# Building-integrated photovoltaic/thermal (BIPVT) systems: Applications and challenges

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## Abstract

A key medium for energy generation globally is the solar energy. The present work evaluates the challenges of building-integrated photovoltaic (BIPVT) required for various applications from techno-economic and environmental points of view. Many challenges are found for applying solar photovoltaics (PVs) modules combined with building systems: supplying hot and cold water and ventilation for the residential and non-residential building. Moreover, efforts and advances achieved in enhancing the BIPVT thermal and electrical performance are explored. Additionally, the review provides further insight into recognizing the fundamental science of the BIPVT systems, explaining its rapid developments and the thermal performance mechanisms. The BIPVT systems designed for rooftops, windows, and facades are specifically highlighted in the present review. Furthermore, the status of PV modules and BIPVT system, benefits, applications, barriers and challenges, and future prospects are discussed. The BIPVT systems require governmental support and a more economically convenient and efficient tariff to maintain the economic feasibility of the system. The key factors impeding the commercialization of BIPVT systems are the implementation of the feed-in tariff, customers' perception, national economic support, technical aspects such as the performance, system management, and architectural and material considerations. Finally, this review indicates that further works concerned the BIPVT systems to enhance the technology and advancements are still required.

**Keywords:**
Building-integrated photovoltaic/thermal (BIPVT); Solar energy; BIPVT application; Barrier; Challenges.

## 1. Introduction

Due to the sharp increase in population growth, human comfort coupled with living standards, energy consumption in the building sector is increasing dramatically and accounted as a primary. This contributes significantly to high energy demand in advanced countries as well as the developing world countries in recent times [1]. Increasing the power generation from traditional fossil-fueled power plants makes the building sector one of the main contributors to global greenhouse gas (GHGs) emissions [2][3]. Fossil commodities continue to play key role in energy generation after world war II. Depletion of fossil reserves, unstable fossil prices coupled with their harmful effect on the environment are the fundamental principles accelerating the need for a paradigm shift in how energy is generated globally [4][5]. The global energy consumption by the buildings sector is almost 36%, which is responsible for nearly 40% of the total $CO_2$ emissions. Buildings also consume more than 55% of the global electricity, which is growing by 2.5% yearly [6]. The energy consumptions in buildings can be decreased by employing the schemes of energy management.

Congruently, the rapid increase in energy production has resulted in critical environmental issues that have triggered extraordinary climate changes such as snow caps melting, global warming, stratospheric ozone depletion, drought and desertification, hurricanes and tsunamis, etc.[7][8]. In most cases, there are two scenarios to overcome the national rising energy demand: connecting the local grid to nearby electrical grids or energy self-supply. The ultimate solution is to have buildings as energy self-supply via the transformation of the structure as energy generating medium with the aid of available renewable energy resources such as solar energy, wind, bioenergy, geothermal, etc. [9][10][11][12]. Due to the pollution-free, availability, and viability for buildings, agricultural, and commercial utilization, solar energy is preferable as compared to other renewable energy resources for this purpose [13].

Generally, the solar energy technology can be categorized into two major classes: photovoltaic (PV) modules that can convert a portion of available solar power directly into electrical energy, as well as solar thermal systems that transform solar energy into thermal energy, i.e., heat. In the latter, electrical energy is required to drive working fluids through the solar system. However, utilizing external electrical energy can be eliminated by combining photovoltaics and the thermal system as an integrated photovoltaic/thermal (PVT) system. The utilization of such an integrated system into buildings results in building-integrated photovoltaic/thermal (BIPVT) systems, which are self-energy supply. The BIPVT systems have huge potential to be the primary source of renewable energy in urban areas for different purposes [14]. In the urban infrastructure, the BIPVT systems can help in maintaining sustainability goals [15]. The BIPVT systems can be installed either in the form of a roof or a façade [16][17][18]. The BIPV is part of 5 main routes for the PV modules market infiltration, along with reduced cost, improved performance, extended lifespan, and facilitated electricity storage [19]. Given the mentioned background and available previous works, the present work is intended to explore applications, techno-economical impediments, as well as challenges and barriers in relation with the application of BIPV systems.

## 2. Status of the solar photovoltaic (PV) modules

Replacing the fossil fuel resources that have a great impact on the global warming and greenhouse effect with eco-friendly energy resources is the great challenge to ensure the energy sustainability, to secured the growing power supply, and to mitigate the environmental critical issues. So, in the last decades, the effort of scientists has been geared towards the development of novel technologies for renewable energy [20]. The photovoltaic modules constructed either from thin-film or crystalline silicon cells convert wavelength of the global irradiance into electricity directly with a limited efficiency of almost 12–20%, depending on the module design and the operating geographical parameters [21][22]. The PV modules have considerable potential to supply the energy required for the rural and remote societies in developing countries [23]. In December 2019, global accumulative capacity of the installed photovoltaic modules had reached 653 GW with the expectation to reach 1,583 GW by 2030 and up to 4,674 GW by 2050 at a share of 16% of the total energy production around the world as indicated in **Fig. 1** [24][25]. As the largest producers of solar energy, China and India produce almost half of the current global solar power energy [26].

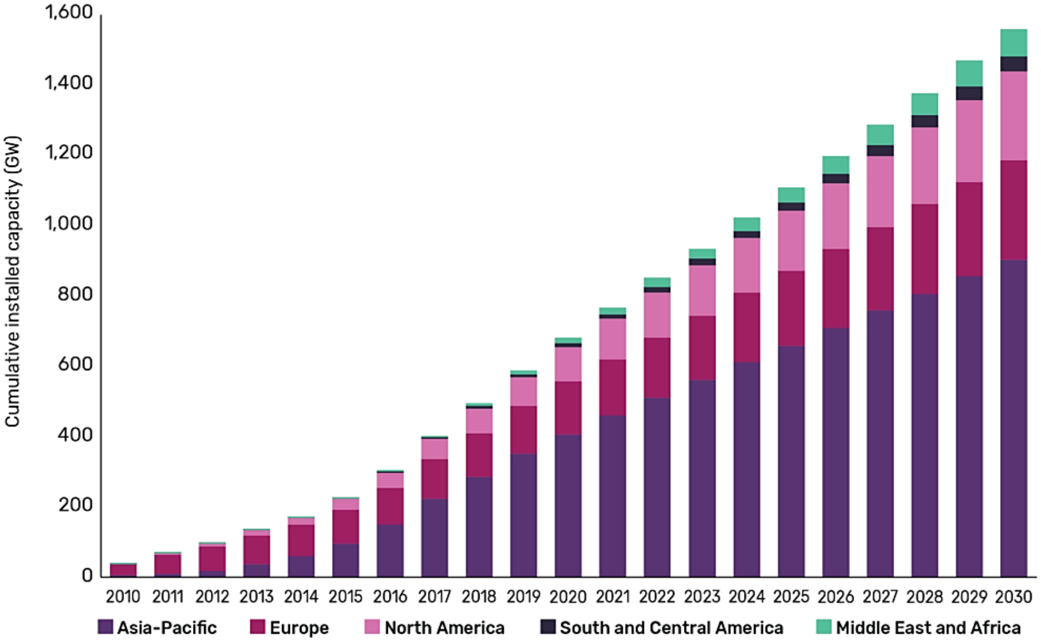


**Fig. 1**. The cumulative capacity of installed PV modules by regions within 2010-2030 [25].

The PV solar energy extraction system includes photovoltaic cells, cables, regulators, batteries, and finally, an electrical inverter to provide alternative current. As the PV partially extracts the incident solar energy, the residual solar energy is gradually accumulated as the thermal energy causing the critical problem of increasing the surface temperature of modules and unfortunately decreases its electrical efficiency [27][28][29][30]. So, the PVT solar systems employing different working fluids, essentially air or water, are designed to absorb and recover the wasted solar energy accumulated in PV modules resulting in significantly improving the electrical efficiency and increasing the PV module life span [9][31][32]. Developing the PV module technologies to enhance the electrical efficiency by reducing the temperature on the surface with the aid of a cooling medium is very critical in the commercialization of photovoltaics. The degradation in PV modules' electrical efficiency is approximately 0.65 %/ $^{o}$C temperature rise in the range from 22 $^{o}$C to 70 $^{o}$C [33]. Furthermore, the PV modules' electrical efficiency and power output are reduced by 0.08 and 0.65 %/ $^{o}$C increment of the surface temperature up to 80 $^{o}$C, respectively [34][35]. Lowering the temperature of the PV modules maximizes the electrical efficiency of the photovoltaic. This approach further enhances the photovoltaic module life span as it minimizes the silicon decay [36][37][38].

