily implemented in any performance calculation tool, in order to carry out the technical-economic assessment of PV/T systems. The experimental validation of the proposed model was performed in outdoor conditions on a commercial PV/T collector in Italy. The PV/T collector consisted of an mc-Si PV sandwich not covered with any additional glass and bonded mechanically with a roll-bond aluminum absorber, with the channel arrangement. The whole component was enclosed in an aluminum frame and a thermal reflective insulation was applied to the rear side of the absorber, in order to reduce the back-side thermal losses. The roll-bond process is common in the manufacturing of PV/T thermal absorbers, since it allows to configure the channel pattern with maximum flexibility, at the same time maintaining low production costs. The validation of the proposed simulation model showed a good agreement with the experimental data. They also studied, both theoretically and experimentally, the effect of glazing on the performance of a flat-plate PV/T water collector with the roll-bond absorbers design, by testing and comparing collectors with and without a cover. The obtained results showed that the annual electrical efficiency of the covered and uncovered collector was 6.0 and 14.2%, respectively, while the annual thermal efficiency was 29.4 and 22.0% for the covered and uncovered collector, respectively [155].

The thermal and electrical performances of several uncovered PVT collectors with a field test have been evaluated by de Keizera et al. (2016) [156]. The three uncovered PVT systems were installed on the middle dummy

Figure 13: The middle dummy building in the front row contains three types of uncovered PVT systems [156].

building in the front row in the Netherlands, namely, c-Si PV with uninsulated absorber clamped to the back of the module, CIGS panel with clamped absorber and insulation and building-integrated c-Si PV with in-roof absorber and insulation (Figure 13). The collectors of each system are thermally connected in a series. The outdoor performance of these collectors was evaluated in an outdoor test setup and the results of this field test were used for dynamic simulations of the annual electrical and thermal energy yields for typical system designs and heat loads. The electrical average efficiency of the three uncovered PVT systems was 12.2–14.2%, while the thermal efficiency parameters were mostly caused by the thermal contact between PV and the thermal collector together with the insulation on the back of the system. Unlike previous research, a numerical method for the thermal yield estimation of unglazed PV/T collectors using indoor solar simulator testing was developed by Katiyar et al. (2017) [157]. The resulting numerical model could be used to optimize the design of the collector and to derive the thermal performance of the unglazed PV/T collector as defined by ST testing standards.

Systematic testing of PV/T collectors in steady-state and dynamic outdoor conditions was performed by Guarracino et al. (2019) in Cyprus [158]. Tests were performed on four PV/T collectors, each of a different design and construction as follows: a commercial PV/T collector, an unglazed PV/T collector with 65% PV covering factor, a glazed PV/T module with 65% PV covering factor and a glazed collector 100% PV covering factor. The authors were presented the results from a series of outdoor tests to characterize the electrical and thermal performance of a range of PV/T collectors. Steady-state and dynamic test methods were adapted from the existing European standard EN 12975-2 for ST collectors, in the absence of a dedicated testing methodology specifically for PV/T collectors.

Yu et al. in 2019 have tested and modeled an unglazed PV/T water collector with a low-cost roll-bond absorber for application in Sichuan Basin of China [159]. The design of the PV/T prototype adopted the available commercial PV modules for reducing the manufacturing cost. The experiment measured all the main performances of the developed PV/T collector. The proposed steady-state numerical models were used to simulate the performance of the PV/T prototype in transient systems simulation program (TRNSYS). Through validating the numerical models with experimental data, the deviation between the simulated and the measured values was further reduced. In addition, a complete PV/T DHW system was developed in TRNSYS, by which the annual system output and efficiency were predicted and analyzed. They also compared the performance of two roll-bond PV/T water collectors, one with a conventional harp-channel configuration and the other with a novel grid-channel arrangement. Simulation and experimental results showed that both the thermal and electrical efficiencies of a grid-channel PV/T collector were higher than a harp-channel PV/T collector [160].

Yazdanifard et al. (2016) proposed the model to simulate a flat-plate PV/T water system with and without glass cover in laminar and turbulent regime and to investigate the effects of solar irradiation, packing factor, Reynolds number, collector length, pipes diameter and the number of pipes on the performance of this system [161]. The results showed good agreement with the available data in the literature. The obtained results showed that the energy efficiency in the glazed PV/T system is higher than unglazed one, while its exergy efficiency depends on the packing factor, Reynolds number and collector length. It has been shown that increasing solar radiation and packing factor increases total energy and exergy efficiency in both laminar and turbulent regime, while in most cases, the total energy efficiency in turbulent regime is higher, whereas the total exergy efficiency in laminar regime is superior.

Along with the numerical models that should predict the electrical and thermal performance of covered and uncovered PV/T collectors, experimental tests of these systems have also been performed. Experimental comparison of electrical and thermal performances of glazed and unglazed PV/T water systems has been conducted by Kim and Kim (2012) [162]. The electrical and thermal performances of the PV/T collectors were measured in outdoor conditions. The results showed that the thermal efficiency of the glazed PV/T collector was higher than that of the unglazed PV/T collector, while the unglazed collector had higher electrical efficiency than the glazed

collector. They also reported an overall energy efficiency of 48.4 and 35.8% for the glazed and unglazed PV/T systems, respectively. Even though the overall performance of the glazed collector was 12.6% higher than that of the unglazed one, it cannot be concluded that it was superior, because the selection of an optimal configuration will depend on the overall cost efficiency and energy balance of the systems.

An experimental study of the glass cover and working fluid effects on a PV/T water system performance has been conducted by Kazemian et al. (2018) [163]. Two similar sheet-and-tube PV/T systems with and without glass cover were designed and fabricated to perform the experiments. The results showed that for the unglazed PV/T system, both the electrical power and current output were higher than that of the glazed PV/T system. This is explained by the fact that the surface temperature of the unglazed PV/T system is lower compared to that of the glazed one. Adding a glass cover into the PV/T system leads to a decrease in the heat loss, which leads to an increase in the PV/T surface temperature. The average electrical and thermal energy efficiency of the unglazed collector was 14.35 and 63.37%, respectively; for the glazed collector, the average electrical and thermal energy efficiencies were 13.15 and 70.89%, respectively. It can be concluded that if electricity is the main interest, the unglazed PV/T is preferred; and if a higher overall energy efficiency is required, the glazed PV/T system is recommended.

It is obvious that the covered PV/T system has to compromise with the electrical efficiency due to the temperature rise, while the uncovered PV/T system suffers from lower thermal efficiency but better electrical efficiency [139]. This means that, for example, an uncovered PV/T collector would be widely used in hot regions where the electrical output is substantially reduced by the edge shading from the cover. On the other hand, a covered PV/T collector would more suitably be installed in cold areas, due to reduced heat loss and better thermal insulation [13]. In general, it can be concluded that the usage of glazing leads to an increase in the thermal efficiency and a slight decrease in the electrical efficiency; higher total efficiency of a PV/T system is obtained when utilizing glazing; unglazed PV/T system is more favorable if high electrical output is required; glazed PV/T system is more favorable if high thermal or overall system efficiency is required, with single glazing being more preferable than double glazing [12].

