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A review on building-integrated photovoltaic/thermal systems for green buildings

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ABSTRACT

Space constraints in urban areas can make it difficult to utilise renewable energy resources, like solar energy systems. However, this limitation can be overcome by utilising building façades to produce energy. Up to 40% of the global energy demand is due to the energy consumed by buildings, which also account for 33% of the global greenhouse gas (GHG) emissions. Buildings have both electrical and thermal energy demand for various processes such as lighting, space heating and hot water supply. The simultaneous production of electrical and thermal energies is possible with photovoltaic thermal (PV/T) systems. Electrical efficiency can be upgraded by decreasing the surface temperatures of the photovoltaic (PV) panels with the working fluid circulating in the system. Building-integrated PV/T (BIPV/T) systems within building façades can successfully produce both electrical and thermal energy and, thus, improve buildings' energy performance. This review study explains the operation of BIPV/T systems, their classification and utilisation benefits, performance improvement techniques, and potential contributions to energy-efficient buildings. The major goal of this study is to present new users and researchers with access to up-to-date sources of information about BIPV/T systems in the literature. This study includes recent BIPV/T technological advancements published in literature, emphasises the primary goals of the cited works and their hotspots, and, thus, provides readers with an overview of the topic rather than a detailed analysis of BIPV/T systems.

1. Introduction

With the increment in the world population [1], the energy need is rising day by day. Fossil fuels are widely used throughout the world in both electrical and thermal energy production to meet this demand. However, fossil fuel reserves are limited and burning fossil fuels has significant negative environmental effects [2]. In this regard, there has been a great trend towards the utilisation of sustainable energy systems in various applications around the world [3]. GHG emissions could be decreased by utilising renewable energy resources. For this reason, many governments support incentives for the utilisation of renewable energy [4].

It is possible to generate electrical and thermal energies using renewable energy resources like solar energy. Compared to other renewable resources, employing solar irradiance is one of the most widespread, practical, and economical ways to generate energy. It should be noted that solar energy has significant global application potential [5]. Numerous operations, including electricity production, building space heating, hot water generation, drying of agricultural crops, desalination and heating, ventilation, air conditioning and refrigeration (HVAC-R) systems, can be powered by solar energy [6].

Solar energy is concurrently converted into thermal and electrical energy utilising hybrid photovoltaic/thermal (PV/T) technology [7]. Buildings can use PV/T systems to upgrade their energy and environmental effectiveness. Net-zero constructions can be supported by building-integrated photovoltaic-thermal (BIPV/T) systems, which could generate electrical and thermal energies as well as act as thermal insulators [8].

The need for energy in buildings accounts for the majority of the global energy demand [9]. Building energy usage can account for up to 40% of global energy supply, with space heating and hot water generation making up the majority of this demand [10]. In 2021, space and

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water heating accounted for almost half of building energy demand, resulting in 2450 Mt of direct CO_2 emissions, according to a publication by the International Energy Agency (IEA) [11]. In order to lower both the negative impacts of environmental factors and the increasing energy demand, the integration of renewable energy resources into buildings has been frequently used recently [12]. BIPV/T systems can be utilised to help meeting these energy demands in buildings.

Buildings require both electrical and thermal energy for tasks including space cooling and heating, water heating, ventilation, lighting, and powering various devices. In addition, compared to residential and commercial buildings, industrial structures and activities (including buildings construction industry) use more thermal and electrical energies [13]. Energy consumption and emissions by sector (for 2019) are presented in Fig. 1. In essence, it takes a lot of energy to maintain safe, healthy and comfortable indoor environments in buildings [12].

According to International Energy Outlook Report [16-18], the global energy consumption would enhance by 56% between 2010 and 2040. Buildings accounted for 32% of world's energy use and 33% of GHG emissions in 2012 [18]. This is the outcome of indirect emissions associated with the utilisation of energy as well as direct emissions from the in-situ combustion of fossil fuels. This calls for the development of numerous techniques to lower building energy use and, consequently, GHG emissions. Moreover, direct or indirect global GHG emissions in buildings have enhanced by 1% per year since 2010 [19]. While the decarbonisation of energy consumption in buildings continues rapidly, all necessary measures must be implemented to attain net zero emissions by 2050 [20]. To meet this goal, 20% of newly developed buildings and existing buildings in the world should be in a carbon-zero state by 2030 according to the International Energy Agency [19]. By meeting both electrical and thermal energy demands in buildings, the hybrid renewable technologies (e.g. photovoltaic-thermal systems, solar-assisted heat pumps) enable buildings to meet the zero-carbon goals.

This review study explains the working principle, classification and usage advantages of BIPV/T systems, performance enhancement methods and possible contributions to energy efficient buildings. The originality and the main purpose of the article is to provide a quick guide for new users and researchers to reach current information sources published in literature that relate to BIPV/T systems. The study does not focus on examining BIPV/T systems in depth, but on referencing publications and their hotspots, and providing readers with an overview of this research topic. In addition, the advantages, challenges and future research directions of the BIPV/T systems are clearly stated and supported by references, in order to provide the readers with knowledge and understanding of renewable systems that will contribute to the goal of zero energy buildings.

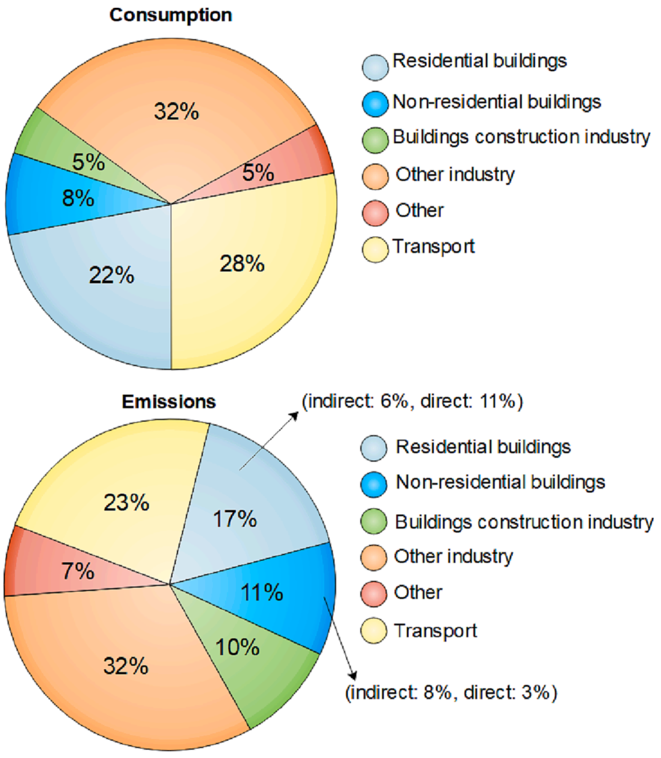


Fig. 1. World's energy consumption and emissions by sector, in 2019 [14,15].

2. Methodology

This article presents recent developments of BIPV/T systems and their possible contributions on the zero energy buildings. The methodology for review of scientific literature relating to BIPV/T systems is illustrated in Fig. 2. It should be indicated that the given chart includes the studies searched through the Web of Science [21]. Moreover, number of publications per year (1996–2022) on BIPV/T systems in Web of Science is illustrated in Fig. 3.

"Topic Search" and "Keyword Plus" tools have been used in the process, which ensures a comprehensive literature search and selection of studies relating to BIPV/T systems that are available in the Web of Science. According to the search, there were nearly 45 times more studies that concerned PV/T systems than studies related to BIPV/T systems. This indicated potential research gaps and opportunities for further research in BIPV/T systems. In this regard BIPV/T systems were selected as a focus point in this review study instead of the studies that analysed PV/T systems. In the initial stage of this review study, working principle and basics of PV/T systems are explained briefly. Then, classification of PV/T and BIPV/T systems is presented. It should be stated that there are various types of classifications can be seen in the academic literature. Therefore, these groups are explained in Fig. 6. In this work, BIPV/T systems are divided into the flat-plate and concentrating systems. Recent developments in BIPV/T systems are presented afterwards. Moreover, the advantages of these systems, their possible contributions to net zero buildings, performance enhancement methods, optimal installation locations, suitable types for building systems, challenges and future perspectives are presented and discussed in detail within the scope of this review study.

3. Hybrid photovoltaic/thermal (PV/T) systems

The hybrid photovoltaic-thermal (PV/T) systems, also known as active photovoltaic (PV) cooling systems, can produce electrical and thermal energy at the same time. By using a working fluid to cool the PV panel's surface in a PV/T system, which generates thermal energy, the electrical yield (efficiency) of the PV panel can be enhanced [22,23]. Fig. 4 illustrates the PV/T system's principle. As it is known, PV panels can only generate electrical energy. The remaining part of the solar energy is released to the environment as thermal loss. In a PV/T system, the thermal loss can be reduced and a significant amount of the solar thermal energy can be utilised. I decrease in panel surface temperature increases the electrical output of a PV panel [24] and, thus, the PV/T systems can produce high electrical output because of the utilised cooling fluid in the system.

Due to the fact that PV/T systems employ the same collector area to generate electrical and thermal energy, significant space savings can be realized. Compared to a similar PV panel working in the same environment, the PV/T system's thermal component removes heat from the PV panel, cools the PV cells, and boosts electrical output.

The PV/T systems are created and constructed from a technological standpoint for low and medium temperature processes (fluid delivery temperature: 20 °C-80 °C) [26,27]. The ideal operating conditions for these systems can only be attained at low ambient temperature values because the temperature parameter affects electrical and thermal systems differently [28,29].

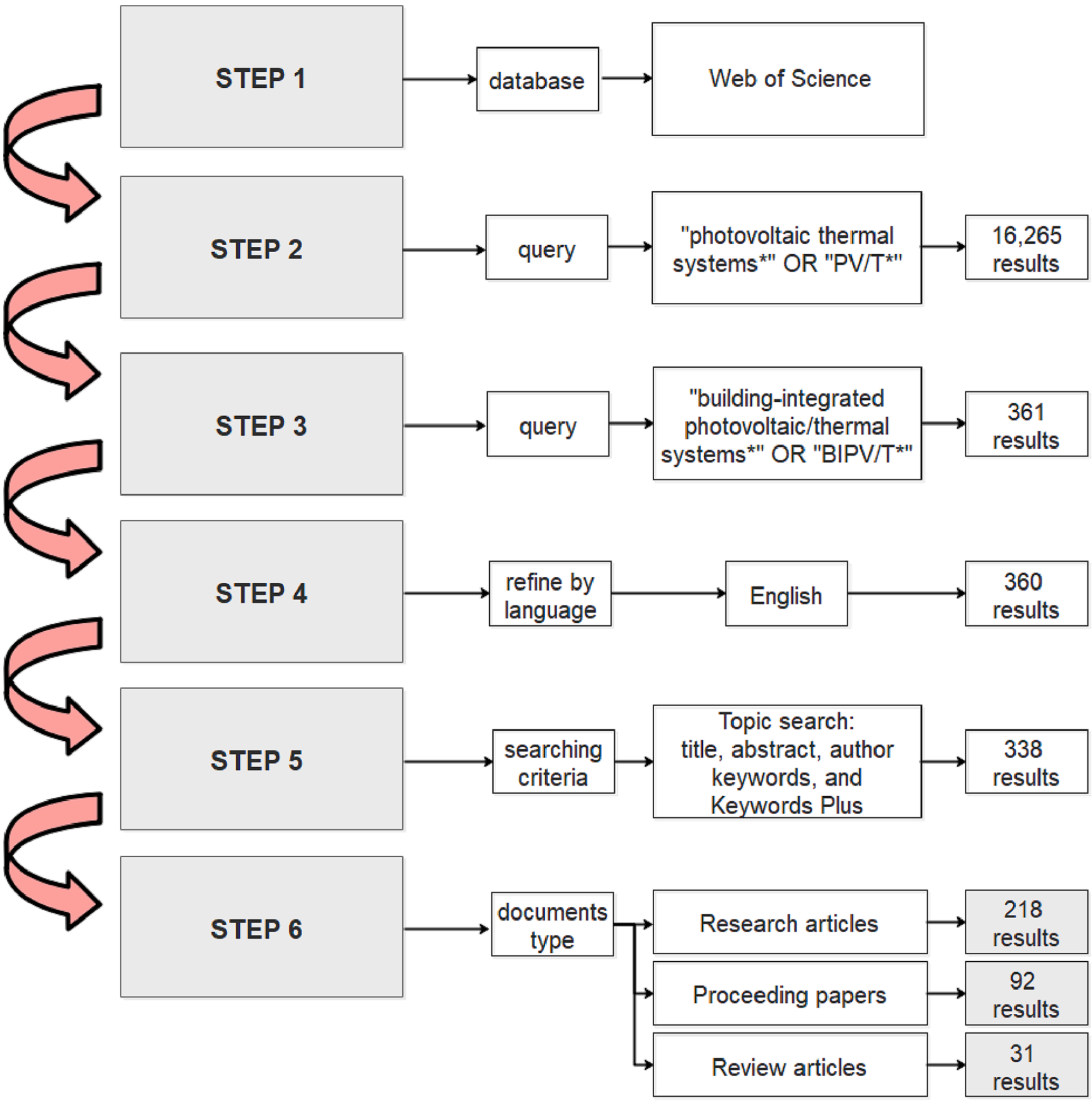


Fig. 2. Systematic review of scientific literature relating to BIPV/T systems.

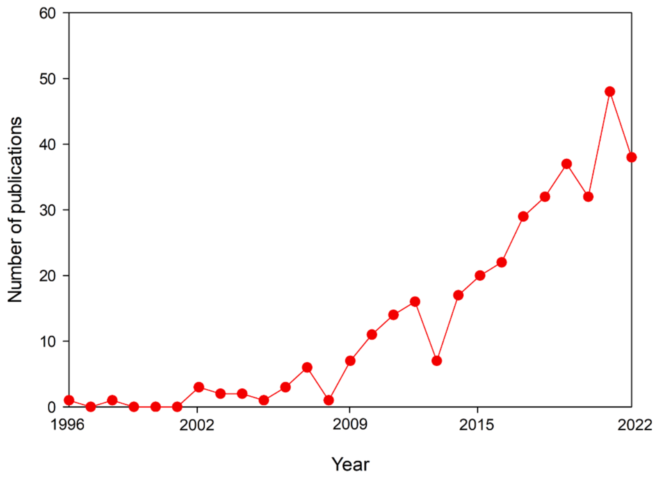


Fig. 3. Number of publications per year (1996–2022) on BIPV/T systems.

