A review on hybrid photovoltaic/thermal collectors and systems

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Abstract

In this paper, a thorough review of the available literature on photovoltaic/thermal (PV/T) systems is presented. The review is performed in a thematic way in order to allow an easier comparison, discussion and evaluation of the findings obtained by researchers, especially on parameters affecting the electrical and thermal performance of PV/T systems. The review covers a comprehensive historic overview of PV/T technology, detailed description of conventional flat-plate and concentrating PV/T systems, analysis of PV/T systems using water or air as the working fluid, analytical and numerical models, simulation and experimental studies, thermodynamic assessment of PV and PV/T systems and qualitative evaluation of thermal and electrical outputs. Furthermore, parameters affecting the performance of PV/T systems such as glazed versus unglazed PV/T collectors, optimum mass flow rate, packing factor, configuration design types and absorber plate parameters including tube spacing, tube diameter and fin thickness are extensively analyzed. Based on the thorough review, it can be easily said that the PV/T systems are very promising devices and PV/T technology is expected to become strongly competitive with the conventional power generation in the near future.

Keywords: photovoltaic; thermal; performance; efficiency

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1 INTRODUCTION

Energy is a thermodynamic quantity that is often understood as the capacity of a physical system to do work. Besides its physical meaning, energy is vital for our relations with the environment. Since life is directly affected by energy and its consumption, research to resolve problems related to energy is quite important [1]. Energy resources based on fossil fuels are still dominant with the highest share in global energy consumption but clean energy generation becomes increasingly crucial due to the growing significance of environmental issues. A strong stimulation of research into renewable energy technologies is observed because of the recent sharp increases in oil prices. At present, renewable energy resources supply 13.3% of the world’s primary energy needs and their future potential is notable [2]. Among the clean energy technologies, solar power is a key item since it provides an unlimited, clean and environmentally friendly energy [3–5]. Moreover, the other forms of renewable energy primarily depend on the incoming solar radiation. The Earth absorbs $\sim 3.85$ million EJ of solar energy per year [6]. Hybrid photovoltaic/thermal (PV/T) systems are quite attractive in order to harness the available solar energy resource at a particular location. A PV/T collector is a combination of photovoltaic (PV) and thermal (T) components and it enables to produce both electricity and heat simultaneously. PV/T collectors produce more energy per unit surface area than side-by-side PV modules and solar thermal collectors [7]. Therefore, these systems are especially appropriate for the applications where the available surface area is limited. Research performed by ECN (Energy Research Centre of the Netherlands) indicates that it is possible to reduce the collector area almost 40% by using PV/T collectors instead of separate systems [8]. PV/T systems are reliable and work on a noiseless environment [9]. Furthermore, life span of these systems is around 20–30 years and maintenance costs are negligible. Depending on these attractive features and the impressive growth in the PV solar electricity industry [10], PV/T technology is expected to expand significantly in the near future.

A significant amount of research on the concept of PV/T has been carried out for more than three decades by many researchers both experimentally and numerically. In this study, a thorough review of the available literature on performance
analysis of PV/T collectors is done. Appropriate recommendations are made in order to enhance PV/T performance and future potential of PV/T technology is evaluated.

2 HISTORY OF PV AND PV/T TECHNOLOGY

The history of PVs goes back to the nineteenth century. In 1839, French physicist Becquerel discovered the photogalvanic effect in liquid electrolytes allowing light–electricity conversion [11]. The photoconductivity of solid selenium was found by Smith in 1873. Then, Adams and Day discovered the photogeneration of current in selenium tubes in 1876. In 1900, Planck presented the quantum nature of light. Thereafter, Wilson proposed the quantum theory of solids in 1930. After a decade, Mott and Schottky developed the theory of solid-state rectifier [12]. In 1954, Chapin et al., while working on silicon semiconductors, developed the first high-power silicon PV cell achieving 6% efficiency, and after 4 years, these PV cells were used to power radios on the Vanguard I space satellite [13]. Sharp Corporation developed the first efficient PV module from silicon PV cells in 1963. After the OPEC oil embargo in 1973, resulting in a massive increase in oil prices, many governments created a strong stimulation of research into renewable energy including PVs [14]. As a result of the intensive efforts, terrestrial applications of PV technology became widespread in the 1970s. In the same decade, researchers discovered the PV/T concept and the first projects concerning the PV/T collectors were launched. In 1973, Boer and Tamm [15] proposed the first work on the air-type PV/T systems which was called Solar One House. It was the first house which enables to directly convert sunlight into both electricity and heat for domestic use. The liquid-type PV/T collectors were first investigated by Wolf [16] in 1976. He analyzed the performance of a combined solar PV and heating system for a single-family residence over a full year. Ventilated PV façades started to become important in the early 1990s and especially in Switzerland several projects were carried out on building-integrated PVs (BIPV) [17, 18]. In recent years, extensive researches have been carried out all over the world to improve the PV/T performance and reduce the cost. Today, PV/T technology is very promising with its potential in order to narrow the gap between renewable and conventional power sources.

3 PV/T COLLECTORS

Hybrid PV/T collectors are very useful devices which enable to produce electricity and heat simultaneously as shown in Figure 1. Simply, PV/T systems consist of PV modules coupled to heat extraction units [19]. Although PV modules convert sunlight directly into electricity, most of the absorbed solar radiation is dumped to the PV modules as waste heat. The heat generated is transferred to the heat exchanger in thermal contact with PV modules in order to supply the heat demand [20]. PV/T collectors can be designed as flat-plate or concentrating and are classified according to the type of heat-removal fluid used.

3.1 Flat-plate PV/T collectors


Flat-plate PV/T collectors can be categorized according to the type of working fluid used: water type, air type or combined (water/air) type flat-plate PV/T collectors. Zondag et al. [24] analyzed the different types of PV/T collectors (sheet and tube, channel, free flow and dual absorber) as shown in Figure 2. The best efficiency was observed for the channel-below-transparent-PV design. Air PV/T collectors are not efficient enough compared with the liquid ones. Although the manufacturing costs of air PV/T collectors are quite low, their applications are relatively few [25].

Flat-plate PV/T collectors can be utilized as either grid-connected or standalone systems. Talavera et al. [26] presented a study to estimate the internal rate of return of PV systems and indicated that grid-connected systems are more profitable investments when some economic conditions are met.

3.2 Concentrating PV/T collectors

In spite of the considerable developments in PV technology, the cost of electricity produced by PV modules is still much more expensive than conventional power [27]. Concentrating sunlight is a key technique in order to reduce the system cost. By concentrating, the area of the PV modules required decreases, and therefore payback time becomes shorter. However, PV module temperature increases with concentration and it should be kept as low as possible in order to achieve higher efficiency [28]. Effects of temperature on performance parameters of PV modules are well documented in the literature [29–33].

Figure 1. Comparison of PV, thermal and hybrid PV/T systems.
Concentrating PV and/or PV/T systems can be classified with respect to the concentration ratio (CR). Winston [34] proposed a new principle for collecting and concentrating solar energy. He underlined that concentrating systems with $CR > 2.5$ should use a system to track the sun, whereas for systems with $CR < 2.5$, stationary concentrating devices can be utilized. Sharan et al. [35] carried out an analysis for the economic evaluation of concentrator-PV systems. Their results indicated that the cost of unit of energy produced by the concentrator PV systems decreases with increasing CR if both electrical and thermal outputs are collected for useful purposes. Al-Baali [36] investigated the effects of illumination intensity and temperature on the performance characteristics of a solar panel. A reflecting mirror was utilized in order to concentrate sunlight on the panel surface and thus to enhance the current parameters. Garg et al. [37] presented a theoretical study to analyze the effects of plane reflectors on the performance of an air PV/T system. Performance of the system was determined for various combinations of reflectors. They recommend that the system cost can be reduced by replacing expensive PV cells with low-cost concentration devices. Garg and Adhikari [38] investigated an air PV/T collector coupled with a compound parabolic concentrator (CPC). They observed that concentrating PV/T collectors provide higher efficiency compared with the systems without a CPC. Brogren et al. [39] analyzed the optical efficiency of a water-cooled hybrid PV/T system with a low-concentrating aluminum CPC. The optical efficiency of the system was determined numerically as $\eta_{opt} = 0.71$ which is in agreement with the efficiency obtained from the measurements. A simple low-concentrating water-type building-integrated PV/T (BIPVT) collector was investigated by Brogren and Karlsson [40]. It is emphasized that the cost of PV electricity can be reduced by using cheap aluminum reflectors. Coventry [41] developed a water-type PV/T collector with a geometric CR of 37 which is called as CHAPS (combined heat and power solar). Thermal and electrical efficiencies of the system were determined to be 58 and 11%, respectively. Rosell et al. [42] investigated a water PV/T collector integrated with a linear Fresnel concentrator and a two-axis solar tracking system. Experimental results indicate that the total efficiency of the system is over 60% when $CR > 6$. Theoretical analysis confirms that thermal conduction between PV cells and the absorber plate is a crucial parameter. Kostic et al. [43] determined the optimal position of reflectors coupled to a water PV/T collector in order to obtain maximum concentration of illumination intensity. Li et al. [44] recently examined the performance of a trough concentrating PV/T system with an energy flux ratio 10.27 using three types of crystal silicon PV cell arrays and the GaAs cell array. The experimental results indicate that the electrical performance of the system with the GaAs cell array is better than that of crystal silicon PV cell arrays. On the other hand, the system with crystal silicon PV cell arrays shows better performance in terms of the thermal output. Kostic et al. [45] investigated the effects of reflectance from flat-plate concentrators made of Al sheet and Al foil on energy efficiency of a PV/T collector. The concentrators made of Al foil provide higher concentrated solar radiation intensity. For the optimal position of concentrators, the total daily thermal output produced by the PV/T system with concentrators made of Al foil is 55% higher than the system without a concentrator. In terms of the electrical output, the same system is 17.1% more efficient compared with the system without a concentrator.