A new PV/T collector concept with variable film insulation and low-emissivity coating was proposed by Lämmle et al. (2016) [164]. The collector concept used a

fluoropolymer film to achieve a variable insulation. In this concept, the film was sealed hermetically at the edges to the low-e glass. A small air pressure stabilized the cushion and ensured low thermal losses. Deflating the cushion increased heat losses and reduced collector temperatures during stagnation. Performance and stagnation tests were carried out with a prototype; and it was shown that during normal operation, the collector achieved a high thermal efficiency. In periods of standstill, the deflated cushion demonstrated a high heat dissipation rate by deactivating the low-e coating. Stagnation temperatures were thus limited to 95°C. The main conclusion was that the PV/T collector combines the advantages of glazed and unglazed PV/T collectors, which include a high thermal efficiency and low stagnation temperatures.

A large number of different alternative absorber-exchanger designs for PV/T water collectors have been proposed by Herrando et al. (2019) [165]. The collectors involved possessed different geometric design properties based on both the conventional sheet-and-tube configuration and a newer flat-box structure constructed from alternative polymeric materials with the aim of maintaining or even improving heat transfer and thermal and electrical performance while achieving reductions in the overall weight and cost of the collectors. The authors developed and validated a 3-D computational finite-element model of the proposed PV/T collector designs and performed comparative technoeconomic analyzes and structural deformation analyzes of the proposed PVT designs. The results showed that the flat-box designs with a thin absorber plate are not sensitive to the flow-channel size or construction material and a polycarbonate PC flat-box design with rectangular channels appeared to be a particularly promising alternative to commercial PV/T collectors, achieving a slightly improved thermal performance, while also lowering the weight by around 9% and investment cost by about 21% of the collector. The improved efficiency of the flat-box PV/T collector over the conventional sheet-and-tube configuration was attributed to the improved surface heat transfer. However, although a polycarbonate flat-box design with rectangular channels showed superior thermal performance in numerical analysis, there is a danger that in reality such an absorber exchanger could probably burst under high water pressure [166].

A design of a grid-connected PV/T water system and performance evaluation from outdoor experiments in weather conditions of Oman has been presented by Kazem (2019) [167]. The PV/T collector was made of stainless-steel material with good thermal conductivity and

the pipe was designed in rectangular shape. The proposed PV/T system showed superior electrical performance during the examination period, with consistent rise in electrical efficiency over conventional PV. The average power of the PV/T collector was 6% higher compared to the average power of the conventional PV module.

The thermal performance analysis of parallel serpentine flow-based PV/T system under composite climate of Malaysia has been carried out by Hossain et al. (2019) [168]. The main disadvantage of the conventional PV/T water collector is that their operation is limited only in the daytime. To overcome these challenges, the novel parallel serpentine pipe flow-based PV/T collector has been designed and studied (Figure 14). The air gap has been kept between each pipe and a parallel gap between the two sides of the absorber. When the sun irradiation fell on the PV module glass plate, the internal air was heated like the inside of a greenhouse. Nevertheless, water flowing inside the copper pipe took time due to frictional pressure drop to reach the outlet and during this time, water flowing inside the absorber tubes was heated because of the hot water from the collector outlet. The experiments were performed at different volume flow rates. The obtained maximum thermal efficiency of PV/T system was 76.58% at 2 L/min, while the electrical efficiency of PV and PV/T was 9.89 and 10.46%, respectively. The maximum exergy efficiency of PV and PV/T system has been found to be 7.16 and 12.98% (0.5 L/min), respectively.

The PV/T system and PV outdoor performance in a hot humid tropical climate in Ghana have been investigated by Abdul-Ganiyu et al. (2020) [169]. A single-crystalline Si PV/T water collector and a conventional single-crystalline Si PV module were used in the experiments. It was observed that the annual total energy output of PV module was 194.79 kW h/m², whereas the electrical and thermal outputs of the PV/T collector were 149.92 and 1087.79 kW h/m², respectively. The highest monthly mean efficiency recorded for the PV was 12.7%,

while the highest combined monthly mean electrical/thermal efficiency of the PV/T was 56.1%. Based on experimental results, it could be concluded that the PV/T is a perspective alternative energy source in off-grid situations.

The economic parameters significantly influence the cost competitiveness of solar PV/T technologies, so along with research and development of new designs of PV/T systems, their applications were economically analyzed. Technical and economical assessments of the opportunity to use PV/T systems for water heating in industry were studied by Hazi et al. (2014) [170]. They proposed a mathematical model to evaluate the energy parameters and economic indicators based on the three variables: solar irradiance, air temperature and water supply temperature. The authors applied this model to simulate the operation of the PV/T system under different climatic locations in Romania and concluded that using the PV/T system for water heating in industry is economically viable and the payback period (PBP) is lower than its lifetime.

A thermoeconomic analysis of a PV/T-combined heating and power system at the University Sport Center of Bari in Italy has been carried out by Wang et al. (2019) [171]. Economic performance was evaluated by considering the investment costs and the cost savings due to the reduced electricity and natural gas consumptions. The results suggested that even though the economic competitiveness of the proposed PV/T system is not yet favorable when compared to the alternative gas-fired internal combustion engine (ICE)-based system, the PV/T solution has an excellent decarbonization potential and that further efforts relating to cost reduction are required before they can become economically competitive with conventional fossil fuel.

Technoeconomic analysis of the PV/T systems for domestic heat and power provision in a typical house in London, UK, was carried out by Herrando and Markides (2016) [172]. After that Herrando et al. (2018) studied the cost competitiveness of a solar-combined heating and power (S-CHP) system based on a novel PV/T collector in three different locations: Zaragoza, London and Athens [173]. They analyzed the influence of several economic parameters on the cost competitiveness of the proposed system. The results showed that the PV/T collector price influences the system's economics, as it is responsible for the highest share of the total investment (~38%; Figure 15). High market discount rates significantly and negatively affect the system's cost competitiveness, leading to higher payback times, except in low-latitude locations where high solar irradiance and

Figure 14: PV module and layout of PV/T collector [168].

Figure 15: Breakdown of the investment costs (including installation) of a representative S-CHP system for a single-family house based on 8 PV/T collectors (0.72 m³ water storage tank) [173].

energy prices lead to reasonable higher payback times. The analysis of potential future scenarios, considering a combination of several economic parameters, points out that the S-CHP system's cost competitiveness is feasible in the short-term.

The thermal, electrical, and cost study of advanced optical PV/T system with heat pipe absorber design was carried out by Brinkley et al. (2020) in California [174]. The PV/T collector consists of glass tubes integrated with non-imaging optics, aluminum mini channel heat pipes sandwiched between commercially available solar cells. The material choices, such as commercial cells, glass tubes, aluminum absorbers and silvering chemical treatment on the tubes, minimize the module costs and make this collector cost competitive compared to other PV/T collectors. The collector provides a low-cost option for use in single- or multifamily homes and commercial buildings and also reduces CO₂ emissions and the need for natural gas.

Road map for the next-generation PV/T collectors has been proposed by Mellor et al. (2018) [175]. In order for PV/T collectors to become competitive in the market, it is necessary to achieve high performance at fluid outlet temperatures of more than 60°C required for space heating and DHW provision, which together make up about 50% of the heat demand. A road map provides strategies for reducing convective, radiative and electrical losses at elevated temperatures as well as an experimental characterization of a novel transparent low-emissivity coating for PV modules. The authors performed a technoeconomic analysis to predict the price points at which the PV/T technologies along the road map become competitive compared to other PV and ST technologies.