3.1. Classification of PV/T and BIPV/T systems

The concept of PV/T systems is to increase their electrical performance by lowering the surface temperature of a PV module while also recovering thermal energy from a PV panel using a working fluid. Thus, it is possible to generate both thermal and electrical energy. As in flat-plate solar collectors, which can use air, water, mineral oils, or nanofluids as working fluids [30]. Depending on the type of a PV panel, thermal collector, working fluid, clear cover (glazing) type, and absorber surface material, PV/T systems can be divided into different categories. Type of the used PV panel is one of the main categories for grouping PV/T systems. PV panels can be divided into 3 groups according to the amount of silicon crystals they contain: monocrystalline, polycrystalline and multi-junction. Monocrystalline PVs have a higher cost than polycrystalline PVs, although they are widely used with their high efficiency and long lifetime. Multi-junction PVs, on the other hand, have significant efficiency and energy conversions within themselves. However, their usage areas are limited due to the high costs. Moreover, concentrated and non-concentrated (flat plate) thermal collector types are classified according to the modifications they are used in.

Numerous studies concerning various working fluid types to test PV/T systems have been published in the literature. Previous studies examined numerous PV/T designs, as well as various working fluids and

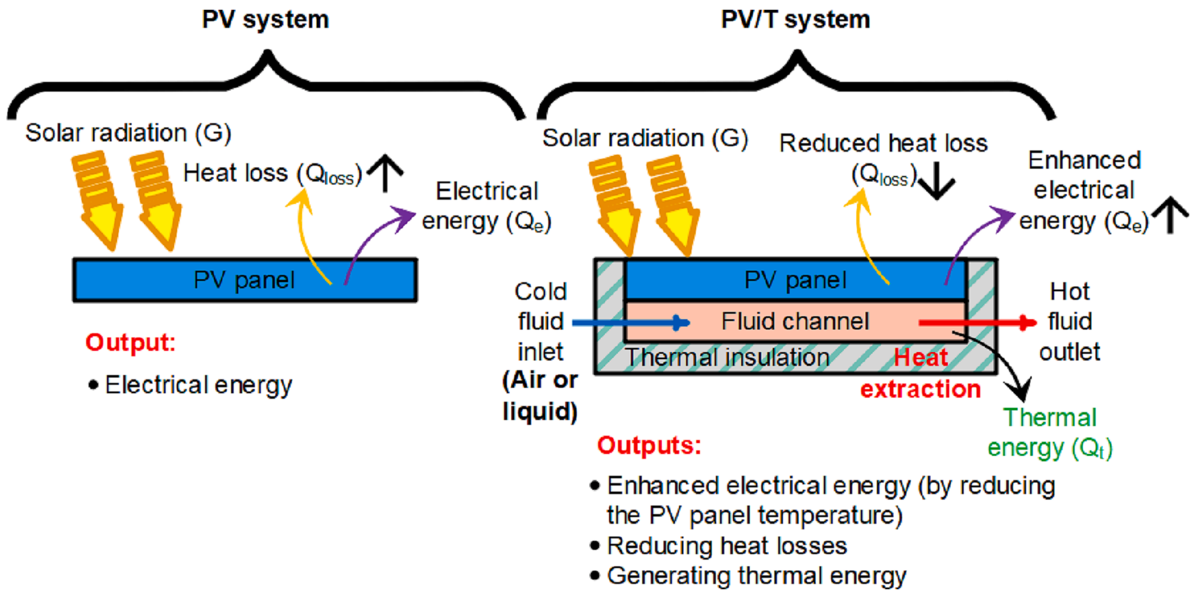


Fig. 4. Concept of PV/T system, adapted from [25].

PV panel types (e.g., monocrystalline [31,32], polycrystalline [33-35], thin-film [36]). PV/T systems can be categorised into several application areas, design details, and end use purpose such space heating, hot water production, ventilation, and electricity generation Fig. 5 presents a classification of hybrid PV/T systems.

The two major goals of using PV/T systems are to concurrently generate thermal energy and electrical energies in order to increase electrical yield by lowering the surface temperature of the PV. In a PV/T, a working fluid conducts heat away from the PV panel surface within the bounds of the reasons. A liquid or a gas can be the working fluid. The thermal energy can be used to generate household hot water in systems that use a liquid phase working fluid, such as water. The thermal energy gained by air-powered devices could be used for space heating and other HVAC-R procedures.

Building-integrated PV/T (BIPV/T) and building-added PV/T (BAPV/T) are the two main types of applying PV/T systems to buildings. The BAPV/T is an addition to the current structure, which is tangentially related to its functional features [39]. They can be applied to a building either by using a standoff or rack-mounted approaches. On the other hand, BIPV/T is a technique for aesthetically integrating a system into a new building structure, and it allows for the replacement of traditional roofing and envelope materials including slate, shingles, tiles, and metal roofing [40]. In short, the major difference between the BIPV/T and BAPV/T systems are the installation method to the building. The better aesthetic value, replacement of the conventional building components, and use of solar energy in buildings make BIPV/T configurations superior to BAPV/T systems in many ways [41,42]. In other words, BIPV/T represents the idea of replacing the conventional building envelop, like window, wall, and roof with PV/T systems. BAPV/T denotes that the PV/T system is attached/added or applied to a building. BIPV/T systems hold great promise as means of achieving net zero buildings [43]. PV/T systems integrated into buildings can also act as building envelope materials. For this reason, it can be said that these applications behave as a thermal insulation material [44]. An extremely energy-efficient building that is entirely powered by on-site and/or off-site sustainable resources, with any leftover carbon balance offset, is known as a net zero building [45]. The use of transparent materials in BIPV/T systems can increase their applicability to windows. In addition, these systems can provide benefits such as shading, as well as electrical and thermal energy production [46]. Innovative BIPV/T systems, which include various modifications in terms of the application area, or the working fluid can be classified as shown in Fig. 6. Moreover, examples of recently published surveys on BIPV/T systems with different configurations are given in Table 1. Studies shown in Table 1 are categorised based on Fig. 6 (final column in Table 1).

As can be seen from Fig. 6, BIPV/T systems can be grouped in terms

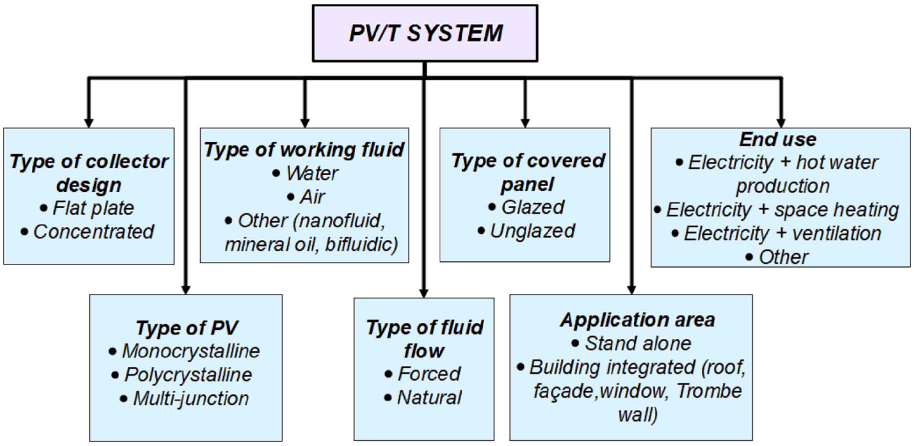


Fig. 5. Classification of PV/T systems, adapted from [37,38].

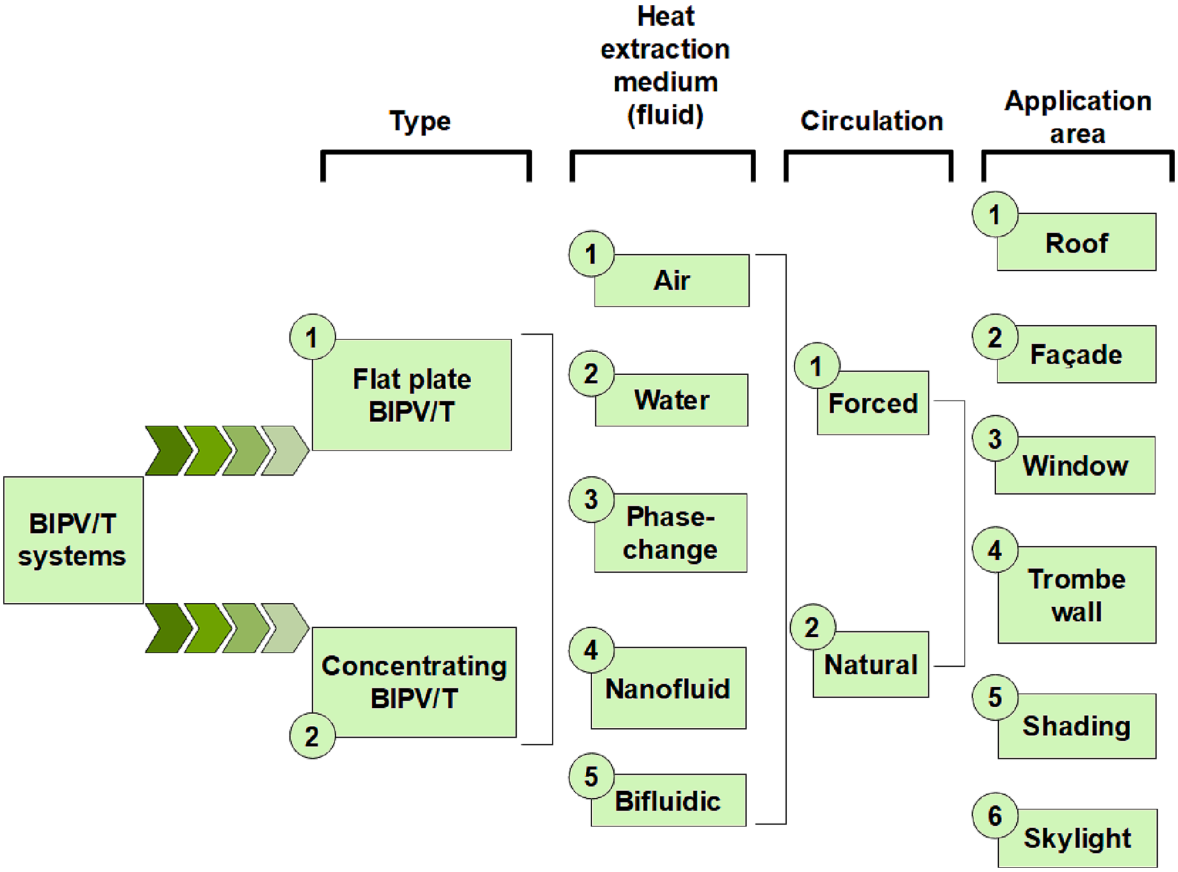


Fig. 6. Categorisation of BIPV/T systems.

of various configurations. Moreover, the recent applications are given in Table 1 in detail. In the next subsections, the BIPV/T systems are grouped in two including flat-plate and concentrating types and related studies are given in the mentioned parts.

3.1.1. *Flat-plate (planar) BIPV/T systems*

The flat-plate systems have a great potential to be utilised in buildings in order to generate both thermal and electrical energy loads [72,73]. There are some studies that used flat-plate BIPV/T systems to cover electrical and thermal energy demand of buildings. Garcia et al. [74] showed that using a BIPV/T-based heating system could meet the large amount of thermal and electrical loads, 34% and 55% respectively, with low carbon footprint. In flat-plate systems, different types of working fluids can be selected, including air, liquid (water) and refrigerant gases depending on the buildings' energy demand (e.g. domestic hot water, space heating), components (e.g. heat pump, heat pipe) and system type (e.g. façade, Trombe Wall). Rooftop applications are one of the most commonly utilised methods for BIPV/T systems [39]. A general view of a rooftop BIPV/T system with air circulation is given in Fig. 7(a). Vats et al. [75] investigated the impact of the packing factor, of a semitransparent PV module integrated to a building's roof, on the temperature of the module and the indoor air, as well as the electrical efficiency of the BIPV/T system. A variety of PV module packing factors, which is the ratio of the area covered by the PV modules to the area, which is black, were taken into account for energy and exergy analyses. The study showed that a PV module's electrical efficiency increased as its temperature decreased because of a packing factor decrease. Moreover, in another work, a roof-mounted BIPV/T-liquid system was investigated [76]. With the aid of a PV/T water heating system and an experimental setup set up on a roof in Korea, the effectiveness of the building heating system was assessed. The researchers concluded that a heating device with a BIPV/T system could lower the building's energy requirements and improve electrical performance by about 16%, while the heating process was in operation. Photographs of the mentioned system are given in Fig. 7(b). Gagliano et al. [77] developed a flexible PV/T system to determine its operative conditions. In order to model various energy demand situations, the PV/T plant's electrical and thermal loads were controlled. Based on experimental observations, the given study described the primary thermal and electrical operating parameters of the PV/T plant with the PV/T modules connected in series. Furthermore, flat-plate BIPV/T systems can be also hybridised with heat pump devices. Shao et al. [78] developed a BIPV/T roof system for electrical energy production and evaporation for a heat pump device. According to their experimentally obtained findings, mean electrical and thermal yields were found as 7.2% and 69.3%, respectively. In another work, Shao et al. [79] experimentally surveyed a direct-expansion PV/T-roof heat pump system. According to their results, the average coefficient of performance value was 5.9 for the heat pump system.