An optimization of reflector and module geometries for static, low-concentrating façade-integrated PV systems was carried out by Gajbert et al. [46]. The maximum annual
electricity production was determined to be 120 kW h/m² PV cell area, using the MINSUN simulation program and measurement data. This result was obtained for the system with a geometric CR of 4.65, a module tilt angle of −15° and a tilt of the optical axis of 35°. The determined annual electricity production is 72% higher than that of the vertical reference module, which would produce 70 kW h/m² PV cell area. Similar asymmetric concentrating collector systems for façade integration have been investigated in the literature [47–49]. Nilsson et al. [50] investigated the electrical and thermal characterizations of an asymmetric CPC PV/T system designed for high latitudes. The output estimates were determined using the MINSUN simulation program. Two different reflector materials were used in the study: anodized aluminum and aluminum-laminated steel. The simulation results showed that there is no difference in the annual output between the two reflector materials. Both back reflectors deliver 168 kW h/m² PV cell area of electricity compared with 136 kW h/m² PV cell area for the case without reflectors. The estimated output of thermal energy is 145 kW h/m² glazed area at 50°C. Hatwamaamo et al. [51] analyzed the three reflector materials for fill factor improvements in a low–concentrating PV system: anodized aluminum, rolled aluminum foil and miro reflectors. The CPC element with a geometric CR of 3.6 was examined for different reflector materials. It was observed that the fill factors decreased from 0.72 for the reference module to 0.65 under concentration. The rolled aluminum reflector did not perform as expected in the fill factor enhancements. However, it is emphasized that the rolled aluminum reflector has a notable potential for use as the PV-CPC reflector for cost reduction. The cost of rolled aluminum is two or three times less than that of anodized aluminum and six times less than that of the miro reflector per square-meter. Solanki et al. [52] developed a V-trough PV module for better concentration and heat dissipation as shown in Figure 3. The V-trough channels were constructed using a thin single Al metal sheet. Six PV module strips each containing a single row of six mono-crystalline silicon (c-Si) cells were fabricated and mounted in six V-trough channels to achieve concentration. Experimental results indicated that the cell temperature in the V-trough module remains nearly same as that in a flat-plate PV module, despite light concentration. Conversion efficiency of the V-trough PV module is 17.1% which is 62% higher than the flat-plate PV module.

3.3 Water PV/T collectors

The first works on water PV/T collectors were performed by Kern and Russell [21, 53] at MIT in 1978. Five hybrid solar heating and cooling system configurations (baseline solar heating system, parallel heat pump system, series heat pump system, absorption-cycle chiller and high-performance series advanced heat pump) were analyzed, and the merits of these systems were assessed for four climatic regions (Boston, Miami, Phoenix and Ft. Worth) in the USA. The results indicated that the greatest energy savings potential in all four geographic areas was provided by an advanced heat pump system. Economic analysis showed that the hybrid systems were quite effective in northern climates dominated by high-heat demands. On the other hand, for the regions with balanced heating and cooling loads or with dominant cooling loads, PV systems appeared to be most economical. Hendrie and Raghuraman [54] carried out the detailed performance testing of a hybrid PV/T collector. The experiments were performed outdoors for varying inlet fluid temperature and climatic conditions. Maximum thermal efficiency of the system was determined to be 42.6%. The heat loss coefficient and the efficiency were calculated to be 6.77 W/m² K and 0.62, respectively. Lalovic [55] developed and tested an amorphous silicon (a-Si) PV/T collector. The a-Si PV cells used in the study had an average efficiency of 4% and a total area of 0.9 m². Experimental results showed that the hybrid PV/T collector performed well as a thermal collector which enabled to heat water up to 65°C. On the contrary, the electrical performance of the system did not demonstrate a notable change. In the early 1990s, many researchers attempted to enhance the hybrid water PV/T collectors [56–60].

Bergene and Lovvik [61] presented a detailed model in order to predict the performance of water-type PV/T collectors. They recommended that the system they proposed might be useful particularly to preheat the domestic hot water. At the Indian Institute of Technology, several researches were carried out on hybrid PV/T solar water heaters [62–64]. It was observed that the amount of water in the tank had a significant effect on the system performance. The cell efficiency showed a slight increase with increasing water mass [62]. They also emphasized that the hybrid PV/T solar water heaters would be suitable for rural areas since a PV/T collector of ~2 m² can generate sufficient electricity to run two tube lights of 20 W each for 5 h and one television of 30 W for 4 h [64].
Fujisawa and Tani [65] designed and constructed a hybrid PV/T collector which consisted of a liquid heating flat-plate solar collector with mono-c-Si PV cells on substrate of the non-selective aluminum absorber plate as shown in Figure 4. Exergy analysis was used in order to analyze the performance of the PV/T collector since it provides a qualitative evaluation of electrical and thermal energies produced. They found that the coverless PV/T collector showed the best performance. They also observed that the performance of the single-covered PV/T collector was comparable with that of the conventional flat-plate collector. Al Harbi et al. [66] carried out an experiment in Saudi Arabian environmental conditions in order to evaluate the performance of hybrid PV/T systems. They concluded that the PV/T system is not suitable to the climatic conditions of Saudi Arabia because of the high ambient temperature in summer. Huang et al. [67, 68] worked on unglazed PV/T collectors at the National University of Taiwan. Their PV/T collector consisted of a 60-W commercial PV module and a heat-collecting plate as shown in Figure 5. Two types of tube-in-sheet heat-collecting plates with \( W/D = 6.2 \) and 10 were used in the study [67]. However, the performance of the PV/T collector with the prescribed heat-collecting plates was not found satisfactory. They thus decided to build a poly-carbonate multichannel structure with \( W/D = 1 \). Experimental results indicated that the PV/T collector made from a corrugated polycarbonate panel shows a good thermal performance. The temperature difference between the water in the tank and the PV module was determined to be 4°C [68].

Kalogirou [69] modeled a hybrid PV/T system for the environmental conditions of Cyprus. The PV system consisted of a series of PV panels, a battery bank and an inverter, whereas the thermal system composed of a hot water storage cylinder, a pump and a thermostat. The simulation results showed that the hybrid PV/T system increases the mean annual efficiency of the PV system from 2.8 to 7.7% and supplies 49% of the hot water demand of a house. Norton et al. [70] presented alternative approaches for performance analysis and characterization of the thermosyphon solar water heaters.

Sandnes and Rekstad [71, 72] investigated the behavior of a hybrid water PV/T collector which was built by pasting single-crystal silicon PV cells on a polymer thermal absorber. The channels of the absorber plate were filled with ceramic granulates to enhance the heat transfer to the working fluid. The results showed that the PV cells and the glass cover reduce the thermal absorption and the optical efficiency, respectively. They recommended that the prescribed design should be used for low-temperature applications in order to improve the electrical efficiency of the PV system.

Zondag et al. [73] proposed several steady-state and dynamic simulation models for water PV/T collectors. They observed that the all models follow the experiments within 5% accuracy. For the calculation of the daily yield, the simple one-dimensional (1D) steady-state model performed almost as good as the much more time-consuming 3D dynamical model. They also concluded that the 2D and 3D models provide more detailed information for design improvement. Chow [74] proposed an explicit dynamic model based on the control-volume finite-difference approach for a single-glazed flat-plate water PV/T collector. The introduced model enabled to generate results for the performance assessment of the PV/T collector including instantaneous energy outputs.

Kalogirou and Tripanagnostopoulos [75] investigated the performance of a hybrid PV/T thermosyphon system for three different climates: Nicosia (Cyprus), Athens (Greece) and Madison (Wisconsin). The system consisted of a glazed flat-plate PV/T collector with a surface area of \( 4 \text{ m}^2 \) and a 160-l hot water storage tank as shown in Figure 6. Both polycrystalline and a-Si PV cells were evaluated in the study. The simulation results showed that the electrical yield of the system, employing polycrystalline silicon (pc-Si) PV cells, is 532, 515 and 499 kWh for the three locations, respectively. On the other hand, the results for the system employing a-Si PV cells are 260, 251 and 224 kWh. They noted that a non-hybrid PV system can generate 30% more electrical energy but they underlined that the hybrid PV/T system enables to supply a large percentage of the hot water demand of a house.

Tiwari and Sodha [76] developed their previous thermal models of integrated PV and thermal solar (IPVTS) system [77] for parametric studies and for comparison of the hybrid water and air PV/T collectors. An analytical expression for the water and the PV cell temperature and an overall thermal efficiency of the IPVTS system were derived as a function of climatic and design parameters. Four configurations, namely (a) unglazed with tedlar (UGT), (b) glazed with tedlar (GT), (c) unglazed without tedlar (UGWT) and (d) glazed without tedlar (GWT) were considered in the study. They concluded that the characteristic daily efficiency of the IPVTS system with water is higher than with air for all configurations except GWT. They also determined the overall thermal efficiency of IPVTS system to be 65 and 77% for summer and winter conditions, respectively.

At the City University of Hong Kong, Chow et al. [78–80] constructed a thermosyphon PV/T system for residential application and examined its energy performance. The absorber plate was built from a multiple of extruded aluminum alloy box-structure modules. Flat-box absorber and the other constituent layers of the PV/T collector are illustrated in Figure 7. The results show that the prescribed system is capable of extending the PV application potential in the domestic sector. He et al. [81] constructed and tested an aluminum-alloy flat-box type hybrid PV/T collector functioned as a thermosyphon system. The test results indicated that the daily thermal efficiency can reach around 40% when the initial water temperature in the system is the same as the daily mean ambient temperature.

Zakharchenko et al. [82] investigated a hybrid PV/T system with very low packing factor. Different kinds of PV panel materials such as c-Si, a-Si and CuInSe₂ were analyzed in the study. In addition, different materials and constructions were evaluated for a better thermal contact between the PV panel
and the collector. It was observed that the commercial PV panels were unable to provide a good thermal contact with the heat collector due to the poor thermal conductivity of the panel substrate material. Therefore, a prototype PV panel was constructed using metallic substrate with a thin insulating layer. It was noted that the power output of the PV panel increased 10% with the new design.