Comprehensive work has been presented in literature to evaluate the design and efficiency improvement for PVT systems [39][40][41][42]. Reducing the surface temperature of PV modules is attainable via various passive or active cooling techniques such as water, air, or refrigerant [43], phase change materials [44][45], thermoelectric cooling [46][47][48][49], and heat pipe [50][51]. Recently a significant enhancement of PVT systems is accomplished based on different design configurations. For residential and non-residential applications, the photovoltaic thermal system (PVT) is usable as integrated component similar to the electrical and mechanical components in the building's services system. The successful integration of the PVT system into the building design mainly depends on the early association and cooperation of the system during the design and construction phases resulting in an efficient building integrated photovoltaic thermal (BIPVT) system.

The BIPVT systems are flexible, lower space requirements, short insulation time, and fully managed. However, there are some obstacles to widespread the BIPVT technology, such as thermal integration issues, solar thermal technology, removal of dust and snow from PV module surface, high cost, reliability issues, and mismatch of the life span between the BIPVT systems and the designed architectural elements. The obtained thermal energy is useful for varying applications such as domestic water heating, residential space heating, drying processes, agricultural process, industrial food processing, and water desalination [52][53][54][55][56][57].

## 3. Status of solar BIPVT systems

The BIPVT system is an innovative, practical, and promising application to achieve net-zero emission buildings, thus a huge market potential for the BIPVT worldwide [58]. The schematic diagram of a BIPVT showing the flow of active air through the system to heat interior spaces is presented in **Fig. 2** [59]. The BIPVT system is an energy-producing technology that integrates the solar photovoltaic modules during the design of windows, roof, facades, as well as shadings [60]. The conventional advantages of PV modules and the additional advantages owed by the BIPVT system are given in **Table 1**. High transparency glazing material in BIPVT systems is the major figure of merit. It increases the harvesting of energy and, hence, supplies a supplementary contribution to power generation and provides various features such as shading [61][62]. The BIPVT systems can be utilized as part of various composition of the structure [63][64] such as wall [65][66][67], roof [68][69][70], window [71][72] [73][74][75], and a shading device [76][77].

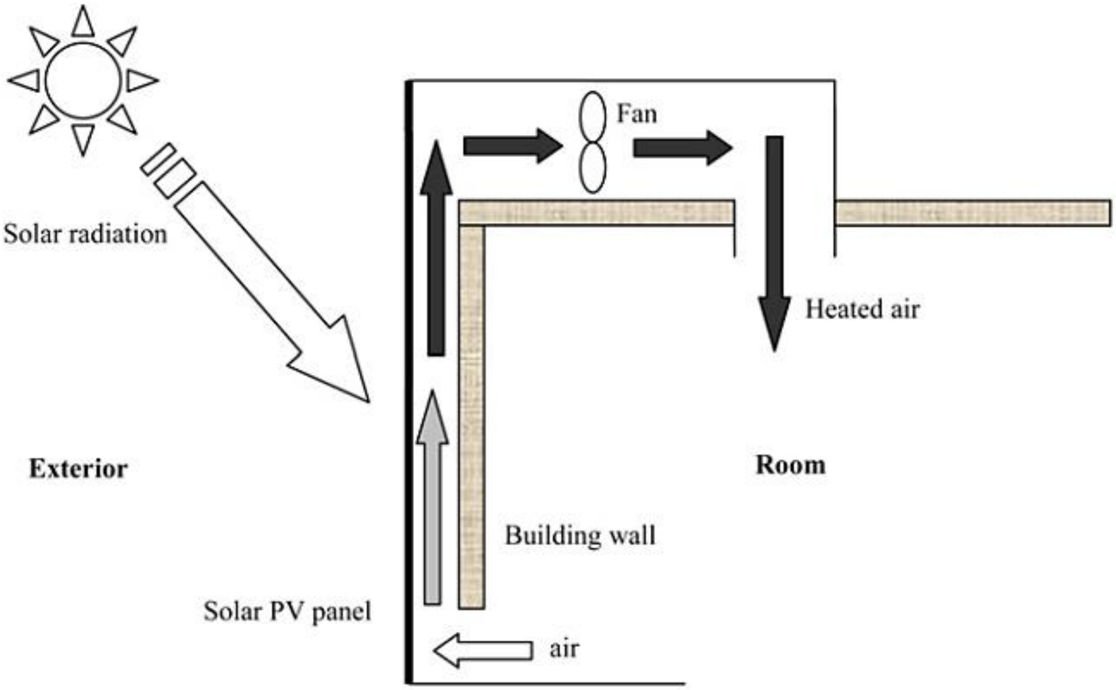


**Fig. 2** Schematic diagram of a BIPVT system [59], reused with permission from Elsevier license number 5017780044603.

**Table 1.** Comparison between PV modules and BIPVT systems.

| System | Advantages | Disadvantages |
|---|---|---|
| **PV modules** | ▪ Global applicability.<br>▪ Electrical efficiency is steadily improving while the cost is decreasing.<br>▪ Long lifetime of about 25 - 30 years.<br>▪ Well-developed and widespread industrial experiences and standards.<br>▪ Ease of installation on building roof at negligible operating costs.<br>▪ Placed either on roof or ground-mounted.<br>▪ Environmentally friendly.<br>▪ Sun and weather protection. | ▪ Limitations in the system availability on the local market.<br>▪ Waste of considerable energy.<br>▪ Heat conduction loss between hot and cold parts through the semiconductors.<br>▪ High initial cost.<br>▪ Installation of big scale PV solar plant requires a large surface area.<br>▪ Dependence on the technology advancement.<br>▪ Impact of geographical conditions such as solar irradiation, temperature, and humidity.<br>▪ Demand cooling systems to intensify the overall performance.<br>▪ Its efficiency depends on the cells’ efficiency. |
| **BIPV system** | ▪ Produce electrical and thermal energies.<br>▪ Remove cooling and heating loads from buildings.<br>▪ Reduce the electricity bills of a building.<br>▪ Reduce operational energy cost.<br>▪ Decrease the carbon emission of the building.<br>▪ Plays as thermal insulation. | ▪ Overheating of the system and building.<br>▪ the maximum performance demands an optimum design parameters and well building's graphical analysis.<br>▪ Have weak thermal point due to using architectural glazing for buildings.<br>▪ Employed high expensive material such as Aluminum. |

| | |
|---|---|
| ▪ Increases building value. | ▪ Its feasibility depends on the national and local supporting policy.<br>▪ The electricity cost is more than that of grid electricity.<br>▪ Up-to-date there is a lack of expertise, planning, operational and maintenance, standardized technology, and commissioning.<br>These systems need special precautions and care with replacing the damaged infill units.<br>The structural loading tolerance of the existing building is not able to sustain BIPV modules' weight. |

## 4. Benefits of the BIPVT systems

Power plants are commonly located far from the urban areas and cities, and more toward rural areas reduce and partially mitigate environmental impacts such as greenhouse gases (GHGs) emissions and noise. However, this results in energy losses during power transmission and distribution, which has a considerable impact on the electricity price [78][79][80]. The dependence of the transmission and distribution of grid power loss on widely available metrics was assessed using a function based on empirical data of gross domestic product per capita, index of corruption perception, country area, level of urbanization, environmental temperature, and grid organization parameter [81]. Utilizing BIPVT systems eliminate the need for electrical energy transmission over long distances that is capable of reducing  the cost through decreasing capital expenditure for grid infrastructure and its maintenance [82][83][84][85][86][87]. Ultimately, the BIPVT applications lead to lower utility and maintenance expenditures [88][89][90]. The BIPVT systems can effectively reduce the social cost of carbon (SCC), reducing the environmental impact and improves the public health [91].