Flat-plate BIPV/T systems can also be used in façades of buildings [80,81]. This approach is beneficial especially in the regions with limited roof areas (e.g. urban areas). This method also ensures maximum utilisation of building surfaces. Shahsavar and Arıcı [82] developed a vertical heat pipe BIPV/T appropriate for building façades. The schematic view of the designed BIPV/T is given in Fig. 8. Moreover, the designed PV/T system is coupled with a heat exchanger. Results showed that the PV/T-heat pipe system can produce more energy than the conventional PV/T system. Pugsley et al. [83] developed a BIPV/T façade system based on a PV panel and an integrated collector-storage solar water heating system. The layers of the developed system can be seen in Fig. 9 in a schematic diagram, which aimed to regulate absorber temperatures and thermal losses using the thermal diode in the system. Saadon et al. [84] designed and simulated a ventilated BIPV/T envelope with natural convection. Their BIPV/T results gave an understanding of

Table 1
Recent works on BIPV/Ts with different configurations.

Technology	Reference	Publication year	Application category	Type	Fluid	Circulation		Application area	Modification	Category (see Fig. 6)
						Forced	Natural			
Thermosyphon PV/T system	[47]	2005	Water pre-heating	flat plate	water	✓	_	façade	Amorphous-silicone hybrid collectors were used, covering 0.66 of the west and south facing facades of an apartment building.	1.2.1.2
PV/T technology, which combines PV cells and solar collectors, focuses solar energy on the cells for a window system utilising reflectors	[48]	2010	Electric and hot water production	concentrated	water	✓	_	window	Modified solar window system was compared to with and without conventional solar energy system.	2.2.1.3
A new BIPV/T collector was modelled using numerical approaches	[49]	2010	Hot water heater	flat plate	water	_	✓	roof	Thermal collector system with active heat recovery	1.2.2.1
A small-size version of the roof-mounted BIPV/T system (net-zero energy solar house)	[50]	2011	Electricity generation and space heating	flat plate	air	_	✓	roof	A roof system with an inclination angle of 30–45°was created with an insulated roof layer and a heating air drawn from the channel formed by the upper roof surface.	1.1.2.1
Shading-formed BIPV and BIPV/T Systems on Building façades	[51]	2011	Cooling, shading	flat plate	air	_	✓	façade	Angular-placed BIPV/T system	1.1.2.2
Glazed air heater based BIPV/T with multiple inlets	[52]	2014	Improving thermal efficiency	flat plate	air	✓	_	façade	Different angles of the solar simulator were tested on the façade system. Using more than one inlet instead of a single inlet in the system has increased the heat transfer coefficient and removed the heat from the PV panel.	1.1.1.2
Flat plate single glazing sheet integrated BIPV/T system	[53]	2014	Electricity generation, hot water production	flat plate	air, water	✓	✓	façade	In the system consisting of a polycrystalline photovoltaic (PV) module and a spiral flow absorber, the PV module is placed under a flat plate glass plate.	1.1.2.2 1.2.1.2
A new HP-BIPV/T system for usage in residences	[54]	2016	Domestic hot water generation	flat plate	water	✓	_	façade	Heat pipe BIPV/T system with latent heat storage and packing material	1.2.1.2
Nanofluids integrated split the solar spectrum PV/T system	[55]	2017	Power generation	concentrated	nanofluid	✓	_	window	Configuration of a nanofluid-through borosilicate glass tube with a transparent quartz plate cover and side walls with cooling channels	2.4.1.3
Building integrated photovoltaic/thermal concentrator system	[56]	2017	Space heating	concentrated	air, water	_	✓	roof, façade	Comparison of system performances of flat reflector and parabolic reflector at different sun angles	2.1.2.2 2.2.2.1
PV/T hybrid solar technology	[57]	2019	Heat recovery, power generation, cooling	flat plate	air	✓	_	roof	PV roof tile without and with cooling system	1.1.1.1

(continued on next page)

Table 1 (*continued*)

Technology	Reference	Publication year	Application category	Type	Fluid	Circulation		Application area	Modification	Category (see Fig. 6)
						Forced	Natural			
Flat plate BIPV/T system integrated into the south façade of a high-rise structure	[58]	2019	Space heating/cooling, hot water generation, electricity generation	flat plate	bifluidic	✓	_	façade	Three thermal zones are determined to consist of reference system and proposed system. The RS is a conventional building modification, while the PS consists of a modified unglazed BIPV/T collector.	1.5.1.2
PV Façades of Reduced Costs Incorporating Devices with Optically Concentrating Elements	[59]	2020	Space heating, water heating air-conditioning, daylighting	concentrated	air, water	✓	✓	Skylight, façade	-Concentrated photovoltaic systems, -Concentrating solar thermal systems -Concentrating solar daylighting systems	2.1.2.6 2.2.1.2
Roof tile PV/T air system with building plates	[60]	2020	Air-cooling	flat plate	air	✓	_	roof	The system, in which structure and electrical parameters are used together, has been tested with nine monocrystalline solar cells. The PV panel is placed in a wooden case to provide roof conditions.	1.1.1.1
Photovoltaic thermal solar collectors	[61]	2021	Cooling absorption, thermal and electricity generation	flat plate	water	✓	_	window	trigeneration system using an absorption cooling	1.2.1.3
Thermal energy storage heat sink and building integrated concentrated photovoltaic system	[62]	2021	Passive and active cooling	concentrated	nanofluid	_	✓	façade	passive and active cooling with nanofluid and phase change material (PCM) unit	2.4.2.2 2.3.2.2
Building Integrated, Transparent, Concentrating, PV/T (BITCoPT) AIF-SC (Active Integrated Façade-Solar Collector) technology	[63]	2021	Electrical generation, thermal collection	concentrated	air	✓	_	façade	First model includes behaviour of the utilised components (glazing types, concentrating optics, water block) and one stack, ten modules was determined as a second model.	2.1.1.2
BIPV/T power/heat technology	[64]	2022	Cooling	flat plate	bifluidic	✓	_	façade	Bi-fluidic BIPV/T system with water-cooled wall	1.5.1.2
BIPV/T Double skin I technology	[65]	2022	Heating/cooling load	flat plate	air	_	✓	façade	Different configurations of glass windows section on façade system	1.1.2.2
Exploiting concentration technology	[66]	2022	Space heating	concentrated	air	✓	_	façade	Concentrating Photovoltaic/Thermal Glazing (CoPV/TG) system	2.1.1.2
Dynamic multi-objective optimisation (MOO) for residential building	[67]	2022	Space heating	flat plate	air	✓	_	façade	The I system with integrated PCM layer and the system without integrated PCM layer	1.1.1.2 1.3.1.2
The refrigerant-added BIPV/T system, combination of the BIPV/T with heat pump	[68]	2022	Power generation, space heating	flat plate	bifluidic	✓	_	roof	Auxiliary equipment such as evaporator, compressor and condenser, the throttle constituted the bi-fluidic PV/T ventilated roof system	1.5.1.1

(*continued on next page*)

Table 1 (*continued*)

Technology	Reference	Publication year	Application category	Type	Fluid	Circulation Forced	Circulation Natural	Application area	Modification	Category (see Fig. 6)
Air-Type BIPV/T Collector with Perforated Baffles	[69]	2022	Space heating, electrical generation	flat plate	air	_	✓	façade	Two type modules are manufactured for indoor and outdoor experiments using perforated thermal plate.	1.1.2.2
Curved PV/T roof system	[70]	2022	Hot water generation, water-natural ventilation	flat plate	water	✓	_	roof	The water cycle is produced with the help of a pipe connected to the inlet of the collector and another pipe integrated to the outlet of the water container.	1.2.1.1
The Artificial Neural Networks (ANN) modelling hybrid BIPV/T façade system.	[71]	2022	Space heating	flat plate	water	✓	_	façade	Double skin ventilated window embedded with CdTe cells and multi-functional PV/T wall (FPV/T wall)	1.2.1.2

The systems that operate with forced or natural convection are marked with a check mark (✓) and those that do not are marked with a minus (-) sign. The systems that include both circulations are indicated with two check marks (✓) (Column 7).

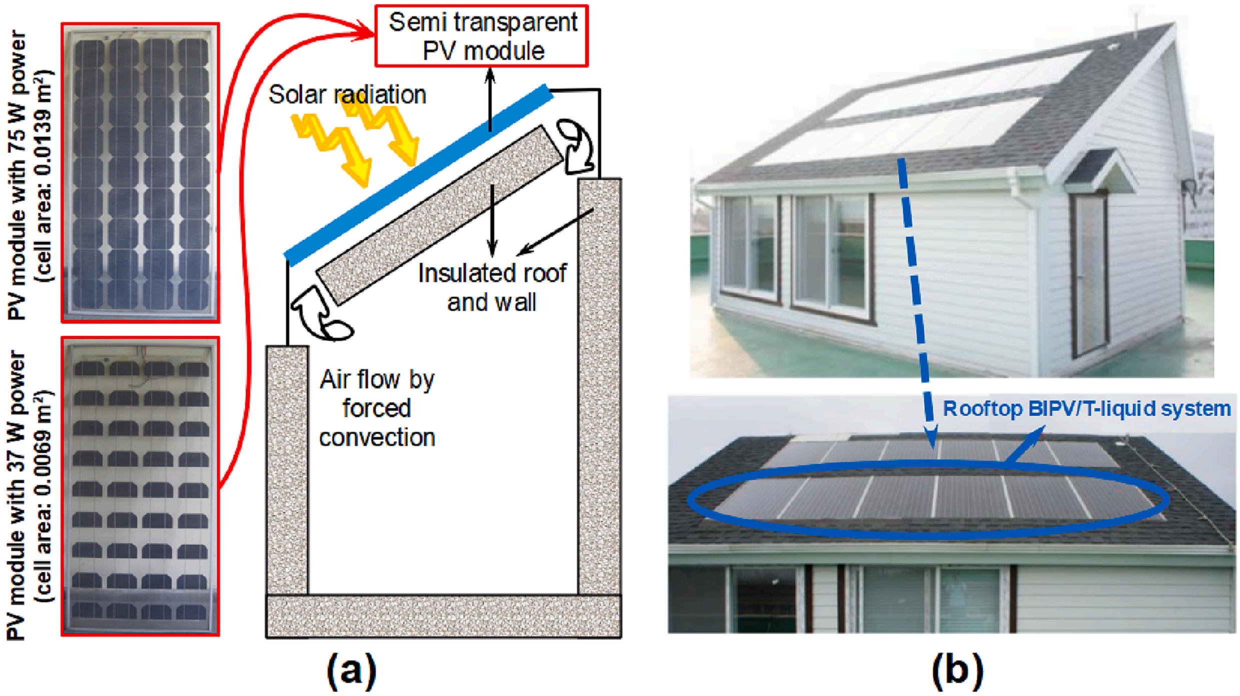


Fig. 7. Views of rooftop BIPV/T systems: (a) rooftop BIPV/T-air system [75], (b) rooftop BIPV/T-liquid system [76], adapted from the given references.

the effect of this component on the building's energy behaviour, particularly the impact of the PV's degree of transparency. The given study stated that a BIPV/T system was an important element for net zero energy buildings and had great potential for lowering cooling requirements. Additionally, it was possible to see BIPV/T façade systems with latent heat storage units. Pereira and Aelenei [85] designed and experimentally analysed a phase change material (PCM)-added BIPV/T façade system for an office building. The system configuration of the given work is presented in Fig. 10. A PCM gypsium board was attached to the system for performance improvement. The system can attain a maximum total yield of 64% with a winter test and 32% with a summer test, according to calculations of the thermal and electrical yields based on optimisation parameters.

One of the other applications of PV/T systems in buildings are Trombe wall systems. Trombe wall system is the most common passive solar heating applications to increase thermal performance in buildings [86,87]. In recent years, many studies have investigated the PV/T integration to Trombe walls. Different configurations used of these systems can be arranged in order to meet the amount of energy needed by the buildings. Abdullah et al. [88] analysed the influence of cooling techniques on the performance of PV-added Trombe walls. The authors investigated conventional system (PV system without cooling), air-

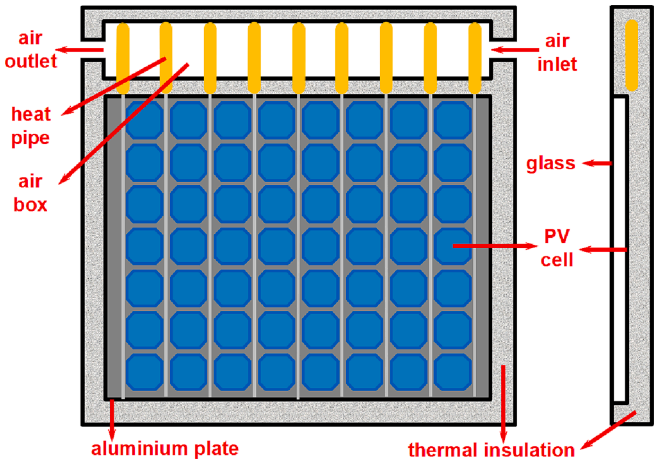


Fig. 8. Schematic view of a vertical heat pipe BIPV/T, adapted from [82].

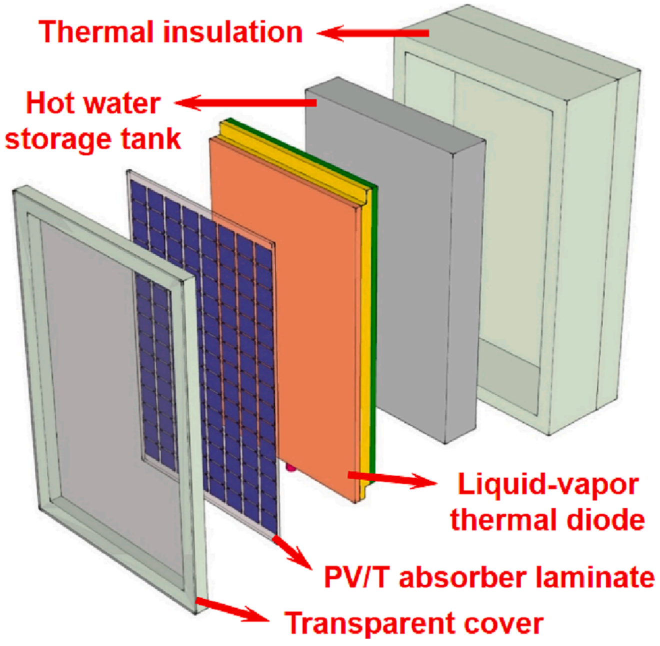


Fig. 9. Layers of a BIPV/T façade system based on a PV panel and an integrated collector-storage solar water heating system, adapted from [83].

cooled, water-cooled and combined air and water-cooled configuration scenarios. The system that employed solely water for cooling showed the highest daily thermal efficiency of 39.81%. In another work, Bruno et al. [89] calculated the monthly auxiliary energy to be covered in buildings with PV/T-Trombe walls for heating applications employing the solar load ratio approach. This approach was optimised using multiple linear regression analyses using data from the TRNSYS software, which made it possible to determine the energy performance of Trombe walls erected on the same building but situated in various locations under the real-world conditions. In another research, Lin et al. [90] developed a “built-middle PV-added Trombe wall system” and analysed it both numerically and experimentally. The system was compared with a conventional PV Trombe wall. The schematic illustration of the developed PV Trombe wall system is given in Fig. 11. The newly developed system’s average total efficiency was 10.83% greater than the conventional configuration.

