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A review of designs and performance of façade-based building integrated photovoltaic-thermal (BIPVT) systems

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Abstract:

A façade-based building integrated photovoltaic-thermal (BIPVT) system combines solar photovoltaics and solar collectors for integration within building façades to generate electrical power and produce hot water for buildings. As a result, solar energy efficiency can be increased significantly while heating/cooling load is reduced. Thus, BIPVT applications provide a promising method to significantly reduce building energy consumption for developing low-energy or even zero-energy buildings. This paper presents a review on BIPVT development and focuses on the designs of integrated solar systems within building façades and its influence on electricity generation, thermal performance of PV cells, and energy consumption of buildings due to space heating and cooling. Façade-based BIPVT systems are first classified into 7 types: no use of heat from PV, space heating, ventilation, water heating, (PV-PCM), BIPVT with heat pump and photovoltaic thermoelectric wall according to the uses of the thermal energy from the claddings. The electrical output, thermal performance and impacts on building's heating/cooling load are then comprehensively reviewed for various typical and novel designs developed globally over the past two decades. The advantages and disadvantages of various designs are discussed. Future research directions are also outlined. The result of this review is useful for researchers and engineers to select appropriate BIPVT designs for renewable energy application in buildings.

Keywords: BIPVT, design, performance, façade

1 Introduction

Buildings consume about 30% of the world's total energy according to the International Energy Agency, hence reducing building energy consumption has become a matter of urgency [1]. Renewable energies, such as solar energy, wind energy, tidal energy and geothermal energy has taken an important role in generating energy within buildings. Notably, the electrical efficiency and cost performance of photovoltaic (PV) technology has been intensively improved in recent years [2]. However, PV panels produce large amounts of heat while producing electricity. This heat increases the temperature of the PV panels and reduces its electrical efficiency, therefore the heat dissipated from the PV cells should be removed effectively to maintain high efficiency and avoid overheating of the cells. In certain systems, heat from PV cells is collected and utilized for heating. These hybrid devices are called photovoltaic thermal (PVT) collectors and they produce electricity and heat with a higher total energy efficiency. A PVT device integrated within a building is called building integrated photovoltaic-thermal (BIPVT) system, which provides a promising method to reduce energy consumption in buildings [3].

Generally, a BIPVT system has the following characteristics:

1) The system is integrated into a building and forms a part of the building;

2) The system converts solar energy into electricity;

3) The thermal energy generated by the systems has significant effects on indoor environment or the energy consumption from heating/cooling or ventilation systems in a building, or the thermal energy is collected and delivered for heating purposes.

Cronemberger et al. [4] reviewed BIPV technology applications in Solar Decathlon Europe events in Madrid, Spain where University teams designed, constructed, and operated 35 solar houses. Baljit et al. [5] conducted a review of BIPVT application in buildings from 2006 to 2016. The study classified roof and wall integrated BIPVT into air-based systems and water-based systems to provide clearer insights. Agathokleous et al. [6] reviewed double skin façades (DSF) and building integrated photovoltaics (BIPV) before 2016 with a focus on their air flow and heat transfer characteristics. Yang et al. [7] reviewed research and developments of BIPVT systems before 2016 based on a classification into BIPVT air systems, BIPVT water systems and other systems. Debbarma et al. [8] reviewed various BIPV and BIPVT technologies considering their functions, cost, aesthetics and applications. Debbarma et al. [9] reviewed thermal modeling, exergy and energy performance of BIPVT before 2017. Hu et al. [10] reviewed studies and application of Trombe wall systems in buildings before 2017. Shukla et al. [11] identified the role of BIPV application to sustainable buildings before 2018 in South Asian countries. Saretta et al. [12] reviewed the application of BIPV in building façades for energy renovation in urban environments before 2019. Riaz et al. [13] reviewed the application of PVT systems in building facades before 2019.

PVT collectors can be integrated within building components such as rooftops, façades, windows and shading devices. Correspondingly, BIPVT systems can be classified into roof-based, façade-based, window-based and shading–based systems. Most of the previous literature reviewed all types of BIPVT systems in one paper. However, this paper will only review researches and development on façade-based BIPVT systems which have been comprehensively studied for about two decades. Also, this paper focuses on the designs and performances of BIPVT systems.

The integration of a PVT collector with a façade is not a simple addition to a building but affects the energy performance of both the building and PVT collector. The performance of façade-based BIPVT systems mainly consists of the following aspects:

(1) Electrical performance which can be evaluated by electrical efficiency (defined as the ratio of output electricity by PV cells to the incident solar irradiance) and electricity output per square meter of PVT during a day, month or a year.

(2) Thermal performance which can be evaluated by temperature of PV and thermal efficiency (defined as the ratio of useful heat gains to the incident solar irradiance) and useful heat gain per square meter of PVT during a day, month or year.

(3) The effects on heat losses/gains through the façade of a building which can be evaluated by heat losses/gains through a square meter of façade, or the reduction/increment of heating/cooling loads or the energy consumption of HVAC systems.

(4) Total efficiency which is often used to evaluate the combined effects of thermal efficiency and electricity. Electricity is often converted to thermal energy by applying a conversion factor.

BIPVT systems were usually classified into air-based and water-based systems according to the working medium in many review papers. Because the performance of BIPVT is usually closely associated with the mode of application, façade-based BIPVT systems are grouped into 4 classes, including cooling of PV by air, space heating, fresh air heating & ventilation and water heating systems in this paper. Due to the importance of phase change materials (PCM) and heat pump, BIPVT-PCM and BIPVT-heat pump are also addressed as classifications in this paper. Each class is further divided into several types according to the design integration of PV within façades, as shown in Fig. 1. It must be noted that some BIPVT systems may overlap between the defined classifications in characteristic or function. For example, PV-trombe wall system can be used for space heating or fresh air heating, hence it is classified according to the purpose of investigation in the literature reviewed.

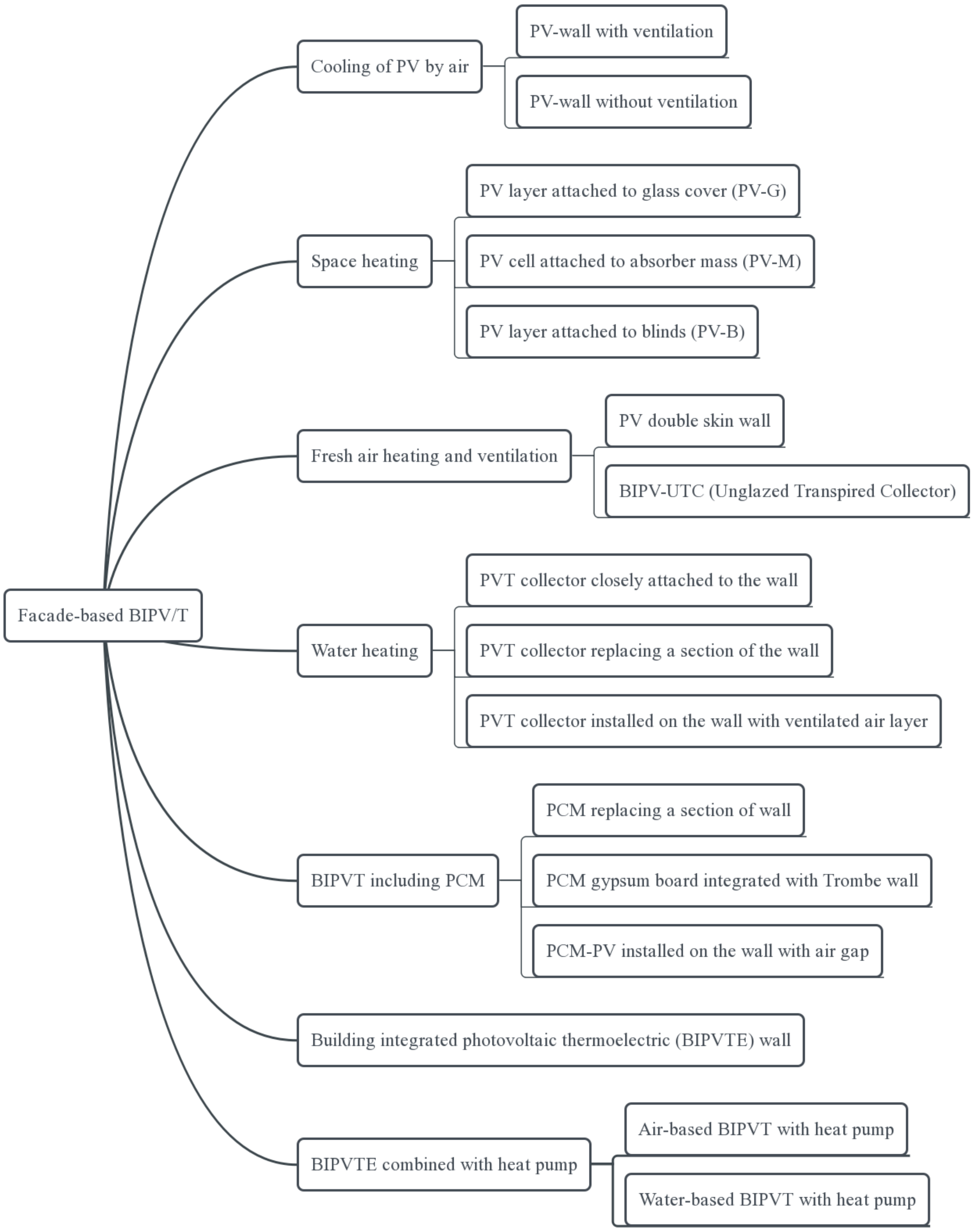


Fig. 1. Classification of façade-based BIPVT systems

2 Cooling of PV by air

In this section, the most common mode of integrating PV and façades, cooling of PV by air is reviewed. Here, the heat from solar cells is not used for heating purpose. Whereas this class is not considered as BIPVT in some literatures, it is included in this paper since the thermal behavior affects the performance of PV cells and heat flow across walls. Two modes of integration are identified according to the configuration of PV and façades; PV-wall with ventilation and PV-wall without ventilation. For PV-wall with ventilation, there is an air layer between the PV panel and the façade for ventilation purposes as shown in Fig. 2 whereas PV-wall without ventilation is directly attached onto the vertical façade as shown in Fig. 3.