Where roof space is not the principal constraining factor, the real measure of competitiveness is the

investment PBP expressed in years. This is the length of time in which the solar energy system has to operate, before the owner has recuperated the cost of purchasing and installing the system. The PBP can be calculated as follows:

$$\text{PBP} = C/\text{AR} \quad (13)$$

where C is the cost of the fully installed system per unit collector surface area and AR ($\text{\$ m}^{-2} \text{ year}^{-1}$) is the annual revenue generated per m² of collector surface area. The annual revenue can be estimated from the annual energy yield for PV, ST and PV/T, respectively, as follows:

$$\text{AR}^{\text{PV}} = p_{\text{el}} Y_{\text{el}}^{\text{PV}} \quad (14)$$

$$\text{AR}^{\text{ST}}(T_d) = p_{\text{th}} Y_{\text{th}}^{\text{ST}}(T_d) \quad (15)$$

$$\text{AR}^{\text{PVT}}(T_d) = p_{\text{el}} Y_{\text{el}}^{\text{PVT}}(T_d) + p_{\text{th}} Y_{\text{th}}^{\text{PVT}}(T_d) \quad (16)$$

where p_{el} and p_{th} are the prices at which the electrical and thermal energies are sold, respectively, Y_{el} ($\text{kW h}_{\text{el}} \text{ m}^{-2} \text{ year}^{-1}$) is the annual electrical energy yield and Y_{th} ($\text{kW h}_{\text{th}} \text{ m}^{-2} \text{ year}^{-1}$) is the annual thermal energy yield.

The cost of the installed solar systems largely depends on the geographical location, site and technology, and changes significantly over time. Figure 16 shows the projected annual revenue and PBP for PV, ST and the different types of PV/T systems at fluid delivery temperature of around $T_d = 60^\circ\text{C}$, for solar systems located in Athens. Glazed collectors in which the cavity contains air or vacuum, with the overall radiative emissivity of $\varepsilon = 0.9$ and 0.15 (the value of $\varepsilon = 0.9$ corresponds to no low-e coating and 0.15 corresponds to the low-e coating), were considered [175].

It can be concluded that the present generation of PV/T (air, $\varepsilon = 0.9$) is economically competitive with PV

Figure 16: Projected annual revenue and payback period for PV, ST and different types of PV/T systems in Athens, at fluid delivery temperature $T_d = 60^\circ\text{C}$.

and ST systems only for low-temperature applications, such as swimming pool heating, whereas the more advanced collectors, which require an evacuated cavity, a transparent low-emissivity coating and Si heterojunction PV cells, become competitive for the much larger space heating and DHW market. An important argument for advancing PV/T along the road map is that the improved performance allows PV/T systems to become competitive at a less demanding production, system and installation costs, which are typically larger than those of equivalent PV and ST systems.

5 Conclusions

Based on the given literature review, it can be noticed that the research in the field of hybrid conversion of solar radiation has been very intensive, especially in the previous decade, and as such remains relevant today. The main task is to increase the efficiency of PV solar cells and thermal absorbers with both new materials and design types as well as their proper integration into the PV/T water systems. The most important points are summarized below.

- When designing a PV/T water collector, it is very important to choose the correct type of the PV module which will be integrated into the hybrid collector, because solar cell materials determine the absorption coefficient, the spectral sensitivity of the solar cell as well as its conversion efficiency. High electrical efficiency is required in most cases of application of PV/T collectors, because these systems generate much higher thermal energy compared to electricity. Recent research shows a significant potential of the third-generation solar cells, which include multiple-junction solar cells. They should enable the use of the entire spectrum of solar radiation and eliminate heat losses in the solar cells. The perovskite solar cells are of great interest due to their potential to achieve high efficiency and very low production costs, making them commercially attractive.
- The type of thermal absorbers that are integrated into PV/T water collectors is of great importance, since the absorbers directly affect the cooling of PV modules and determine the overall efficiency of PV/T systems. Compared to the traditional thermal absorbers, such as those with a sheet-and-tube structure, a rectangular tunnel with or without fins/grooves and flat-plate tube, new types of thermal absorber design, i.e., micro-

channel heat pipe array/heat mat, extruded heat exchanger and special roll-bond heat exchanger have promising potential for application due to the significant enhancement in efficiency, their structure, weight and cost.

- The appropriate integration method for combining thermal absorbers and PV modules is very important because it directly influences a PV/T module's thermal efficiency, due to the thermal resistance between the PV modules and the thermal absorber. Compared to the conventional methods, such as direct contact, thermal adhesive and mechanical fixing, recent research indicates the advantages of the EVA-based lamination method. In any case, further research and results are expected in this part of the development of PV/T collectors.

In addition to the intensive research by using numerical models that predict the electrical and thermal performance of PV/T water systems as well as experimental laboratory research and short-term testing of PV/T systems in real climatic conditions, it is necessary to conduct investigations in the field of application of PV/T systems for long-term operation. These studies are important for resolving different practical uncertainties, especially for the BIPV/T systems.

The importance of PV/T systems also lies in providing the necessary energy in clean and environmental-friendly ways. In this sense, decarbonization is one of the significant challenges faced by researchers.

In addition, it is necessary to reduce the cost of these systems and make them more competitive in the market. A huge potential of PV/T water technology for useful and multipurpose applications is obvious, where a special place is occupied by BIPV/T technology. It is clear from the literature review that PV/T water collectors are very promising devices, and the market potential of PV/T technology is significantly higher than for individual PV and ST systems. Some researchers predict that the potentials of PV/T systems are such that they will be able to completely suffice the need for energy consumption in the near future.

Nomenclature

A_c	collector surface area (m^2)
AR	annual revenue ($\$ \text{m}^{-2} \text{year}^{-1}$)
E_E	total generated electrical energy during the day (Wh)

E_S	total solar radiation energy during the day (Wh)
E_T	total generated thermal energy during the day (Wh)
F^*	collector efficiency factor
F_R	heat-removal factor
G_{tot}	total solar radiation on the PV/T collector surface (W m^{-2})
I_m	PV current at the maximum power point (A)
$\dot{m}$	water mass flow rate (kg s^{-1})
PBP	payback period (years)
T_a	ambient air temperature ($^{\circ}\text{C}$)
T_i	water input temperature ($^{\circ}\text{C}$)
T_o	water output temperature ($^{\circ}\text{C}$)
V_m	PV voltage at maximum power point (V)
ΔT	temperature difference (K)
U_L	overall heat transfer loss coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
Y_{el}	annual electrical energy yield ($\text{kWh}_{\text{el}} \text{m}^{-2} \text{year}^{-1}$)
Y_{th}	annual thermal energy yield ($\text{kWh}_{\text{th}} \text{m}^{-2} \text{year}^{-1}$)
η_E	total daily electrical efficiency
η_T	total daily thermal efficiency
η_e	PV electrical efficiency
η_{th}	PV/T system thermal efficiency
η_{tot}	total PV/T system efficiency
η_f	energy-saving efficiency