At the University of Patras, Kalogirou and Tripagnostopoulos [83] presented the simulation results of hybrid PV/T systems for domestic hot water applications. pc-Si and a-Si PV modules integrated with water heat extraction units were tested with respect to their electrical and thermal efficiencies. The simulation study was carried out for three locations: Nicosia, Athens and Madison. The results showed that the electrical production of the system employing pc-Si PV cells is higher than that employing amorphous ones, but the solar thermal contribution is slightly lower. Although a non-hybrid PV system produces 38% more electrical energy, it is emphasized that the hybrid PV/T system enables to supply a large percentage of the hot water demands of the buildings considered.

Ji et al. [84] designed, constructed and tested a flat-box aluminum-alloy water PV/T system in a moderate climate zone. The experiments were carried out for different water masses and initial water temperatures. Packing factor and front-glazing emissivity of the system were 0.63 and 0.83, respectively. The daily electrical efficiency, the characteristic daily thermal efficiency, the characteristic daily total efficiency and the characteristic daily primary-energy saving were determined to be \( \approx 10.15\), 45, 52 and 65%, respectively. Saitoh et al. [85] experimentally investigated the performance of a hybrid sheet-and-tube PV/T collector which uses brine as the coolant. The efficiency of the hybrid PV/T collector was compared with those of a PV and a solar collector. It was observed that the PV/T collector is better in terms of exergy efficiency. A theoretical study of a hybrid PV/T system for domestic heating and cooling was performed by Vokas et al. [86]. The performance

![Cross-section of the PV/T collector](https://academic.oup.com/ijlct/article-abstract/6/3/212/681067/1)

Figure 4. Cross-section of the PV/T collector [9, 65].

![Schematic diagram of a hybrid water PV/T collector](https://academic.oup.com/ijlct/article-abstract/6/3/212/681067/2)

Figure 5. Schematic diagram of a hybrid water PV/T collector [9, 68].
of the PV/T collector with respect to the variation of the geographical region as well as to different total surface areas of the system was analyzed. It was noted that the percentage of the domestic heating and cooling load covered by the conventional system decreases 11.9 and 21.4%, respectively, in the case of the hybrid PV/T system. The results also indicated that the percentage of solar coverage of the domestic heating and cooling load is considerably affected by the region. At the University of Science and Technology of China, Ji et al. [87] presented the findings of the effect of water-flow channel dimensions on the performance of a box-frame hybrid PV/T collector. Dynamic simulation results showed that both the number and the height of the water-flow channels notably affect the PV/T performance. Chow et al. [88] studied the performance of a PV/T thermosyphon system for subtropical climate application. A dynamic simulation model was developed in order to predict the energy output and the payback period of the system. The numerical results showed that the payback period of the PV/T system is much shorter than the non-hybrid PV system.

Dubey and Tiwari [89] designed, constructed and tested a hybrid PV/T collector for the environmental conditions of New Delhi. An analytical expression for the characteristic equation of the hybrid flat-plate PV/T collector was derived and experimentally validated for various configurations. Two flat-plate collectors with each having a surface area of 2.16 m² were connected in series and a PV module with an effective area of 0.66 m² was integrated at the bottom of one of the collectors. The cross-sectional view of the system is shown in Figure 8. The experiments were performed during February–April 2007. The results indicated that the hybrid flat-plate PV/T collector partially covered with a PV module shows better performance in terms of thermal and average cell efficiency. Fraisse et al. [90] studied the energy performance of a hybrid water PV/T collector combined with a Direct Solar Floor (DSF). They pointed out that the low operating temperature requirement of the DSF system is quite suitable for the application of the hybrid water PV/T collector [91]. For the system including a glass covered collector, the annual PV cell efficiency was determined to be 6.8% which represents a decrease of 28% in comparison with a non-hybrid PV module of 9.4% annual efficiency. This decrease arises from the temperature increase related to the cover. On the other hand, it was observed that the system without cover shows 6% better performance because of the cooling effect.

Dubey and Tiwari [92] evaluated the performance of partially covered hybrid flat-plate PV/T collectors connected in series using theoretical modeling. Basic energy balance equations and computer-based thermal models were used to derive suitable analytical expressions. Four weather conditions for five different cities of India (New Delhi, Bangalore, Mumbai, Srinagar and Jodhpur) were considered in the study. Annual thermal and electrical energy yield was
evaluated for four different series and a parallel combination of collectors for comparison purpose considering New Delhi conditions. It was observed that the collectors partially covered by a PV module combines the production of hot water and electricity generation, and it is recommended for the consumers whose primary requirement is hot water production. However, collectors fully covered by a PV module are suggested for the consumers whose primary demand is electricity generation.

Chow et al. [93] investigated the appropriateness of glass cover on a thermosyphon-based water PV/T system from the viewpoint of thermodynamics. The influences of six selected operating parameters were considered in the study. It was observed that the glazed PV/T system is always suitable in order to maximize the quantity of either the thermal or the overall energy output. From the exergy analysis point of view, the increase in PV cell efficiency, packing factor and wind velocity was found favorable for an unglazed system, whereas the increase in illumination intensity and ambient temperature was favorable for a glazed system.

Tiwari et al. [94] obtained an analytical expression for the water temperature of an IPVTS water heater under a constant flow rate hot water withdrawal. Analysis was based on the basic energy balance for a hybrid flat-plate collector and a storage tank, respectively. Numerical computations were performed for the design and the climatic parameters of the system developed by Huang et al. [68]. It was found that the daily overall thermal efficiency of the IPVTS system increases with increasing constant flow rate and decreases with increasing constant collection temperature. It was also observed that the overall exergy and the thermal efficiency of the system is maximum at the hot water withdrawal flow rate of 0.006 kg/s.

Chow et al. [95] investigated the annual performance of a building-integrated water PV/T system for the environmental conditions of Hong Kong. The results showed that the PV/water-heating system has much economical advantages over the conventional non-hybrid PV installation. The thermal performance of the system under natural water circulation was found better than the pump-circulation mode. The payback period of the system was determined to be 14 years when serving as a water pre-heater.

Dubey and Tiwari [96] evaluated the overall thermal energy and exergy provided in the form of heat and electricity from a hybrid PV/T water-heating system considering five different cases with and without withdrawals. Four types of weather conditions for five different cities of India (New Delhi, Bangalore, Mumbai, Srinagar and Jodhpur) were considered in the study. It was observed that the annual maximum and minimum energy gains and efficiency are obtained for Jodhpur and Srinagar, respectively. It was also noted that the hybrid PV/T system analyzed in the study is very useful for the remote and urban areas.

Touafek et al. [97] proposed a new hybrid PV/T collector on the basis of a new approach of design, which aims to increase the energy effectiveness of electrical and thermal conversion with the lowest cost compared with the conventional hybrid collector. The experimental results, approximately similar to the theoretical ones, showed that the thermal performance of the new hybrid PV/T collector is better than the classic hybrid collectors. It was also emphasized that the new PV/T configuration is a good alternative to the side-by-side PV module and the solar thermal collector.

Daghigh et al. [98] investigated the performance of a-Si- and c-Si-based building-integrated PV/T collectors for the...
climatic conditions of Malaysia. At a flow rate of 0.02 kg/s, a
illumination intensity level between 700 and 900 W/m² and an
ambient temperature between 22 and 32°C, the electrical,
thermal and combined efficiencies of the a-Si PV/T collector
were determined to be 4.9, 72 and 77%, respectively. On the
other hand, those efficiencies for the c-Si PV/T collector were
11.6, 51 and 63%, respectively.

3.4 Air PV/T collectors
As reported by Zondag [14], the first work on air PV/T collect-
ors which was called as Solar One House was performed by
Boer and Tamm [15] at the University of Delaware. In the
mid-1970s, Florschuetz [23, 99, 100] carried out theoretical
and experimental studies on PV/T collectors which use air or
water as the coolant. Hendrie [101] proposed two configu-
rations of hybrid air PV/T collectors as shown in Figure 9. For
the first design, air flows through holes of 0.25 cm diameter in
the secondary absorber and impinges on the primary absorber.
For this system, thermal and electrical efficiencies were deter-
mined to be 42 and 8.9%, respectively. The second design con-
ists of a V-corrugated secondary absorber in which the tips of
the V’s are in contact with the primary absorber. Thermal and
electrical efficiencies of the second configuration were deter-
determined to be 40 and 7.8%, respectively. Younger et al. [102]
analyzed an air PV/T system in which the upper side of the air
channel consisted of a PV laminate. The backside of the PV
laminate was integrated with a roughened Teflon which has a
roughness of 60 µm. Raghuraman [103] investigated an
air-type PV/T collector in which the PV cells were glued
directly to the absorber plate. A layer was used between the PV
cells and the absorber plate to avoid short-circuiting the PV
laminate. The thickness and the thermal conductivity of the
layer were 0.5 cm and 0.2 W/mK, respectively. Thermal effi-
ciency of the PV/T collector was determined to be 42%. It was
noted that the thermal efficiency notably decreases due to the
considerable temperature difference between the PV cells and
the absorber plate. At the Brown University, an air PV/T
system was constructed to supply the electrical and thermal
energy requirements of a building [104, 105]. The system
consisted of 20 air PV/T collectors and each collector had a
surface area of 1.8 m². The results indicated that the 65% of
the total energy demand could be met by the prescribed
system. Komp and Reeser [106] investigated a glazed air PV/T
system which was designed for an off-grid dwelling. In
summer, heat was dissipated to the ambient via natural convec-
tion, and in winter, the heated air was circulated into the
house by a fan.