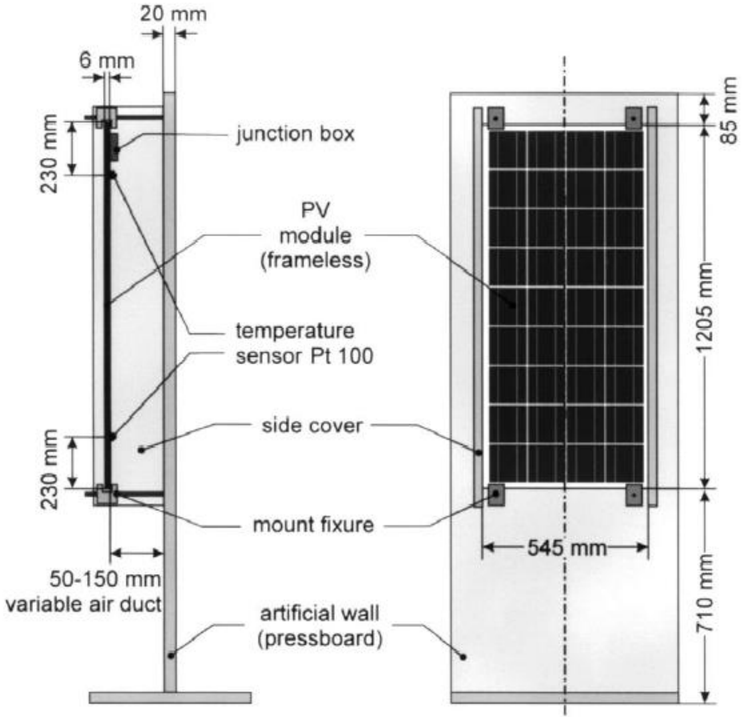


Fig. 2. PV-wall with ventilation [14]

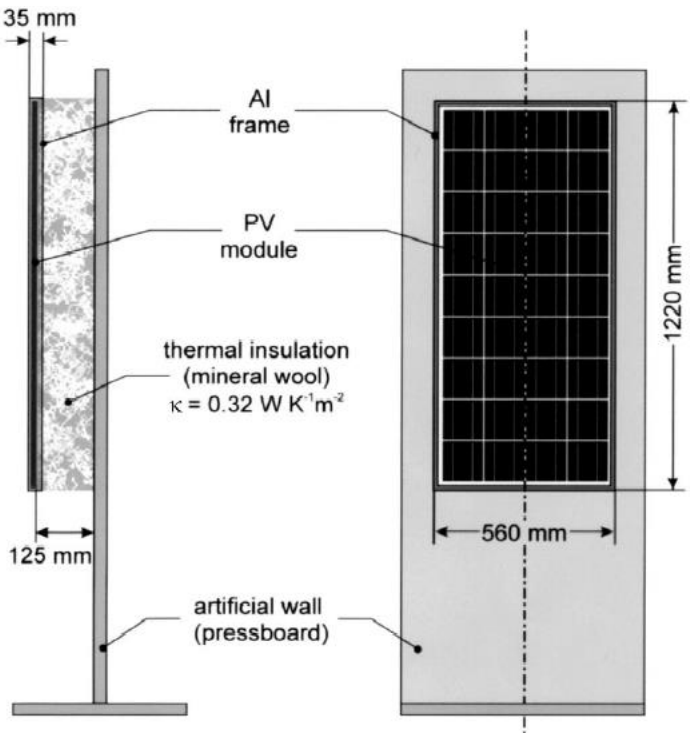


Fig. 3. PV-wall without ventilation [14]

2.1 PV-wall with ventilation

(1) Performance of PV-wall with ventilation and comparison with PV-wall without ventilation

The PV-wall with ventilation is widely used and studied. As shown in Fig. 2, there is a ventilation space between the PV panel and wall, through which air flows from the bottom to top. The air absorbers heat from PV panels thus reducing PV temperature. The air layer can be mechanically or naturally ventilated.

Krauter et al. [14] conducted an experimental study to compare the performance of a polysilicon solar cell using mechanical ventilation and water loop to cool the photovoltaic panel. Compared with PV-wall without ventilation, the system's installation cost was reduced by about 20%. The temperature of PV cell decreased by 18 K while its electrical efficiency increased by 8% at a wind speed of 2 m/s. Chow et al. [15] compared the performance of three designs of BIPVT systems in Macao using ESP-r software: 1) PV/C case in which an air layer is provided at all four sides (top, bottom, left and right); 2) PV/T case in which an air layer is provided at the top and bottom ends whereas the left and right sides are concealed); and 3) BIPV case in which PV cell are directly attached to the façade without an air layer). The results showed that the long-term electricity output of the three systems do not differ significantly, however PV/C and PV/T were more efficient at reducing heat transfer into the building envelope.

(2) Effects on heating/cooling load and energy performance of buildings

When PV is integrated with a wall, heat flow through BIPV wall is different from a conventional wall. Yang et al. [16] compared the cooling load of buildings with PV-walls in Beijing, Shanghai and Hong Kong, and found that the cooling load in the case of BIPV wall was decreased by 33-55% compared with that of a conventional building. Also, PV area with stronger solar radiation had a greater impact in reducing cooling loads. Ji et al. [17] conducted mathematical modeling of PV-walls with different combination modes and orientations based on outdoor meteorological parameters in Hong Kong in 1989. The study revealed that PV systems located in the west direction had the highest solar energy utilization rate. Also, PV-walls with ventilation had little influence on the conversion of electric energy but reduces the cooling load for air conditioning. Sanjuan et al. [18] used CFD simulation to compare the energy performance of an openly ventilated PV-wall and a PV-wall without ventilation in Madrid, Spain. The results indicated that temperatures of ventilated PV-wall are lower than PV-wall without ventilation, hence less heat is transferred into the building envelope with a ventilated PV-wall. The PV-wall with ventilation was beneficial in reducing the cooling load in summer whereas the PV-wall without ventilation was beneficial to reducing heating load in winter.

Infield et al. [19] developed a simplified approach to evaluate the thermal performance of a ventilated BIPV wall based on an extension of G-values and U-values. Virtuani et al. [20] simulated the energy performance of c-Si and a-Si modules for different types of BIPV installations at Lugano (46°N, 8°E) under sunny weather conditions. The results showed that in summer the main loss mechanism of c-Si is temperature loss, while in winter the main loss mechanisms of a-Si are spectral effects and a "degraded" state due to mean low temperatures and Staebler-Wronsky effect. Additionally, there were significant reflection losses in winter and summer for the ventilated PV at 45°-tilt, 90°-tilt (vertical) and 0°-tilt (horizontal).

Athienitis et al. [21] developed a numerical model for a ventilated PV-walls using a detailed transient finite difference method and thermal network, which was verified with experimental results. Through the proposed dynamic simulation model, the electrical energy output of the ventilated PV-wall and its influence on the cooling and heating load, and energy uses of buildings were evaluated. The simulation results showed that the final building energy consumption is reduced by 56.8-104.4%, which is near net zero energy goals for building in southern Europe.

Hassan Radhi [22] studied the total energy uses of a commercial building with PV-wall in United Arab Emirates. The results showed that the ratio of PV electricity output to energy saving for space cooling due to installation of PV panels ranged from 1:3 to 1:4. This means that the energy reduction for space cooling is much larger than the electricity production in such hot regions. The embodied energy pay-back period for PV installation in western or southern façades in UAE was found to range within 12–13 years. Chen et al. [23] studied the influence of prototypes and design factors on the holistic design optimization of high-rise office buildings with BIPV façades in Hong Kong. It was found that the shape coefficient is almost linearly related to the space heating and cooling load, and the net energy consumption of offices with high shape coefficients can be reduced by 48.77%. Chen et al. [24] carried out a multi-criteria optimization of BIPV façade with building interaction for different neighborhood densities. Kyritsis et al. [25] studied the energy benefits of applying Fibre Reinforced Composite BIPV modules in residential buildings in Southern Europe. The study proposed suitable BIPV systems with various orientations and tilt angles.

(3) Heat transfer in the air gap

The internal ventilated air layers between the PV panels and the wall can effectively improve the thermal performance of PV-walls. Besides, these air layers can be used for fresh air preheating, ventilation, space heating and passive cooling. The designs and construction of air layers in PV-walls are vital to the electrical and thermal performances of PV-walls.

Athienitis et al. [21] investigated the impacts of air channel length on the performance of ventilated PV-walls in high-rise buildings. Sandberg et al. [26] developed analytical expressions of the relationships between heat input and flow rate, velocity and air temperature increase for different flow regimes and geometries of air layers in PV-walls. Guohui Gan [27] employed numerical simulation to study the impacts of air layer designs on the performance of PV-walls. The results indicated that the PV temperatures decreased with the increase of panel length if the thickness of air gaps is larger than 0.08 m. Zogou et al. [28][29] carried out experiment and simulation to study the airflow and turbulence field in air gaps of a double-skin PVT façade. Lai et al. [30] carried out full size experiment and CFD simulation to study the flow characteristics, thermal performance, wall thickness and opening types of PV-wall with ventilation. The results showed that the total heat transfer coefficient is between 0.11 W /m^2 K and 0.14 W /m^2 K which is barely affected by the channel width and solar heat flow. Agathokleous et al. [31] [32] studied convective heat transfer in the air gap of naturally ventilated PV-wall through experiments and numerical simulation. The results showed that an open air gap of 0.1 m can generate sufficient air flow to ensure low PV temperature and avoid PV efficiency reduction.

Peng et al. [33] simulated the thermal performance of a ventilated PV-wall in Hong Kong. The simulation results showed that when compared with ordinary walls, heat gain of the building could be reduced by up to 51% in summer while heat gain and heat loss could be reduced by 69% and 32%, respectively in winter. Zhang et al. [34] conducted numerical studies on factors influencing heat flow and transfer processes as well as temperature and velocity fields. For vertical air layers within a height of 2–4 m, a width of 0.1–0.8 m, and an input heat flux of 100–400 W/m^2, air flowrate ranged between 0.042 kg/s and 0.255 kg/s, and temperature rise ranged between 0.66–14.70 °C. For the purpose of lowering PV temperature, the channel width (distance between PV panel and wall) should not be greater than 0.6 m, while for the purpose of providing warm air, the channel width should be less than 0.2 m.