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References

- [1] Zondag HA, van Helden WGJ, Bakker M, Affolter P, Eisenmann W, Fechner H, et al. PVT Roadmap: a European guide for the development and market introduction of PVT technology. 20th European Photovoltaic Solar Energy Conference. 2005. p. 4.
- [2] Chow TT. A review on photovoltaic/thermal hybrid solar technology. *Appl Energy*. 2010;87(2):365–79. doi: 10.1016/j.apenergy.2009.06.037.
- [3] Chen H, Riffat SB. Development of photovoltaic thermal technology in recent years: a review. *Int J Low-Carbon Technol*. 2011;6(1):1–13.
- [4] Chauhan A, Tyagi VV, Anand S. Futuristic approach for thermal management in solar PV/thermal systems with possible applications. *Energy Convers Manag*. 2018;163(March):314–54. doi: 10.1016/j.enconman.2018.02.008.
- [5] Wang J, Chen Y, Lior N. Exergo-economic analysis method and optimization of a novel photovoltaic/thermal solar-assisted hybrid combined cooling, heating and power system. *Energy Convers Manag*. 2019;199(June):111945. doi: 10.1016/j.enconman.2019.111945.
- [6] Yousef H. Experimental study of design a hybrid photovoltaic thermal collector (PVT-collector) for a domestic use [MSc thesis]. Hebron, Palestine: Palestine Polytechnic University; 2019.
- [7] Heng Z, Haowen L, Haiping C, Xinxin G, Kai L, Pengbo Y. Research on the performance of flat-box photovoltaic/thermal collector with cooling channels. *J Sol Energy Eng Trans ASME*. 2018;140:2.
- [8] Shan F, Tang F, Cao L, Fang G. Performance evaluations and applications of photovoltaic-thermal collectors and systems. *Renew Sustain Energy Rev*. 2014;33:467–83. doi: 10.1016/j.rser.2014.02.018.
- [9] Supekar S, Malvi CS, Solar PVT. Technology and its commercial applications: a review. *TERI Inf Dig Energy Env*. 2018;17(2):165–74.
- [10] Daghigh R, Ruslan MH, Sopian K. Advances in liquid based photovoltaic/thermal (PV/T) collectors. *Renew Sustain Energy Rev*. 2011;15(8):4156–70. doi: 10.1016/j.rser.2011.07.028.
- [11] Das D, Kalita P, Roy O. Flat plate hybrid photovoltaic-thermal (PV/T) system: a review on design and development. *Renew Sustain Energy Rev*. 2018;84(October 2017):111–30. doi: 10.1016/j.rser.2018.01.002.
- [12] Herez A, El Hage H, Lemenand T, Ramadan M, Khaled M. Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems. *Sol Energy*. 2020;207(May):1321–47.
- [13] Pang W, Cui Y, Zhang Q, Wilson GJ, Yan H. A comparative analysis on performances of flat plate photovoltaic/thermal collectors in view of operating media, structural designs, and climate conditions. *Renew Sustain Energy Rev*. 2020;119(June):109599. doi: 10.1016/j.rser.2019.109599.
- [14] Riffat SB, Cuce E. A review on hybrid photovoltaic/thermal collectors and systems. *Int J Low-Carbon Technol*. 2011;6(July):212–41.
- [15] Diwania S, Agrawal S, Siddiqui AS, Singh S. Photovoltaic-thermal (PV/T) technology: a comprehensive review on applications and its advancement. *Int J Energy Env Eng*. 2020;11(1):33–54. doi: 10.1007/s40095-019-00327-y.
- [16] Tyagi VV, Kaushik SC, Tyagi SK. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. *Renew Sustain Energy Rev*. 2012;16(3):1383–98. doi: 10.1016/j.rser.2011.12.013.
- [17] Chow TT, Tiwari GN, Menezo C. Hybrid solar: A review on photovoltaic and thermal power integration. *Int J Photoenergy*. 2012;2012:307287.
- [18] Wu J, Zhang X, Shen J, Wu Y, Connelly K, Yang T. A review of thermal absorbers and their integration methods for the combined solar photovoltaic/thermal (PV/T) modules. *Renew Sustain Energy Rev*. 2017;75:839–54. doi: 10.1016/j.rser.2016.11.063.
- [19] Babu C, Ponnambalam P. The role of thermoelectric generators in the hybrid PV/T systems: A review. *Energy Convers Manag*. 2017;151(August):368–85. doi: 10.1016/j.enconman.2017.08.060.
- [20] Sridharan M, Vimal M. Performance improvement analysis on PV/T water collectors connected in series and parallel. *Int J Adv Res Methodol Eng Technol*. 2017;1(3):283–8.

- [21] Sharma S, Rabia S, Chuahan A, Pathak AK. Photovoltaic thermal (PV/T) and its recent developments. *Int J Sci Tech Adv.* 2016;2(4):27–32.
- [22] Sultan SM, Efsan MNE. Review on recent photovoltaic/thermal (PV/T) technology advances and applications. *Sol Energy.* 2018;173(August):939–54. doi: 10.1016/j.solener.2018.08.032.
- [23] Sharaf OZ, Orhan MF. Concentrated photovoltaic thermal (CPVT) solar collector systems: Part I – Fundamentals, design considerations and current technologies. *Renew Sustain Energy Rev.* 2015;50:1500–65. doi: 10.1016/j.rser.2015.05.036.
- [24] Khalil O, Mohammed S. Reflective mirrors effect on the performance of the hybrid PV/thermal water collector. *Energy Sustain Dev.* 2018;43:235–46. doi: 10.1016/j.esd.2018.02.001.
- [25] Zhang H, Chen H, Liu H, Huang J, Gup X, Li M. Design and performance study of a low concentration photovoltaic-thermal module. *Int J Energy Res.* 2018;42(January):2199–212.
- [26] Sharaf OZ, Orhan MF. Comparative thermodynamic analysis of densely-packed concentrated photovoltaic thermal (CPVT) solar collectors in thermally in-series and in-parallel receiver configurations. *Renew Energy.* 2018;126:296–321. doi: 10.1016/j.renene.2018.03.026.
- [27] Haiping C, Kai L. Research on the performance of flat-box photovoltaic/thermal collector with cooling channels. *J Sol Energy Eng.* 2018;140(April):1–10.
- [28] Zhang H, Liang K, Chen H, Gao D, Guo X. Thermal and electrical performance of low-concentrating PV/T and flat-plate PV/T systems: a comparative study. *Energy.* 2019;177:66–76. doi: 10.1016/j.energy.2019.04.056.
- [29] Coventry JS. Performance of a concentrating photovoltaic/thermal solar collector. *Sol Energy.* 2005;78:211–22.
- [30] Ziapour BM, Palideh V, Mokhtari F. Performance improvement of the finned passive PVT system using reflectors like removable insulation covers. *Appl Therm Eng.* 2016;94:341–9. doi: 10.1016/j.applthermaleng.2015.10.143.
- [31] Liu HW, Zhang H, Chen HP. Performance analysis of a novel LCPV/T system. *IOP Conf Ser Earth Env Sci.* 2018;188:012067.
- [32] Syu CJKS, Huang CSWLC. Optimization and practical verification of system configuration parameter design for a photovoltaic thermal system combined with a reflector. *J Intell Manuf.* 2017;28(4):1017–29.
- [33] Su Y, Kulacki FA, Davidson JH. Experimental and numerical investigations on a solar tracking concentrated photovoltaic-thermal system with a novel non-dimensional lattice Boltzmann method. *Sol Energy.* 2014;107:145–58. doi: 10.1016/j.solener.2014.05.033.
- [34] Bernardo LR, Perers B, Håkansson H, Karlsson B. Performance evaluation of low concentrating photovoltaic/thermal systems: A case study from Sweden. *Sol Energy.* 2011;85(7):1499–510.
- [35] Li W, Paul MC, Rolley M, Sweet T, Gao M, Baig H, et al. A coupled optical-thermal-electrical model to predict the performance of hybrid PV/T-CCPC roof-top systems. *Renew Energy.* 2017;112:166–86.
- [36] Zhang L, Jing D, Zhao L, Wei J, Guo L. Concentrating PV/T hybrid system for simultaneous electricity and usable heat generation: a review. *Int J Photoenergy.* 2012;2012:869753.
- [37] Chaabane M, Charfi W, Mhiri H, Bournot P. ScienceDirect Performance evaluation of concentrating solar photovoltaic and photovoltaic/thermal systems. *Sol Energy.* 2013;98:315–21. doi: 10.1016/j.solener.2013.09.029.
- [38] Naik PS, Palatel A. Energy and exergy analysis of a plane reflector integrated photovoltaic-thermal water heating system. *ISRN Renew Energy.* 2014;2014:180618.
- [39] Sharaf OZ, Orhan MF. Concentrated photovoltaic thermal (CPVT) solar collector systems: Part II – Implemented systems, performance assessment, and future directions. *Renew Sustain Energy Rev.* 2015;50:1566–633. doi: 10.1016/j.rser.2014.07.215.
- [40] Mohsenzadeh M, Hosseini R. A photovoltaic/thermal system with a combination of a booster diffuse reflector and vacuum tube for generation of electricity and hot water production. *Renew Energy.* 2015;78:245–52. doi: 10.1016/j.renene.2015.01.010.
- [41] Li G, Pei G, Ji J, Yang M, Su Y, Xu N. ScienceDirect numerical and experimental study on a PV/T system with static miniature solar concentrator. *Sol Energy.* 2015;120:565–74. doi: 10.1016/j.solener.2015.07.046.
- [42] Ju X, Xu C, Liao Z, Du X, Wei G, Wang Z, et al. A review of concentrated photovoltaic-thermal (CPVT) hybrid solar systems with waste heat recovery (WHR). *Sci Bull.* 2017;62(20):1388–426. doi: 10.1016/j.scib.2017.10.002.
- [43] Hasanuzzaman M, Malek ABMA, Islam MM, Pandey AK, Rahim NA. Global advancement of cooling technologies for PV systems: a review. *Sol Energy.* 2016;137:25–45. doi: 10.1016/j.solener.2016.07.010.
- [44] Ibrahim A, Othman MY, Ruslan MH, Mat S, Sopian K. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. *Renew Sustain Energy Rev.* 2011;15(1):352–65. doi: 10.1016/j.rser.2010.09.024.
- [45] Michael JJ, Iniyar S, Goic R. Flat plate solar photovoltaic-thermal (PV/T) systems: a reference guide. *Renew Sustain Energy Rev.* 2015;51:62–88.
- [46] Kern EC, Russell MC. Combined photovoltaic and thermal hybrid collector systems. 13th IEEE photovoltaic specialists conference. Washington, DC, USA: 1978. p. 1153–7.
- [47] Florschuetz LW. Extension of the Hottel–Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. *Sol Energy.* 1979;22(4):361–6.
- [48] Raghuraman P. Analytical predictions of liquid and air photovoltaic/thermal, flat-plate collector performance. *J Sol Energy Eng Trans ASME.* 1981;103(4):291–8.
- [49] Takashima T, Tanaka T, Doi T, Kamoshida J, Tani T, Horigome T. New proposal for photovoltaic-thermal solar energy utilization method. *Sol Energy.* 1994;52(3):241–5.
- [50] Bergene T, Løvvik OM. Model calculations on a flat-plate solar heat collector with integrated solar cells. *Sol Energy.* 1995;55(6):453–62.
- [51] Sopian K, Yigit KS, Liu HT, Kakaç S, Veziroglu TN. Performance analysis of photovoltaic thermal air heaters. *Energy Convers Manag.* 1996;37(11):1657–70.
- [52] Sopian K, Liu HT, Kakaç S, Veziroglu TN. Performance of a double pass photovoltaic thermal solar collector suitable for