Cox and Raghuraman [107] performed simulations on flat-
plate air PV/T collectors employing single-crystal silicon PV
cells. They concluded that the selective absorber reduces the
thermal efficiency when PV cells cover greater than ~65% of
the total collector area. The optimum combination of an air
PV/T collector was found to consist of gridded-back PV cells,
a non-selective secondary absorber and a high-transmissivity/
low-emissivity cover above the PV cells. At the Indian Institute
of Technology, several studies were carried out on air PV/T col-
lectors for solar drying in the early 1990s [37, 108]. Posnansky
et al. [18] investigated a building-integrated air PV/T system
and they observed that the system could produce 12 kW
thermal energy for the heating demand of the building.
Posnansky and Eckmanns [109] analyzed a hybrid air PV/T
system in the environmental conditions of Switzerland. In
summer, the thermal energy produced by the system was
stored in an underground storage, and in winter, this
energy was utilized for the heating demand of the building.
They noted that the thermal efficiency of the PV/T system
varied in the range of 32–45%. In Italy, a building-integrated
air PV/T system employing a-Si PV modules was investigated
[110–113]. Shaw et al. [114] emphasized that for the
building-integrated applications of hybrid air PV/T collectors,
asuitable height should be provided in order to generate the
buoyancy required.

Sopian et al. [115] investigated the performance of single-
and double-pass hybrid air PV/T collectors with steady-state
models. The double-pass PV/T collector considerably showed
better performance due to the reduction in the front cover
temperature. Garg and Adhikari [116] developed a simulation
model for hybrid air PV/T collectors in order to analyze the
directive parameters on performance. Single-glass and double-
glass configurations as shown in Figure 10 were considered in
the study. Parametric studies indicated that the system effi-
ciency increases with an increase in collector length, mass flow
rate and cell density and decreases with an increase in duct
depth for both configurations. It was also observed that for
larger values of duct depth, the percentage decrease in the per-
fomance of the double-glass configuration is smaller than that
of the single-glass configuration.

Mosleghi and Sandberg [117] numerically and experimentally
investigated the flow and heat transfer characteristics of
buoyancy-driven air convection behind PV panels. Numerical
and experimental results were obtained for a channel of 7.0 m in
height and the channel walls were separated by a distance of
0.23 m. The results showed that for input heat flux ≥200 W/m²,
~30% of the input heat is transferred to the unheated wall via
radiation and then it is dissipated to the air through convection.
Garg and Adhikari [118] developed a computer simulation
model to predict the transient performance of an air PV/T col-
clector with single- and double-glass configurations for the envi-
ronmental conditions of New Delhi, India. They observed that
the performance of the double-glass configuration is better than that
of the single-glass configuration. Hollick [119] analyzed the per-
fomance of the solar cogeneration system which composed of
PV cells integrated with SOLARWALL panels as it is illustrated in
Figure 11. The test results showed that combining the PV cells
with SOLARWALL panels enhances the PV cell efficiency and
provides a greater total efficiency. It was also observed that the
solar cogeneration panels considerably reduce the payback time.

In the late 1990s, at the University of Gävle, researches were
focused on PV roofs [120–123]. Air and heat flow for roof-
integrated hybrid air PV/T systems were analyzed numerically and experimentally. Garg and Adhikari [124] proposed a simulation model to investigate the performance of hybrid air PV/T collectors for the climatic conditions of New Delhi, India. Thermal efficiency curves for the hybrid air PV/T collectors corresponding to various types of absorbers were derived. It was observed that the thermal performance of a selective coated absorber is better than the normal black paint absorber. It was also found that the thermal performance without PV cells is higher than when absorber is fully covered with PV cells for both kinds of absorbers. Pottler et al. [125] introduced an optimization method for hybrid air PV/T collectors. Four
different configurations were analyzed in the study as shown in Figure 12. The first design consisted of a single pane cover and an absorber plate integrated with fins. In the second design, a wavy absorber plate was used. The third and the fourth configurations utilized rectangular and triangular fin profiles, respectively. The results indicated that the continuous fins provide the highest net energy gain if they are spaced close to each other. The optimal distance between the fins was determined to be 5–10 mm. It was noted that the optimal flow regime is laminar, accompanies with low Nusselt numbers and large heat exchange areas.

Sopian et al. [126] developed and tested a double-pass hybrid PV/T collector which is suitable for solar drying applications. A steady-state closed form solution to determine the outlet and the mean PV panel temperature was obtained for the differential equations of the upper and lower channels of the collector. The results showed that for a mass flow rate of 0.036 kg/s and an illumination intensity level of 800 W/m², the expected temperature rise is 18°C and the total efficiency of the collector is 60%. Hegazy [127] presented an extensive investigation of four air PV/T collectors. The effects of an air-specific flow rate and the selectivity of the absorber plate on performance were examined. It was observed that the PV/T collector with the air flowing either over or under the absorber plate has the lowest performance, whereas the other PV/T collectors show comparable thermal and electrical output gains. At the University of Patras, various techniques were performed to increase the thermal efficiency of hybrid air PV/T collectors. Tripanagnostopoulos et al. [128] used a blackened metal sheet at half height along the length of the air channel in order to enhance the heat transfer. Brinkworth [129] investigated the flow and convective heat transfer in inclined cooling ducts designed for building-integrated PV cells. The heat transfer coefficients for the duct walls were set out. Bazilian et al. [130] presented an extensive research on the feasibility of PV and PV/T applications in the built environment. They observed that the PV/T systems are well suited to low-temperature applications. They also noted that further research is needed for PV/T systems to have a higher percentage in the renewable market. Jie et al. [131] proposed a detailed simulation model for a PV wall structure with different integration modes (with and without ventilation). Environmental conditions of Hong Kong were considered in the study. The effects of different integration modes on the annual power output and heat gain...
were analyzed. The results indicated that the PV wall with ventilation has a very little improvement on the power output. However, the PV wall with ventilation decreases much the heat gain in comparison with that without ventilation. This means the saving of much energy for the air-conditioning system. Bazilian and Prasad [132] developed a numerical model to simulate the performance of a residential-scale building-integrated cogeneration system. They observed that the simulations show excellent agreement with the experimental studies in predicting the output temperatures of the air and the PV cells. Mei et al. [133] presented a dynamic model based on TRNSYS for an air PV/T collector integrated with the building. The heating and cooling loads for the building in different European locations were estimated. The impact of climatic variations on the performance was investigated. The results showed that the 12% of the heating load can be supplied from the façade in Barcelona, whereas only 2% of the ventilation heat load in Stuttgart and Loughborough.

Cartmell et al. [134] simulated a roof mounted, multi-operational ventilated hybrid PV/T collector and monitored the findings of 6 months period. The system consisted of 37-m² PV cells and a 12.5-m² thermal collector. Simulation findings showed that significant contributions to space heating can be made throughout the year from the system proposed in the study. Janjai and Tung [135] investigated a solar dryer for drying herbs and species using hot air from hybrid air PV/T collectors. Total area of the collectors was 72 m². It was observed that the dryer can be used to dry 200 kg of rosella flowers and lemon grasses within 4 and 3 days, respectively. Naphon [136] developed a mathematical model for predicting the heat transfer characteristics, performance and entropy generation of the double-pass air PV/T collector augmented with longitudinal fins. Effects of the height and the number of fins on the performance and entropy generation were evaluated. It was observed that the thermal efficiency increases with increasing the height and number of fins. It was also noted that the entropy generation is inversely proportional to the height and number of fins.

Guiavarch and Peyroutier [137] analyzed a building-integrated air PV/T system for the environmental conditions of Paris and Nice. In the case of a multi-c-Si PV collector integrated on the roof of a single-family house located in Paris, the efficiency of unventilated PV modules fixed on the roof was determined to be 14%. If the PV collector was used to preheat the ventilation air, the efficiency reached 20%. Tonui and Tripanagnostopoulos [138] analyzed the performances of two low-cost heat extraction modifications coupled to the channel of an air PV/T system in order to achieve higher thermal and electrical outputs. They emphasize that the suggested heat extraction methods can easily be incorporated into the building façades and roofs. Assoa et al. [139] developed a new hybrid air PV/T collector which can be integrated in roofs or in façades. The collector consisted of a ribbed sheet steel absorber combined with PV cells and a layer of tedlar as it is illustrated in Figure 13. They found that the thermal efficiency of the PV/T collector can reach 80% with appropriate collector length and mass flow rate.

Joshi and Tiwari [140] investigated the energy and exergy efficiencies of a hybrid air PV/T collector for the environmental conditions of Srinagar, India. The climatic data of Srinagar for the period of 4 years (1998–2001) were obtained from Indian Metrological Department. It was found that the instantaneous energy and exergy efficiencies of the PV/T collector were varied between 55 and 65% and 12 and 13%, respectively. Alfegi et al. [141] presented a mathematical model and solution procedure of a single-pass hybrid air PV/T collector with CPC and fins with both sides of the absorber as shown in Figure 14. Air as the working fluid flows between top glass and absorber plate and between absorber and bottom plates. The temperature of the circulated air as a function of distance in the flow direction for both sides was determined. For the illumination intensity level of 400 W/m², it was observed that the total efficiency of the PV/T collector increases from 26.6 to 39.1%, whereas the mass flow rate varies from 0.0316 to 0.09 kg/s. Raman and Tiwari [142] investigated the annual thermal and exergy efficiency of a hybrid air PV/T collector for five different Indian climate conditions: Srinagar, Mumbai, Jodhpur, New Delhi and Bangalore. It was observed that the most economical region for the hybrid air PV/T collector is Jodhpur.

At the University of Science and Technology of China, Ji et al. [143] theoretically and experimentally analyzed a PV-Trombe wall. They concluded that the indoor temperature can be increased 5–7°C in winter and electrical efficiency can be maintained at 10.4% using the system proposed in the study. Dubey et al. [144] developed analytical expressions for electrical efficiency of a PV module with and without flow as a function of design parameters. Four different configurations of PV modules were considered in the study: glass-to-glass PV module with a duct, glass-to-glass PV module without a duct, glass-to-tedlar PV module with a duct and glass-to-tedlar PV module without a duct. It was observed that the glass-to-glass PV module with a duct has better electrical efficiency as well as the higher outlet air temperature among all four configurations. The annual average efficiency of the glass-to-glass PV module with and without a duct was determined to be 10.41 and 9.75%, respectively.