2.2 PV-wall without ventilation

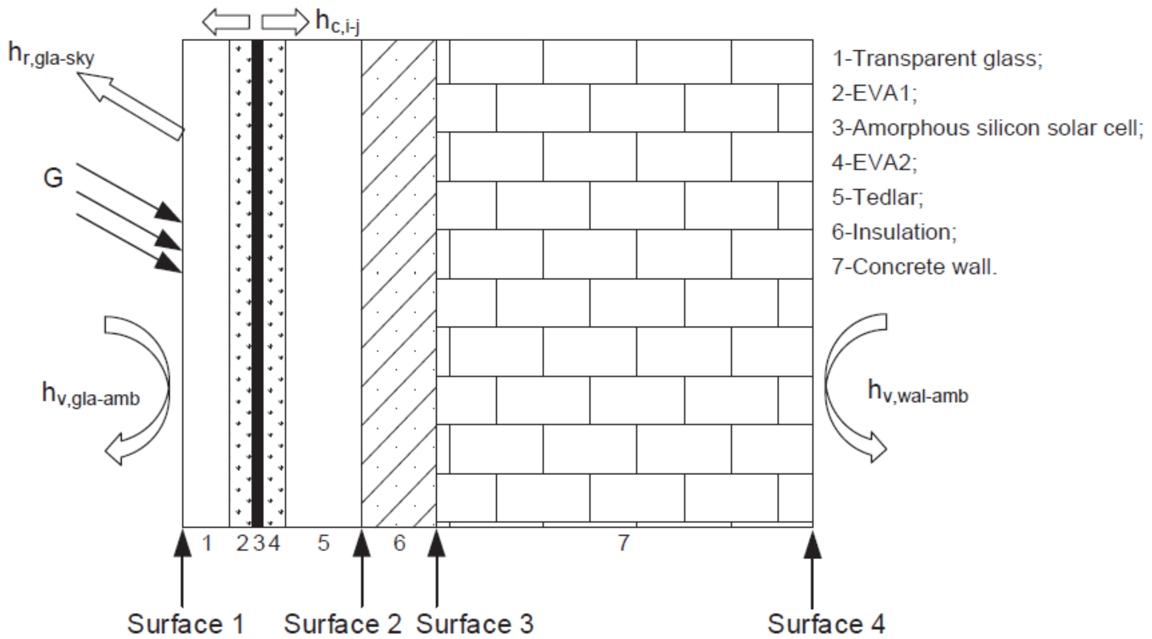


Fig. 4. PV-wall without ventilation layer [35]

Little attention has been given to PV-walls without ventilation. Krauter et al. [14] and Chow et al. [15] compared PV-with ventilation and PV-without ventilation. They found that the PV temperature of PV wall without ventilation was higher than that with ventilation which made the former's electrical efficiency lower. Sanjuan et al. [18] found that the PV-wall without ventilation was beneficial to reducing heating load in winter.

Li et al. [35] analyzed the performance of a PV-wall without ventilation in Shanghai, China through experiment and simulation. The results of the designed system shown in Fig. 4 indicated an annual electricity output of 62.56 kWh /m^2. Also, the annual electricity consumption for air conditioning was reduced by 64.34 kWh/m^2 in comparison with an ordinary concrete wall. It should be highlighted that the insulation layer between the PV panel and concrete wall significantly contributes to the reduction of heat gains through the wall in summer. Heat loss in winter mainly occurred through the PV-wall. The maximum temperature difference between the external surface and internal surface of the PV-wall is approximately 35.0 °C in winter and 16.0 °C in summer. The reason for a lower temperature difference in summer was the lower irradiance on the façade.

2.3 Summary

For the class of cooling of PV by air, there are two designs: PV-wall with ventilation and PV-wall without ventilation. PV-wall with ventilation have been extensively studied whereas only a few studies have addressed PV-wall without ventilation. Mostly, the cell temperature of PV wall with ventilation can be lower and its electrical efficiency higher (if the air gaps are well designed), especially in hot climates. Although the long-term electricity output of the two designs do not differ significantly, either design has different effect on the heat flux through the PV-walls with regards to reducing heat transfer. Generally speaking, PV-wall with ventilation are beneficial to reducing cooling load in summer while the PV-wall without ventilation are beneficial to reducing heating load in winter. In regions with long and severe cold winter, PV-wall without ventilation may perform better than PV-wall with ventilation considering both electricity output and heat loss reduction of a building. Therefore, a detailed and holistic annual analysis based on local weather conditions should be conducted in order to determine a suitable design. With good design of the air gaps between PV panel and wall, air is able to cool down the temperature of PV panel. Naturally ventilated systems can provide satisfactory performances at a low cost and convenience. Hence, natural ventilation is widely used in most applications.

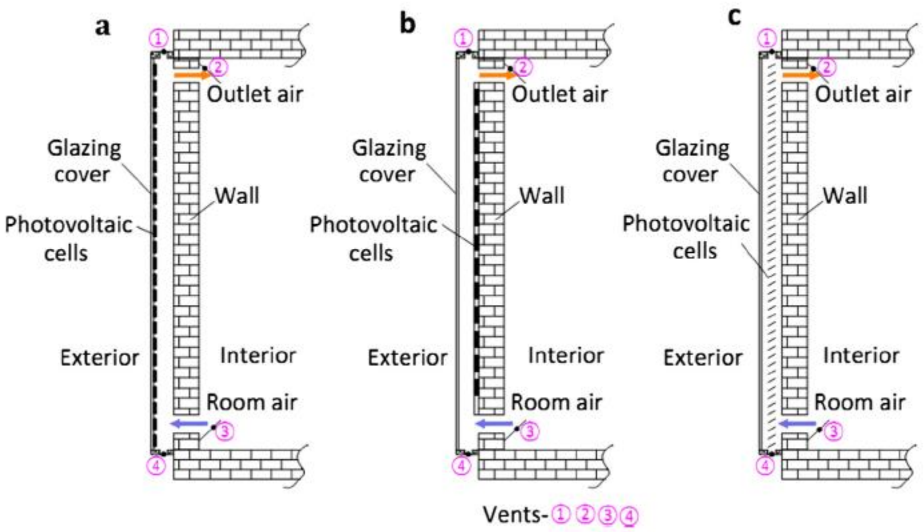
Summaries of designs and performance the PV-walls are listed in Table 1.

Table 1 Summary of designs and performance of BIPVT with cooling of PV by air

Authors year	PV type	Approach	Performance focused	Conditions	Locations
1. PV-wall with ventilation					
Krauter et al. 1999 [14]	m-Si	Experiment	1） PV cell temperature	Indoor test	Berlin Germany
Yang et al. 2000 [16]	-	Simulation	1） Heat flow into room and cooling load component	A typical summer day	Shanghai Beijing Hong Kong China
Ji et al. 2002 [17]	-	Simulation	1） Electrical efficiency and output 2） Heat flow into room	A whole year 1989	Hong Kong China
Sandberg et al. 2002 [26]	-	Simulation Experiment	1） Air flow in the air gaps	Assumed conditions	Gavle Sweden
Chow et al. 2003 [15]	m-Si	Simulation	1） PV cell temperature 2） Electricity output 3） Heat flow into room	A whole year	Macau China
Infield et al. 2006 [19]	c-Si	Simulation	1） Thermal efficiency and output 2） Heat flow into room	17 Oct. 1998	Mataro Stuttgart Europe

Authors year	PV type	Approach	Performance focused	Conditions	Locations
Guohui Gan 2009 [27]	c-Si	Simulation and Experiment	1） Air flow and temperature in the air gaps	Assumed conditions	Nottingham UK
Sanjuan et al. 2011 [18]	c-Si	Simulation	1） Velocity and temperature in air layer 2） Heat flow into room	A typical summer and winter day	Madrid Spain
Zogou et al. 2012 [28] 2011 [29]	m-Si	Simulation and Experiment	1） Air flow and temperature in the air gaps	June and July in 2010	Volos Greece
Peng et al. 2013 [33]	-	Simulation	1） Electrical efficiency and output 2） PV temperature 3） Heat flow into room	A whole year 2006	Hong Kong China
Virtuani et al. 2017 [20]	m-Si and c-Si	Simulation	1） Electrical performance losses	Three years 2011-2013	Lugano Switzerland
Lai et al. 2017 [30]	-	Simulation and Experiment	1） Air flow and heat transfer in the air gaps	Assumed conditions	Tainan China
Agathokleous et al. 2018 [32][32]	p-Si	Simulation and Experiment	1） Air flow and heat transfer in the air gaps	Assumed conditions	Limassol Cyprus
Zhang et al. 2019 [34]	-	Simulation	1） Air gap temperature 2） Flow pattern characteristics 3） Energy performance	Assumed conditions	Hong Kong China
2. PV-wall without ventilation					
M. Li et al. 2019 [35]	-	Simulation Experiment	1） Electrical efficiency and output 2） PV temperature 3） Heat flow into room	A whole year	Shanghai China

3 Space Heating



(a) PV in glass cover; (b) PV in absorber mass; (c) PV in blinds

Fig. 5. Three BIPVT systems for space heating [36]

It is beneficial to use heat generated from PV Panels to reduce heat demands during winter, hence improving the overall efficiency of a building. Façade-based BIPVTs for space heating have been well studied for many years.

There are three designs of façade-based BIPVT systems for space heating as shown in Fig. 5. An image of each designs is also provided in Fig. 6. According to the illustration on Fig. 5, the three typical designs are described as follows:

1) The PV cell is attached to the inside surface of a glass cover (PV-G). As shown in Fig. 5(a), there is an air space between the PV cell and the wall, the indoor air enters the air space from the lower opening of the wall, absorbs heat from the PV panel, then enters the room through the upper outlet. This design is usually named as PV Trombe wall.

2) The PV layer is closely attached to the front surface of the absorber mass (PV-M). As shown in Fig. 5(b), there is an air space between the PV layer and the glass cover while the others are same as PV-G. This design can also be named as PV Trombe wall.

3) The PV cells are attached to the front surfaces of the blinds (PV-B). As shown in Fig. 5(c), blinds are placed between the glass cover and the wall, and the PV cells are integrated within the blinds. Other characteristics are same as PV-G. This system has more flexibility in operation than the other two designs, since blinds can be put down or hung up in addition to adjusting the tilt of louvre blades.

(a) PV in blinds (b) PV in glass cover (c) PV in absorber mass

Fig. 6. Three different forms of BIPVT systems [53]

3.1 PV layer attached to glass cover (PV-G)

PV-G design is similar to a Trombe wall and is used for space heating of the indoor environment. Bloem [37] developed a common Test Reference Environment (TRE) which was placed outdoors to evaluate the electrical and thermal performance of PV-G designs. Also, the study evaluated the thermal efficiency and power output of a PV module equipped with forced ventilation by experiment.