Latent heat storage units have also been preferred in BIPV/T Trombe wall systems in recent years [91]. Therefore, PV panels in the system could be thermally controlled and the stored heat could be used at night when the solar radiation is not available. Ke et al. [92] investigated the impact of PCM layer placement on the performance of a PV Trombe wall system. The tested configurations are presented in Fig. 12. According to their results, the system with PCM unit placed on the back of the absorber gave the best electrical output, but lowest space heating effectiveness. In addition, the PCM unit performed differently depending on where it was located in the system. When the PCM unit was on the inner surface of the wall, there was no visible decrease in PCM temperature during the night due to heat accumulation. However, when the PCM unit was placed on the back of the absorber, it had the highest temperature variations during the whole day. The minimal PCM temperature that could be achieved at night for the configuration with PCM unit placed close to the thermal insulation section was progressively rising. The configuration with PCM unit placed on the back of the absorbing surface was most influenced by the thickness of the PCM unit. The effects were minimal for the other Trombe wall configurations with PCM unit. Furthermore, some innovative PV Trombe wall applications were identified in literature that integrated nanofluids [93] and porous surfaces [94] for performance enhancement.

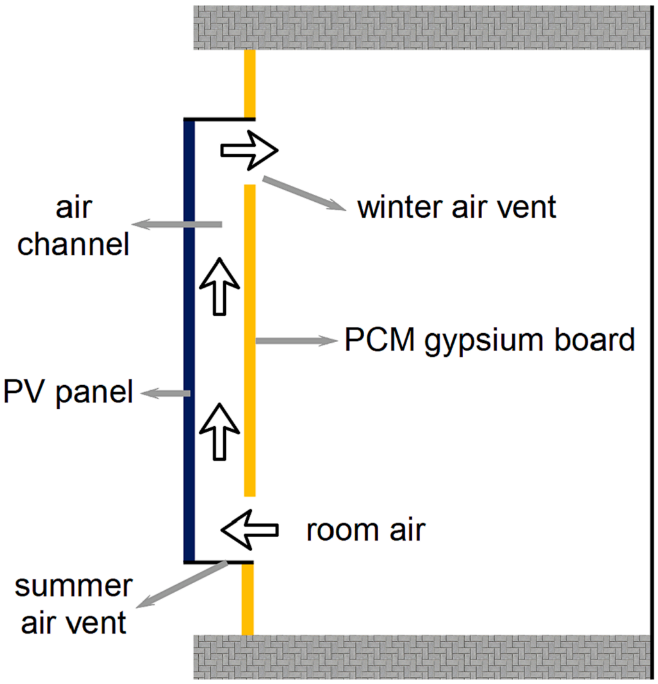


Fig. 10. System configurations of a PCM-added BIPV/T façade system, adapted from [85].

3.1.2. Concentrating BIPV/T systems

Using concentrator equipped BIPV/T systems placed within buildings is a practical approach to use solar energy inside the structures [56]. Using concentrating components in BIPV/T systems allows to improve the amount of the receiving solar irradiance on the PV surface [95]. There are different types of concentrator configurations that can be employed in PV/T systems. Different types of concentrating PV/T configurations are presented in Fig. 13. However, there is a need to determine suitable areas for the application of all these system types to buildings. While many are suitable for flat roofs, not all applications may be suitable for pitched roofs and façades.

The amount of received solar irradiance in the building systems can be improved using concentrating BIPV/T systems. Moreover, this approach can be used to increase the incoming solar radiation in buildings that receive limited solar radiation. Although not as common as flat-plate BIPV/T systems, there are some studies in academic literature where concentrated systems were integrated into buildings. In a

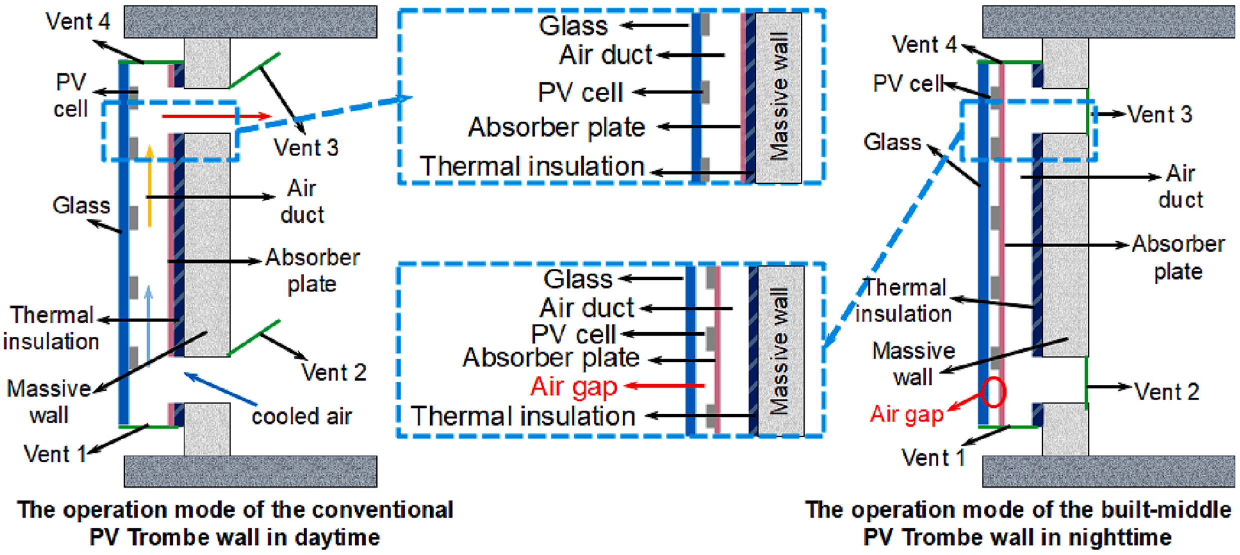
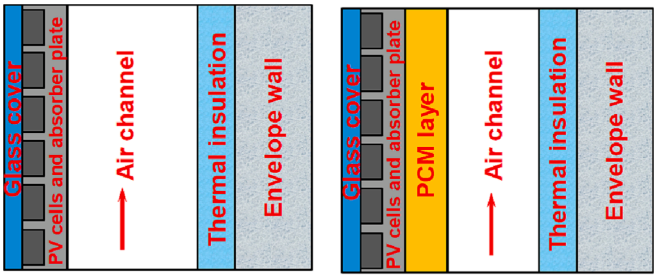
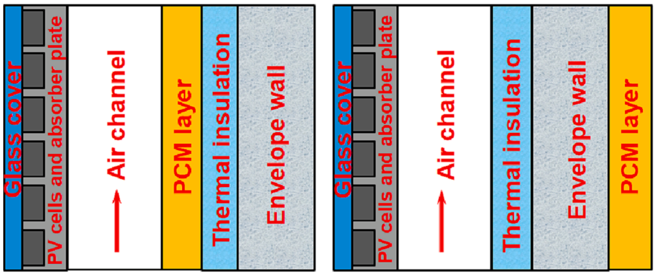


Fig. 11. Schematic diagrams and operation modes of the developed built-middle PV-integrated Trombe wall and conventional Trombe wall systems, adapted from [90].



PV Trombe wall without PCM layer

PV Trombe wall with PCM layer (placed on the back surface of the absorber)



PV Trombe wall with PCM layer (placed close to the insulation board)

PV Trombe wall with PCM layer (placed on the inner surface wall)

Fig. 12. Various PCM layer placements in a PV Trombe wall system, adapted from [92].

study, Chemisana et al. [100] presented a concentrated BIPV/T-liquid system. The developed PV/T module contained a transparent cover (glass) a longitudinal PV module, absorber surface, fins and fluid tube made from copper and aluminium casing. The structure of the developed system is presented in Fig. 14, which compares the developed concentrating system with a system without concentrator (on the right, reference module vs. concentrating module). The concentrating reflector outperformed the reference (without concentrator) system both thermally and electrically. The heat output of the concentration module was about twice of the base system, while the electrical power measured in the concentration arrangement was more than 4.5 times that of the reference system. Similarly, Novelli et al. [63] analysed a novel BIPV/T with concentrators to improve the amount of the solar radiation incoming to the building façade. The schematic view and a photograph of the system is given in Fig. 15. The study obtained the cogeneration efficiency of the system of 43.6% at the operation temperature of 58 °C. Concentrating BIPV/T systems can be also integrated to the building louvres to benefit as a shading device as well as electricity and thermal energy generation. Previous research integrated a concentrating BIPV/T system into the shading louvre of a building [101], Fig. 16. With the applied area of the system, it was possible to altitude track the solar beams for improving the performance. The developed dynamic model was simulated for two cities in Israel (Sde Boker) and France (Avignon), where the concentrator obtained yearly average optical yields of 43.0% and 30.3%, respectively.

3.2. Advantages of BIPV/T systems

The decarbonisation of buildings is one of the main obstacles and an area of emphasis for all stakeholders in reducing the harmful effects of climate change [102]. To suit the needs of buildings, BIPV/T systems can produce both thermal and electrical energy to support heating and cooling systems. The application of emerging technologies, such as BIPV/T to buildings, helps in reducing the carbon footprint of buildings and is also an important factor to sustainable design and operation [103]. PV/T systems could create more energy per unit surface area and at a lower cost of production and installation than solar thermal collectors and side-by-side photovoltaic panels. For applications with a limited amount of roof area and those that require both power and heat, BIPV/T systems are especially well suited. BIPV/T systems, therefore, have considerable promise for the household cooling and heating market [104,105]. BIPV/T systems have many advantages when compared to conventional PV systems. Space savings can be achieved by employing PV/T systems in buildings, because both electrical and thermal energies can be produced in the same collector area. Moreover, BIPV/T reduce heating and cooling loads and electricity bills. These systems are claimed to have a maximum thermal efficiency of circa 55% [44]. The cost of electrical energy produced by BIPV systems is higher than the (conventional) electricity received from the network. As a result, upgrading a BIPV to a BIPV/T has favourable effects on the current system from an economic and thermal standpoint. The technique utilised in BIPV/T systems to recover heat using air or a fluid significantly lowers the demand for electrical energy. According to a case study

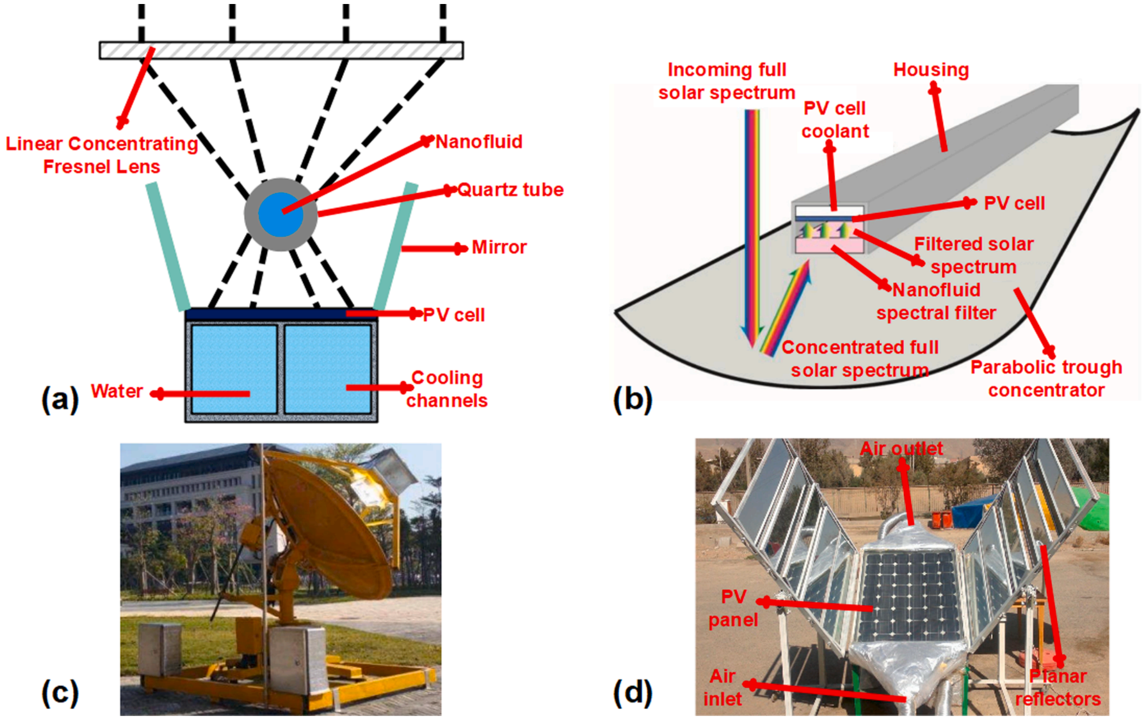


Fig. 13. Various types of concentrating PV/T applications: (a) PV/T system with Fresnel lens [96], (b) Parabolic trough concentrated PV/T system with spectral filter [97], (c) A concentrating dish PV/T with PCM [98], (d) A concentrating PV/T with planar reflectors [99], adapted from the given references.