A new hybrid air PV/T collector was designed, fabricated and tested for different operating parameters by Solanki et al. [145]. A steady-state thermal model was developed based on the energy balance equations. The thermal and the electrical efficiencies of the collector were determined to be 42 and 8.4%, respectively. Mittelman et al. [146] performed a numerical study to predict the passive air cooling rate of an open channel beneath PV panels. A correlation for the combined heat transfer coefficient was presented. Gan [147, 148] investigated the effect of air gap size on the performance of PV modules for various roof pitches and PV module lengths for different illumination intensity levels. Fudholi et al. [149] presented a review on solar dryers for agricultural and marine
products. Jin et al. [150] developed a single-pass air PV/T collector with a rectangle tunnel absorber as shown in Figure 15. The rectangle tunnel acted as an absorber and was located at the back side of the PV panel. The PV/T collector was tested under a solar simulator. For the illumination intensity level of 817.4 W/m², mass flow rate of 0.0287 kg/s and ambient temperature of 25°C, the electrical, the thermal and the total efficiencies of the PV/T collector were determined to be 10.02, 54.70 and 64.72%, respectively.

Kumar and Rosen [151] recently investigated a hybrid air PV/T collector with a double-pass configuration and vertical fins. The fins were arranged perpendicular to the direction of air flow to enhance the heat transfer rate and efficiency. The effects of design, climatic and operating parameters on outlet air temperature, cell temperature, thermal efficiency, electrical efficiency and total efficiency were evaluated. It was observed that the extended fin area notably reduces the PV cell temperature, from 82 to 66°C. Alta et al. [152] analyzed three different air PV/T collectors. The collectors were tested for three different mass flow rates (25, 50 and 100 m³/m² h) and tilt angles (0, 15 and 30°). It was found that the efficiencies of the finned collectors are higher than that of the collector without a fin. Attaching fins on the absorber surface increased the efficiency of the collector. It was also noted that using more transparent cover and fins increases the temperature differences. Zhao et al. [153] designed a novel PV/e roof module acting as the roof element, electricity generator and the evaporator of a heat pump system. The results indicated that the PV/e-based heat pump system has superior performance over the PV, PV/T and PV-heat pump systems.

3.5 Ventilated PV with heat recovery

The term ‘ventilated PV’ means PV roofs or PV façades which have often an air gap that provides an air flow to cool the PV cells via natural convection. If the dissipated heat from PV roofs or PV façades is recovered, the system is called as ventilated PV with heat recovery and provides additional benefits as well as producing electricity and heat. PV façades decrease the thermal losses of the buildings in winter. In summer, they shield the buildings from the unwanted solar radiation and hence enable to reduce the cooling load. As reported by
Zondag [14], ventilated PV façades started to become important in the early 1990s. In 1994, Ricaud and Roubeau [154] investigated the performance of a 66% efficient hybrid PV/T collector which is known as ‘Capthel’. The system was glass covered and composed of square aluminum channels. It was noted that the a-Si PV modules are best suited for solar cogeneration systems. At the University of Cardiff, the group of Brinkworth carried out several researches on PV roofs and PV façades [129, 155–158]. Krauter et al. [159] evaluated the hybrid PV/T systems in terms of façade integration and building insulation. It was observed that the conventional PV façades with ventilation allow a reduction in the PV cell temperature of 18°C. An 8% increase in electrical energy was obtained for an air speed of ~2 m/s. Cross [160] constructed an integrated solar roof system and analyzed it under a solar simulator. Takashima et al. [161] theoretically investigated a PV roof which is cooled via natural convection.

At Hokkaido University, Nagano et al. [162, 163] carried out some researches on solar wallboards. Schematic configuration of the solar wallboard is illustrated in Figure 16. Six different PV/T collectors design as wallboards were tested for an inclination of 80°. It was observed that the wall-integrated PV/T systems are more preferable than the roof-integrated ones due to the winter conditions. Thermal efficiencies of unglazed and glazed systems were determined to be 20–22 and 29–37%, respectively. Ji et al. [164] developed a thermal model for analyzing the annual performance of a façade-integrated hybrid PV/T collector system in Hong Kong. Performances of thin-film and single c-Si PV panels were compared in the study. The annual thermal efficiencies of the systems with thin-film PV panels and with single c-Si PV panels were determined to be 47.6 and 43.2%, respectively. It was also noted that the façade-integrated hybrid PV/T collector system could reduce the cooling load of the building. At the University of Nottingham, two examples of building-integrated PV systems were analyzed by Omer et al. [165]. The first system that consists of a thin-film PV façade was installed on an educational building. The second system that uses crystalline PV roof slates was combined with a detached house. It was underlined that the investigation-assisted identification of shortfalls in performance. Benemann et al. [166] gave examples from the projects on building-integrated PV systems. In the Samsung Institute of Engineering and Construction Technology, Yoo and Lee [167] investigated the building-integrated PVs as a shading device. The PV modules were carefully integrated with the building in order to provide shading and hence to reduce the cooling load of the building in summer. Performance analysis of the system including the system efficiency and the power output was analyzed for 1-year operation. It was found that the yearly average efficiency of the sunshade solar panel was 9.2%. Mei et al. [168] designed a desiccant cooling system which is regenerated by solar heat. In the system, the surplus heat is utilized from the ventilated PV façade and shed elements during summer to meet the cooling load of the building. A desiccant cooling machine was mounted on the library roof with an additional solar air collector and connected to the existing ventilated PV façade and PV sheds. They observed that a solar fraction of 75% can be achieved by such an innovative system. They also determined the COP of the cooling machine to be 0.518. Matuska and Sourek [169] studied the façade-integrated solar thermal collectors. The cross-sectional view of the façade solar collector is shown in Figure 17. Thermal behavior of the façade collectors was compared with the conventional roof-located collectors. The results showed that the façade solar collectors should have an area increased by ~30% to achieve the usual 60% solar fraction compared with the conventional roof solar collectors with a 45° slope. It was also noted that the building behavior is not strongly affected by façade collectors when sufficient insulation is provided.

Ji et al. [170] presented a study on a PV-Trombe wall assisted with a DC fan. Theoretical simulations were performed for the PV-Trombe wall with and without a DC fan. They observed that a significant temperature increase in indoor temperature with a maximum of 14.42°C, if compared with the reference room, can be obtained by the PV-Trombe wall assisted with a DC fan by testing. They also noted that the average electrical efficiency of the PV-Trombe wall assisted with
A DC fan can reach 10–11%, due to the glass cover. In addition, the results indicated that the assisted DC fan can help improving the indoor temperature and cooling the PV cells. Agrawal and Tiwari [171] developed a 1D transient model in order to optimize the building-integrated PV/T systems for the cold climatic conditions of India. The PV performances, net energy gain and the exergy of the building were determined. It was observed that for a constant mass flow rate, the combination of the building-integrated PV/T systems connected in series provides the maximum air outlet temperature. It was also noted that the building-integrated PV/T system, mounted on the roof top with an effective area of 65 m², is capable of annually producing the net electrical and thermal exergies of 16 209 and 1531 kW h, respectively, with an average thermal efficiency of 53.7%. Chow et al. [172] presented a dynamic simulation model of a building-integrated PV water-heating system. The model was based on a finite difference control volume approach. The validity of the model was demonstrated by comparing the predicted temperature changes and system daily efficiencies with the measured data obtained experimentally. It was emphasized that the proposed model was quite useful to predict the system dynamic behavior as well as long-term energy performance. Chow et al. [173] carried out an experimental study on a façade-integrated PV water-heating system in Hong Kong. Different operating modes were performed with measurements in different seasons. Natural water circulation was found more preferable than forced circulation in the hybrid solar collector system. The thermal and the electrical efficiency of the system were determined to be 38.9 and 8.56%, respectively. Tian et al. [174] developed a model to evaluate the effects of building-integrated PVs on the microclimate of an urban...
canopy layer. The simulation results indicated that the PV roof and the PV façade with a ventilated air gap significantly change the building surface temperature and the sensible heat flux density. On the other hand, the air temperature of the urban canyon with PV modules varies little compared with the urban canyon without PV modules. It was also noted that the increase in the conversion efficiency of PV modules not only improves the power output, but also reduces the air temperature of the urban canyon. Anderson et al. [175] theoretically investigated a building-integrated PV/T collector using the modified Hottel–Whillier model. The results indicated that the design parameters such as fin efficiency, lamination method and thermal conductivity between the PV cells and their supporting structure have a significant influence on both the electrical and the thermal efficiencies of the building-integrated PV/T collector. Anderson et al. [176] also examined the effect of absorber color on the thermal performance of building-integrated solar collectors. Five different colors ranging from white to black were considered in the study. The results showed that colored solar collector absorbers can make significant contributions to heating loads. Lu and Yang [177] carried out a payback time analysis of a roof-mounted 22 kW building-integrated PV system in Hong Kong. It was observed from the results that the sustainability of a PV system is affected by its installation orientation and location.

4 DIFFERENT DESIGNS OF PV/T COLLECTORS

Design of hybrid PV/T collectors has an important impact on performance parameters. In the literature, various system configurations of water and/or air PV/T collectors were investigated in detail. The most common designs analyzed by researchers are illustrated in Figure 18a–d. In the first design, a PV module is attached on an absorber plate with metallic elements as shown in Figure 18a. In the second design, the working fluid flow over the PV module as it is clear in Figure 18b. The third design consists of multiple channels beneath the PV module as shown in Figure 18c. In the fourth configuration, transparent PV modules are utilized with multiple working fluids as it is illustrated in Figure 18d. The last design is preferable since it provides a lower PV cell temperature but the complexity of the dual absorber geometry makes the module difficult to manufacture [2, 178].