- solar drying systems. *Energy Convers Manag.* 2000;41(4):353–65.
- [53] Fujisawa T, Tani T. Annual exergy evaluation on photovoltaic-thermal hybrid collector. *Sol Energy Mater Sol Cell.* 1997;47(1–4):135–48.
- [54] Hegazy AA. Comparative study of the performances of four photovoltaic/thermal solar air collectors. *Energy Convers Manag.* 2000;41(8):861–81.
- [55] Zondag HA, De Vries DW, Van Helden WGJ, Van Zolingen RJC, Van, Steenhoven AA. The thermal and electrical yield of a PV-thermal collector. *Sol Energy.* 2002;72(2):113–28.
- [56] Zondag HA, de Vries DW, van Helden WGJ, van Zolingen RJC, van Steenhoven AA. The yield of different combined PV-thermal collector designs. *Sol Energy.* 2003;74(3):253–69.
- [57] Zondag HA. Flat-plate PV-thermal collectors and systems: a review. *Renew Sustain Energy Rev.* 2008;12(4):891–959.
- [58] He W, Chow TT, Ji J, Lu J, Pei G, Chan LS. Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water. *Appl Energy.* 2006;83(3):199–210.
- [59] Ji J, Lu JP, Chow TT, He W, Pei G. A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. *Appl Energy.* 2007;84(2):222–37.
- [60] Assoa YB, Menezo C, Fraisse G, Yezou R, Brau J. Study of a new concept of photovoltaic-thermal hybrid collector. *Sol Energy.* 2007;81(9):1132–43.
- [61] Huang BJ, Lin TH, Hung WC, Sun FS. Performance evaluation of solar photovoltaic/thermal systems. *Sol Energy.* 2001;70(5):443–8.
- [62] Tiwari A, Sodha MS, Chandra A, Joshi JC. Performance evaluation of photovoltaic thermal solar air collector for composite climate of India. *Sol Energy Mater Sol Cell.* 2006;90(2):175–89.
- [63] Tiwari A, Barnwal P, Sandhu GS, Sodha MS. Energy metrics analysis of hybrid - photovoltaic (PV) modules. *Appl Energy.* 2009;86(12):2615–25.
- [64] Raman V, Tiwari GN. Life cycle cost analysis of HPVT air collector under different Indian climatic conditions. *Energy Policy.* 2008;36(2):603–11.
- [65] Joshi AS, Tiwari A. Energy and exergy efficiencies of a hybrid photovoltaic-thermal (PV/T) air collector. *Renew Energy.* 2007;32(13):2223–41.
- [66] Joshi AS, Dincer I, Reddy BV. Thermodynamic assessment of photovoltaic systems. *Sol Energy.* 2009;83(8):1139–49. doi: 10.1016/j.solener.2009.01.011.
- [67] Raman V, Tiwari GN. A comparison study of energy and exergy performance of a hybrid photovoltaic double-pass and single-pass air collector. *Int J Energy Res.* 2009;33:605–17.
- [68] Dubey S, Tiwari GN. Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater. *Sol Energy.* 2008;82(7):602–12.
- [69] Dubey S, Sandhu GS, Tiwari GN. Analytical expression for electrical efficiency of PV/T hybrid air collector. *Appl Energy.* 2009;86(5):697–705. doi: 10.1016/j.apenergy.2008.09.003.
- [70] Dubey S, Solanki SC, Tiwari A. Energy and exergy analysis of PV/T air collectors connected in series. *Energy Build.* 2009;41(8):863–70.
- [71] Solanki SC, Dubey S, Tiwari A. Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. *Appl Energy.* 2009;86(11):2421–8. doi: 10.1016/j.apenergy.2009.03.013.
- [72] Yang T, Athienitis AK. A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. *Renew Sustain Energy Rev.* 2016;66:886–912. doi: 10.1016/j.rser.2016.07.011.
- [73] Bazilian MD, Prasad D. Modelling of a photovoltaic heat recovery system and its role in a design decision support tool for building professionals. *Renew Energy.* 2002;27(1):57–68.
- [74] Cartmell BP, Shankland NJ, Fiala D, Hanby V. A multi-operational ventilated photovoltaic and solar air collector: application, simulation and initial monitoring feedback. *Sol Energy.* 2004;76(1–3):45–53.
- [75] Chow TT, Hand JW, Strachan PA. Building-integrated photovoltaic and thermal applications in a subtropical hotel building. *Appl Therm Eng.* 2003;23(16):2035–49.
- [76] Mei L, Infield D, Eicker U, Fux V. Thermal modelling of a building with an integrated ventilated PV façade. *Energy Build.* 2003;35(6):605–17.
- [77] Crawford RH, Treloar GJ, Fuller RJ, Bazilian M. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. *Renew Sustain Energy Rev.* 2006;10(6):559–75.
- [78] Chow TT, Fong KF, He W, Lin Z, Chan ALS. Performance evaluation of a PV ventilated window applying to office building of Hong Kong. *Energy Build.* 2007;39(6):643–50.
- [79] Mittelman G, Alshare A, Davidson JH. A model and heat transfer correlation for rooftop integrated photovoltaics with a passive air cooling channel. *Sol Energy.* 2009;83(8):1150–60.
- [80] Gan G. Effect of air gap on the performance of building-integrated photovoltaics. *Energy.* 2009;34(7):913–21. doi: 10.1016/j.energy.2009.04.003.
- [81] Piratheepan M, Anderson TN. Performance of a building integrated photovoltaic/thermal concentrator for facade applications. *Sol Energy.* 2017;153:562–73. doi: 10.1016/j.solener.2017.06.006.
- [82] Cappelletti A, Ceccherini L, Reatti A. Integration and architectural issues of a photovoltaic/thermal linear solar concentrator. *Sol Energy.* 2018;169(May):362–73. doi: 10.1016/j.solener.2018.05.013.
- [83] Yang T, Athienitis AK. A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets. *Sol Energy.* 2014;104:82–92. doi: 10.1016/j.solener.2014.01.049.
- [84] Yang T, Athienitis AK. Experimental investigation of a two-inlet air-based building integrated photovoltaic/thermal (BIPV/T) system. *Appl Energy.* 2015;159:70–9. doi: 10.1016/j.apenergy.2015.08.048.
- [85] Ji J, Chow TT, He W. Dynamic performance of hybrid photovoltaic/thermal collector wall in Hong Kong. *Build Env.* 2003;38(11):1327–34.
- [86] Chow TT, He W, Ji J. An experimental study of façade-integrated photovoltaic/water-heating system. *Appl Therm Eng.* 2007;27(1):37–45.
- [87] Chow TT, He W, Chan ALS, Fong KF, Lin Z, Ji J. Computer modeling and experimental validation of a building-integrated photovoltaic and water heating system. *Appl Therm Eng.* 2008;28(11–12):1356–64.
- [88] Chow TT, Chan ALS, Fong KF, Lin Z, He W, Ji J. Annual performance of building-integrated photovoltaic/water-