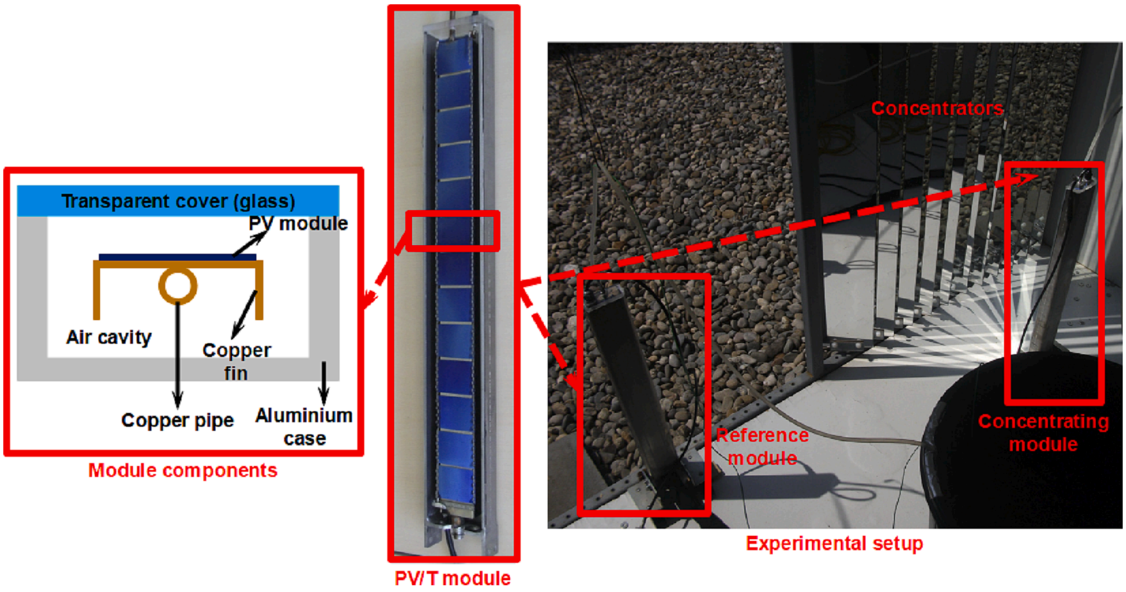


Fig. 14. A Fresnel-transmission concentrating BIPV/T-liquid system: schematic view (left), photograph of the developed PV/T module (middle), photograph of the experimental setup (right), adapted from [100].

carried out in Canada, BIPV/T systems consistently generate more usable energy than BIPV do, and an outcome, their break-even expense when compared to BIPV is always positive [106].

The power plants established for electricity generation are generally located outside the urban areas. This causes additional costs and losses in the transmission and distribution processes of electrical energy [107]. With the use of BIPV/T technology, the need for electrical power transmission and additional costs of maintaining the power grid infrastructure and related components can be reduced [108,109].

Moreover, BIPV/T systems can be used as construction components for thermal insulation. Building façade systems that operate as thermal diodes have grown in significance recently [110]. Systems that allow heat to flow, preferably in one direction. The effectiveness of the building structure is improved by the addition of a thermal diode, which permits heat transfer in one direction but offers thermal insulation when transfer of heat is undesirable [111].

3.3. Performance increment methods of photovoltaic-thermal (PV/T) systems

PV/T system’s yield (efficiency) could be increased using a variety of configurations. The material and system geometry serve as the

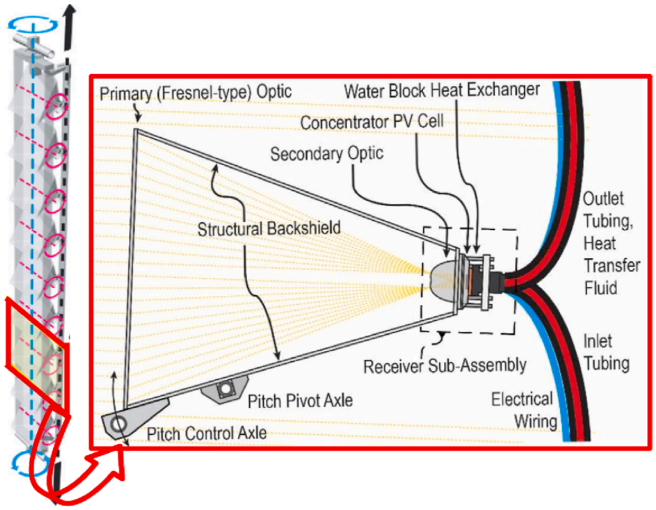


Fig. 15. A view of a concentrating BIPV/T for façade applications, adapted from [63].

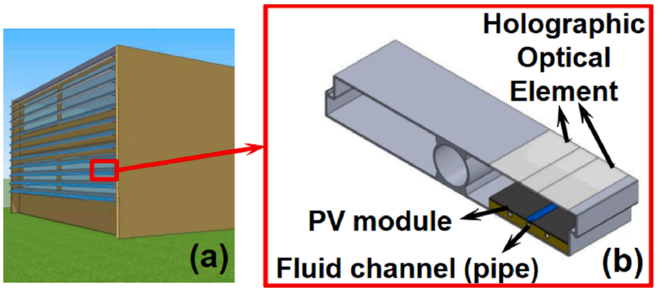


Fig. 16. The image of the reference building (a) and the section of a concentrating BIPV/T-liquid system applied to shading louvres (b), adapted from [101].

foundation for these designs. The performance enhancement methods of PV/T systems are mainly grouped in three categories including geometrical modifications, working fluid modifications and utilisation of thermal energy storage systems.

3.3.1. Geometrical modifications in PV/T systems for performance enhancement

Heat transfer is considerably increased by using materials with high heat conductivity, like aluminium and copper. Additionally, it is feasible to enhance the thermal and electrical yield by lengthening the working liquid's time in the system and expanding the fluid flow's surface area for heat transfer using various fluid channel changes, particularly for PV/T air collectors. Employing extended heat transfer surfaces like fins and baffles can help improve the yield of PV/T systems [112,113]. Longitudinal fins are one of the most utilised geometrical modifications in PV/T-air systems to upgrade the heat transfer surface area. In a study, Mojumder et al. [114] structured a PV/T system with longitudinal fins and experimentally analysed. The designed fins were placed under the PV panel to convey the heat using the working fluid (air). The experiments were performed using various fin numbers, solar radiation values and flow rate vales. Using longitudinal fins significantly improved both electrical and thermal performance of the analysed PV/T system. The schematic view of the system is presented in its reproduced version in Fig. 17. Chandrasekar et al. [115] analysed PV/T systems with and without longitudinal fins including flat and wavy configurations in their experimental study. Their experimentally obtained results showed that average electric power improved by 19.29%.

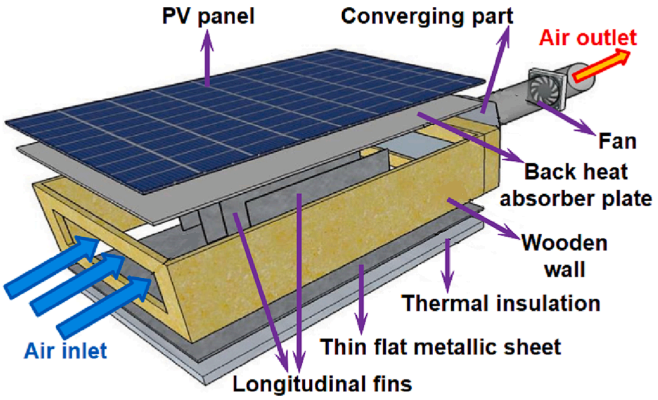


Fig. 17. Schematic view of a finned PV/T-air system, adapted from [114].

Baffles and obstacles are also widely utilised geometrical modifications to upgrade the effectiveness of PV/T systems. They generally utilised to improve the turbulence intensity inside the air channel and lengthen the residence time of the fluid in the PV/T system. Yu et al. [116] developed a single-flow PV/T system with triangular baffles. Schematic view and a photograph of the system is presented in Fig. 18. The authors examined the effects of adding triangle-shaped obstacles on the performance of an air-flowing PV/T system. Using baffles improved the thermal performance by 31%. In another work, Tuncer et al. [117] developed PV/T-air systems with various geometrical modifications including grooved absorber surface, spherical obstacles, and rectangular baffles. It should be indicated that numerically attained findings showed that using three different geometrical modifications upgraded the outlet temperature by 15.77% in comparison to the unmodified system. The geometry of the system and temperature contours of the various modifications are presented in Fig. 19. Experimental outcomes showed that mean total exergetic yield of the PV/T system was attained between the range of 10.65–11.17%. In addition, Shrivastava et al., [118] designed five different PV/T-air collector design in their numerical and experimental examination. They analysed a conventional PV/T, a PV/T with fully transverse fins, a PV/T with semi-transverse fins, a PV/T with longitudinal fins and planar baffles and a PV/T with longitudinal fins and inclined baffles. The maximum exergetic efficiency was improved from 20% to 28% employing longitudinal fins and inclined baffles.

Flow path modifications can be also grouped in geometrical modifications and widely used to improve the performance of both air type and liquid type PV/T systems. In a work, Hoseinzadeh et al. [119] investigated three types of flow paths in a PV/T-water system including direct, spiral and curved types. According to their outcomes, the highest electrical efficiency was attained in the configuration with curved flow path. In another work, Ooshaksaraei et al., [120] four different types of air type PV/T systems based on a bifacial PV modules and internal reflectors. The schematic views of the analysed systems are presented in Fig. 20. According to their experimentally obtained outcomes, overall energetic and exergetic yields of the unmodified PV/T (single air channel) varied between 23 and 52% and 4–10%, respectively. The other systems with extra glazing gained higher thermal exergy values; however, adding extra glazing reduced the electrical output. Moreover, the parallel-flow configuration gave better thermal output. However, the exergy production and exergy efficiency of a PVT collector were greatly impacted by the electrical exergy since it had a greater value. In this case, a single-flow system with single air channel was stated as ideal due to the second law of thermodynamics. In another scientific study, Rajoria et al. [121] analysed a BIPV/T-air system with different flow path configurations. The authors introduced room air temperature expressions for BIPV/T systems installed on building roofs, and investigated the BIPV/T system's performance. A comparative examination of BIPV/T systems has been conducted based on the solar cell tile and the

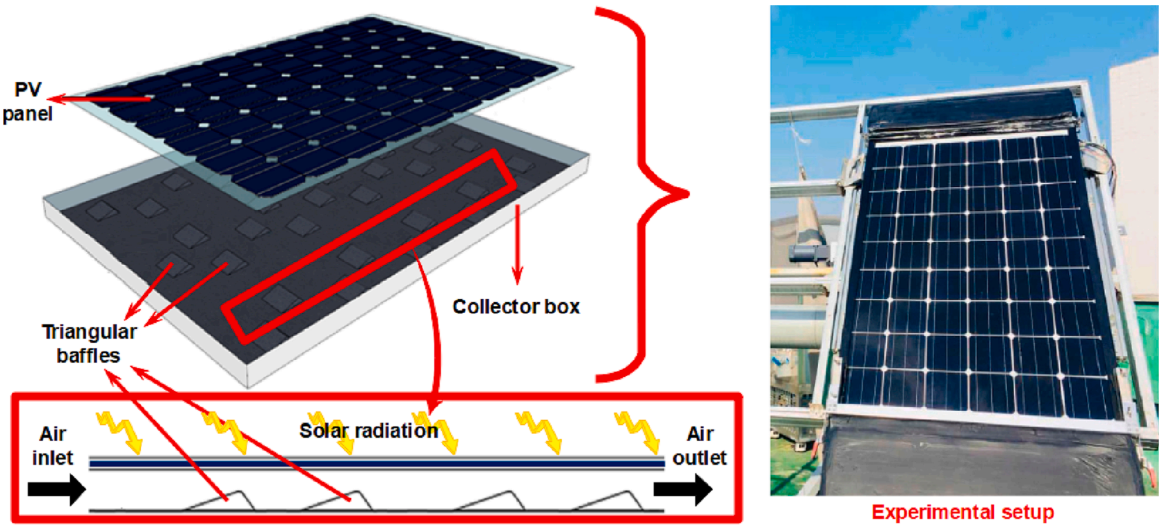


Fig. 18. A PV/T system with triangular baffles; schematic view of the system (left), a photograph of the experimental setup (right), adapted from [116].

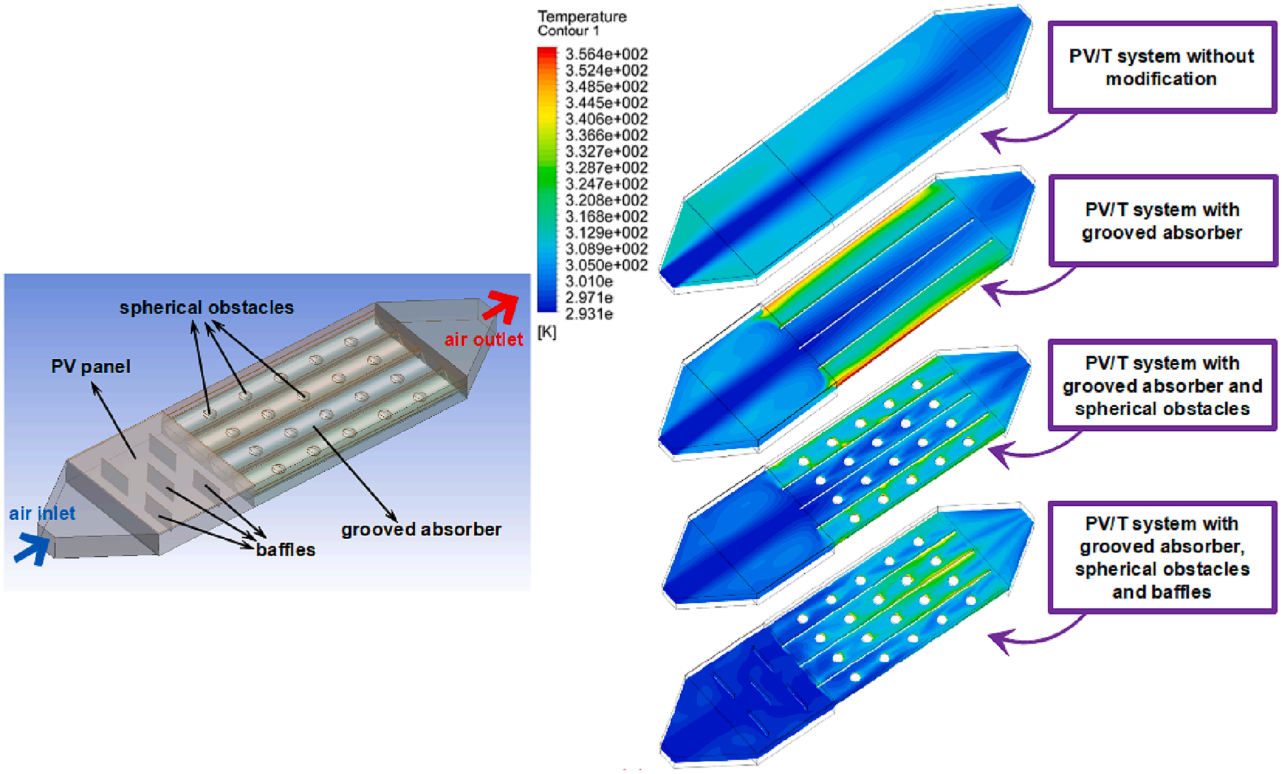


Fig. 19. The geometry of the PV/T-air system (left) and temperature contours of the various modifications (right), adapted from [117].

semi-transparent PV/T arrays. It has been noted that semi-transparent PV/T roofs had a substantially better usable thermal energy gain than solar cell tile roofs. Schematic view of the flow path of a BIPV/T-air system with solar cell tile configuration is given in Fig. 21. The semi-transparent PV/T roof's greater heat removal qualities result in a higher useful thermal energy gain of 2.0 kWh.