## 5. Applications of the BIPVT systems

### 5.1. Combined solar cooling/heating and power

The building integration with BIPVT systems can supply electrical and thermal energy provided by hot water, air, or other fluids for the buildings with an acceptable flexibility degree in energy demand; hence it is economically and effectively attractive for residential and non-residential buildings such as houses, hospitals, and many others [92][93][94][95][96][97][98]. The BIPVT systems mainly use commercially available working fluids such as water, air, refrigerant, or bi-fluid for cooling have poor thermal performance [99]. The renewable energy resources contribution in the global energy demand is slightly rising from 9% in 2015 to 11% in 2022. Using non-renewable energy resources for space heating and industrial processes produce almost 40% of the global emission of $CO_2$. Thus, minimizing the utilization of conventional fossil fuels and reducing the operation of baseload power plants by employing the BIPVT systems remains an important challenge [100][101][102]. The Layout of the BIPVT market is presented in **Fig. 3**. Additionally, the different BIPVT system applications are presented in **Fig. 4** where 80% of the BIPVT installed are positioned on the roof, and  enduring 20% are facade applications [103][104]. Subject to the dimensions as well as type, the BIPVT system can be installed with different configurations that it is aesthetically and invisible with a convenient architectural appearance [91].

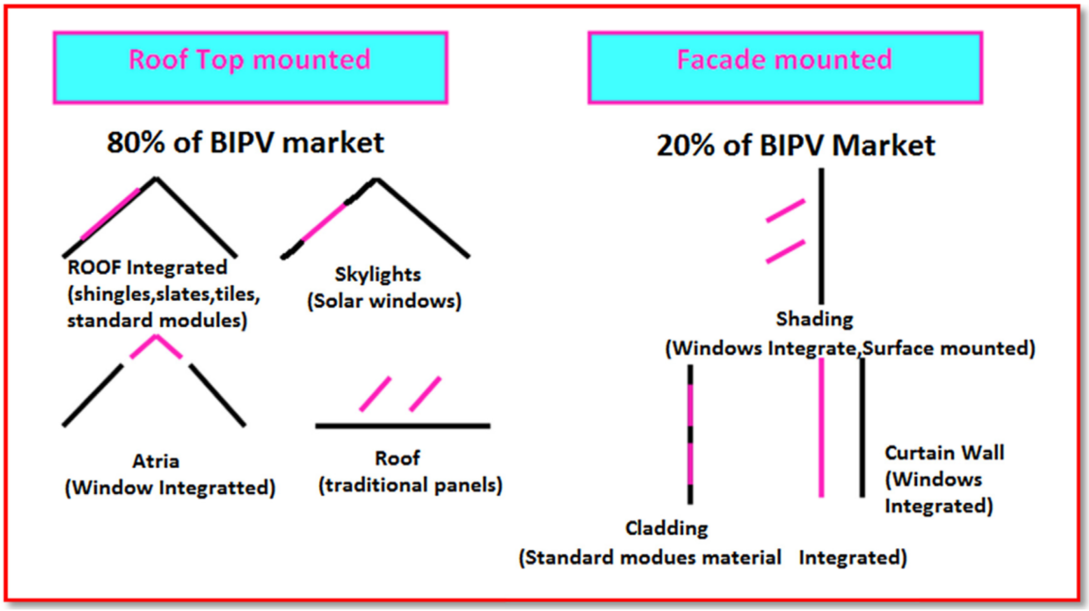


**Fig. 3.** Layout of the BIPVT market [58], reused with permission from Elsevier license number 5017780314718.

Skylight

Shading

BIPV Solar Facade

BIPVT In-Roof Systems

Semi-Transparent Facades BIPVT with PCM

Transparent thin-film BIPV modules Curved clay solar tiles

BIPV modules with glass ceiling External building walls

BIPVT Duct design BIPVT fitted on the rooftop

**Fig. 4.** Various applications of BIPVT systems.

Several research works have been conducted on experimental, theoretical, and numerical modeling to examine the PVT involving BIPVT systems fully. The PVT systems that generate simultaneously thermal and electrical energies have high overall efficiency per unit surface area and potentially low installation cost. As well, it is particularly appropriate for appliances that require both heat as well as power with available roof space [105][106][107][108]. Jakhar et al. studied the earth-air heat exchanger performance connected by rooftop PVT air collectors numerically [109]. The earth-air heat exchanger, combined with a PVT system, was suggested mainly in space heating of buildings during the colder weather conditions as well as the supply of power. It was however deduced that temperature of photovoltaic modules coupled with heating capacity of the air heat exchanger were improved.

A genetic approach for the optimization of the energetic and exergetic characteristics of a BIPVT system from January to April was suggested by Khaki et al. [110]. The group of researchers evaluated building cooling coupled with heating during warmer and colder seasons. Exposed area of collector and channel dimensions were investigated to optimize the airflow rate, channel depth, and heat loss coefficient. The outcome for the investigation highlighted the fact that the optimum conditions was subject to the importance of the system. Additionally, the aspect ratio had a negligible effect on the objective functions; however, it impacted other performance parameters. A brief review of the phase change materials (PCMs) based on air or water, focusing on their solar application, particularly for thermal control, was studied [108][111]. The PCMs that are generally available, cheap, non-toxic, and non-hazardous, have a wide range of melting point temperatures. However, in the PVT system, these materials should be selected with higher melting temperatures during sunshine to attain high heat removal. The BIPVT with PCM based on air supplies hot air that is useful for utilized for heating ventilation and air-conditioning systems (HVAC), and crop drier, etc. [112][113].

Using conventional working fluids in different thermal engineering applications is not adequate to transfer the required heat so dispersing various nanoparticles or utilizing phase-change materials (PCM) into the base fluids such as gases or liquids enhanced the system thermal performance [114] [115][116]. Nanofluids (NFs) that are formed by adding nanoparticle (NPs) to base fluids enhance the thermal conductivity for different thermal engineering requirements such as water desalination, heat storage, heat exchangers, etc. [117][118]. The Nano-enhanced phase change materials (NEPCM) is a promising material for enhancing the thermal characteristics of BIPVT systems due to increasing the thermal conductivity, modifying density, viscosity, latent heat, and specific heat [119][120][121][122][123]. The recent advances in PVT systems revolves around cooling as well as energy storage system using phase change materials and Nano-enhanced phase change materials in various engineering applications for heating ventilation and air-conditioning systems [124]. Similarly, the different techniques of preparing the NEPCM as well as the thermophysical properties at different temperatures were presented.

A hybrid PV integrated with phase change material (PCM) as well as graphene nanofluid (NF) having different volume concentrations was studied by Wahab et al. [125]. It was deduced that the maximum thermal coupled with electrical exergy performance for PV/PCM/NF were 1.78% at 20 l/min and 13.02% at 40 l/min with 0.1 vol.% of nanofluid as represented in **Fig. 5**. Fang et al. explored the efficiency for a PVT heat pump system, as depicted in **Fig. 6** to compute temperature as well performance of the PV module [126]. The photovoltaic/thermal solar heat pump system was integrated from indoor and outdoor units. The refrigeration circulation operates when the electromagnetic valves (7, 13, and 15) were opened and the four-way electromagnetic valve was on cooling mode. However, the PV/T circulation operated when the electromagnetic valves (8 and 13) were opened and the four-way electromagnetic valve was on the cooling mode to absorb heat from the solar PV cells. The investigation highlighted that the efficiency of the photovoltaic/thermal solar heat pump system was enhanced by 23.8% compared to the conventional PV module.