- heating system for warm climate application. *Appl Energy*. 2009;86(5):689–96. doi: 10.1016/j.apenergy.2008.09.014.
- [89] Agrawal B, Tiwari GN. Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions. *Appl Energy*. 2010;87(2):417–26. doi: 10.1016/j.apenergy.2009.06.011.
- [90] Gaur MK, Tiwari GN. Optimization of number of collectors for integrated PV/T hybrid active solar still. *Appl Energy*. 2010;87(5):1763–72. doi: 10.1016/j.apenergy.2009.10.019.
- [91] Anderson TN, Duke M, Morrison GL, Carson JK. Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. *Sol Energy*. 2009;83(4):445–55. doi: 10.1016/j.solener.2008.08.013.
- [92] Kim JH, Park SH, Kang JG, Kim JT. Experimental performance of heating system with building integrated PVT (BIPVT) collector. *Energy Procedia*. 2014;48:1374–84. doi: 10.1016/j.egypro.2014.02.155.
- [93] Ibrahim A, Fudholi A, Sopian K, Othman MY, Ruslan MH. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. *Energy Convers Manag*. 2014;77:527–34. doi: 10.1016/j.enconman.2013.10.033.
- [94] Chen F, Yin H. Fabrication and laboratory-based performance testing of a building-integrated photovoltaic-thermal roofing panel. *Appl Energy*. 2016;177:271–84. doi: 10.1016/j.apenergy.2016.05.112.
- [95] Vorobiev YV, González-Hernández J, Kribus A. Analysis of potential conversion efficiency of a solar hybrid system with high-temperature stage. *J Sol Energy Eng Trans ASME*. 2006;128(2):258–60.
- [96] Mittelman G, Kribus A, Dayan A. Solar cooling with concentrating photovoltaic/thermal (CPVT) systems. *Energy Convers Manag*. 2007;48(9):2481–90.
- [97] Al-Baali AA. Improving the power of a solar panel by cooling and light concentrating. *Sol Wind Technol*. 1986;3(4):241–5.
- [98] Garg HP, Agarwal RK, Kumar, Bhargava A. The effect of plane booster reflectors on the performance of a solar air heater with solar cells suitable for a solar dryer. *Energy Convers Manag*. 1991;32(6):543–54.
- [99] Tripanagnostopoulos Y, Nousia T, Souliotis M, Yianoulis P. Hybrid photovoltaic/thermal solar systems. *Sol Energy*. 2002;72(3):217–34.
- [100] Tripanagnostopoulos Y, Souliotis M, Battisti R, Corrado A. Energy, cost and LCA results of PV and hybrid PV/T solar systems. *Prog Photovolt Res Appl*. 2005;13(3):235–50.
- [101] Tripanagnostopoulos Y. Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. *Sol Energy*. 2007;81(9):1117–31.
- [102] Tonui JK, Tripanagnostopoulos Y. Air-cooled PV/T solar collectors with low cost performance improvements. *Sol Energy*. 2007;81(4):498–511.
- [103] Tonui JK, Tripanagnostopoulos Y. Performance improvement of PV/T solar collectors with natural air flow operation. *Sol Energy*. 2008;82(1):1–12.
- [104] Seitel SC. Collector performance enhancement with flat reflectors. *Sol Energy*. 1975;17(5):291–5.
- [105] Grassie SL, Sheridan NR. The use of planar reflectors for increasing the energy yield of flat-plate collectors. *Sol Energy*. 1977;19(6):663–8.
- [106] Pancotti L. Optical simulation model for flat mirror concentrators. *Sol Energy Mater Sol Cell*. 2007;91(7):551–9.
- [107] Tanaka H. Solar thermal collector augmented by flat plate booster reflector: Optimum inclination of collector and reflector. *Appl Energy*. 2011;88(4):1395–404. doi: 10.1016/j.apenergy.2010.10.032.
- [108] Tanaka H. Theoretical analysis of solar thermal collector with a flat plate bottom booster reflector. *Energy Sci Technol*. 2011;2(2):26–34. Available from <http://cscanada.net/index.php/est/article/view/2070>.
- [109] Kostić LT, Pavlović TM, Pavlović ZT. Optimal design of orientation of PV/T collector with reflectors. *Appl Energy*. 2010;87(10):3023–9.
- [110] Kostić LT, Pavlović ZT. Optimal position of flat plate reflectors of solar thermal collector. *Energy Build*. 2012;45:161–8.
- [111] Pavlović ZT, Kostić LT. Variation of reflected radiation from all reflectors of a flat plate solar collector during a year. *Energy*. 2015;80:75–84.
- [112] Arata AA, Geddes RW. Combined collector-reflector systems. *Energy*. 1986;11(6):621–30.
- [113] Dang A. Collector, collector-reflector systems-an analytical and practical study. *Energy Convers Manag*. 1986;26(1):33–9.
- [114] Perers B, Karlsson B. External reflectors for large solar collector arrays, simulation model and experimental results. *Sol Energy*. 1993;51(5):327–37.
- [115] Perers B, Karlsson B, Bergkvist M. Intensity distribution in the collector plane from structured booster reflectors with rolling grooves and corrugations. *Sol Energy*. 1994;53(2):215–26.
- [116] Bollentin JW, Wilk RD. Modeling the solar irradiation on flat plate collectors augmented with planar reflectors. *Sol Energy*. 1995;55(5):343–54.
- [117] Kumar R, Kaushik SC, Garg HP. Analytical study of collector solar-gain enhancement by multiple reflectors. *Energy*. 1995;20(6):511–22.
- [118] Ronnelid M, Karlsson B. The use of corrugated booster reflectors for solar collector fields. *Sol Energy*. 1999;65(6):343–51.
- [119] Hussein HMS, Ahmad GE, Mohamad MA. Optimization of operational and design parameters of plane reflector-tilted flat plate solar collector systems. *Energy*. 2000;25(6):529–42.
- [120] Kostic LT, Pavlovic TM, Pavlovic ZT. Influence of reflectance from flat aluminum concentrators on energy efficiency of PV/Thermal collector. *Appl Energy*. 2010;87(2):410–6.
- [121] Kalogirou SA, Tripanagnostopoulos Y. Hybrid PV/T solar systems for domestic hot water and electricity production. *Energy Convers Manag*. 2006;47:3368–82.
- [122] Zhao J. Recent advances of high-efficiency single crystalline silicon solar cells in processing technologies and substrate materials. *Sol Energy Mater Sol Cell*. 2004;82(1–2):53–64.
- [123] Green MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N, Ho-Baillie AWY. Solar cell efficiency tables (Version 55). *Prog Photovolt Res Appl*. 2020;28(1):3–15.
- [124] Hermann AM. Polycrystalline thin-film solar cells – a review. *Sol Energy Mater Sol Cell*. 1998;55(1–2):75–81.
- [125] Yang S, Fu W, Zhang Z, Chen H, Li CZ. Recent advances in perovskite solar cells: Efficiency, stability and lead-free perovskite. *J Mater Chem A*. 2017;5(23):11462–82.