The use of porous surfaces in PV/T systems as extended heat transfer surfaces to improve the thermal and electrical performances has been studied in previous scientific publications. For instance, porous plates added to a bifluidic PV/T collector showed the maximum values of thermal and overall efficiency values as 70.59% and 81.61%, respectively [122]. Additionally, generated electrical power was improved as 22.56 W by adding bifluidic fluid channel and porous baffles. In another work [123], an air type PV/T system was modified with porous media. The PV panel was placed in the middle of the flow channel to remove the heat from both upper and lower surfaces.The air travelled through the ducts in the same directions, while the bottom path was lined with porous material (glass balls, porosity: 0.437) from the start of the solar panel to its conclusion. The system with the highest daily electrical efficiency had a porous media content of 8.7%. In another work, Fu et al. [124] numerically analysed different types of absorber tubes, including plain, ribbed and porous ribbed types, to improve the performance of a PV/T-liquid system. According to their findings, total yield value of the PV/T system was significantly upgraded employing the porous-ribbed absorber tube.

Table 2 presents recent studies that analysed various types of flow

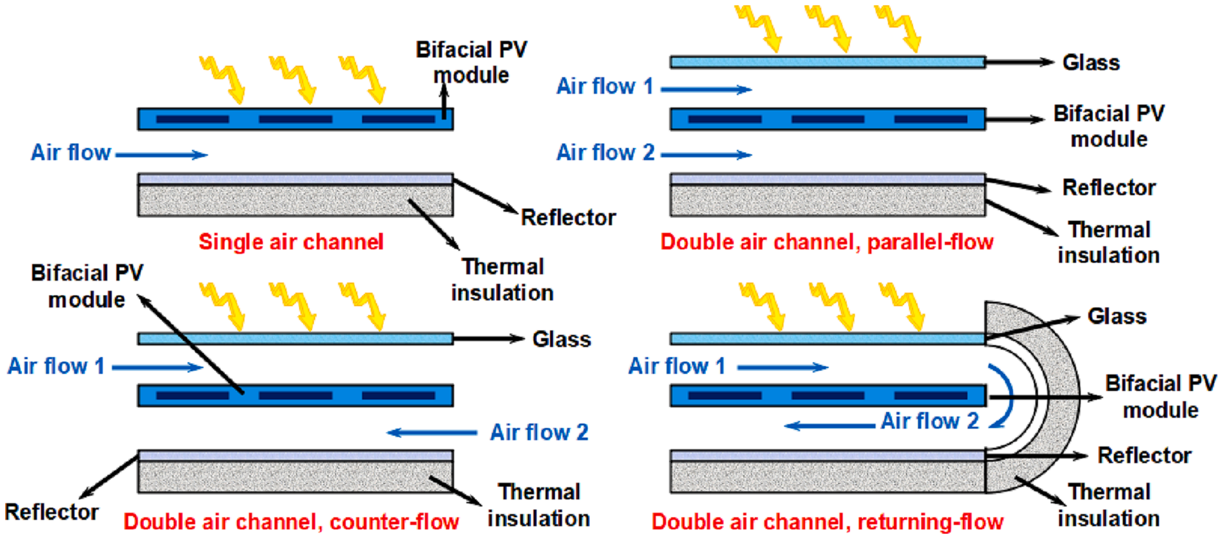


Fig. 20. Schematic view of PVT/T-air systems with different flow paths, adapted from [120].

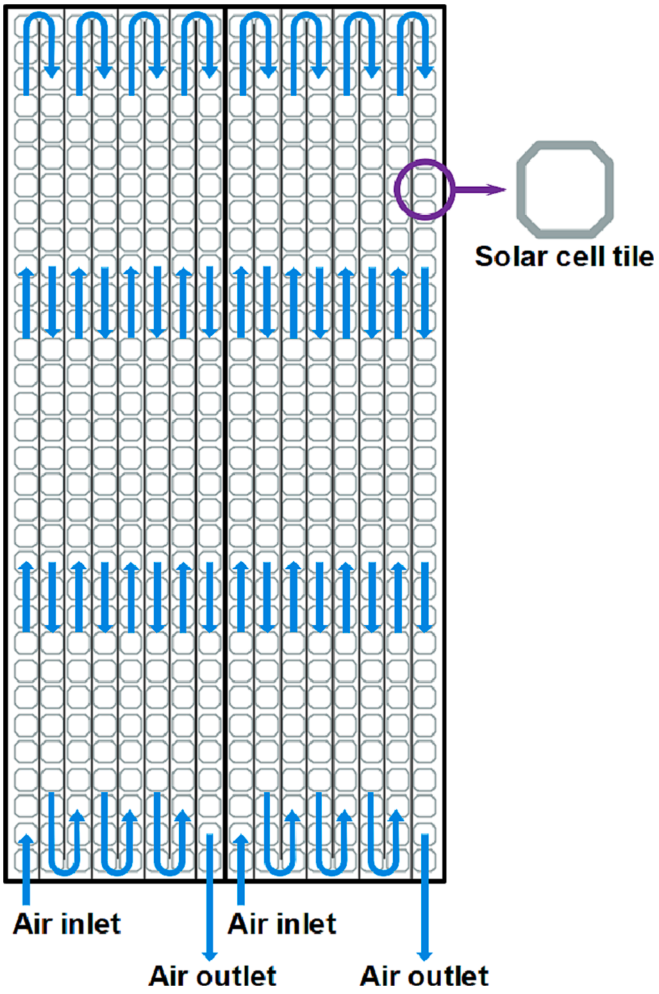


Fig. 21. Schematic view of the flow path of a BIPV/T-air system with solar cell tile configuration, adapted from [121].

channel modifications in PV/T-air systems. It can be seen that polycrystalline and mono-crystalline PV panels were utilised in the given studies. Monocrystalline PV panels could be preferred instead of polycrystalline PV panels for enhanced electrical efficiency. Monocrystalline solar cells are more effective, because they are produced from a single source of silicon. Polycrystalline solar cells are made from a combination of silicon sources and have lower efficiency than monocrystalline solar cells [125]. However, it is crucial to take into account the price differential between the two types of PV panels at the design stage.

The published literature indicates the positive effects of using geometrical modifications in PV/T systems and BIPV/T systems. However, considering that some modifications, such as fins and baffles, may decrease pressure, particularly in PV/T-air systems, it is suitable to assess the thermo-hydraulic performance of the intended PV/T collector to prevent pumping power losses. In this regard, pressure drop-related effectiveness indicators such as thermal performance factor could be analysed for the developed hybrid PV/T systems [126,127].

3.3.2. Working fluid modifications in PV/T systems for performance increment

The yield of PV/T systems is significantly impacted by the working fluid selection. Numerous examinations on the application of nanofluids in PV/T-liquid systems have been conducted recently [e.g., 142,143]. By evenly blending nanoparticles with high (thermal) conductivity into the base fluid, one could create nanofluids that would improve the yield of PV/T systems. Table 3 presents recent works that analysed various types of working fluids in PV/T-liquid systems. It can be seen that the thermal, electrical and exergetic yields were improved between the ranges of 1.66–42%, 0.3–15.44% and 1.1–23%, respectively.

It should be indicated that there are some disadvantages of employing nanofluids in commercial systems. Since nanofluids are prone to sedimentation over time, it is highly uncertain whether research findings can be successfully applied to commercial products [144,145]. Thus, it does not appear that using nanofluids for PV/T systems is appropriate until the sedimentation problem is resolved. Therefore, in liquid PV/T collectors, working liquids like ethylene glycol and mineral oil can be considered as good options, instead of water and nanofluids. Moreover, utilisation of hybrid nanofluids instead of single nanofluids can be an alternative for attaining stable working fluids in PV/T systems.

3.3.3. Utilisation of thermal energy storage units in PV/T systems for performance enhancement

Thermal energy storage is an effective technique that can be applied to improve the utilisation rate of PV/T systems especially by using PCMs. Employing thermal storage can also avoid energy losses to the environment [158]. In different words, produced energy can be stored

Table 2
Recent studies that analysed various types of flow channel modifications in PV/T-air systems.

Ref.	Modification	Investigation		PV panel type	Test location	Flow rate	Electrical efficiency	Thermal efficiency	Exergy efficiency
		Num.	Exp.						
[128]	applying different number of fans	–	+	poly-crystalline	Asalluyeh and Karaj, Iran	–	10.18% (average)	30.95% (enhancement)	–
[129]	various fin geometry	+	+	mono-crystalline	Burdur, Turkey	0.010, 0.012 and 0.014 kg/s	3.10%-3.61% (without fins) 3.41%-3.67% (with fins) (average)	47.46%-54.86% (finless) 50.25%-58.16% (finned) (average)	0.46%-0.53% (without fins) 0.51%-0.56% (with fins) (average)
[130]	desiccant air-cooling system	+	–	poly-crystalline, mono-crystalline	Izmir, Turkey	0.008 kg/s	–	–	0.84% (conventional analysis method) 0.18% (extended exergy analysis method) (maximum)
[131]	air-cooled channel and empty, sparse fins and frequent fins	+	–	poly-crystalline, mono-crystalline	Erzurum, Turkey	0.05–0.065 kg/s	–	33–35% (polycrystalline, unmodified) 51–54% (polycrystalline, sparse fins) 56–59% (polycrystalline, frequent fins) 38–40% (monocrystalline, unmodified) 58–60.5% (monocrystalline, sparse fins) 64–65.5 (monocrystalline, frequent fins) (average)	70% (monocrystal) (enhancement), 30% (polycrystal) (enhancement)
[132]	square tube channel	+	+	poly-crystalline	–	0.0235 kg/s	13.27% (maximum)	45.5% (average)	–
[133]	fluid channel fully filled with aluminum foam	+	–	–	–	–	3–4% (enhancement)	10–40% (enhancement)	–
[134]	V-groove modification	+	+	poly-crystalline	–	0.007–0.07 kg/s	9.83–11.51% (average)	21.3–82.9% (average)	11.72–13.06% (average)
[135]	applying longitude fins inserted in the air channel	+	–	poly-crystalline	Darwin, Australia	24.5, 24.7, 30 kg/m^2h	20% (average)	21.9% (average)	–
[136]	finned back wall of an air channel	–	+	–	Greece	0.02 kg/s	9–10% (average)	52% (average)	–
[137]	foldable geometry	+	+	mono-crystalline	Burdur, Turkey	0.008, 0.013 kg/s	3.96–4.38% (average)	51.11–67.05% (average)	5.18 and 6.14%
[138]	transverse triangular-shaped block	+	+	mono-crystalline	Kwangju, Korea	0.09, 0.13 and 0.17 kg/s	2.59% (enhancement)	36.97% (enhancement)	–
[139]	triangle-shaped obstacles geometry	+	–	mono-crystalline	Ulsan, Korea	0.055 kg/m^2s	24.73% (average)	15.59% (average)	15.57% (average)
[140]	unglazed, single pass, open loop system	–	+	mono-crystalline	Sydney, Australia	0.02, 0.1 kg/m^2s	10.6%-12.2% (enhancement)	28.55% (enhancement)	–
[141]	a thin aluminum sheet suspended at the middle of air channel	–	+	poly-crystalline	Kerman, Iran	0.05–0.35 kg/s	~1%-9.5% (average)	~20%-60% (average)	~39%-72% (average)

In column 3, Exp: Experimental, Num: Numerical. Studies that include numerical or experimental analysis are indicated with a plus (+) sign. Studies that do not include the relevant analysis type are indicated with a minus (-) sign.

and used in future applications [159]. Thermal energy storage can be divided into three approaches, including sensible, latent and chemical energy storage [160]. All of these approaches have some advantages and limitations. Sensible energy storage is the most commonly used technique because of its simple structure and cost-effectiveness. Nonetheless, the major bottlenecks include a larger system requirement and low storage capacity. Chemical energy storage is the most complex technique, which contains chemical reactions. Its disadvantages include chemical instability and irreversibility of the process [161]. The method with a higher heat storage capacity is latent heat energy storage technique, which requires high power capacity in charge and discharge processes of the energy and high energy storage density.

PV/T collectors can use latent heat storage devices to lower the temperature of the PV module and store thermal energy for usage during times of low solar radiation [162,163]. A schematic of a BIPV/T with PCM is shown in Fig. 22. In previous research [164], BIPV/T was coupled with a thermal energy storage unit based on PCM, in order to reduce PV panel temperature and improve the overall efficiency of the

Table 3
Recent studies that analysed various types of working fluids in PV/T-liquid systems.