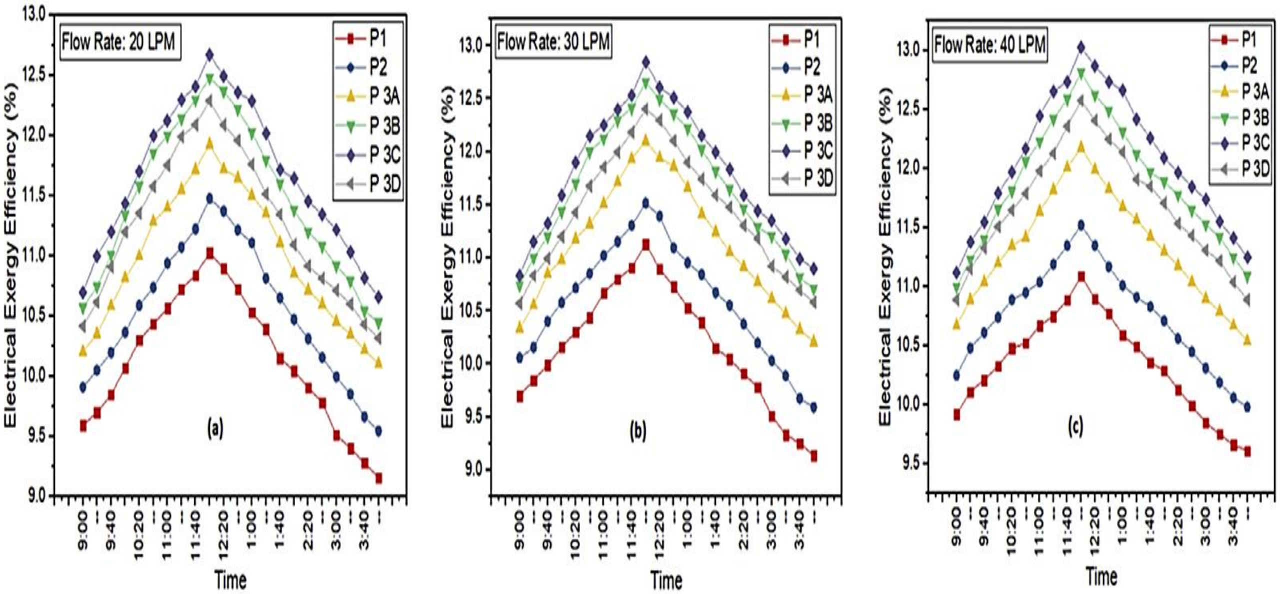
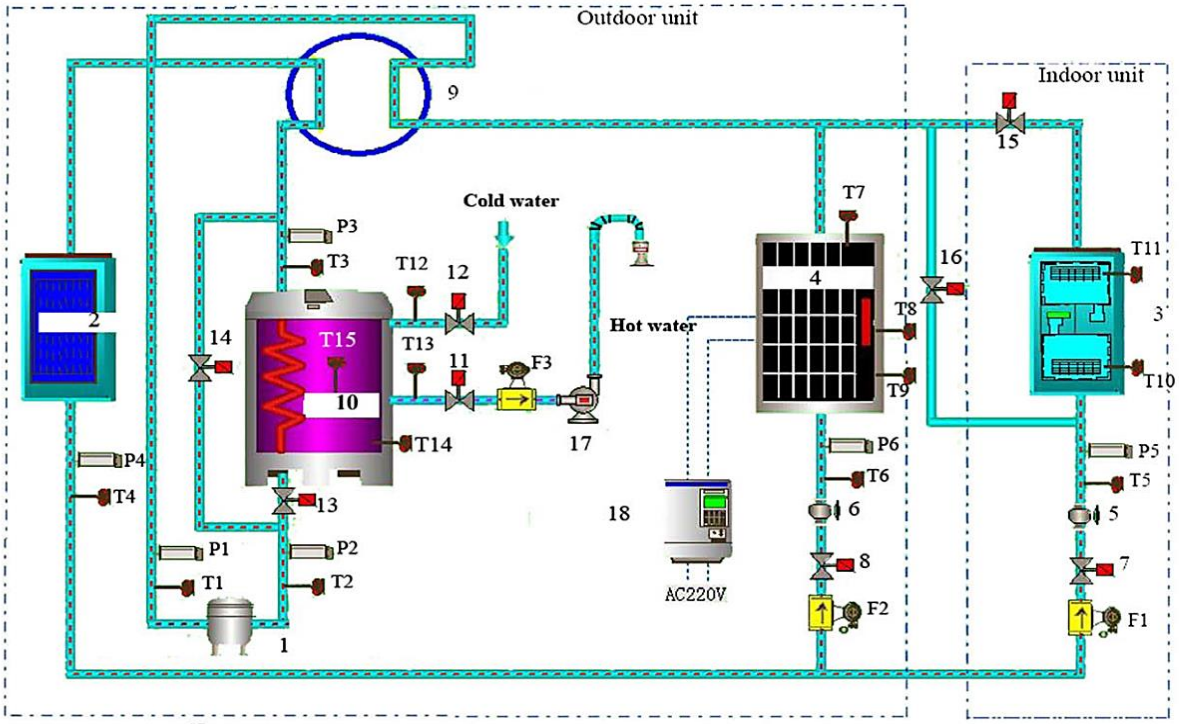


**Fig. 5.** Electrical Exergy Efficiency for various system configurations at different flow rates [125]. P1: Conventional PV system; P2: PV with PCM; P 3A: PV with PCM and distilled water; 3B: PV with PCM and 0.05% graphene nanofluid; 3C: PV with PCM and 0.10% graphene nanofluid; 3D: PV with PCM and 0.15% graphene nanofluid, reused with permission from Elsevier license number 5017780546642.

Chow et al. [127] conducted an investigation into a vertical façade-integrated PVT for a water-heating technology under varying natural and forced circulation modes for different seasons, as presented in **Fig.**

7. The experimental conclusion presented captured the fact that the natural water circulation was ideal compared to forced one. In addition, Chow et al. explored the BIPVT system for hotel in subtropical regions [128]. Three different options depended on the air passages over the PV modules were examined numerically. The results indicated that the various proposed systems almost the same electrical performance, and the environmental conditions had a considerable effect on the PV power generation. Additionally, an open-air gap at all sides of PV modules appeared to be better choice for the tropical regions due to its simple design., high effectiveness, reduced cooling energy consumption, although of lower improvement in PV performance.



| | | | | | |
|---|---|---|---|---|---|
| 1 | compressor | 2 | heat exchanger of outdoor unit | 3 | heat exchanger of indoor unit |
| 4 | PVT evaporator | 5,6 | throttle valve | 7,8,9,11-16 | electromagnetic valves |
| 10 | water heater | 17 | pump | 18 | convertor |

**Fig. 6.** Experimental system [126], reused with permission from Elsevier license number 5017780781023.

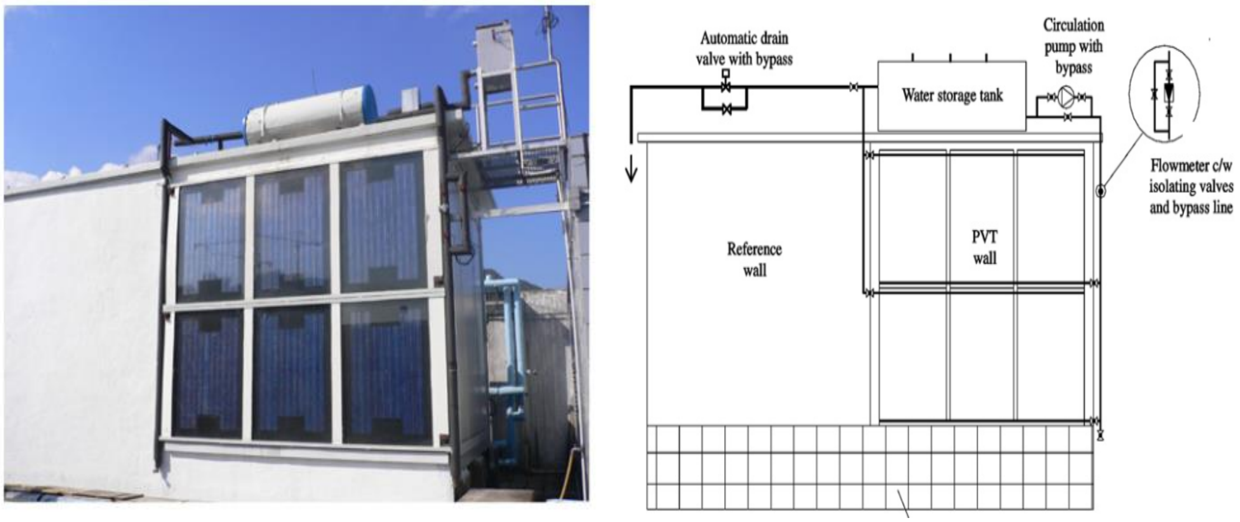


**Fig. 7**. Experimental setup of BIPVT **(a)** real photo with the environmental chamber **(b)** water-heating circuit [127], reused with permission from Elsevier license number 5017780950696.

Anderson et al. presented the characteristics of the BIPVT system theoretically, as illustrated in **Fig. 8** using the Hottel–Whillier modified model [129]. The results revealed that material used in the development of the collector base had marginal effect on the thermal performance of the BIPVT system, then the lowest cost material, such as steel, would be preferred. However, the most important parameters were the fin efficiency and thermal conductivity between the photovoltaic module as well as the supporting structure. Lamination of the photovoltaic had a considerable impact on the electrical coupled with the thermal performance of the BIPVT system. A one-dimensional transient model was presented subject to fundamental heat transfer formulae to select convenient configuration of six BIPVT systems appropriate for the cold climate [130]. The results indicated that at constant air flowrate, the systems connected in series maintained better performance.