Tripanagnostopoulos et al. [179] investigated a PV/T system with dual heat extraction operation, either with water or with air circulation. The experimental model consisted of a pc-Si PV module with an air channel at a PV rear surface, properly constructed for flexibility in changing the place of the heat exchanger element of circulating water. The PV/T system was tested in three design modes as shown in Figure 19. The results indicated that the placement of heat exchanger on the PV rear surface (Mode A) provides the most effective combination of water and air heat extraction. Tripanagnostopoulos et al. [180] analyzed the performances of two types of air PV/T collectors. In the first system, a commercial pc-Si PV module was combined with a black tedlar. The second system composed of a transparent tedlar on the front and the glass on the rear surface of the PV module. The two systems were tested in vertical position with natural and forced air circulation. It was observed that the second air PV/T collector provides ~6°C lower PV cell temperature which results in an increase in electrical efficiency. Tiwari and Sodha [181] investigated the different configurations of hybrid air PV/T collectors which are considered as unglazed and glazed PV/T air heaters, with and without a tedlar. Numerical computations were performed for the environmental conditions of New Delhi, India, and the results for different configurations were compared. It was observed that the glazed hybrid PV/T collector without tedlar presents the best performance. It was also noted that the overall efficiency of the hybrid PV/T collector decreases with an increase in the length of the PV module due to more losses from the system. Joshi et al. [182] analyzed two types of PV/T collector which are called as glass-to-glass PV/T system and glass-to-tedlar PV/T system. The results of both PV/T systems were compared for the climatic conditions of New Delhi, India. It was observed that the glass-to-glass PV/T system gives better performance in terms of overall thermal efficiency.

Erdil et al. [183] designed, constructed and tested a hybrid PV/T system for the environmental conditions of Cyprus. Water was used as the cooling fluid in the study. The cooling fluid was circulated between the glazing and the PV module in order to preheat it for domestic applications. It was observed that the payback period of the configuration is <2 years which makes the hybrid PV/T system economically attractive. Recently, Kamthania et al. [184] studied the performance analysis of a hybrid PV/T double-pass façade for the composite climate of New Delhi. The annual thermal and electrical energies of the system were determined to be 480.81 and 469.87 kWh, respectively. It was also observed that the room air temperature increases by 5–6°C than the ambient air temperature for a typical winter day. Kumar and Rosen [185] presented a review on the recent developments of air PV/T collectors. They concluded that further research is needed to improve the efficiency and to reduce the cost of PV/T systems.

5 PERFORMANCE ANALYSIS OF PV/T COLLECTORS

A hybrid PV/T collector is basically a combination of a flat-plate thermal collector and a PV module. Therefore, theory of flat-plate thermal collectors and theory of PV modules will be investigated separately.
5.1 Theory of flat-plate thermal collectors

It is well known in the literature [186] that the useful heat gain of a flat-plate thermal collector is given by:

\[ Q_u = mC_p(T_{fo} - T_{fi}) \] (1)

where and \( T_{fo} \) and \( T_{fi} \) are the fluid outlet and the fluid inlet temperature, respectively. The steady-state thermal efficiency of a flat-plate thermal collector is calculated as follows:

\[ \eta_{th} = \frac{Q_u}{G} \] (2)

where \( G \) is the illumination intensity level. Equation (1) can be rewritten in terms of the absorber plate temperature as follows:

\[ Q_u = A_c[S - U(T_{ap} - T_{amb})] \] (3)

where \( A_c \), \( S \), \( U \), \( T_{ap} \) and \( T_{amb} \) are the area of the PV/T collector, absorbed solar energy, overall heat loss coefficient, absorber plate temperature and ambient temperature, respectively. Hottel and Willier [187] simplified Equation (3) since it includes difficulties to calculate:

\[ Q_u = A_c F_r [S - U(T_{fi} - T_{amb})] \] (4)
where $F_r$ is the heat removal factor of the PV/T collector. $F_r$ is calculated by the following equation:

$$F_r = \frac{mC_p}{A_cU} \left( 1 - \exp \left( \frac{A_cUe}{mC_p} \right) \right)$$

In Equation (5), $F_e$ is the collector efficiency factor given by:

$$F_e = \frac{1/U}{W[1/U[D_o + (W - D_o)F_{fe}] + 1/C_b + 1/\pi D_i h_i]}$$

where $W$, $D_o$, $D_i$, $C_b$, $h_i$ and $F_{fe}$ are the tube spacing, outside tube diameter, inside tube diameter, thermal conductivity of the bond between the fin and tube, heat transfer coefficient of fluid and fin efficiency factor, respectively. The fin efficiency factor is calculated as follows:

$$F_{fe} = \frac{\tanh(x)}{x}$$

where

$$x = \sqrt{\frac{U}{k\delta} \left( \frac{W - D_o}{2} \right)}$$

In Equation (8), $\delta$ represents the fin thickness. The system details of a conventional solar thermal collector are illustrated in Figure 20.

5.2 Theory of PV modules
For a constant illumination intensity level ($G$), maximum power generated by a PV module is observed at the maximum
power point (MPP). The electrical efficiency of a PV module for the MPP is calculated as follows:

\[ \eta_{el} = \frac{I_m V_m}{G A_c} \]  

(9)

PV modules harness only a limited part of the incoming solar radiation. Most of the absorbed solar radiation is dumped to the PV modules as waste heat and thus a considerable increase in the PV module temperature occurs. The efficiency of a PV module dramatically decreases with increasing cell temperature. This increase can be expressed by the following equation:

\[ \eta_{el} = \eta_{ref}(1 - \xi(T - 25)) \]  

(10)

In Equation (10), \( \eta_{ref} \) is the reference efficiency of the PV module which is obtained for the standard test conditions \((G = 1000 \text{ W/m}^2 \text{ and } T = 25^\circ\text{C})\). \( \xi \) is the PV module efficiency temperature coefficient. As it is clear, a PV module produces not only electrical energy but also thermal energy. Enhancing the electrical efficiency of a PV module by reducing the PV module temperature is the main idea behind the hybrid PV/T system technology.

5.3 Analytical models of PV/T collectors

The earliest studies on the analytical investigation of PV/T systems were carried out by Fiorschuetz [23] and Raghuraman [103]. Fiorschuetz [23] extended the well-known Hottel–Whillier [187] model developed for the thermal analysis of flat-plate collectors to the analysis of hybrid PV/T systems. He proposed a simple linear relationship to demonstrate the cell temperature effect on the efficiency of PV/T collectors. Raghuraman [103] developed a model for both air and water PV/T collectors in which the PV cells were glued directly to the absorber. He determined the thermal efficiency of the air PV/T collector to be 42%. Evans [188] and Schott [189] presented an expression for temperature-dependent electrical efficiency of a PV module. Bergene and Lovvik [61] developed a detailed model based on energy transfer analysis in order to predict the performance of water-type PV/T collectors. Their model enabled to predict the amount of heat, which can be recovered, as well as the theoretical power output. Total efficiency of the PV/T collector was determined to be \( \approx 60–80\% \). Sopian et al. [115] analyzed the performance of single- and double-pass hybrid air PV/T collectors with steady-state models. It was observed in the study that the double-pass PV/T collector shows better performance compared with the single-pass PV/T collector due to the reduction in the front cover temperature. Ito et al. [190] carried out theoretical and experimental studies on the thermal performance of a heat pump which uses a flat-plate collector as the evaporator. In the early 2000s, Hegazy [127] carried out a simulation study comparing four air PV/T collectors. The effects of the air-specific flow rate and the selectivity of the absorber plate on performance were investigated. It was observed that the PV/T collector with the air flowing either over or under the absorber plate has the lowest performance, whereas the other PV/T collectors show competitive thermal and electrical outputs. Chow [74] proposed an explicit dynamic model for performance analysis of a single-glazed flat-plate water PV/T collector. The proposed model allowed a detailed analysis of the transient energy flow across various collector components.

Tiwari et al. [191] examined the performance of an air PV/T collector for the composite climate of India. An analytical expression for the overall efficiency was obtained by using energy balance equations for each component. A fair agreement between theoretical and experimental results was observed. It was also noted that the overall efficiency of the PV/T collector increased \( \approx 18\% \) due to the utilization of thermal energy in a PV module. Joshi and Tiwari [140] investigated the performance of a parallel plate hybrid air PV/T collector for the environmental conditions of Srinagar, India. The climatic data of Srinagar were obtained from Indian Metrological Department. The instantaneous energy and exergy efficiencies of the PV/T collector were determined to be 55–65 and 12–15%, respectively. The results obtained were in agreement with the results presented by Bosanac et al. [192]. Dubey and Tiwari [92] analyzed the performance of partially covered hybrid flat-plate PV/T collectors connected in series using theoretical modeling. The performance simulation was carried out for five different locations in India (New Delhi, Bangalore, Mumbai, Srinagar and Jodhpur). It was observed that the outlet water temperature notably increased from 60 to 86°C, whereas the number of PV/T collectors connected in series increased from 4 to 10. Joshi et al. [193] investigated the performance characteristics of a PV and a PV/T system in terms of energy and exergy efficiencies. It was found that exergy efficiency of the PV/T system varies between 11.3 and 16%, whereas the exergy efficiency of the PV system ranges from 7.8 to 13.8%.

Dev and Tiwari [194] utilized two analytical models in order to establish the characteristic equation of a PV/T active solar still based on annual experimental observations. It was observed that the performance of the non-linear characteristic equation is better than the linear characteristic equation. Sarhaddi et al. [195] recently proposed a detailed thermal and electrical model in order to investigate the thermal and electrical performances of a hybrid air PV/T collector. The results were in good agreement with the previous literature. The overall energy efficiency of the PV/T collector was determined to be 45%.