Ji et al [38] developed a model for a PV-G system where PV is attached to the glass cover in 2007. Using measured local weather data during winter in Hefei, China, the simulations showed that the temperature of the glass cover with PV cell was lower than the glass without PV cell by a maximum value of 10.6 °C. Accordingly, the indoor temperature of room with PV-G Trombe wall was higher than the room without PV-G wall by a highest value of 12.3 °C during three days. They found that the mean indoor air temperature in the room with PV-G Trombe wall was higher than that in the reference room without PV-G wall with ranges from 5-7 °C. Ji et al [39][40][41][42] studied the effects of thermal insulation and shading curtain on the performance of PV-G systems in Hefei, China through simulations. They found that with the application of thermal insulation to PV-G, the electrical efficiency was decreased by 2% while the indoor air temperature was increased by 2.4 °C in winter and decreased by 2.5 °C in summer. With the application of curtain shading, the indoor air temperature was decreased by 2.0 °C in summer while the electrical efficiency was increased by 1%. They also studied the effects of using direct current (DC) fan to cool the PV cells and to improve the indoor temperature and evaluated the effects of fenestrated rooms with heat storage through experiments in Hefei, China.

Jiang et al. [43] developed a detailed simulation models to study the impact of PV coverage ratio on the thermal and electrical performance of PV-G systems. The simulation results showed that as the coverage ratio increased, the electrical output of PV-G increased, but the indoor temperature and the thermal efficiency of PV-G decreased. Sun et al. [44] studied the electrical and thermal efficiency of PV-G systems during winter in Hefei, China. The increase of PV coverage on the front glazing decreased thermal efficiency by 17%. Also, the total electrical efficiency was decreased by 5% in comparison with PV cells fully covered with glazing. The electrical efficiency of the PV-G reached 11.6%.

Friling et al. [45] suggested the use of non-linear state space models to depict the dynamics of PV-G systems. Koyunbaba et al. [46] compared PV-G wall systems with single-glass-wall and double-glass-wall systems in Izmir, Turkey, as shown in Fig. 7. The electrical efficiency of PV cell was 4.5% and the highest electrical power PV module was 35.79 W/m^2 on a single day. Although the double glass had higher insulation performance during nighttime, the use of a single sheet of glass with blinds at night provided more heat for winter heating. In order to achieve higher electrical efficiency, the air temperature in the air layer of the PV-G should be lower than that of the dual and single glass modules. Koyunbaba et al. [47] analyzed the energy performance of a-Si translucent PV-G system by experiment in Izmir, Turkey. The solar radiation transmittance of the translucent a-Si solar cells was about 10%. The daily average electrical efficiency was as low as 4.52% and the daily thermal efficiency was 27.2%. A novel system consisting of a PV-G wall combined with an air source heat pump system (ASHP) for providing space heating and domestic hot water was analyzed by Martin-Escudero et al. [48]. The ASHP system supplied nearly all the thermal energy demand, and its Seasonal Performance Factor (SPF) was increased by 14.8%. The PV-G system supplied about 70% of the electricity used by the ASHP and that used by the fans of the PV-G system.

K. Ahmed et al. [49] investigated the performance of PV Trombe wall using porous medium and DC fan. They found that the use of porous medium with DC fan increased thermal and electrical efficiencies by about 13% and 4%, respectively.

Left: single-glass wall; Middle: PV-wall; Right: Double-glass-wall

Fig.7. Photograph of the test room [46]

3.2 PV cell attached to absorber mass (PV-M)

PV-M design is very similar to a Trombe wall and is used for space heating of immediate spaces. Lin et al. [50] proposed the PV-M design shown in Fig. 5(b). A mathematical model of the PV-M system was developed and verified through experiments in Hefei, China. The average daytime thermal efficiency of the PV-M system was higher than the ordinary Trombe wall by 65.2% whereas the temperatures of indoor air and internal wall of the PV-M system were nearly the same as an ordinary Trombe wall. The average electrical efficiency was 12.0% and the average total efficiency (including electrical and thermal) was 58.5%. Lin et al. [51] also found that the variations of PV cells coverage ratio, the cells position and the channel height, have significant effects on thermal performance, but nearly do not affect the electricity efficiency of PV-M systems. The optimum values of thermal efficiency and electrical efficiency were 38.3% and 12.0%, respectively, and the total efficiency reached 57.3%, when the spacing of air layer ranged from 12 mm to 30 mm.

3.3 PV layer attached to blinds (PV-B)

Studies on PV-G design as shown in Fig. 5(c), are fewer than PV-G designs. Nagano et al. [52] evaluated the electrical and thermal energy output of six types of PVT wallboard during winter in Sapporo, Japan. The study concluded that the average electrical efficiency was about 11.2% for p-Si modules at a tilt angle of 80°. Also, the mean thermal efficiency ranged from 29.2% to 36.9% when the wallboards were covered by glass and in the range of 20.2%-22.3% when wallboards were not covered by glass.

3.4 Comparison among the three designs and summary

Hu et al. [53] compared the thermal and electrical performance of three BIPVT systems under all year-round weather conditions in Hefei, China through experiments and simulations. They discovered that the annual electricity output of PV-B system was similar to that of PV-G system but higher than that of the PV-M system by about 20%. Also, the PV-G system was better than the PV-B and PV-M systems in reducing cooling load whereas PV-B and PV-M performed better than PV-G in reducing heating load. Considering both electricity generation and air conditioning load reduction, the total electricity saving of PV-B system was the highest among the three designs and higher than PV-G or PV-M systems by about 45%.

With regards to space heating, there are three designs of BIPV Trombe wall systems: PV-G, PV-M and PV-B. PV-G is the typical design of integrating PV with Trombe wall which is well researched than the other two designs. The PV-G system is relatively better than the PV-M systems in reducing cooling load but worse than PV-M in reducing heating loads. Therefore, a holistic performance assessment including electricity generation and cooling/heating load reduction should be based on detailed annual analysis under local weather conditions and a specific design. The annual electricity output of PV-B system is similar to PV-G but higher than that of PV-M systems. The PV-B also has satisfactory performance in reduction of cooling load in summer and heating load in winter. With regards to energy performance and operational flexibility, PV-B systems are promising if cost can be lowered and product reliability can be guaranteed. However, the costs of PV-B systems are usually higher than PV-G or PV-M systems. Additionally, the PV-B system is more fragile than the PV-G and PV-M system due to the easy operational failure of blinds. More efforts should be invested to improve its reliability and to reduce costs.

Summaries of the BIPVT systems for space heating are listed in Table 2.

Table 2 Summary of designs and performance of BIPVT for space heating

Authors year	PV type	approach	Performance focused	Conditions	Locations

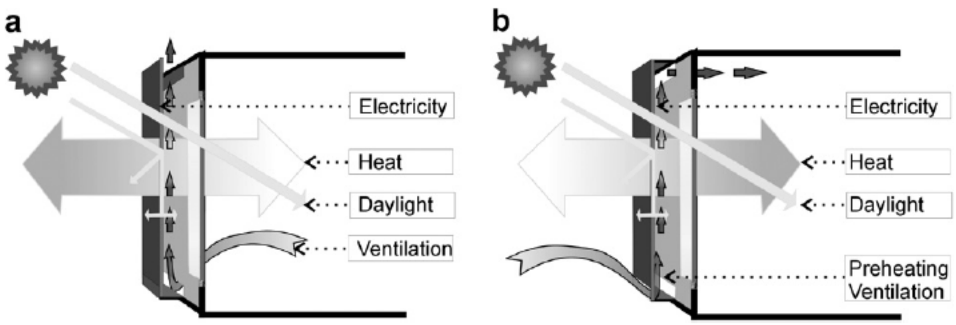
Authors year	PV type	approach	Performance focused	Conditions	Locations
1. PV cell attached to glass cover (PV-G)					
Ji et al. 2007 [38]	p-Si	Simulation	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Room temperature	Several days in winter	Hefei China
Ji et al. 2007 [40]	p-Si	Simulation	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Room temperature	In winter and summer	Hefei China
Ji et al. 2007 [41]	p-Si	Simulation and Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Room temperature 4) Energy for DC fan	In winter and summer	Hefei China
Ji et al. 2007 [42]	p-Si	Simulation and Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Temperature of Room with storage	On February, 2005	Hefei China
Ji et al. 2008 [39]	p-Si	Simulation and Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Room temperature	January, February and March	Hefei China
J.J. Bloem 2008 [37]	a-Si	Simulation and Experiment	1） Electrical efficiency and output 2） Thermal efficiency	Standard test condition	Ispra Italy
Friling et al. 2009 [45]	p-Si	Simulation	1) Heat dynamics of building 2) Heat flow into room	Assumed conditions	Ispra Italy
Jiang et al. 2008 [43] Sun et al. 2011 [44]	p-Si	Simulation and Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Thermal efficiency and output 4) Room temperature	2nd and 3rd January 2008	Hefei China
Koyunbaba et al. 2012 [46] 2013 [47]	a-Si	Simulation and Experiment	1) Electrical efficiency 2) Flow and Temperature distribution of the PV-wall and the room	Several days in February	Izmir Turkey
Martin-Escudero et al. 2019 [48]	-	Simulation	1) Electrical efficiency and output 2) Thermal efficiency and output 3) Seasonal Performance Factor (SPF) 4) Economical ananlysis	A whole year	Bilbao Spain
K. Ahmed 2019 [49]	p-Si	Simulation and Experiment	1) Electrical efficiency and output 2) Thermal efficiency and output 3) PV temperature 4) Room temperature	From December 2017 to February 2018	Kirkuk Iraq
2. PV cell attached to absorber mass (PV-M)					
K. Nagano et al. 2003 [52]	a-Si and m-Si	Simulation and Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Thermal efficiency and output 4) Room temperature	From November 22 to April 5 1999	Sapporo Japan

Authors year	PV type	approach	Performance focused	Conditions	Locations
Lin et al. 2019 [50][51]	m-Si	Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Thermal efficiency and output 4) Room temperature	December, 2017	Hefei China
3. PV cell attached to blinds (PV-B)					
Nagano, et al 2003[47]	a-Si p-Si	Experiment Simulation	1) Electrical efficiency and output 2) Air outlet temperature 3) Thermal efficiency and output	Winter	Sapporo, Japan
Hu et al. 2017 [53] 2017 [36]	p-Si	Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Thermal efficiency and output 4) Room temperature	March and April	Hefei China

4 Fresh air heating and ventilation

The heat from PV cells can be used to heat fresh air in winter and to enhance ventilation in summer. There are two designs of PVT for this purpose: PV double skin wall and PV- transpired collector.