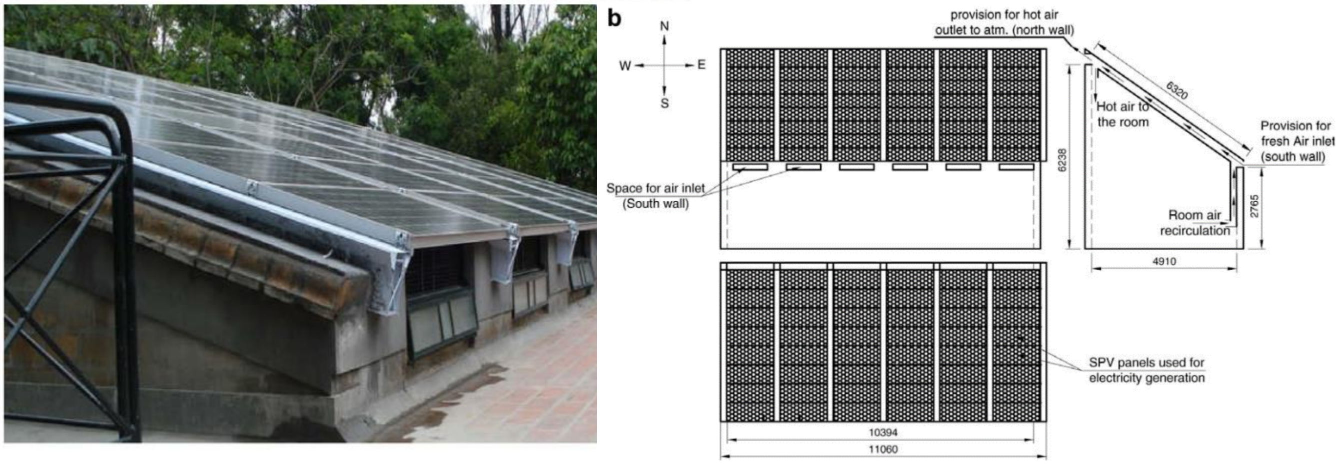


**Fig. 8**. BIPVT positioned on a roof (a) Perspective view. (b) Projected view [130], reused with permission from Elsevier license number 5017781185171.

An investigation to replace traditional heating method utilizing fossil fuels or external electrical energy suitable for food industry has been carried out [131][132][133][134]. The PV modules was employed to produce electrical power as well as thermal energy required for chiller; this concept was utilized to milk chiller [135]. The system cooled the milk at a rate of 600 liters/day and supplied hot water for milk tank cleaning. The thermal model of milk pasteurization using PV modules integrated with a parabolic concentrator was proposed by Meraj et al. [136]. The electrical efficiency of PV modules, electrical and thermal energy generated, and milk temperature were evaluated for different milk mass flowrate values, the quantity of collectors, PV modules packing factor, and working fluid mass flowrate in a solar collector. The results revealed that the presented pasteurization system produced about 216 kg of pasteurized milk as well as 5.7 kWh of energy at the optimal operating and design parameters. The developed concept was self-sustained for 6hrs during the day.

Enhancing the solar flat-plate solar collector using $TiO_2$/water nanofluid was investigated by Moravej et al. [137]. The results revealed that the maximum system efficiency was 78% at 1 wt% TiO2/water nanofluid. On the other hand, the performance of a hemispherical solar collector using Ag/water nanofluid with different concentrations was studied experimentally [138]. Moreover, the performance of a circular flat-panel collector with spiral pipes was implemented experimentally [139]. It was concluded that the system efficiency was enhanced compared that for rectangular collectors and its maximum value was 75.3%. The BIPVT with movable shading compared to that of the fixed modes includes BIPV over the window was investigated by Paydar [76] as illustrated in **Fig. 9**. The outcome of the investigation showed that annual thermal load for the BIPVT with the movable technology was lower compared to the other concepts investigated by 12, 16, 15, and 20%, and the electrical energy generation was higher by 70%, 142%, 113%, and 290%, respectively.

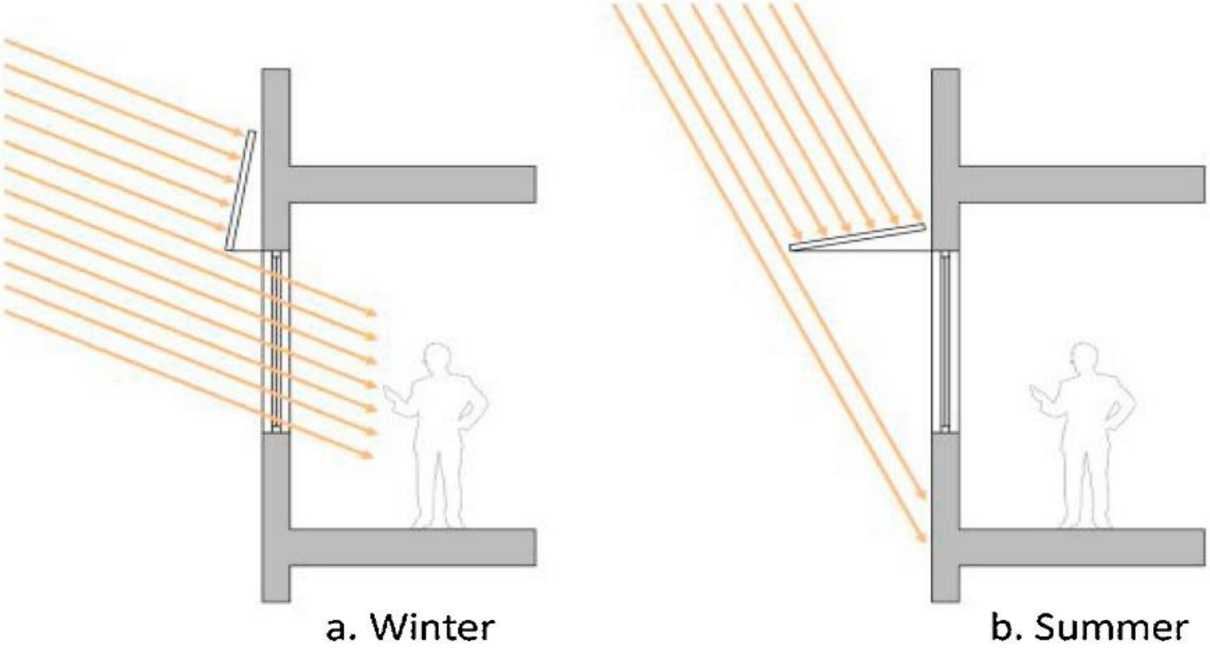


**Fig. 9**. PV module with movable shade device in winter and summer seasons [76], reused with permission from Elsevier license number 5017781424458.

Nada et al. [140] used a passive cooling system for the PV module by phase change material as well as $Al_2O_3$ nanoparticle material in the BIPVT system. The experimental results showed that using Nano-PCM coupled with PCM reduced the PV module's temperature by 10.6 $^oC$ and 8.1 $^oC$, respectively. So, the corresponding parameters for the electrical performance of the photovoltaic module were improved by 13.2% and 5.7%, respectively in comparison to the photovoltaic module without the passive cooling technology. Therefore, the efficiency for the photovoltaic module with Nano-PCM was superior in comparison to the PV-PCM technology. Two configurations of BIPVT earth-air heat exchanger (EAHE) for heating as well as cooling purposes were suggested by Afrand et al. [141] depicted in **Fig.10**. The impact of width, length, as well as depth of the air duct installed on backside of photovoltaic module, air flowrate, pipe diameter coupled with length of the EAHE system were evaluated. Moreover, the annual thermal energy, thermal exergy, and electrical energy obtained from configuration (a) were 3499.6, 55.6, and 5908.2 kWh, respectively, while the corresponding values for configuration (b) were 3468.2, 51.8, and 5969.9 kWh, respectively.