5.4 Numerical models of PV/T collectors

In the mid-1980s, Cox and Raghuraman [107] carried out simulations on flat-plate air PV/T collectors employing single-crystal silicon PV cells. The main objectives of their study were increasing the solar absorptance and reducing the infrared emittance. At the Indian Institute of Technology, Garg and Adhikari [124] developed a numerical model to analyze the performance of hybrid air PV/T collectors for the
environmental conditions of New Delhi, India. Thermal efficiency curves for the hybrid air PV/T collectors corresponding to various types of absorbers were obtained. It was found that the thermal performance of the selective coated absorber is better than the normal black-paint absorber. It was also observed that the thermal performance without PV cells is higher than when the absorber is fully covered with PV cells for both kinds of absorbers. In the late 1990s, at the University of Gävle, extensive numerical studies on PV roofs were done [120–123]. Zondag et al. [73] proposed four numerical models in order to predict the performance water PV/T collectors. They noted that the all models follow the experiments within 5% accuracy. For the calculation of the daily yield, the simple 1D steady-state model performed almost as good as the much more time-consuming 3D dynamical model. They also concluded that the 2D and 3D models provide more detailed information for design improvement. The useful collected heat was determined to be 54.2% of the incoming solar radiation. Mosfegh and Sandberg [196] investigated the fluid flow and heat transfer in a vertical channel heated from one side by PV elements. Numerical results were derived for a channel of 6.5 m in height and various widths of the channel. The study was carried out for different heat fluxes in order to demonstrate the effect of input heat on the heat transfer across the air layer. Velocity and the temperature profiles of the outlet air and the surface temperature of the heated and insulated wall were obtained. Zhu et al. [197] presented a numerical analysis of heat transfer in a PV panel for indoor cases. Numerical results indicated that the thermal contact resistances at interfaces have a dominant effect on the temperature field in a PV panel. On the other hand, the extinction coefficient of the transparent glass cover shows just a slight influence on the temperature field. Huang et al. [198] evaluated the use of phase change material for moderating building-integrated PV temperature rise. A numerical model was developed to predict the temperature distributions for different illumination intensity levels and ambient temperatures. It was observed that the moderation of temperature achieved can significantly enhance the operational efficiency of PV façades. Ji et al. [199] developed a model for a hybrid PV/T water-heating system by modifying the Hottel–Whillier model [187]. The combined effects of packing factor and water mass flow rate on the thermal and electrical efficiencies were investigated. It was noted in the study that the utilization of PV/T façades has many advantages, such as reducing the energy consumption in buildings and providing electrical and thermal energies for domestic usages. Gaur and Tiwari [200] presented an optimization of number of PV/T collectors integrated with an active solar still. The optimization was carried out for different heat capacity of water based on energy and exergy. Kim et al. [201] recently investigated the thermal characteristics of a PV module by change of ambient temperature. A 125-W PV module was considered in the study. The results indicated that the open-circuit voltage ($V_{oc}$) considerably decreases with increasing ambient temperature while short-circuit current ($I_{sc}$) increases.

5.5 Modeling and simulation
Kalogirou [69] studied the modeling and simulation of a hybrid PV/T system for the environmental conditions of Cyprus. The system was modeled using a well-known transient system simulation program (TRNSYS). The results indicated that the optimum flow rate of the system is 25 l/h. It was also observed that the hybrid PV/T system increases the mean annual efficiency of the PV system from 2.8 to 7.7% and meets 49% of the hot water demand of a house. Ji et al. [202] developed a mathematical model in order to analyze the performance of a PV heat pump. They observed that the electrical and thermal efficiencies of the system were above 12 and 50%, respectively. Again, Ji et al. [203] presented a dynamic model for a novel PV/T solar-assisted heat pump system. The proposed model enabled to determine the spatial distributions of refrigerant conditions, including pressure, temperature, vapor quality and enthalpy. Liu et al. [204] developed mathematical models to analyze the performance of a PV solar-assisted heat pump with variable-frequency compressor for the climatic conditions of Tibet. The simulation results showed that on a typical sunny winter day with light breeze, the average COP, thermal efficiency, electrical efficiency and total efficiency of the system were 6.01, 47.9, 13.5 and 62.5%, respectively. da Silva and Fernandes [205] modeled hybrid PV/T systems with Simulink/Matlab. They made some recommendations such as the use of vacuum or a noble gas at low pressure for reducing the emittance from PV modules. The results indicated that this technique provides an 8% increase in optical thermal efficiency and a notable reduction in thermal losses. Zhao et al. [206] presented the design optimization of a hybrid PV/T system for both concentrated and non-concentrated solar radiation. The system consisted of a PV module employing silicon solar cells and a thermal unit based on the direct absorption collector concept. The results showed that the optimum system can effectively and separately use the visible and infrared part of the solar radiation. The thermal unit absorbs 89% of the infrared radiation for photothermal conversion and transmits 84% of the visible light to the PV cell for photoelectric conversion. It was also observed that when the illumination intensity level increases from 800 to 8000 W/m², the system generates 196°C working fluid with a constant thermal efficiency around 40%, and the exergetic efficiency increases from 12 to 22%. Shahsavar and Ameri [207] carried out theoretical and experimental studies on a direct-coupled air PV/T collector. The results indicated that there are an optimum number of fans to obtain the maximum electrical efficiency. It was also noted that the glass cover on PV panels leads to an increase in thermal efficiency and decrease in electrical efficiency due to the increase in cell temperature.

5.6 Experimental work
Hybrid PV/T collectors have been experimentally investigated by many researchers since 1970s. The general aim of those studies was to design an optimum PV/T system configuration...
and/or to enhance the thermal and electrical efficiencies of the system. Choudhury and Garg [208] presented a comparative theoretical parametric analysis of air PV/T collectors with and without packing in the flow passage above the back plate. Tripanagnostopoulos et al. [128] experimentally investigated an air PV/T collector with three modifications in its air channel. In the first configuration, an air PV/T collector, as shown in Figure 21a, was tested for various air channel depths. In the second configuration, the PV/T collector was augmented with fins and tubes as it is illustrated in Figure 21b. Lastly, a flat metallic sheet was placed in the middle of the air channel in the third configuration as shown in Figure 21c. Experimental results indicated that wide air channel depth results to a decrease in the thermal output of the system. It was concluded that the use of fins and tubes is preferable in terms of the thermal and electrical performances of the PV/T collector, but it was noted that the additional cost and pressure drop should be taken into consideration. In addition, it was found that the metallic sheet in the middle of the air channel increases the thermal and electrical outputs of the system.

Tomui and Tripanagnostopoulos [20] evaluated the use of a suspended thin flat metallic sheet at the middle or fins at the back wall of an air duct as heat transfer augmentations in a hybrid air PV/T collector to improve its overall performance. They underlined that the increased performance of the modified air PV/T systems will contribute to the development of PV applications. He et al. [209] carried out an experimental and numerical study on a double-glazed window integrated with a-Si PV cells. The study was performed in Hefei, east region of China. It was found that the indoor heat gain significantly reduces with the PV double-glazed window. It was noted that the PV double-glazed window is quite promising in office buildings to decrease the cost and to increase the efficiency. Sun et al. [210] recently investigated the performance of a PV-Trombe wall with different south façade designs. It was observed that the increase in PV coverage on the glazing can reduce the thermal efficiency of the PV-Trombe wall by up to 17%. By taking account of electrical conversion, the total efficiency of solar utilization is reduced by 5% at most while the glazing is fully covered with PV cells. Li et al. [211] experimentally analyzed the electrical and thermal performances of a 2-m² trough concentrating PV/T system. A single c-Si PV cell array, a pc-Si PV cell array, a super PV cell array and a GaAs PV cell array were, respectively, utilized in the experiments. The experimental results indicated that the electrical performance of the system with the GaAs PV cell array is better than that of c-Si PV cell arrays. On the other hand, the thermal performances of the system using a single c-Si PV cell array and a pc-Si PV cell array are better.

5.7 Effective parameters on PV/T performance
Performance of hybrid PV/T systems is affected by some parameters such as number of covers, mass flow rate and inlet temperature of the working fluid and absorber plate parameters including tube spacing, tube diameter and fin thickness.

5.7.1 Glazed and unglazed PV/T collectors
Fujisawa and Tani [65] examined a hybrid PV/T collector which consisted of a liquid heating flat-plate solar collector with mono-c-Si PV cells on the substrate of a non-selective aluminum absorber plate. Exergy analysis was performed in the study since it provides a qualitative evaluation of electrical and thermal energies produced. They noted that the exergy output of the unglazed configuration is a little higher than the single-glazed configuration. Sandnes and Rekstad [72] investigated a hybrid water PV/T collector with a polymer absorber plate. They concluded that the heat loss from the PV/T collector can be reduced by an additional cover glass, but glazing designs result to an increase in reflective losses. Zondag et al. [24] analyzed nine types of PV/T collectors and compared their performances. The results indicated that the single cover sheet-and-tube design is the most promising of the examined concepts for domestic hot water production. On the other hand, the uncovered PV/T collector will be better for a low-temperature application since the reflection losses at the cover are foregone. Tiwari and Sodha [77] evaluated the performances of a hybrid PV/T water/air heating system with four configurations: (a) UGT, (b) GT, (c) UGWT and (d) GWT. They observed that the UGWT provides better performance at lower operating temperature. However, the GT gives better performance at high operating temperature. Fraisse et al. [90] studied the energy performance of a hybrid water PV/T collector combined with a DSE. Four different configurations of the PV/T collector were considered: regarded glazed and unglazed concepts. For the PV/T collector with a glass cover, the annual electrical efficiency was determined to be 6.8% which represents a decrease of 28% in comparison with a conventional non-integrated PV module of 9.4% annual efficiency. Chow et al. [93] analyzed the factor of a glass cover on a hybrid water PV/T system from the viewpoint of thermodynamics. It was found that the glazed PV/T system is always suitable for maximizing the thermal or the overall energy output. In terms of exergy analysis, the increase in PV cell efficiency, packing factor and wind velocity was found favorable for an unglazed system, whereas the increase in illumination intensity and ambient temperature was favorable for a glazed system. They also emphasized that if the design target is to acquire either more electrical energy or more overall energy output in ‘quality’, the exergy efficiency will be more appropriate for assessment. Pantic et al. [212] investigated the energy performances of three different open loop air heating building-integrated PV/T systems. They concluded that the glazed configuration significantly reduced the electricity production and leads to excessively high PV panel temperatures.