4.1 PV double skin wall



(a) summer (b) winter

Fig. 8. PV-double skin wall for fresh air heating and ventilation [55]

PV-double skin wall can be used for space heating besides ventilation in summer and fresh air preheating too, which is similar to PV-Trombe wall. As shown in Fig. 8, there is an air gap between PV panels and the ordinary wall. Fig. 8(a) illustrates the ventilation mode. During summer, air in the room space moves through the air inlet into the lower portion of the air gap, gets heated and then released outside. Fig. 8(b) illustrates the fresh air heating mode for winter. Here, fresh air enters into the lower portion of the air gap, gets heated, goes up, and flows into the room through the upper opening of the wall.

Guiavarch et al. [54] developed a model for BIPV systems used in a dynamic simulation tool through a case study in Paris, France. The results showed that attaching a PV panel on a façade without air gap for ventilation reduced electrical efficiency of the modules. However, when a mc-PV panel is combined with an air collector for ventilation air preheating, the global efficiency (electricity + heat) was significantly increased to 20%, a 6% increase in comparison to the reference case.

Yun et al. [55] analyzed the influence of proportion of transparent glass in wall and design factors of PV/T panels on the power generation efficiency of two PV façades. Ventilation effect under different conditions were also studied and a new efficiency index to depict the holistic performance of BIPVT façades was deduced. It revealed that the use of this ventilated photovoltaic system had little effect on increasing annual power generation, but the air space between the PV panel and the wall is critical to the stability of the system in Europe. Himanshu Dehra [56] focused on the ventilation efficiency in different seasons. By establishing a mathematical model to address the temperature distribution of the PV layer surface and conducting experimental verification, the ventilation effect of the PVT layer in summer and winter can be predicted. Olympia et al. [57] studied the influence of PVT modules installed on the façade of an office through simulation and experiment in Volos, Greece. The results showed that the optimal size of PV panels and the optimal design of air duct systems were critical to the economic efficiency of BIPVT systems. Besides, a nighttime cooling system during summer is critical to its economic efficiency. The flowrates and duct sizes affected the performance of the BIPVT systems significantly.

Bloem et al. [58] presented a standard Test Reference Environment for evaluating electrical and thermal performance of BIPVT wall systems with experiments. Agathokleous et al. [59] examined the energy and exergy performance of the naturally ventilated BIPVT system through theoretical analysis and experiment in Limassol, Cyprus. The system's lowest total energy efficiency was 26.5% while the highest was 33.5%. Also, the minimum exergy efficiency was 13% while the maximum was 16%. The exergy output of the system was much less than its exergy input. Shahsavar et. al [60] studied the exergoeconomic and enviroeconomic performance of an air-based BIPVT system under climatic conditions of Kermanshah, Iran.

Barbosa et al. [61] investigated the energy performance of PV integrated office buildings with fan-assisted double skin façades. The results demonstrated wide variations of energy performance in relation to the climatic conditions. In the 'cool' climate zone, it resulted in electricity surplus. In the moderate climate zone, the electricity generated from PV could only cover about 30% of the HVAC energy consumption. In the 'hot' zone, energy savings was lowest with only 15% of electricity contributed from the PV systems.

Toffanin et al. [62] used the heat generated by BIPVT system to pre-heat incoming fresh air in HRV (heat recovery ventilation) in order to reduce its defrost cycle for a 120 m^2 house located in Iqaluit, NU, Canada through simulations. The results showed that the outlet air of a BIPVT façade installation could be 14.8 °C higher than outdoor air on a clear sky winter day and that the defrost cycle could be reduced by 13%.

4.2 BIPV-UTC (Unglazed Transpired Collector)

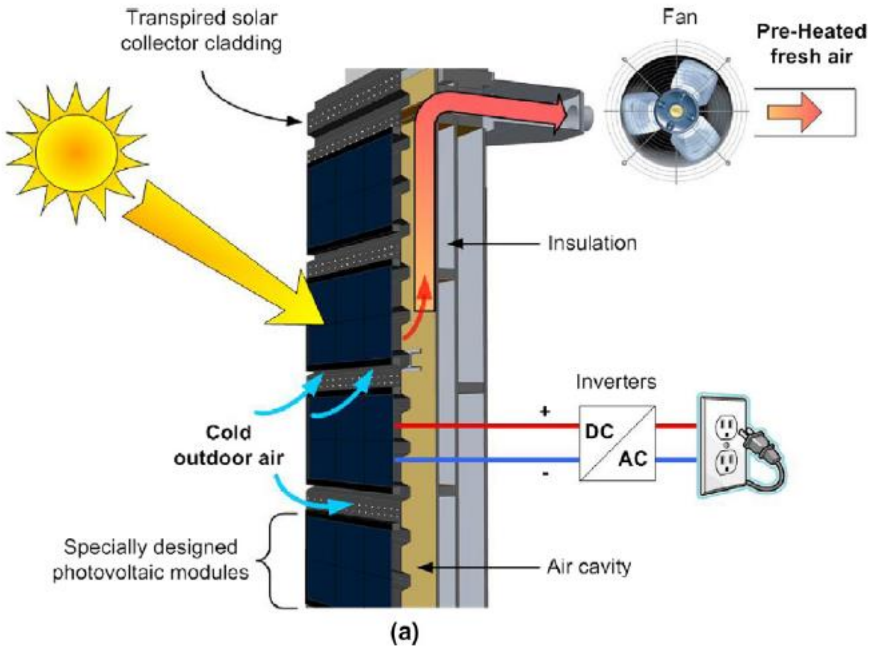


Fig. 9. BIPV-UTC [64]

In order to increase the energy conversion efficiency of photovoltaic façades, a novel design combining of PV and unglazed transpired collector (UTC) installed on façade was developed by Naveed et al. [63]. As shown in Fig. 9, the

BIPV-UTC system draws outdoor air through a dark porous plate, which is heated by solar energy absorbed by the porous plate and PV panels, and then enters indoor space. The performance of the BIPV-UTC was studied and compared with photovoltaic modules without UTC through simulations under the weather conditions of Daejeon, South Korea. On a typical day in February 2005, the temperature difference under forced ventilation ranged from 3-9 ° C and the recovered electrical output was nearly 5%. The static payback period of BIPV-UTC fresh air heating system was 15 years while that of BIPV systems without UTC was 23 years.

Athienitis et al. [64] used PV modules to cover 70% of the area of the UTC and compared with the same size of UTC under the same weather conditions in Montreal, Canada. Experimental results showed that the total equivalent thermal efficiency of the BIPV-UTC system (if assuming that 1 unit of electricity was equivalent to four units of heat) is higher than single UTC by 7–17%. Li et al. [65] [66] carried on a series of studies to obtain an optimal design of UTC with BIPV module through experiments and simulations. They found that the wavelength and the height of PV panel have the largest influence on BIPV-UTCs while the corrugation wavelength and length of slope have the highest influence on UTC performance.

4.3 Summery

The PV double skin wall systems can be used for fresh air heating in winter and enhancement of ventilation in transitional seasons and summer. However, caution should be taken to avoid low temperature outdoor air from directly entering room space and when used in severe cold winter. PV-UTC system provides an interesting method to heat fresh air, however the total energy efficiency has no significant improvement than single UTC at present, hence more efforts should be taken to improve the design in order to increase its total efficiency. Summaries of the BIPVT systems for ventilation are listed in Table 3.

Table 3 Summary of designs and performance of BIPVT for ventilation

Authors year	PV type	approach	Performance focused	Conditions	Locations
1. PV-double skin wall					
Guiavarch et al. 2006 [54]	m-Si	Simulation	1) Electrical efficiency and output 2) Thermal efficiency and output	Annually	Paris, France
Yun et al. 2007 [55]	-	Simulation	1) Electrical efficiency and output 2) PV temperature 3) Building energy consumption 4) Ventilation performance	A whole year	Stockholm, London, Madrid
Himanshu Dehra 2009 [56]	-	Simulation	1) PV temperature 2) Air temperature in the gaps	Various assumed solar radiation	Montreal Canada
Zogou et al. 2011 [57]	m-Si	Simulation	1) Electrical efficiency and output 2) Thermal efficiency 3) Building energy consumption	A whole year	Volos Greece
J.J. Bloem et al. 2012 [58]	p-Si	Experiment	1) Test Reference Environment for electrical and thermal performance evaluation	Outdoor Standard Test Conditions (STC)	Ispra, Lleida Europe
A. Agathokleous et al. 2018 [59]	p-Si	Simulation and Experiment	1) Electrical efficiency 2) Thermal efficiency 3) Exergy efficiency	Mid-September	Limassol Cyprus

Authors year	PV type	approach	Performance focused	Conditions	Locations
1. PV-double skin wall					
Shahsavar et.al 2018 [60]	-	Simulation	1) Electricity output 2) Thermal output 3) Exergy 4) Exergo-economics 5) Enviro-economics	A year	Kermanshah Iran
Barbosa et al. 2019 [61]	m-Si	Simulation	1) Electricity output 2) Thermal output 3) HVAC energy consumption 4) Thermal comfort acceptance	A year	A wide spectrum of Brazilian climates
Toffanin et al. 2019 [62]		Simulation	1) Electrical efficiency and output 2) Thermal efficiency and output 3) BIPV/T cladding temperature 4) Outlet air temperature 5) Defrost cycle	A year	Iqaluit Canada
2. PV-UTC (unglazed transpired collector)					
Naveed et al. 2006 [63]	p-Si	Simulation Experiment	1) Electrical efficiency and output 2) PV temperature/air outlet temperature 3) Thermal efficiency and output 4) Room temperature	Feb. 26, 2005	Daejeon South Korea
K. Athienitis et al. 2011 [61]	p-Si	Experiment	1) Electrical efficiency 2) Air flow outlet temperature 3) Thermal efficiency	Spring	Montreal Canada
Li et al. 2014 [65][66]	c-Si	Simulation and Experiment	1) Air flow and temperature in air gaps 2) Heat transfer correlations in the air gaps	July/12/2013 Assumed conditions	West Lafayette USA

5 Water heating

The above mentioned BIPVT systems are all air based, which are convenient for space heating or ventilating room spaces bounded by a façade. However, they are not convenient to deliver the collected heat to spaces far from the BIPVT modules. Rather, water (or refrigerant) based PVT collectors can perform this function. Water-based PVT collectors generally are constructed as a separate unit and then attached to a façade. There are many designs of water-based PVT collectors such as uncovered water system, single glazed water PVT system, roll bond absorber PVT system and pancake-shaped flow channel PVT system [67] [68] [69] [70]. The configuration of a typical PVT collector is shown in Fig. 10. From the top to bottom, the PVT collector consists of a glass cover, air space, water pipes, thermal absorber and heat insulation layer.