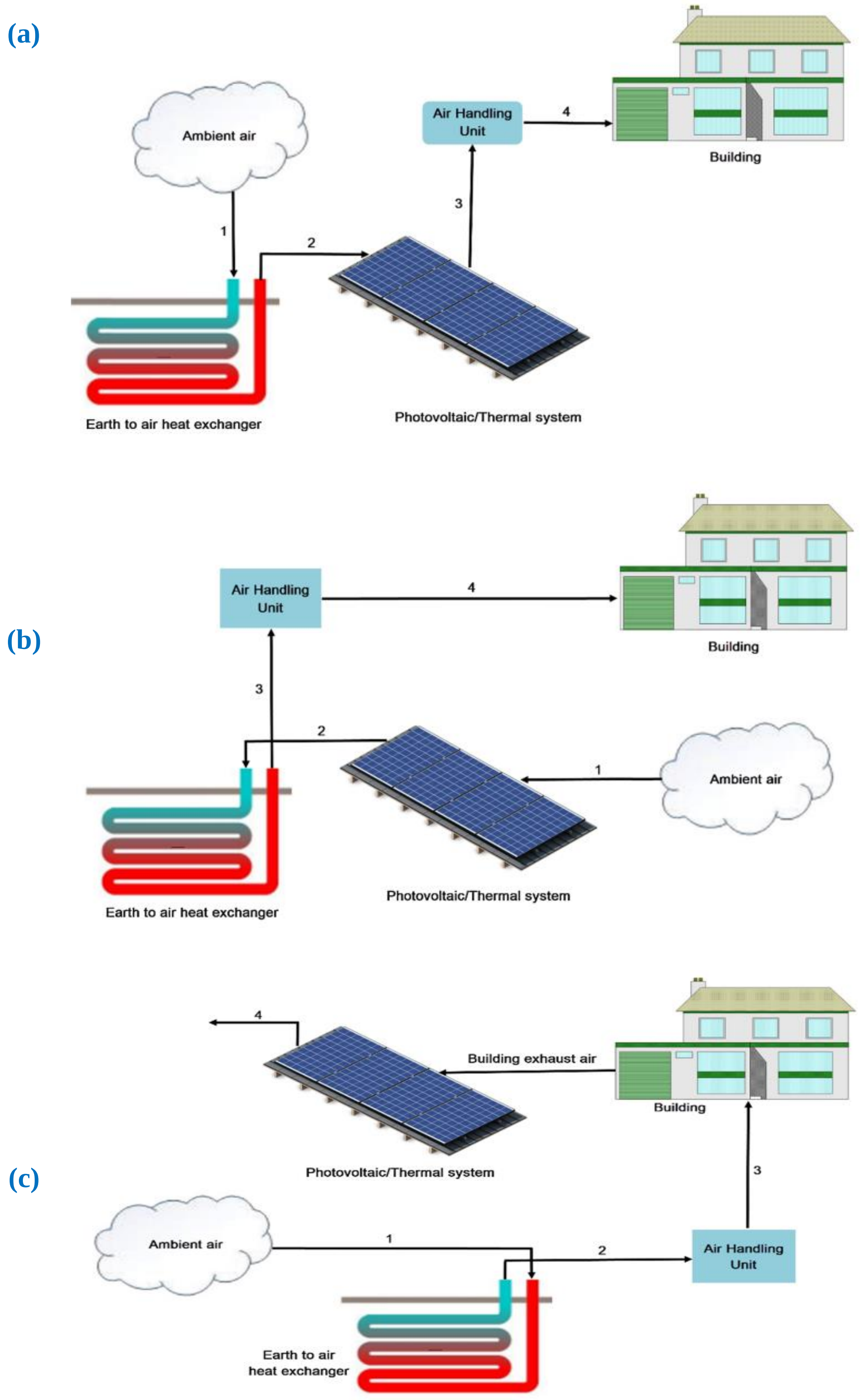


**Fig. 10.** The working principles with different configurations **(a)** heating mode (system A) **(b)** heating mode (system B) **(c)** cooling mode [141], reused with permission from Elsevier license number 5017790129087.

### 5.2. Solar ventilation system

In the HVAC technology, the air ventilation is the required volume of outside air having suitable indoor air quality (IAQ). Heating load for air ventilation contributes significantly to total heating load of the building. The heat recovery technology is a popular appliance for decreasing energy consumption; accordingly, the solar energy resource can be employed for air ventilation heating. Photovoltaic modules reject more than three-quarters of incident solar energy, increasing its temperature. The accumulated waste heat can be utilized for air preheating in ventilation technology. When ventilation air is introduced into the structure, excess air becomes exhaustible via the exhaust systems. The exhaust air tends to have lower temperature in comparison to the outside ambient temperature particularly in summer months in hotter regions. Passing active or passive air over the PV modules is employed to attain their cooling via natural convection as well as forced convection [142][143].

Energy performance of a wall combined with a PV module by either induced buoyancy system or assisted ventilation system was assessed by Dehra [144]. The vertical wall was constituted on façade test-room located in Montréal, Canada, as illustrated in **Fig. 11**. The experimental setup of the PV wall was built and installed with back layer, air cavity coupled with two PV modules. The electrical as well as thermal characteristics of ventilated PV façade was analysed for varying operating characteristics. Outcome of the investigation highlighted that the maximum combined electrical as well as thermal efficiencies were 37.6% and 31.4% for fan-assisted and buoyancy-induced air PV ventilation, respectively. A numerical model for studying the BIPVT for air ventilation in structures for cooling photovoltaic modules as well as heating ventilation air was developed by Shahsavar et al. [145] as presented in **Fig. 12**. It was however deduced that exhaust air from the building is useful for cooling photovoltaic modules to enhance the overall electrical performance.

Pantic et al. [146] explored the efficiency of varying BIPVT systems with recovered open-loop air heating for building heating both theoretically as well as experimentally. The first configuration was constructed with unglazed BIPVT with air pass underneath, while the second configuration was manufactured with glazed solar air collector positioned vertically with the previous configuration, and the third one was built in by adding glazing over the PV as illustrated in **Fig. 13**. The investigation reported that the first concept was a suitable arrangement for air preheating and hot water.

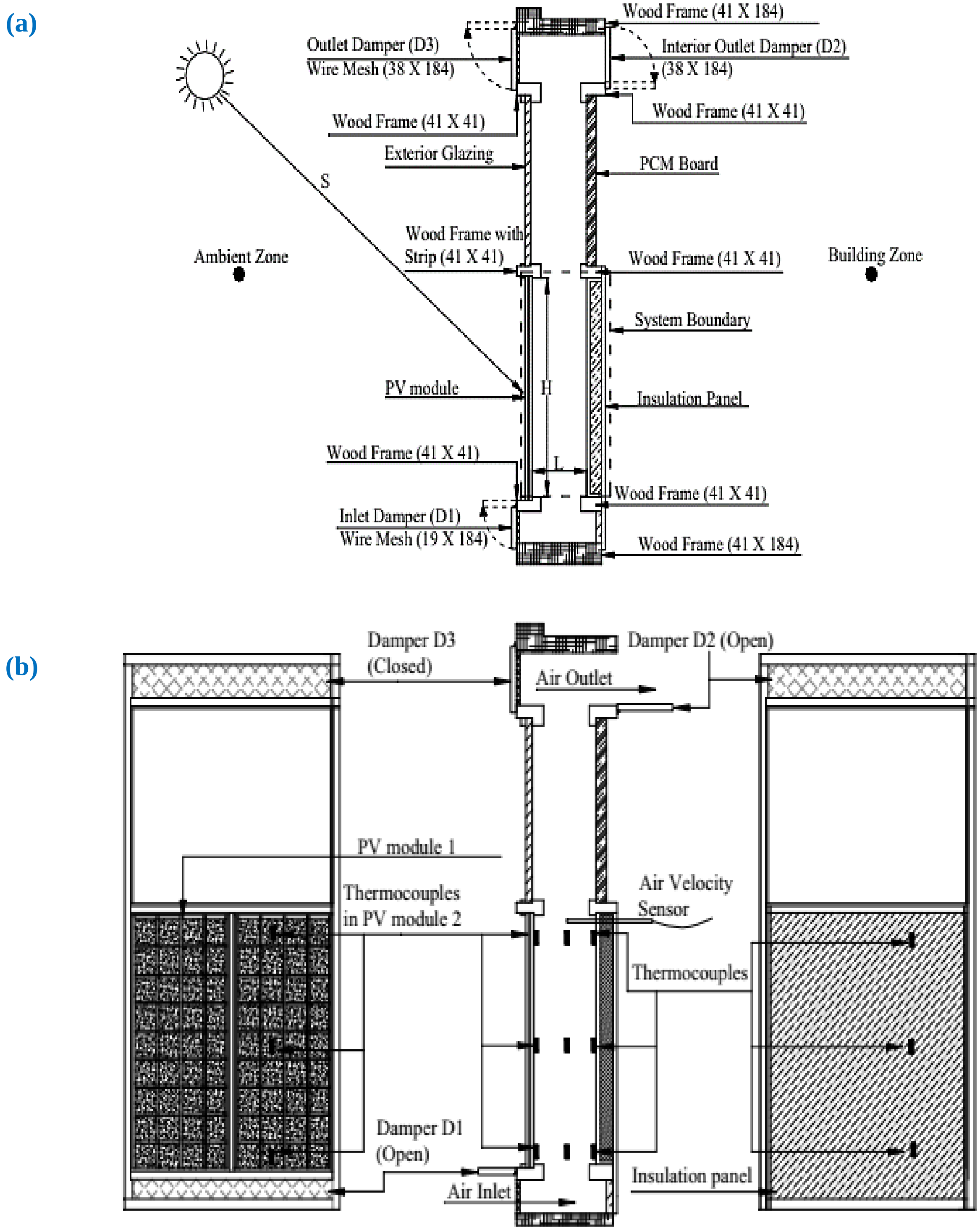


**Fig. 11.** Experimental setup **(a)** side-elevation **(b)** arrangement of façade [144], reused with permission from Elsevier license number 5017790325724.