- [126] Eperon GE, Leijtens T, Bush KA, Prasanna R, Green T, Wang JT, et al. Perovskite-perovskite tandem photovoltaics with optimized bandgaps. *Science*. 2016;9717:1–10.
- [127] Zhao D, Yu Y, Wang C, Liao W, Shrestha N, Grice CR, et al. Low-bandgap mixed tin-lead iodide perovskite absorbers with long carrier lifetimes for all-perovskite tandem solar cells. *Nat Energy*. 2017;2(4):1–7.
- [128] Tian X, Stranks SD, You F. Life cycle energy use and environmental implications of high-performance perovskite tandem solar cells. *Sci Adv*. 2020;6(31):eabb0055.
- [129] Saxena P, Gorji NE. COMSOL simulation of heat distribution in perovskite solar cells: Coupled optical-electrical-thermal 3-D analysis. *IEEE J Photovolt*. 2019;9(6):1693–8.
- [130] Ibrahim A, Othman MY, Ruslan MH, Alghoul MA, Yahya M, Zaharim A, et al. Performance of photovoltaic thermal collector (PVT) with different absorbers design. *WSEAS Trans Env Dev*. 2009;5(3):321–30.
- [131] Poredoš P, Tomc U, Petelin N, Vidrih B, Flisar U, Kitanovski A. Numerical and experimental investigation of the energy and exergy performance of solar thermal, photovoltaic and photovoltaic-thermal modules based on roll-bond heat exchangers. *Energy Convers Manag*. 2020;210(February):112674. doi: 10.1016/j.enconman.2020.112674.
- [132] Makki A, Omer S, Sabir H. Advancements in hybrid photovoltaic systems for enhanced solar cells performance. *Renew Sustain Energy Rev*. 2015;41:658–84. doi: 10.1016/j.rser.2014.08.069.
- [133] Duffie J, Beckman WA. *Solar engineering of thermal processes*, 3rd edn. New York: John Wiley & Sons; 2006.
- [134] Chow TT, He W, Ji J. Hybrid photovoltaic-thermosyphon water heating system for residential application. *Sol Energy*. 2006;80(3):298–306.
- [135] Dubey S, Tiwari GN. Analysis of PV/T flat plate water collectors connected in series. *Sol Energy*. 2009;83(9):1485–98. doi: 10.1016/j.solener.2009.04.002.
- [136] Tiwari A, Dubey S, Sandhu GS, Sodha MS, Anwar SI. Exergy analysis of integrated photovoltaic thermal solar water heater under constant flow rate and constant collection temperature modes. *Appl Energy*. 2009;86(12):2592–7. doi: 10.1016/j.apenergy.2009.04.004.
- [137] Shyam, Tiwari GN, Fischer O, Mishra RK, Al-Helal, IM. Performance evaluation of N-photovoltaic thermal (PVT) water collectors partially covered by photovoltaic module connected in series: An experimental study. *Sol Energy*. 2016;134:302–13. doi: 10.1016/j.solener.2016.05.013.
- [138] ShyamTiwari, GN, Al-Helal IM. Analytical expression of temperature dependent electrical efficiency of N-PVT water collectors connected in series. *Sol Energy*. 2015;114:61–76. doi: 10.1016/j.solener.2015.01.026.
- [139] Chow TT, Pei G, Fong KF, Lin Z, Chan ALS, Ji J. Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover. *Appl Energy*. 2009;86(3):310–6. doi: 10.1016/j.apenergy.2008.04.016.
- [140] Chow TT, Ji J. Environmental life-cycle analysis of hybrid solar photovoltaic/thermal systems for use in Hong Kong. *Int J Photoenergy*. 2012;2012:101968.
- [141] Sun LL, Li M, Yuan YP, Cao XL, Lei B, Yu NY. Effect of tilt angle and connection mode of PVT modules on the energy efficiency of a hot water system for high-rise residential buildings. *Renew Energy*. 2016;93:291–301.
- [142] Shan F, Cao L, Fang G. Dynamic performances modeling of a photovoltaic-thermal collector with water heating in buildings. *Energy Build*. 2013;66:485–94. doi: 10.1016/j.enbuild.2013.07.067.
- [143] Nahar A, Hasanuzzaman M, Rahim NA. Numerical and experimental investigation on the performance of a photovoltaic thermal collector with parallel plate flow channel under different operating conditions in Malaysia. *Sol Energy*. 2017;144:517–28. doi: 10.1016/j.solener.2017.01.041.
- [144] Nahar A, Hasanuzzaman M, Rahim NA. A three-dimensional comprehensive numerical investigation of different operating parameters on the performance of a photovoltaic thermal system with pancake collector. *J Sol Energy Eng Trans ASME*. 2017;139(3):031009.
- [145] Nahar A, Hasanuzzaman M, Rahim NA, Parvin S. Numerical investigation on the effect of different parameters in enhancing heat transfer performance of photovoltaic thermal systems. *Renew Energy*. 2019;132:284–95. doi: 10.1016/j.renene.2018.08.008.
- [146] Rahman MM, Hasanuzzaman M, Rahim NA. Effects of operational conditions on the energy efficiency of photovoltaic modules operating in Malaysia. *J Clean Prod*. 2017;143:912–24.
- [147] Nasrin R, Hasanuzzaman M, Rahim NA. Effect of high irradiation and cooling on power, energy and performance of a PVT system. *Renew. Energy*. 2018;116:552–69.
- [148] Sakellariou E, Axaopoulos P. Simulation and experimental performance analysis of a modified PV panel to a PVT collector. *Sol Energy*. 2017;155:715–26. doi: 10.1016/j.solener.2017.06.067.
- [149] Hocine HBCel, Touafek K, Kerrou F, Haloui H, Khelifa A. Model validation of an empirical photovoltaic thermal (PV/T) collector. *Energy Procedia*. 2015;74:1090–9. doi: 10.1016/j.egypro.2015.07.749.
- [150] Touafek K, Khelifa A, Adouane M. Theoretical and experimental study of sheet and tubes hybrid PVT collector. *Energy Convers Manag*. 2014;80:71–7. doi: 10.1016/j.enconman.2014.01.021.
- [151] Khelifa A, Touafek K, Ben Moussa H, Tabet I. Modeling and detailed study of hybrid photovoltaic thermal (PV/T) solar collector. *Sol Energy*. 2016;135:169–76. doi: 10.1016/j.solener.2016.05.048.
- [152] Pierrick H, Christophe M, Leon G, Patrick D. Dynamic numerical model of a high efficiency PV-T collector integrated into a domestic hot water system. *Sol Energy*. 2015;111:68–81.
- [153] Aste N, Leonforte F, Del Pero C. Design, modeling and performance monitoring of a photovoltaic-thermal (PVT) water collector. *Sol Energy*. 2015;112:85–99.
- [154] Aste N, Del Pero C, Leonforte F, Manfren M. Performance monitoring and modeling of an uncovered photovoltaic-thermal (PVT) water collector. *Sol Energy*. 2016;135:551–68.
- [155] Aste N, Del Pero C, Leonforte F. Water PVT collectors performance comparison. *Energy Procedia*. 2017;105:961–6. doi: 10.1016/j.egypro.2017.03.426.
- [156] De Keizer C, De Jong M, Mendes T, Katiyar M, Folkerts W, Rindt C, et al. Evaluating the thermal and electrical