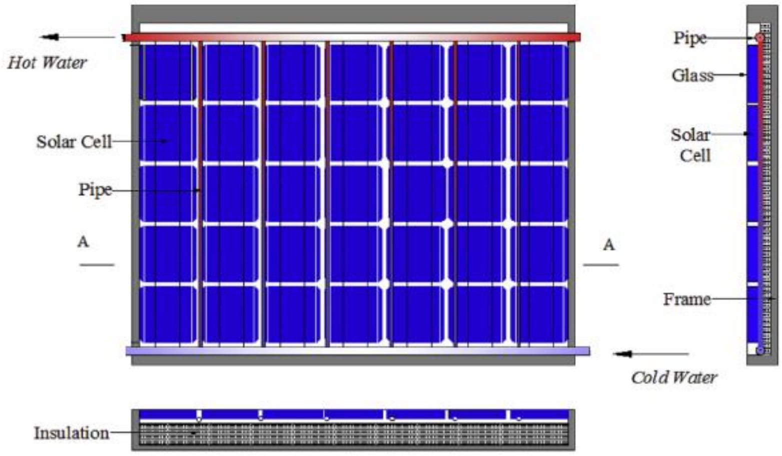


Fig.10. Configuration of a PVT collector [67]

According to the modes of integrating PVT collectors with façades, there are three designs of BIPVT for water heating as shown in the following section.

5.1 PVT collector closely attached to the wall

For the first design, the PVT collector is directly attached to the wall, as shown in Fig. 11.

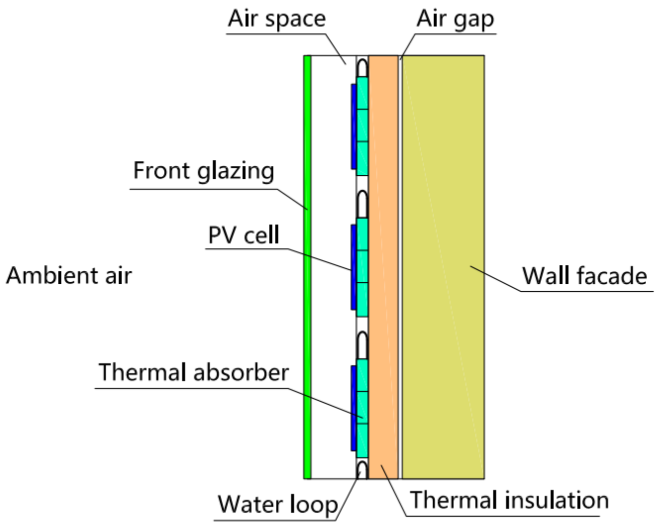


Fig. 11. PVT collector closely attached to the wall

Chow et al. [71] [72][73] conducted experimental studies and developed a simulation on direct natural circulation water BIPVT system for domestic hot water heating in late summer of Hong Kong as shown in Fig. 12. The study found that the performance of natural circulation water loop was better than the performance of forced circulation water loop. The air conditioning load of the spaces bounded by the wall was greatly reduced compared with the traditional PV façade in both summer and winter with great implications for energy use. In addition, the model developed could effectively predict the electrical and thermal output of the system under different operating conditions. The simulation and experimental results show that the annual thermal efficiency was 37.5%, the electrical efficiency was 9.9%, and the commercial payback period was about 14 years when the system was used for domestic hot water pre-heating.

Fig. 12. BIPVT water heating system [71]

Gautam et al. [74] compared the performance of BIPVT systems with other building-integrated solar systems. They found that BIPVT system in cold climates like Denmark (under certain conditions, such as favorable ratio of electrical/thermal prices or a particular range of collector area) can match the performance of traditional technology. In warmer climates like Seville, Spain, the BIPVT systems are competitive against separate solar thermal and PV systems. Wang et al. [75] developed a new BIPVT system employing a novel design of PVT collectors consisting flat-plate heat pipes. Under an assumed irradiance of 300 W/m^2 and a flow rate of 600 L/h, the maximum average efficiency, thermal efficiency and electrical efficiency of the new system were 50.4%, 45.9% and 4.5%, respectively. The thermal efficiency of the proposed system was also higher than the two systems employing PVT collectors consisting of ordinary heat pipes.

K. Ahmed et al. [76] developed a new design of bi-fluid PV Trombe wall to heat air and water supplied to a room. The maximum thermal and electrical efficiencies for average daily evaluation were 79.89% and 10.69% under 300 liters/day for bi-fluid with DC fan glazed and unglazed PV-TW systems respectively.

Xu et al. [77] developed a new hybrid BIPV Trombe wall system. In winter, PV/Air mode was adopted to provide space heating and to generate electricity for the building. During the rest of the year, the system was operated in PV/Water mode to produce hot water and electricity simultaneously. The daily experimental electrical output and efficiency were 0.12 kWh & 7.6% in summer and 0.65 kWh & 12.5% in winter.

5.2 PVT collector replacing a section of the wall

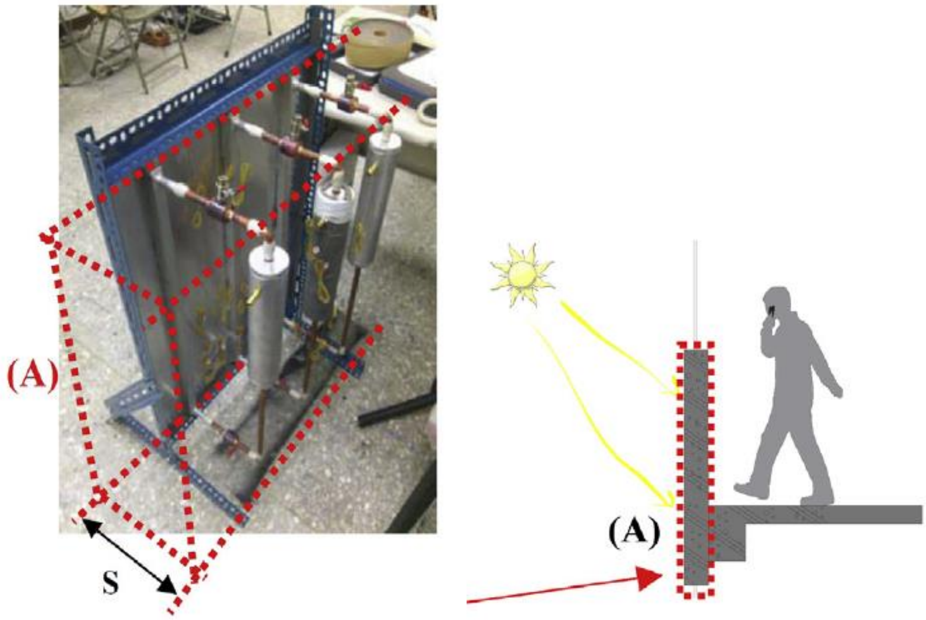


Fig. 13. PVT collector replacing a section of the wall (A is the part that replaces the wall)[78].

Lai et al. [78] proposed a new way to combine the façade and PVT collector for domestic hot water heating. The PVT collector including storage was inserted into the interior of a wall and replaces a section of the wall, as shown in Fig. 13. They conducted a series of experimental studies on PVT collector embedded into a wall. The results indicated that the average Nusselt numbers in both the heated and cooled sections increased while the flow thermal resistances decreased, provided the modified Rayleigh number increases. Under typical daily conditions, the energy efficiency of the new system ranged from 45% to 78% which was not heavily influenced by the water flow rates.

M. Smyth et al. [79] developed a new type of modular Hybrid Photovoltaic/Solar Thermal (HyPV/T) Façade with water storage and conducted experiments at Ulster University. The results showed that the daily thermal collection efficiencies for the 'traditional' flat ICSSWH units were better than the unglazed HyPV/T, by 5-10%. However, when additional electrical power produced by the HyPV/T was included, the overall system collection efficiencies were equal.

5.3 PVT collector installed on the wall with ventilated air layer

Liang et al. [80] developed a new way to combine the façade and PVT collector for water heating. The approach configured a ventilated air gap between the PVT collector and wall as shown in Fig. 14. Considering low temperatures during winter, a refrigerant of R134a and a refrigerant pump were used for forced circulation to deliver heat from PV panels instead of water in a tube.

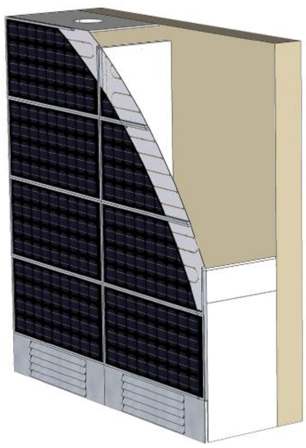


Fig.14. PVT collector installed on the wall with ventilated air layer [80]

Liang et al. [80] conducted a series of experiments to evaluate PV electrical efficiency, useful heat output and coefficient of performance (COP) during heating of a proposed BIPVT systems in Dalian, China. The PV electrical efficiency was nearly 9% on average during the experiment period. The heating COP of the system reached 3.1, and the maximum water temperature in the storage tank was 43.9°C. Meanwhile the heat loss through the wall was reduced compared with ordinary walls. The system was operated by a refrigerant (R134a) pump which performed steadily during the experiment period. This BIPVT system provided an efficient method to use solar energy in severe cold regions without concerns for frozen water during winter.

5.4 Summary

There are three designs integrating water/refrigerant PVT collectors with walls. For the design of PVT collector closely attached to a wall, it is convenient to install and maintain, especially when it is installed for existing buildings. For the design of PVT collector replacing a section of the wall, it provides a new way to combine solar collection and heat storage, and it may be attractive for new buildings. For the design of PVT collector installed on walls with ventilated air layer, it provides a flexible way to control the heat gains or losses through the wall into the building. Summaries of the BIPVT systems for water heating are listed in Table 4.