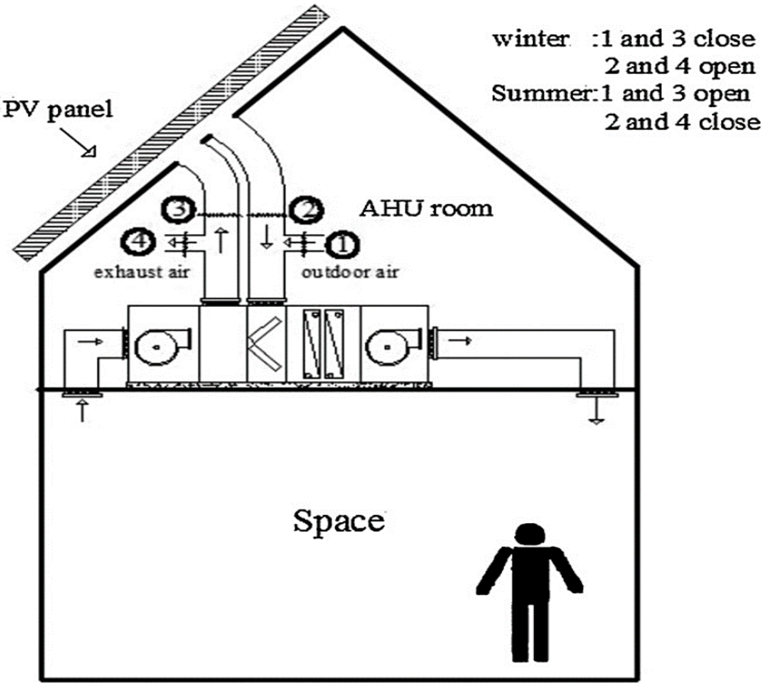


**Fig. 12.** Schematic diagram for proposed BIPVT system [145], reused with permission from Elsevier license number 5017790434535.

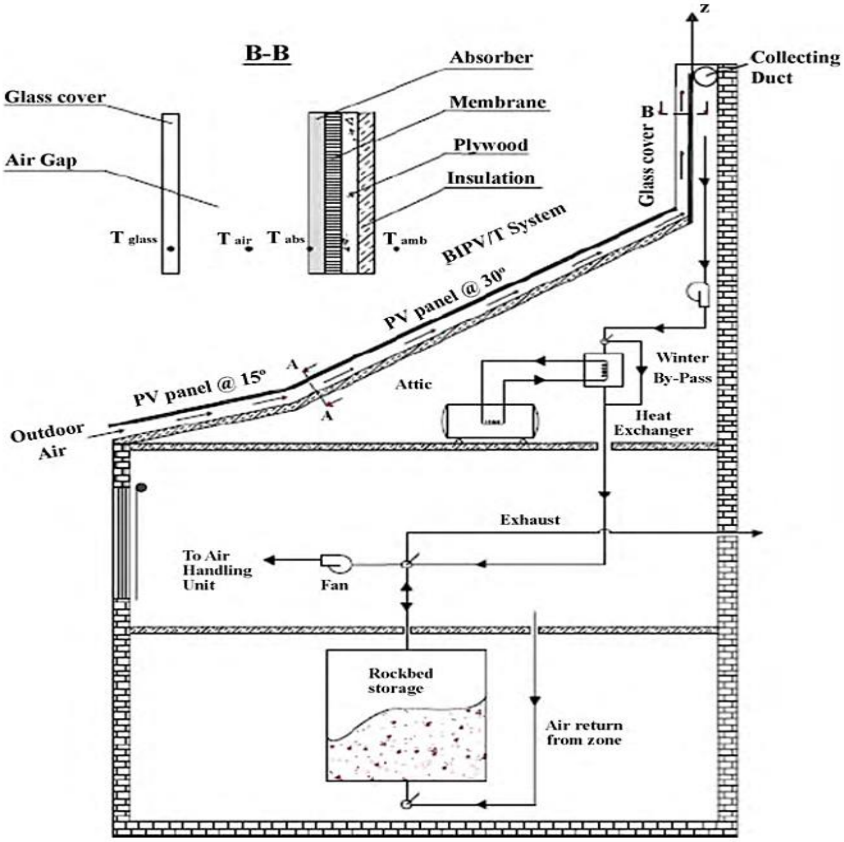


**Fig. 13.** The second configuration with unglazed BIPVT system with solar air collector [146], reused with permission from Elsevier license number 5017790781708.

### 5.3. Architectural envelopes

Smart windows for BIPVT systems is a promising technology with high expectations to play an important role as an architectural element to optimize the use of the daylighting and cooling requirements [147][148][149]. The dynamic behavior of glazed windows plays a natural evolution of innovative PV modules for intelligent building [61]. The most promising BIPVT candidates are the ones with high transparency in the visible region of the incident wavelengths [150]. Potential benefits deriving from perovskite-based BIPVT systems with semi-transparent cells for a real office building decreased total energy by 4% [151][152]. The architectural envelopes of the BIPVT systems offset the system's mere cost compared to the traditional elements [105]. The architectural component of the BIPVT system should be light-weight with high efficiency for the building development [153].

## 6. Barriers to the BIPVT systems

In the near future, the BIPVT systems will contribute significantly in designing and attaining zero energy buildings (ZEBs). However, it should successfully overcome the economic and technical constraints, aesthetical aspects before being integrated into building envelopes to achieve the desirable requirements [154][155] [106][106]. The BIPVT systems are required to overcome some barriers that still limit their widespread, including the considerations of maintenance and replacement, standards and codes, building loads, cost-efficiency, social and psychological factors [61][80][105][156]. Additionally, there are some barriers to expedite the progress in the BIPVT systems, such as lack of operational expertise, planning, maintenance, standardized technology, and commissioning. The limitation of data collection and analysis, localized manufacturing, and limited data on the national market potential are considered.

### 6.1. Techno-economic feasibility of BIPVT systems

The costs associated with low-weight BIPVT facade systems are not considerably higher compared to similar facade materials, while prices of BIPVT glazed technology could be even cheaper by about 20% compared with the conventional materials such as polished stone facades [105]. The costs of BIPVT systems are dedicated to the electrical power generation and for the building envelope function and hence avoid the employing of other materials [85][157][158]. A monthly monitoring procedure of the system is probably necessary to follow any fault alerts and make a suitable decision for the required system changes and the modifications to secure the best performance for a long time [159].

Number of precautions should be considered, such as the negative impact on the building itself and by avoiding the overheating of the system and building [60]. Ensuring the maximum system performance requires an advanced analysis, including the building's graphical and design parameters. The evolved framework technology using architectural glazing for buildings, particularly in the developed countries, remain weak thermal point [61]. Aluminum and glass are the commonly used façade materials, which are quite expensive, while the initial price for the BIPVT system barely equal prices for the photovoltaic modules [104].