5.7.2 Mass flow rate
The effect of the mass flow rate on the performance of PV/T collectors was studied by many authors. The general conclusion of those studies is that the mass flow rate has a notable influence on PV/T performance. Garg and Adhikari [116] introduced a simulation model for hybrid air PV/T collectors
in order to investigate the effective parameters on performance. Parametric studies indicated that the system efficiency increases with an increase in mass flow rate and decreases with an increase in duct depth for both configurations. Bergene and Lovvik [61] presented a detailed model in order to predict the performance of water-type PV/T collectors. They observed that the thermal efficiency of the system increases only by a factor of 0.1 as the mass flow rate increases from 0.001 to 0.075 kg/s. They noted that the system they proposed might be useful particularly to preheat the domestic hot water. Sopian et al. [126] designed and tested a double-pass hybrid PV/T collector which is suitable for solar drying applications. The results indicated that for a mass flow rate of 0.036 kg/s and an illumination intensity level of 800 W/m², the expected temperature rise is 18°C and the total efficiency of the collector is 60%. They concluded that increasing the mass flow rate increases the heat transfer coefficient, resulting in a lower PV panel temperature. Kalogirou [69] studied the modeling and simulation of a hybrid PV/T system for the climatic conditions of Cyprus. The system was modeled using a well-known TRNSYS. The results indicated that the optimum flow rate of the system is 0.007 kg/s for a 5.7-m² collector area. Morita et al. [213] performed a numerical analysis in order to analyze the performance of two types of hybrid PV/T collectors (single glass cover PV/T collector and coverless PV/T collector) from the viewpoint of thermodynamics. The mass flow rates of a single glass cover PV/T collector and a coverless PV/T collector at maximum exergy efficiencies were determined to be 0.0014 and 0.0049 kg/s, respectively.

5.7.3 Absorber plate parameters
The tube spacing (W) to tube diameter (D) ratio was studied by Bergene and Lovvik [61], and it was observed that the outlet fluid temperature decreases as the W/D ratio increases from 1 to 10. As reported by Charalambous et al. [186], the total efficiency is largely dependent on fin size even though the electrical efficiency is not heavily affected by the fin size. It was also noted that it is not meaningful to increase the system cost by decreasing the W/D ratio if the aim is cooling of PV cells. Charalambous et al. [214] developed a novel mathematical model in order to determine the optimum absorber plate configuration having the least material content and thus the cost. They concluded that the optimum serpentine absorber plate contains 40.5% less material content and mass. Huang et al. [67, 68] constructed two unglazed PV/T collectors and tested them at the National University of Taiwan. Two types of tube-in-sheet heat-collecting plates with W/D = 6.2 and 10 were analyzed in the study. Since the thermal performance of the configurations was not satisfactory, a novel polycarbonate multichannel structure with W/D = 1 was manufactured. The daily efficiency of the system was determined to be 38%.

Figure 21. Hybrid air PV/T collector with three different configurations [128].
6 THERMODYNAMIC ASSESSMENT OF PV/T COLLECTORS

At the University of Ontario Institute of Technology, several researches were carried out on thermodynamic investigation of PV and hybrid PV/T systems [1, 12, 193]. The exergy analysis of PV systems was studied by many researchers [65, 85, 215, 216]. At Karadeniz Technical University, Cuce and Bali [4, 5] analyzed and compared the performances of mono-c-Si PV and pc-Si PV modules for different illumination intensities and cell temperatures from the viewpoint of thermodynamics.

6.1 PV systems

Efficiency for a PV cell measures the ability to convert radioactive energy into electrical energy. There are three main efficiency expressions which characterize the performance evaluation of PV cells. These are called as energy, exergy and power conversion efficiencies. Energy efficiency is determined by the ratio of the theoretical electrical power output of a PV cell divided by the input illumination intensity.

$$\eta_e = \frac{I_{sc} V_{oc}}{G_A c}$$

(11)

Power conversion efficiency is determined by the ratio of the area under the current–voltage characteristic curve of a PV cell divided by the input illumination intensity.

$$\eta_{pce} = \frac{\int_{0}^{V_{oc}} I(V) dV}{G_A c}$$

(12)

Exergy efficiency is calculated as the maximum useful energy produced by a PV cell divided by the input exergy of illumination intensity.

$$\eta_{ex} = \frac{I_{m} V_{m}}{G_{ex} A_c}$$

(13)

The exergy efficiency can also be written in terms of fill factor (FF) as follow:

$$\eta_{ex} = \frac{I_{sc} V_{oc}}{G_{ex} A_c} \text{FF}$$

(14)

The exergy content of thermal radiation was presented by Petela [217] with the following equation:

$$G_{ex} = \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun}}\right)\right] G$$

(15)

6.2 PV/T systems

Apart from PV systems, PV/T systems utilize the waste heat from PV cells as well as producing electricity. That means the exergy output of a PV/T system is the sum of the electrical and thermal exergy outputs of the system. Then, the exergy efficiency of a PV/T system ($\eta_{ex-h}$) can be given by:

$$\eta_{ex-h} = \frac{E_{ex} + T_{ex}}{G_{ex} A_c}$$

(16)

In Equation (16), $E_{ex}$ and $T_{ex}$ are the electrical and thermal exergy outputs of the system, respectively. Equation (16) can also be rewritten as follows:

$$\eta_{ex-h} = \frac{V_m I_m + (1 - (T_{amb}/T_{cell}))Q}{1 + 1/3(T_{amb}/T_{sun})^4 - 4/3(T_{amb}/T_{sun})GA_c}$$

(17)

where $T_{cell}$, $T_{sun}$ and $Q$ are the PV cell temperature, sun temperature and available thermal energy, respectively.

![Three modifications to improve the heat extraction in the air channel of a PV/T collector](images/22.png)

Figure 22. Three modifications to improve the heat extraction in the air channel of a PV/T collector [2, 219].
7 OPTIMUM ELECTRICAL/ThERMAL RATIO OF PV/T COLLECTORS

It is well known in thermodynamics that electrical and thermal energies are qualitatively different. As reported by Charalambous et al. [186], thermal energy cannot produce useful work unless a temperature difference exists between a high-temperature source and a low-temperature source. On the contrary, electrical energy can completely transform into work irrespective of the ambient conditions. However, there is not a definite value of the optimum electrical/thermal ratio for PV/T collectors. Because this ratio changes according to the type of energy needed.

Coventry and Lovegrove [218] investigated the methods that can be employed to develop a ratio between electrical and thermal outputs from a domestic-style PV/T system. Analysis based on 2001 US financial data for flat-plate PV and domestic solar hot water systems introduced a value of 4.24. It was noted that this ratio is expected to be reasonably independent of time and location. Also, it was underlined that the ratio chosen can have an important impact on the optimum design of a PV/T concentrating system.

8 METHODS TO ENHANCE PV/T PERFORMANCE

Several attempts have been made in the literature in order to improve the performance parameters of PV/T systems. At the University of Patras, Tripanagnostopoulos [219] evaluated various PV/T system modifications in terms of performance improvement. These modifications included (a) placement of a sheet combined with small ribs on the opposite air channel wall, (b) interposition of a corrugated sheet and (c) placement of tubes inside air channel as shown in Figure 22. Steady-state test results of the modified air PV/T systems indicated that the thermal efficiencies are quite satisfactory for air heat extraction. Tonui and Tripanagnostopoulos [138] analyzed the performances of two low-cost heat extraction modifications coupled to the channel of an air PV/T system in order to achieve higher thermal and electrical outputs. The cross-sectional views of the studied models are illustrated in Figure 23. It was observed that both the metal sheet (TMS) suspended at the middle of the air channel and the fins arrangements at the opposite wall of the channel increase the electrical and thermal performance of the PV/T system. The glazed designs with finned back wall provide sufficiently higher thermal efficiency compared with the conventional system. The system with a suspended thin metal sheet in the middle of the channel also shows better protection of the building structure from the undesirable overheating by shielding the back wall of the channel. It was also noted that the proposed methods can easily be incorporated into the building fabric.

9 FUTURE POTENTIAL OF PV/T COLLECTORS

As reported by Hasan and Sumathy [2], the feasibility of the hybrid PV/T systems is dependent on their technical and economical competitiveness with respect to the alternatives. Fossil fuel-based energy resources are still dominant with the highest share in global energy consumption but clean energy generation becomes increasingly crucial due to the growing significance of environmental issues. It is expected that the viability of the hybrid PV/T systems will be more pronounced when the environmental costs of conventional electricity production are
difficult to be compensated. The researches carried out on PV/T systems both theoretically and experimentally indicate that PV/T systems have a great potential in order to have a higher percentage in the renewable market in the near future. But, it is also noted that further research is needed to meet the expectations.

10 CONCLUSION

In this paper, a thorough review of the available literature on PV/T systems is presented. The review is performed in a thematic way in order to allow an easier comparison, discussion and evaluation of the findings obtained by researchers, especially on parameters affecting the electrical and thermal performance of PV/T systems. Some concluding remarks are as follows:

- PV/T collectors produce more energy per unit surface area than side-by-side PV modules and solar thermal collectors. Therefore, PV/T systems are especially appropriate for the applications where the available surface area is limited.
- PV/T systems can completely meet the electricity and heat demand of the buildings as significantly lowering CO₂ emission.
- PV/T systems are reliable and work on the noiseless environment. Life span of these systems is around 20–30 years and maintenance costs are negligible.
- The thermal efficiency of water PV/T collectors are higher than the air PV/T collectors. Sheet-and-tube is the most promising design since it is the easiest configuration to manufacture.
- Thermal and electrical efficiencies of PV/T systems can considerably be enhanced using low-cost reflecting surfaces.
- Glazed PV/T systems are always suitable for maximizing the thermal or the overall energy output.
- Unglazed PV/T systems provide better electrical performance compared with the glazed PV/T systems.
- Absorber plate parameters have a significant influence on the thermal efficiency of PV/T systems.
- In order to minimize the heat resistance between the absorber surface and the heat transfer medium, the layers between the PV cells and the absorber plate should be kept as thin as possible.
- Exergetic assessment should be used in order to make a realistic evaluation of PV/T systems.
- Further research should be carried out for optimizing the air channel geometry of PV/T systems.

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