Table 4 Summary of designs and performance of BIPVT for water heating

Authors year	PV type	approach	Performance focused	Conditions	Locations
1. PVT collector closely attached to the wall					
Chow et al. 2007 [71]	p-Si	Experiment	1) Electrical efficiency and output 2) Thermal efficiency and output 3) Heat flow into room	July to Dec.	Hong Kong China
Chow et al. 2008 [72] 2009 [73]	m-Si	Simulation and Experiment	1) Electrical efficiency and output 2) Thermal efficiency and output 3) Heat flow into room	Some days in July, December; A whole year	Hong Kong China
Gautam et al. 2017 [74]	RAcell	Simulation	1) Electrical efficiency 2) Thermal efficiency	Assumed conditions	Denmark Spain
Wang et al. 2018 [75]	p-Si	Experiment	1) Electrical efficiency 2) Thermal efficiency 3) Water temperature	Various assumes solar radiation	Guangzhou China
K. Ahmed 2019 [76]	p-Si	Simulation and Experiment	1) Electrical efficiency 2) Thermal efficiency 3) Outlet water temperature 4) Outlet air temperature	From December 2017 to February 2018.	Kirkuk Iraq
Xu et al. 2019 [77]	-	Simulation and Experiment	1) Electrical efficiency and output 2) Thermal efficiency and output 3) Water tank temperature 4) Room experimental 5) Optimal water flow velocity	June 24th, 2018 December 18th, 2018	Hefei China
2. PVT collector replacing a section of the wall					
Lai et al. 2014 [78]	c-Si	Experiment	1) Temperature and flow in water loop 2) Heat transfer characteristics	Assumed conditions	Tainan China

Authors year	PV type	approach	Performance focused	Conditions	Locations
1. PVT collector closely attached to the wall					
M. Smyth et al. 2019 [79]	m-c Si	Experiment	1) Electrical efficiency and output 2) Thermal efficiency and output 3) Heat retention	Over time periods of between 20 and 100 h	Northern Ireland UK
3. PVT collector installed on the wall with ventilated air layer					
Liang et al. 2018 [80]	m-Si	Experiment	1) Electrical efficiency and output 2) Thermal efficiency and output 3) Water temperature	A week in October	Dalian China

6 BIPVT including PCM

With the enhancement of solar irradiance, the operating temperature of PV cell will rise, and the electrical efficiency and electricity output will be reduced. In order to reduce the temperature of PV cell, phase-change materials (PCM) can be employed to contain the temperature of the PV layer within a lower range. Many researches have been conducted on the combination of PV and PCM. Ma et al. [81][82] presented comprehensive literature reviews on state-of-the-art PV-PCM systems, with a focus on an overview of technologies and materials selection before 2019. Ali [83] reviewed the research activities performed in the last 5 years, on cooling of PV and efficiency enhancement with PCMs, nano-fluids and their combined use. Diwania et al. [84] conducted a review on the electrical and thermal aspects of PVT systems before 2020, in which some BIPVT with PCM were addressed.

Karthick et al. [85] optimized the performance of a BIPV system by changing the combination ratio of PCM materials and conducting a one-year experiment in 2018. The experimental results showed that the instantaneous peak temperature was reduced by up to 12 ^{o}C for the BIPV-PCM system when compared to the non-PCM counterpart. The annual output power generated from the BIPV module was 34,287 W h/year which increased to 37,024 W h/year by using PCM.

According to the method of integrating PVT-PCM within buildings, BIPVT-PCM systems are grouped into three designs as shown in the following subsections.

6.1 PCM replacing a section of wall

Ho et al. [86] proposed BIPVT integrated PCM which is named as PV/MEPCM. The construction of PV/MEPCM wall is illustrated in Fig. 15. PV cell and PCM have respective frames embedded in the wall, and heat of the PV layer is taken away by the PCM.

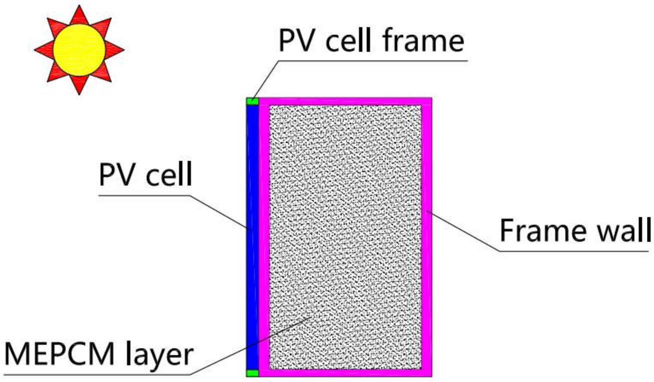


Fig. 15. PCM replacing a section of wall [86]

A mathematical model and simulation analysis of the combination of water-saturated microcapsules PCM and BIPV system were established by Ho et al. [86] based on Taiwan's condition. The results showed that the electricity output and heat output of the PV/PCM system were significantly improved compared with the ordinary BIPV system. A PV/PCM unit with a melting temperature of 30 °C and a thickness of 3 cm was recommended. The type of PCMs, fins and design factors also influenced the energy output of the PV/PCM system. Huang et al. [87] combined experiments and numerical simulation to evaluate several PCMs combinations with different melting temperatures. The results indicated that the temperature regulation function of PCM was mainly determined by the thermal mass and thermal characteristics of PCMs, and the structure of the PV/MEPCM.

6.2 PCM gypsum board integrated with Trombe wall

Omara et al. [88] presented a comprehensive review on Trombe walls with PCMs. Zalewski et al. [89] conducted an experimental study on a small-scale Trombe composite solar wall. In their study, a phase change material was inserted into the wall in the form of a brick-shaped package. The study focused on the delay between the absorption of solar radiation and the energy supplied to the room. The energy performance of the wall from heat flux measurements and enthalpy balances were also presented.

Aelenei et al. [90] proposed a new type of Trombe wall which adopted PCM gypsum board, as shown in Fig. 16. The PV cell was installed on the glass cover with an air space between the PV cell and the wall. Also, there is an air inlet and outlet to the room at bottom and top of the module respectively. If necessary, outdoor fresh air can also be introduced below for indoor ventilation. PCM gypsum board is movable and can be used to change the size of the middle air space. Theoretical and experimental studies were performed on a BIPV-PCM integrated within an office building façade which indicated that the maximum electrical efficiency and thermal efficiency could reach 10% and 12%, respectively. Pereira et al. [91] carried out experimental and mathematical theoretical analysis of the PV/PCM Trombe wall system in Lisbon, Portugal. Various operation strategies and optimum variables were identified to improve the overall energy performance of the system in summer and winter. The highest overall efficiency could reach 64% during winter and 32% during summer if all the optimized variables were used in the calculation.

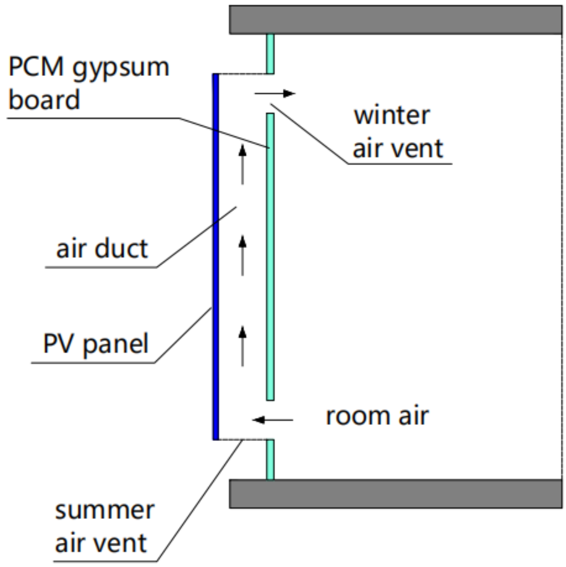


Fig. 16. PCM gypsum board integrated with Trombe wall [91]

Ziasistani et al. [92] compared the performance of PV-PCM/DSF wall with that of DSF (double skin façade) wall under six different working conditions. They found that BIPV glazing could provide a large amount of building energy demand. The annual cooling load of the building with PCM located in Tehran, Tabriz, Shiraz, Esfahan, BandarAbas and Yazd was reduced by 39.28, 27.48, 49.92, 48.24, 77.53 and 64.47 MWh/yr in comparison to the case without PCM.

6.3 PCM-PV installed on the wall with air gap

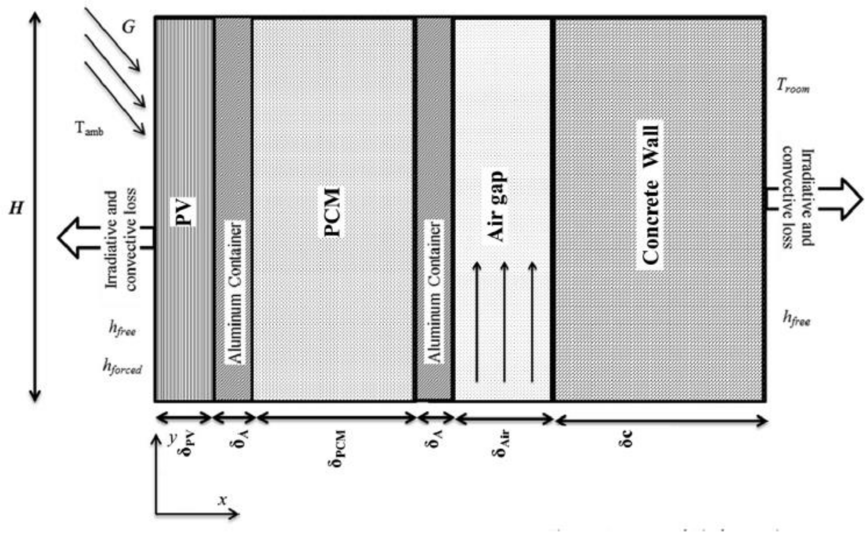


Fig. 17. PCM container integrated with PV and installed on the wall with air gap [93]

Kant et al. [93] proposed a novel configuration of PV-PCM wall with an air layer between the PCM container and the wall, as shown in Fig. 17. The outermost layer is a PV layer, followed by an aluminum plate, PCM, another aluminum plate, an air space and a wall. The design was evaluated by numerical simulation to explore the effects of the height of BIPV, air gap thickness, thickness of the PCM, air mass flow rate on the electricity output, extracted heat, PV operating temperature, air outlet temperature. Three types of PCM including n-octadecane, capric acid and RT-25 were studied. Their melting temperature ranged between 26°C and 32°C of the PCMs and the latent heat of fusion was about 152–245 kJ/kg. For the maximum amount of electricity output, the optimum PCM thickness, height and air gap thickness were 0.04 m, 3 m and 0.02 m respectively. The optimum air flow rate was 0.18 kg/s. For the maximum heat gains, the PCM thickness, optimum height and air gap thickness were 0 m, 3 m and 0.08 m respectively. The optimum flow rate was 0.091 kg/s.