### 6.2. Inefficient economic support mechanisms

Besides the electrical and thermal efficiencies, the economic payback time is a vital indicator for evaluating the overall BIPVT systems performance by combining its electrical and thermal energy output, [160]. Accordingly, the market is affected by the national and local supporting policy. There is a set of mechanisms for establishing renewable energy projects for demand and production, including commercial projects, competitive tenders, net metering, and feed-in tariff (FIT) [161][162][163][164]. The cost of electricity is more than that of grid electricity; feed-in ensures that the BIPVT system's electrical energy is supplied directly into the national grid. [165]. Applying the feed-in tariff with high tariffs for BIPVT systems was widely implemented and resulted in massive growth in the BIPVT installations [166]. Additionally, small scale economies, high capital costs, long payback period, weak energy policy, and incredulity of feed-in tariff policy limit encouragement for private sectors participation [159][167]. The overall willingness will increase should government decide to make provision for the technology, and feed-in-tariff scheme gives a good opportunity for many households to adopt BIPVT systems [168]. The yearly cost saving of a solar tri-generation system without utilizing the feed-in tariff was 0.24M €, which accomplished a payback period of 15 years [169].

### 6.3. Maintenance and replacement of BIPVT systems

The most technical design issue raised by owners and occupants due to using BIPVT is the difficulties with the external fixings and wiring [170]. The BIPVT system designers should pay great attention to the replacement and maintenance of PV modules and other ancillaries [171]. The integrated PV modules need special precautions as well as care with replacing the damaged infill units, i.e., screws, gaskets, toggle fixings, and pressure plates [172]. These issues usually appear when refurbishment or renovating the existing building and when its structural loading tolerance is not able to sustain BIPV modules' weight. While, for the new buildings, the architects and engineers can develop the building in accordance to the dead loads.

### 6.4. Standards coupled with codes for BIPVT systems

The combination of BIPVT systems into the structural envelope leads to replacement as well as change of some constructional and structural elements or components but this comes with some limitations on where the BIPVT system could be installed on the roof façade of building [173]. Up to date, many countries do not include the design criteria of BIPVT systems in building codes and standards, hence containing architects and designers decisions on how and where the PVs are to be positioned [60][80]. Accordingly, there is the need for clear instructions in the building codes on ideal practice in relation to BIPVT systems installation to attain the best performance [174]. Inverter efficiency of the individual PV modules depends on the hourly radiation per year, frequency distribution, and optimum operation has an essential impact on entire efficiency of BIPV systems [175]. Subject to the geometrical and operating parameters, the inverter size is the key factor that will support engineers in evaluating the BIPVT systems' performance [176].

### 6.5. Strength of building structure

Ideally, the roof-integrated BIPVT systems are a good choice for insulation with exquisite requirements; however, it is feasible only if the roof structure could support the systems with its different components. But, there is an issue in relation to the building loading capacity being unable to hold up massive weight of the PV modules [177]. The PV modules of the BIPVT system are heavy, and the building structures should be developed to sustain this added weight; otherwise, the building may collapse. Reducing the BIPVT weight implies that thin-film PV cells are used instead of the crystalline silicon cells; however, this will be at an additional cost as thin-film PV is more expensive [178]. The buildings should be well designed to withstand the live loads on the BIPVT system, such as wind, snow, and earthquake. Further load causes the PV modules to bend, requiring serious repair or replacement, which is costly and unfavorable, as it requires BIPVT modules to be detached from envelopes of the building [179].

## 7. Discussions on the BIPVT systems

As BIPVT system produces energy only during the daytime, it helps to decrease the energy needed when demand is high from the power grid. Meanwhile, solar heat gains via the BIPVT could support the daytime heating load, and recovered heat can be stored for reuse during cold night hours in the winter seasons. Applying BIPVT systems in urban infrastructures is a promising solution in achieving sustainable development goals. The BIPVT's are more convenient for constructing residential and non-residential buildings, reducing or eliminating the need for fossil fuels. The benefits of BIPVT systems to communities is enormous, mainly: economic as well as environmental advantages, structural material prices offsets, as well as ensuring a reduction in electrical bills on buildings in spite of the high investment cost on BIPVT systems. The BIPVT systems have a societal benefit by reducing capital investment.

The conversion efficiency of BIPVT technology is low. It is also subject to the weather conditions. Low efficiency of the photovoltaic modules reduces the electrical efficiency of BIPVT systems as well as payback period. The efficiency of BIPVT system depends mainly on the design parameters and seasonal climatic conditions. Tall buildings near the BIPV system increase the shading-effect, hence reducing the thermal as well as electrical energy efficiencies and, consequently, the system's economic viability. Subject to electrical energy generation as well as thermal energy reduction in buildings that change daily, monthly, and seasonally, the BIPVT systems should be installed at the optimum tilt angle of photovoltaic modules, particularly when used as a shading device. Thermal and electrical performance of the BIPVT can be enhanced using the PCM integrated with nanoparticles.

## 8. Challenges and future prospects

In the last few decades, expensive cost of electricity as well as environmental pollution are driving forces to focus on developing renewable energy resources in the building sector. The high capital cost of PV modules needs innovative implementations to encourage the widespread of such promising technology. The cost of BIPVT exporting electricity to the national grid over its lifetime depends on the national policy designed to guarantee and support renewable energy resource development. The electricity cost from traditional energy resources has a considerable effect on cost-effectiveness of the BIPVT systems. Several policies are established to support the strategies to provide the benefits for PV systems; however, limited ones are directed to the BIPVT systems. So, it is substantial to support a specific policy for maintaining, advertising, and establishing the BIPVT systems to general stakeholders and different communities to sustain its market growth. Reducing the cost of building envelope material by using the BIPVT system and saving on monthly bills is a substantial issue that depends on the geographical locations of the application. However, no systematic investigation evaluates the material cost offsets due to using the BIPVT to substitute other traditional building materials.

The economic viability of BIPVT systems depending on amount of electricity required to operate the fan/pumps to circulate air/water in the system has not been fully considered for judging the reliability of the system. Critical improvements in building codes should be achieved to integrate the different buildings with PV modules. Additionally, sufficient efforts should be given to accredit specific standards and policies to BIPVT to support rapid growth. Workshops for builders etc cane be championed to highlight on the various BIPVT system modifications for different applications. Rigorous, consistent work can help to eliminate the doubtfulness concerning the application of BIPVT systems.

The utilization of the BIPVT systems is mainly during the daytime, so there is a critical need for means of energy storage for use during the night hours. PCMs were employed in the BIPVT system for thermal control. The cost of using the PCM to improve thermal as well as electrical performance for BIPVT is a critical issue in the reliability of these systems. Integration of BIPVT systems encompasses further complexity in design procedure for both buildings as well as PV modules to incorporate architecturally the BIPVT systems into the buildings envelopes. So, due to this complexity, the BIPVT systems are mainly employed for highly customized commercial buildings.

BIPVT systems were mainly investigated using water as the heat transfer fluid; however, other fluids, such as ethylene glycol and its water mixtures, oil, etc., should be investigated as well. Ultimately, there is an insistent need for further work, testing, and analysis of BIPVT systems. Water penetration as well as poor heat transfer issues caused by inefficient design integration coupled with complicated maintenance approach have resulted in impacting the commercialization of BIPVT systems negatively. Considerable research in the area of BIPVT is desired regarding the material utilized, absorber design, cost minimize, payback period, environmental conditions, and performance testing, and delicate system controls.

## 9. Conclusions

The building-integrated photovoltaic/thermal BIPVT systems convert the available solar energy into electricity as well as heat for various purposes in the residential and non-residential buildings. The BIPVT systems are a foreseeable solution to guarantee energy security and to mitigate greenhouse gas emissions. A number of installations of BIPVT systems are initialized as the adherence for reduction of carbon dioxide emissions into the atmosphere is being enforced globally. In this review, a number of BIPVT systems accomplished over the last decades were discussed and summarized with emphasis on the benefits, limitations, applications, electrical and thermal efficiencies, the scope for barriers, challenges, and future prospects. The future developments and sustainable perspectives of the BIPVT systems depend on the different barriers discussed, and it is announced diverse solutions for enhancing the BIPVT systems in different applications.

The review has discussed the ability to increase performance of the BIPVT systems as well as identified the research gaps and future prospects and improvements that can be achieved. The policies of the BIPVT systems obviously indicate a considerable effort in the energy scenarios in the green building applications. This review shows that the adoption of the BIPVT system considering the performance and the optimization are necessary for different applications, and it has gained significant attention in the past two decades. The BIPVT systems have been suggested for specific applications, including residential and non-residential buildings. The selection of appropriate PV module material contributes significantly in the system performance as it affects energy harvesting and life span of the module. Similarly, the overall economics of BIPVT systems has to be considered and has to be made favorable by adopting encouraging and supporting policies and regulation toward the great cause of societal benefits such as zero energy buildings (ZEBs) and eliminated or reduced environmental pollution.

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