Ref.	Used working fluid	Investigation		PV panel type	Test location	Efficiency enhancement
		Num.	Exp.			
[146]	SiO_2/water	+	–	mono-crystalline	–	Exergy: 7%
[147]	TiO_2/water	+	–	–	–	Exergy: 33.65%
[148]	ZnO/water	–	+	mono-crystalline	Mashhad, Iran	Electrical: 13% Thermal: 42% Exergy: 23%
[149]	Al_2O_3/methanol	–	+	–	–	Electrical: 1% Thermal: 27.3% Exergy: 1.1%
[150]	MWCNT/water, Graphene/water	–	+	mono-crystalline	Karabuk, Turkey	Electrical: 9–10.6% Thermal: 3.4–8.6% Exergy: 12.1–20.6%
[151]	CuO/Syltherm 800	+	–	mono-crystalline	–	Electrical: 5.17% Thermal: 1.66% Exergy: 3.05%
[152]	Mxene/Soybean oil	+	–	poly-crystalline	–	Electrical: 15.44% Thermal: 33.09%
[153]	TiO_2/water	–	+	poly-crystalline	Indoor tests	Electrical: 0.3% Thermal: 10.51–12.77% Exergy: 1.2–6.31%
[154]	TiO_2/water	+	–	mono-crystalline	–	Electrical: 1.54% Thermal: 4.57%
[155]	Carbon black/water	–	+	poly-crystalline	Indoor tests	Electrical: 15% Exergy: 2%
[156]	Ag/water	–	+	mono-crystalline	Indoor tests	Electrical: 0.51–0.58% Thermal: 10.69–21.95% Exergy: 1.12–2.59%
[157]	Fe_3O_4/water	–	+	mono-crystalline	Indoor tests	Electrical: 12.1–12.26% Thermal: 35.4–40.5% Exergy: 4.09%

Exp: Experimental, Num: Numerical. Studies that include numerical or experimental analysis are indicated with a plus (+) sign. Studies that do not include the relevant analysis type are indicated with a minus (-) sign (Column 3).

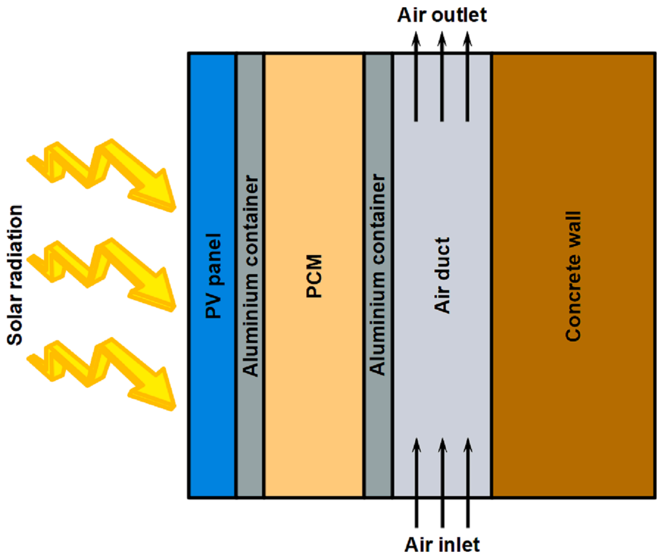


Fig. 22. Schematic view of a PCM-integrated BIPV/T, adapted from [164].

system. The impact of different types of parameters, such as system height, air gap thickness, PCM thickness and flow rate of air, on the performance of a BIPV/T was analysed. Moreover, the study investigated three different PCMs, including RT-25, capric acid and n-octadecane. The capric acid utilisation gave the best PV panel energy output. However, when designing a PV/T collector, it is important to carefully account for the thermal storage systems. It should be noted that low thermal conductivity of the materials, used in latent heat storage process, causes low power capacity. To improve the effectiveness of these systems, larger heat transfer areas are required. In this regard, extended heat transfer surfaces can be utilised in thermal energy storage containers of PV/T systems. For example, slotted fins and nanoparticles have been integrated previously to the thermal storage unit of a PV/T-liquid system [165]. The study investigated three different fin configurations, including plain fins, slotted fins with single slot and slotted fins with double slots. The schematic view of the system is presented in Fig. 23. $CaCl_2 \cdot 6H_2O$ were selected as PCM in the designed PV/T. According to the numerically attained outcomes, the lowest temperature and least amount of thermal resistance were produced on the PV panel with double slotted fins (Case 3 in Fig. 23). The fins with double and single slots (Cases 3 and 2) created the least and most molten PCM, respectively.

Table 4 presents recent works that analysed different types of latent heat thermal energy storage units in PV/T systems. Wide range of PCMs have been utilised in the investigated systems. Electrical efficiency,

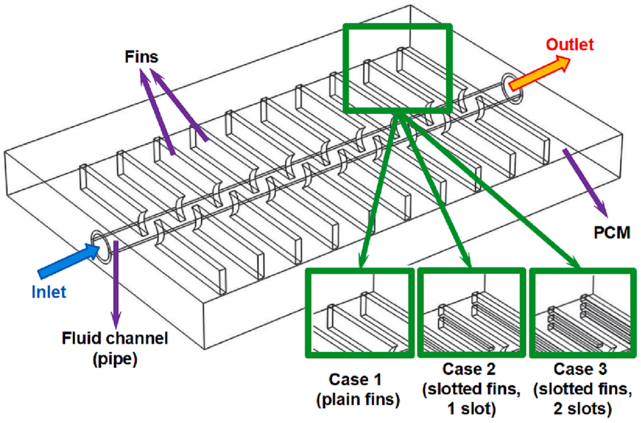


Fig. 23. Schematic view of a PV/T-liquid system modified with thermal storage unit with slotted fins, adapted from [165].

Table 4

Recent studies that analysed various types of latent heat storage systems in PV/T systems.

Ref.	Utilised energy storage medium	Investigation		Test location	Flow rate	Electrical efficiency enhancement	Thermal efficiency enhancement	Exergy efficiency enhancement
		Num.	Exp.					
[166]	Paraffin wax	+	–	–	21 L/h	6.5%	–	–
[167]	OM37 bio-PCM	+	–	–	0.04 kg/s	0.53–5.84%	36.42–60.50%	–
[168]	A44	+	+	Indoor tests	0.5–3 L/min	12.75%	7.18%	–
[169]	PCM-biochar composite	–	+	Guwahati, India	0.0015 kg/s	18.4%	–	–
[148]	Merck 107,151	–	+	Mashhad, Iran	30 kg/h	13%	9%	23%
[162]	Rubitherm RT-35	–	+	Barranquilla, Colombia	0–1.2 L/min	7.43%	–	–
[170]	A44	+	+	Malaysia	0.5 L/min	4.8–7.6%	5.62%	–
[171]	PCM32/280			Tehran, Iran		9%		
[172]	Merck 107,158	–	+	Tehran, Iran	30–50 kg/h	4.2%	23.52%	8.27%
[173]	Nano-enhanced paraffin wax	–	+	Selangor, Malaysia	0.084–0.583 kg/s	92.6%	42.6%	–
[174]	PLUSICE S25	–	+	Indoor tests	15–20 L/s	10%	–	–
[175]	RT-35HC	–	+	Kottayam, India	0.33–0.67 kg/s	10.4%	20.8%	–
[176]	Lauric acid	–	+	Malaysia	0.5–4 L/min	9.88%	–	5%
[177]	Paraffin wax	+	+	Chengdu, China	–	14%	6.3%	–
[178]	Not specified (melting temperature: 15 °C)	+	–	–	0.0024 kg/s	12.11%	0.31%	–

Exp: Experimental, Num: Numerical. Studies that include numerical or experimental analysis are indicated with a plus (+) sign. There are double plus (+) in studies involving both approaches. Studies that do not include the relevant analysis type are indicated with a minus (-) sign (Column 3).

thermal efficiency and exergetic efficiency values were improved between the ranges of 0.53–92.6%, 0.31–60.50 and 5–23%, respectively. The investigated systems showed the positive effects of using latent heat storage system in PV/T systems. In the design and manufacturing process, volume expansion rate of the specific PCM should be considered. Moreover, it should be indicated that PCMs pose some risks, such as leakage and being flammable. These risks should be carefully considered in the design, manufacturing, and operation of PV/T systems in buildings.

4. Contributions of PV/T systems to net zero buildings

In recent years, utilising and developing new designs in renewable technologies have become popular in net zero buildings. Energy consumption is a crucial challenge in the discussion about the global climate change. From 31.2 billion tons in 2010 to 36.4 billion tons in 2020 and estimated 45.5 billion tons in 2040, carbon dioxide emissions related to energy are rising globally [179]. The continuous use of fossil fuels like coal, oil, and natural gas for power, heating, and cooling is expected to cause a faster increase in building-related GHG emissions in the next 25 years [180]. The energy intensity per square meter of the building sector should decrease by 30% in 2030, as compared to 2015, according to the International Energy Agency [181], in order to meet the global climate goals outlined in the Paris Agreement. Buildings with lower embodied energy (EE), reduced carbon fuel use, and rapid implementation are all contributing factors to the global transition to sustainability. As a result, environmentally friendly building techniques are being developed to meet the growing need for energy services [182].

A rating methodology called green building certification systems (GBCS) is used to raise a building or construction project's sustainability as well as to confirm and evaluate how much of an influence structure have on the environment [183]. More than 100 GBCS, such as German Sustainable Building [184], Green Star [185], Leadership in Energy and Environmental Design (LEED) [186], Comprehensive Assessment System for Built Environment Efficiency (CASBEE) [187] and Building Research Establishment's Environmental Assessment (BREEAM) [188] have been used in various countries and regions for thorough building assessment [189,190]. For grading buildings for their energetic and environmental efficiency, LEED [186] and BREEAM [188,191] are the most popular certification methodologies.

BIPV/T systems can provide sustainable electrical and thermal energy supply. Therefore, these systems have a great potential to decreasing GHG emissions [192]. BIPV/T systems fulfil a large part of LEED Credit Categories such as "Energy and atmosphere", "Indoor environmental quality" and "Innovation in design" [193]. "Energy and atmosphere" category of the LEED certificate is related to the use of sustainable resources in structures and the improvement of building energy performance. In other words, this category promotes the use of clean energy sources and the regulation of building energy performance [194]. By integrating BIPV/T systems and keeping track of the quantity of energy produced and used in a building, obligations in this category can be satisfied. The "interior environmental quality" category includes information about things like preventing indoor air pollution and supplying the inside environment with clean air. Buildings can be heated or cooled to the desired temperature using the thermal energy that BIPV/T systems will create and fresh air that is drawn in from the outside. In addition, with the use of automatic control systems, these operations can be performed more easily and accurately. In addition, BIPV/T systems, which are innovative applications, will also improve the sustainability operations of buildings. Integration of BIPV/T systems into buildings can also have positive contributions to BREEAM categories including "Pollution", "Energy", "Health and wellbeing" and "Innovation" [195,196]. Additionally, the type of material and its lifetime affect the materials utilised in BIPV/T applications, including facades, walls, roofs, and storage systems. The environmental effectiveness of the entire structure can be greatly impacted by these materials [197]. BIPV/T systems replace conventional energy consumption, and during their use in buildings, energy savings, a decrease in carbon emissions, waste management, and other environmental effects are noticed. Studies on this subject that use life cycle assessment (LCA) offer helpful details showing ways to minimise these environmental impacts. It helps with life-cycle impact analysis in terms of cost and carbon emissions, as well as life-cycle inventory and payback durations [198,199]. Fig. 24 presents possible contributions to LEED and BREEAM certification, by integrating BIPV/T systems in buildings.

Net zero buildings aim to provide most of the energy they need from renewable energy sources and energy-efficient technologies. Central to this concept is the motivation to meet the overall energy demand of buildings from affordable, locally available, clean and sustainable sources. Additionally, the preference of building materials that contribute to sustainability and waste management in the construction of buildings, the use of renewable energy sources instead of fossil fuels, the dissemination of water saving, and waste management system applications are among the zero building strategies. These strategies also support and contribute significantly to a net zero carbon footprint policy [200,201]. The development in solar renewable technologies led to a

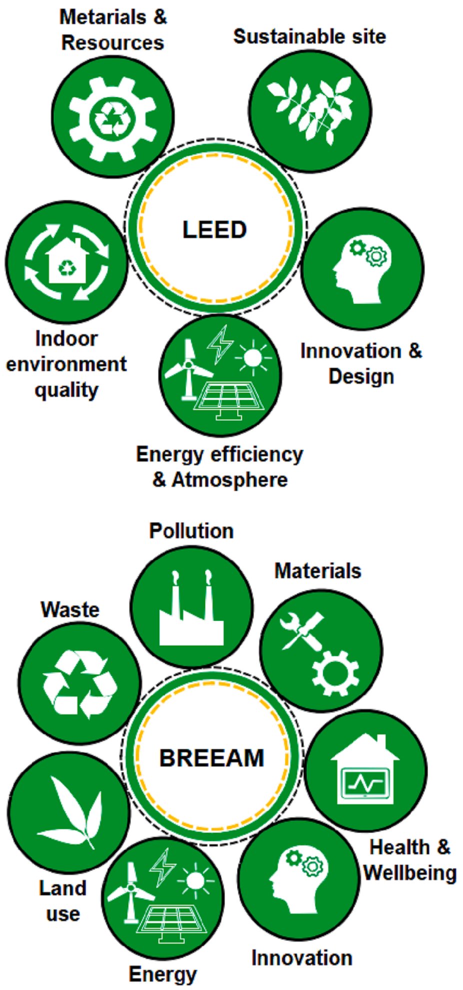


Fig. 24. Possible contributions to LEED and BREEAM certification by integrating BIPV/T systems in buildings.

rise in popularity for BIPV/T technology [202]. BIPV/T systems have the potential to solve energy challenges in buildings, such as decreasing dependency on non-renewable energy sources and eliminating carbon emissions, meeting energy demands, combining energy efficient construction approaches with renewable energy applications [203]. Establishing a strategy based on the target building's energy consumption pattern is essential for achieving net zero buildings. A way of providing renewable energy should also be described, as well as an energy-saving application appropriate for the structure's characteristics [204]. Since electricity is an important energy type to reach the net zero buildings, the electrical energy that the building needs and can supply could be obtained from BIPV/T systems. BIPV/T systems ensure their efficiency by conveying the heat from their modules and reducing the heat losses, in addition to producing electrical energy [205]. If the temperature of the fluid in the system is high enough, it can be directly used as domestic hot water in the building [204]. In addition, a BIPV/T system may contain thermal energy storage system and extended heat transfer surfaces/geometries for enhanced heat transfer [206-208].