- performance of several uncovered PVT collectors with a field test. *Energy Procedia*. 2016;91(0):20–6. doi: 10.1016/j.egypro.2016.06.166.
- [157] Katiyar M, van Balkom M, Rindt CCM, de Keizer C, Zondag HA. Numerical model for the thermal yield estimation of unglazed photovoltaic-thermal collectors using indoor solar simulator testing. *Sol Energy*. 2017;155:903–19. doi: 10.1016/j.solener.2017.07.012.
- [158] Guarracino I, Freeman J, Ramos A, Kalogirou SA, Ekins-Daukes NJ, Markides CN. Systematic testing of hybrid PV-thermal (PVT) solar collectors in steady-state and dynamic outdoor conditions. *Appl Energy*. 2019;240(November 2018):1014–30. doi: 10.1016/j.apenergy.2018.12.049.
- [159] Yu Y, Long E, Chen X, Yang H. Testing and modelling an unglazed photovoltaic thermal collector for application in Sichuan Basin. *Appl Energy*. 2019;242(November 2018):931–41. doi: 10.1016/j.apenergy.2019.03.114.
- [160] Yu Y, Yang H, Peng J, Long E. Performance comparisons of two flat-plate photovoltaic thermal collectors with different channel configurations. *Energy*. 2019;175:300–8.
- [161] Yazdanifard F, Ebrahimnia-Bajestan E, Ameri M. Investigating the performance of a water-based photovoltaic/thermal (PV/T) collector in laminar and turbulent flow regime. *Renew Energy*. 2016;99:295–306. doi: 10.1016/j.renene.2016.07.004.
- [162] Kim JH, Kim JT. Comparison of electrical and thermal performances of glazed and unglazed PVT collectors. *Int J Photoenergy*. 2012;2012:ID 957847.
- [163] Kazemian A, Hosseinzadeh M, Sardarabadi M, Passandideh-Fard M. Effect of glass cover and working fluid on the performance of photovoltaic thermal (PVT) system: An experimental study. *Sol Energy*. 2018;173(June 2017):1002–10.
- [164] Lämmle M, Thoma C, Hermann MA. PVT collector concept with variable film insulation and low-emissivity coating. *Energy Procedia*. 2016;91:72–7. doi: 10.1016/j.egypro.2016.06.174.
- [165] Herrando M, Ramos A, Zabalza I, Markides CN. A comprehensive assessment of alternative absorber-exchanger designs for hybrid PVT-water collectors. *Appl Energy*. 2019;235(November 2018):1583–602. doi: 10.1016/j.apenergy.2018.11.024.
- [166] Pang W, Zhang Y, Duck BC, Yu H, Song X, Yan H. Cross sectional geometries effect on the energy efficiency of a photovoltaic thermal module: Numerical simulation and experimental validation. *Energy*. 2020;209:118439. doi: 10.1016/j.energy.2020.118439.
- [167] Kazem HA. Evaluation and analysis of water-based photovoltaic/thermal (PV/T) system. *Case Stud Therm Eng*. 2019;13(January):100401. doi: 10.1016/j.csite.2019.100401.
- [168] Hossain MS, Pandey AK, Selvaraj J, Abd Rahim N, Rivai A, Tyagi VV. Thermal performance analysis of parallel serpentine flow based photovoltaic/thermal (PV/T) system under composite climate of Malaysia. *Appl Therm Eng*. 2019;153(January):861–71. doi: 10.1016/j.applthermaleng.2019.01.007.
- [169] Abdul-Ganiyu S, Quansah DA, Ramde EW, Seidu R, Adaramola MS. Investigation of solar photovoltaic-thermal (PVT) and solar photovoltaic (PV) performance: A case study in Ghana. *Energies*. 2020;13:11.
- [170] Hazi A, Hazi G, Grigore R, Vernica S. Opportunity to use PVT systems for water heating in industry. *Appl Therm Eng*. 2014;63(1):151–7. doi: 10.1016/j.applthermaleng.2013.11.010.
- [171] Wang K, Herrando M, Pantaleo AM, Markides CN. Thermoeconomic assessment of a PV/T combined heating and power system for University Sport Centre of Bari. *Energy Procedia*. 2019;158:1229–34. doi: 10.1016/j.egypro.2019.01.312.
- [172] Herrando M, Markides CN. Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations. *Appl Energy*. 2016;161:512–32.
- [173] Herrando M, Ramos A, Zabalza I. Cost competitiveness of a novel PVT-based solar combined heating and power system: Influence of economic parameters and financial incentives. *Energy Convers Manag*. 2018;166(March):758–70.
- [174] Brinkley J, Jiang L, Widyolar B, Hota SK, Bhusal Y, Diaz G, et al. Thermal, electrical, and cost study of advanced optical photovoltaic thermal system (ADOPTS). *Appl Energy*. 2020;269(August 2019):115105. doi: 10.1016/j.apenergy.2020.115105.
- [175] Mellor A, Alonso Alvarez D, Guarracino I, Ramos A, Riverola Lacasta A, Ferre, et al. Roadmap for the next-generation of hybrid photovoltaic-thermal solar energy collectors. *Sol Energy*. 2018;174(September):386–98. doi: 10.1016/j.solener.2018.09.004.