5. Optimal location of PV/T systems in buildings

PV/T systems have a wide range of applications in buildings, as shown in Fig. 25. These applications range from improving the indoor environment (e.g., in terms of supporting space heating, ventilation, lighting) to supporting the energy efficiency of the structure (e.g. electricity production, water heating). The BIPV/T systems enable cooling of the PV by air [60,209], which improves the efficiency of the PV panel.

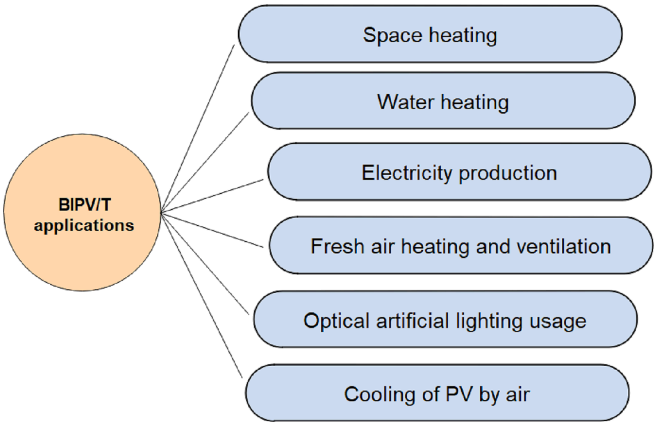


Fig. 25. Utilisation areas of BIPV/T systems, adapted from [8].

The flow rate of the cooling air and the depth of the cooling channel are other important parameters in increasing the efficiency of the panel. For instance, a previous experimental study [210] used air to cool the PV panel, which was then directed to the ventilation system, increasing the panel's thermal efficiency by 22%.

In order to achieve the maximum yield from an installed PV/T system, the location of the system, the type of building and the sun inclination angle are among the important factors [211]. When designing PVT systems, similar factors to those of PV systems, must be considered, including:

- Type of a building, i.e., domestic, commercial, agricultural, educational, hospital, etc.
- Size of a building.
- Optimal location of the system in the building.
- Type and amount of energy required (i.e., utilisation area).

The best performance is achieved for PV/T systems positioned in the South direction for regions located in the northern hemisphere, and North direction for regions in southern hemisphere [212]. PV/T systems can be placed on building roofs, façades and on the ground. Rooftop systems are frequently used in buildings, parking areas, transportation stops, as roofs provide advantageous space for system installation. Furthermore, the performance of PV/T systems vary according to their utilisation aims. While roof top opaque PV/T systems generate both heat and electricity, roof top semi-transparent PV/T systems contribute to the lighting of buildings thanks to their solar radiation transmissivity [213].

BIPV/T systems can also be applied to building façades, where they perform as a thermal insulation material and thermal diode. Semi-transparent systems can be integrated with technologies such as Trombe walls [214] and applied to the façades of buildings to influence the indoor environment [215]. In addition, PV/T systems can be applied to create shading on windows and provide seasonal use of daylight [216].

Moreover, in the process of installation of PV/T systems in buildings, building codes and regulations should be strictly followed to ensure safe, healthy, and durable built environment. As an example, for application of PV/T-liquid systems, leakage risk should be carefully considered before installation. For instance, utilisation of sealed heat pipes reduces the leakage risk and ensures more even fluid distribution from manifold to riser pipes [207].

5.1. *Types of PV/T systems that are suitable for use in buildings*

The type of energy demands for the individual building and the choice of solar-receiving sections of the building are two important criteria for PV/T system selection to be used in buildings. Air circulation systems are favoured when designing for a building's heating, cooling, and air conditioning requirements; whereas liquid (water) circulation systems are chosen when the building's demand for hot water is considerable. The working fluid should be chosen based on the intended performance objective. The thermal management of the building and overall energy efficiency can improve by adding nanoscale materials to the fluid in BIPV/T systems [217]. However, due to ongoing research on the stability of nanofluids, the use of such fluids in commercial applications is difficult. Thus, this approach includes a more future-oriented application. Bi-fluidic technology is used in buildings to provide hot air, hot water and electricity at the same time, as it has lower operating costs and minimum material usage [218,219]. Heat pump or heat exchanger technology to BIPV/T systems will increase the heat transfer in the system and provide higher thermal and electrical efficiency depending on the thermal conductivity of the fluid used. If the building's demand is based on a long-term thermal storage need, the PCMs should be used [220].

The installation of BIPV/T systems according to the amount of sunlight on a building façade is another important factor. If a system to be positioned on a building façade is air-circulated, then heating–cooling and thermal insulation applications can be facilitated. In addition, if a building façade is designed as a solar wall or Trombe wall, air circulation can be provided without the need for forced convection. This would prevent the use of components that allow air flow and consume additional energy. With the use of Trombe wall systems, seasonal maximum benefit from daylight (for the winter season) or the reduction of thermal comfort by solar radiation in the building (for the summer season) can be prevented.

The energy demands of net zero buildings have been investigated previously [221]. The annual energy demand of a two-storey residential building was studied in Oslo, Norway with 160 m^2 heated floor developed by Houlihan Wiberg et al. [222]. The study demonstrated how to meet the zero emissions in operation (ZEB-O) criterion, and the importance of utilising only roof-mounted PV production to balance emissions from both operation and materials (ZEB-OM). In a different study [223], various solar energy system functions for a net zero single-family building were simulated. The study assessed if the building with various systems could achieve a net zero energy balance, and showed that even though the solar thermal component in this case was zero, the system using solely high-yield PV modules came the closest to achieving net zero energy balance. The parameters utilised in the nZEB expression, the boundary conditions employed, and the decision to use a heat pump as an auxiliary device all have a substantial impact on how the results should be interpreted. According to their findings, unglazed PV/Ts were suggested to be utilised where electricity is favoured.

6. Challenges for BIPV/T systems

BIPV/T systems have a good potential in obtaining net zero buildings; however, some challenges, including technical and economical restrictions, need to be addressed. The challenges for BIPV/T systems include:

At design stage:

- The impact of BIPV/T systems on the structural bearing capacity of the building is one of the key obstacles to their deployment. It can be difficult to integrate BIPV/T air collectors into structures. One of the reasons is that demand and supply for solar energy do not always coincide. From the viewpoint of the building, this is not really an issue with energy since any surplus production can either be momentarily stored on-site or returned to the grid for buildings that are wired into it (for off-grid or autonomous structures). On a thermal level, hot air may be beneficial for space heating in heating-dominated places in winter season, but it is not as needed in summer.
- Obtained fluid output temperature is lower in the PV/T systems in comparison to the traditional solar thermal collectors and this issue is one of the challenges in the design stage. Therefore, pairing BIPV/T products with storage options or transferring the generated energy into another medium is more challenging [224].

At construction/installation stage, including climatic conditions:

- Installation of BIPV/T systems must be carried out by the qualified personnel. The maintenance of system components also requires special precautions, including close consideration of the weight of the system to be installed and careful determination of the load bearing components [225]. Often, roofs provide a better location and slope to achieve maximum solar panel efficiency, than envelope. BIPV/T systems which are applied to roofs depend on roof strength and the ability of the related roof to support the weight of the system. Roofs with weaker statics or roofs exposed to heavy snowfall due to the heavy weight of solar panels pose risks in terms of system lifetime and installation [226].
- Concentrated direct sun radiation causes the operational solar cell temperature to rise on the PV module, which in turn reduces solar cell efficiency and shortens the PV module's lifespan [227,228]. Therefore, this fact should be carefully considered in designing and installation of concentrating BIPV/T system.
- The climatic conditions of the structure's location is one of the challenges and they must be taken into consideration [229]. BIPV/T systems must be designed and installed to resist all loading effects (including wind, snow, etc.) that may act on the building. Furthermore, the installation of BIPV/T systems in buildings should not create any thermal bridging and limit the thermal losses.
- From economic point of view: Application of BIPV/T systems should also be examined from an economic point of view. In the literature, the payback and self-depreciation time of a BIPV/T system installed or targeted to be established have been calculated using various analyses [230]. The reduction in solar cell temperature brought on by fluid flow in the BIPV/T is what defines the improvement in payback time performance. In addition, the materials to be used in the system may be less costly than traditional building materials in terms of improved technology and, thus, contribute to waste management by reducing the carbon footprint [231]. Building-integrated photovoltaics (BIPVs) can be made more cost- or benefit-competitive with other solar technologies like solar thermal collectors or PV modules installed on roofs or façades by either lowering costs or raising benefits. BIPV/T's cost-benefit ratio may be raised if the price of converting thermal energy into usable energy remains feasible [106].
- For BIPV/T systems to be commercially viable, the government must provide funding as well as a more advantageous tariff. The commercialisation of BIPV/T systems is hampered by factors like the execution of the tariff guarantee, customer perception, national economic assistance, and system management [232]. Since negative environmental effects are the common concern of all humanity, the support of local and national governments and the presence of international support mechanisms are important in the integration of clean and renewable energy technologies into buildings. For this reason, the importance and support required for BIPV/T systems in line with various installations and policies is increasing day by day [43,103,233,234]. BIPV/T systems could be widely used with the application of tariffs and tax reductions for building systems that produce their own electricity and utilise this energy internally and supply the national grid in appropriate conditions [235,236]. Building renewable energy projects for consumption and production can be done through a variety of different channels, such as commercial initiatives, open tenders, net metering, and feed-in tariffs [237-239]. Due to feed-in tariffs, the electrical energy produced by the BIPV/T system is directly injected into the national grid, where it is less expensive than grid electricity [240]. If feed-in tariffs with high tariffs for BIPV/T systems are extensively deployed [236], a

significant increase in BIPV/T installations is possible. A weak energy strategy, high capital costs, a lengthy payback time, limited scale economies, and scepticism regarding feed-in tariff policy are additional barriers to convincing the private sector to participate [237,241]. The level of interest will increase if governments choose to support the technology, and the feed-in-tariff program may offer many consumers a fantastic opportunity to adopt BIPV/T systems, as demonstrated, for example, by [242]. The private sector should also be involved in the design and implementation processes of these systems [43]. However, this participation can be possible only with the tariff guarantees, appropriate energy policies and the low payback periods.

Building codes and standards:

- The lack of inclusion of BIPV/T systems in building codes is an important constraint for the applicability of these systems. This prevents designers, architects, and engineers, from utilising BIPV/T systems in their building designs, making it difficult to determine the areas where BIPV/T systems can be located [243]. In order to expand the use of BIPV/T systems, it is necessary that the systems are comprehensively tested and obtain relevant certification relating to quality and environmental management (e.g., ISO 9000 and ISO 14000) [244,245] and PV design and installation (e.g. IEC 61215, IEC 61646, IEC 61730–1/2) [246] for the use in buildings. The creation of standards and installation guides is necessary to ensure these systems can be safely used. In terms of system state, benefits, applications, obstacles and problems, and prospects for deploying BIPV/T systems, there are also certain legislative and funding challenges.

7. Future research directions for BIPV/T systems

There is a need for integration of renewable energy technologies in buildings, in order to meet the demands of net zero energy buildings. Increasing energy costs and GHG emissions require next generation thinking when designing new and retrofitting existing buildings. The current costs and performances of PV panels encourage the use of these technologies by applying different modulations. Thus, high initial cost and limited yields can be balanced with high performance hybrid applications. Net zero buildings can, in the end, greatly benefit the economy and the environment. The successful implementation of the BIPV/T system necessitates regulation and ongoing assistance from the government or decision-makers and other stakeholders in the fields of technology, sensible finance, and smart policy. In order to motivate the appropriate measures for calculating the costs of building restoration, financial incentives and subsidies may be essential. The results of this research indicate that thorough understanding of the BIPV/T system is crucial for system design and implementation in the future, particularly in regions with difficult climatic conditions [103].

In the thermal units integrated into PV modules in BIPV/T systems, various modifications such as integrating extra surface areas, using various latent heat storage materials, using nanoparticle-embedded PCMs are preferred in order to increase the heat transfer. The electrical energy demand for heating in buildings will decrease simultaneously depending on this improvement. Therefore, the financial return of energy produced from renewable resources makes more economic sense in the end. The selection of PV module material has a significant impact on the BIPV/T system's performance since it affects the module's lifespan and energy-gathering capacity. Similar to this, laws and regulations that promote and encourage the construction of net zero buildings as well as the elimination or reduction of environmental pollutants must be established in order to improve the overall economics of BIPV/T systems. In this way, one more way to benefit from solar energy in full efficiency will be realised. BIPV/T systems can support the growth of environmentally friendly and sustainable structures in the future, especially in light of the global efforts being made to minimise the reliance on fossil fuels in response to climate change.

8. Conclusion

The application of BIPV/T technologies is an opportunity for the net zero building target. BIPV/T systems are designed to meet the electrical and thermal energy needs of domestic and commercial buildings. The utilisation of BIPV/T systems ensures high performance of next generation green buildings. In addition, these systems can significantly increase building performance, as well as reducing harmful emissions. During the design and operation phase, the energy loads (by type) required in a building should be determined. Material selection and determination system location in a building are also necessary to increase the effectiveness of this technology. In this regard, innovative materials such as concentrators, PCMs and extended heat transfer surfaces can be utilised for performance improvement of BIPV/T systems. Furthermore, all innovative technologies face certain challenges before they are widely used in buildings. Apart from the optimal engineering design and performance, energy policies and incentives will also determine the future of BIPV/T systems. In summary, BIPV/T systems are an important technology for buildings, flexible to improvement that can help achieve sustainable buildings which are net zero (or positive) energy buildings that provide safe, healthy and comfortable conditions for their occupants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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