7 Building integrated photovoltaic thermoelectric (BIPVTE) wall

A thermoelectric (TE) module can be considered as a special static heat pump which is driven by direct current electricity. It absorbs heat from one side of the chip and releases heat to the other side. When the direction of voltage is changed, the heating side turns to be the cooling side. A TE module can be powered by a PV cell. Luo et al. [94] combined PV cell with TE to develop a novel radiant system (BIPVTE) as shown in Fig. 18. In this BIPVTE, the PV cells were attached to the internal surface of the cover glass. The TE modules were attached to the external surface of the aluminum radiant panel facing indoors. There was an air layer between the cover glass and radiant panel. The PV cells and TE modules are connected by electrical wires. The electricity produced by the PV cells are directed to the TE modules. The radiant panel was cooled by TE modules in summer daytime and heated in winter daytime.

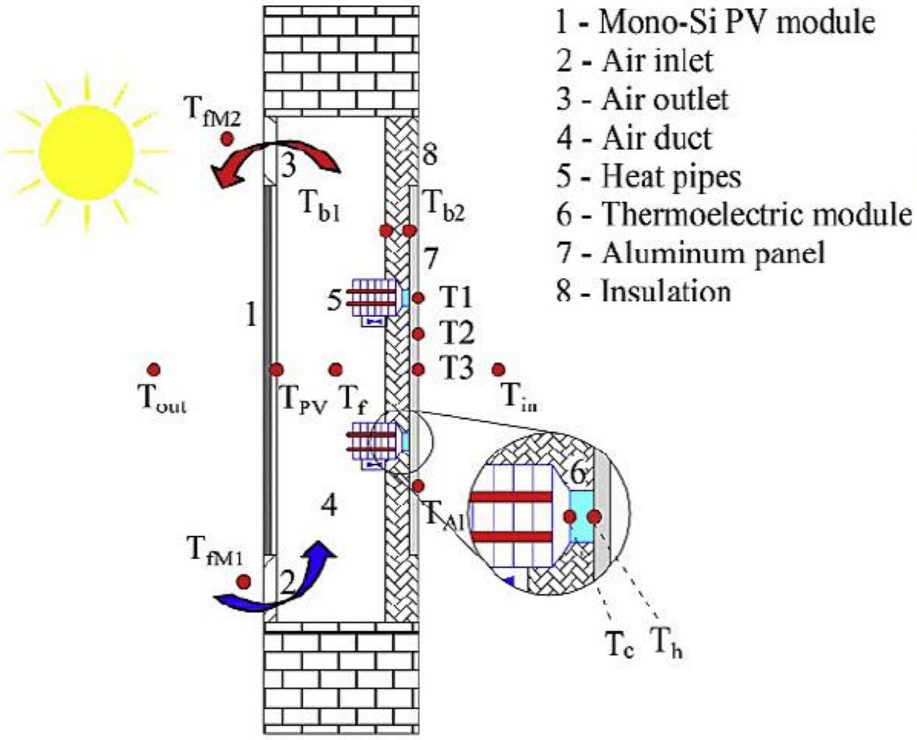


Fig. 18. BIPV with thermoelectric wall [94]

Luo et al. [94] experimented a BIPVTE wall and compared the results to a conventional PV-wall and an ordinary wall in Changsha, China. In summer of Changsha, the cooling capacity of BIPVTE wall was 44.2 kWh/m^2. Also the heat gains of the conventional PV wall and ordinary wall were 3.95 kWh/m^2 and 6.69 kWh/m^2 respectively, which is required to be removed by air conditioning systems. In winter of Changsha, the heat losses by the BIPVTE wall was 36.7 kWh/m^2 whereas the total heat losses by conventional PV wall and ordinary wall were 36.9 kWh/m^2 and 50.2 kWh/m^2 respectively. The results showed that the BIPVTE wall could reduce the energy for air conditioning significantly, especially in summer. Luo et al. [95] established an effective model and conducted theoretical analysis based on a controlled experiment to study the internal energy flow of a BIPVTE system. During summer in Hong Kong, the BIPVTE had a cooling capacity of 30.91 kWh/m^2 which could reduce electricity consumption by 11.12 kWh/m^2 for air conditioning whereas the ordinary wall resulted in a heat gain of 42.9 kWh/m^2 and consumed 15.43 kWh/m^2 of electricity. The BIPVTE wall could produce additional electricity of 32.57 kWh/m^2 during winter and transitional season.

8 BIPVT with heat pump

In some cold climates, the outlet air (or water) temperature from BIPVT systems is not high enough to meet requirement. Although the COP (Coefficient Of Performance) of heat pump is low, a combination of solar heating with heat pump is a promising method which has been widely studied. S. Kamel et al. [96] presented a review of available solar systems (solar thermal collectors and PVT collectors) and their integration with heat pumps. A. James et al. [97] conducted a review on the thermal analysis of heat pump systems using PVT collectors before 2020. In their study, energy balance equations used for modelling PVT collectors were also addressed. M. Mohanraj et al. [98][99] comprehensively reviewed researches and developments including modelling and applications of solar assisted compression heat pump systems within the last two decades. It should be noted that studies on the combination of BIPVT with heat pump are presently limited.

8.1 Air-based BIPVT with heat pump

Hailu et al. [100] conducted a theoretical analysis of PV-double skin wall system coupled with an air source heat pump to heat fresh air for a room under two different conditions using TRNSYS software. The simulation results showed that for an average ambient temperature above -3°C, the couple systems' COP was improved. However, when the average ambient temperatures was below -10°C or above 10°C, no improvement in COP was observed.

Martin-Escudero et al. [101] explored the energy and economic performances of PV-double skin wall system combined with an air source heat pump for space heating and domestic hot water supply through experiment and simulation. It was proved that a very high percentage of thermal energy demand can be supplied with the ASHP system, which improves its Seasonal Performance Factor (SPF) by 14.8%. Regarding electric energy, the PV panels could supply approximately 70% of the electricity consumed by the ASHP system and the fans of the PV. The results also showed that the investment cost can be amortized in 6.4 years.

Bigaila et al. [102] established a mathematical model for a combined PCM, micro air source heat pump and PV system integrated within a façade. The results showed a reduction in electric power demand and coil heating power demand of 14.5% and of 11.3%, respectively.

8.2 Water-based BIPVT with heat pump

Araz et al. [103] studied the exergy and energy performance of a combined water source heat pump and BIPVT system. In this study, a water PVT collector was attached to the wall and the outlet water from PVT collector was increased by the heat pump. It was discovered that the exergy efficiency values for the heat pump and the whole system were 72.23% and 64.98% on product/fuel basis, while their functional exergy efficiencies were 20.93% and 11.82%, respectively.

8 Economics of BIPVT systems

The economic performance of a BIPVT systems is crucial to its application. Naves et al. [104] conducted a review which focused on Life Cycle Cost Assessment (LCCA) and its adoption as an economic pillar for the evaluation of sustainability in the solar energy sector. Ansah, et al. [105] conducted an integrated life cycle assessment of different façade systems for a typical residential building in Ghana. Debbarma et al. [8] reviewed the functions, costs, aesthetics and application of BIPV and BIPVT installations. In comparison to BIPV systems, BIPVT system had significant benefits and potential for a wide range of application in buildings.

Agrawal et al. [106] conducted a series of comparative studies on the life cycle cost of some BIPVT systems with different solar cells under climatic condition of New Delhi. The results showed that the use of BIPVT systems was more advantageous that BIPV systems from both economic and energy efficiency perspectives.

Delisle et al. [107] evaluated the cost-benefit of BIPVT systems that used air as the heat recovery fluid using the concept of break-even cost. The study integrated BIPVT systems into an all-electric energy-efficient homes located in heating dominated climates. The results indicated that, compared to BIPV, BIPVT systems always produced more useful energy and as a result, the break-even cost was always positive.

Asaee et al. [108] evaluated techno-economic impact of retrofitting houses in Canadian housing stock with PV and BIPVT systems using the Canadian Hybrid End-use and Emission Model. The study predicted the energy savings, greenhouse gas (GHG) emission reductions and tolerable capital costs for regions across Canada. The results indicated that PV system retrofit yields 3% energy savings and 5% GHG emission reduction, while the BIPVT system yields 18% energy savings and 17% GHG emission reduction in the Canadian housing stock.

From the above review, it can be identified that studies on economic performance of BIPVT systems in general and façade-based BIPVT are very limited.

9. Discussions

In the present paper, the design, electrical and thermal performances (including impacts on the heating and cooling load) of various façade-based BIPVT systems have been reviewed. Façade-based BIPVT are grouped into seven classes: cooling of PV by air, space heating, fresh air heating & ventilation, water heating, BIPVT-PCM, BIPVT with heat pump and BIPVTE wall. Each class is further divided into several types according to the mode of integrating PV within façades.

For BIPVT with cooling of PV by air, the key issue is to cool down the PV cells and to increase the electrical efficiency. Due to the relatively low cost and convenience of installation, this kind of designs are widely applied. Since the heat from PV cells is not used, the total efficiency is low, with annual average values of about 10% in practical applications. There are two designs: PV-wall with ventilation and PV-wall without ventilation. Comparatively, the PV-wall with ventilation have been extensively studied and widely used. Studies on PV-wall without ventilation are very limited. PV cell temperature can be lower, and the electrical efficiency may be higher (if the air gaps are well designed) than PV-wall without ventilation in most circumstances, especially in hot climates. Naturally ventilated systems can provide satisfactory performances in most circumstances and are widely used.

With regards to BIPVT for space heating, BIPV Trombe wall systems are widely used. The electrical efficiency is usually slightly lower than designs with no use of heat, but the total efficiency is significantly improved due to the much higher thermal efficiency, with values ranging from 30% to 50%. The BIPV Trombe wall systems can also be used for fresh air heating in winter and enhancement of ventilation in transitional seasons and summer. Overheat problems can be solved with a ventilated air layer between glass cover and building wall. In general, BIPV Trombe wall systems are very attractive for regions with long and cold winter. Among the three designs, PV-G is the typical design for integrating PV with Trombe wall and is well researched than the other two designs. With regards to energy performance, PV-B systems are very promising. More efforts should be invested to improve its reliability and to reduce costs.

For fresh air heating, caution should be taken to avoid low temperature outdoor air from directly entering indoor spaces especially when used in severe cold winter. It is suitable to use PV double skin wall systems to preheat the fresh air, and auxiliary heating measures should be provided to guarantee that the air temperature supplied to the room can meet the requirement of comfort.

BIPVT systems with no use heat from PV, space heating and ventilation are mainly air-based systems and are the most commonly studied BIPVT systems. Air-based BIPVT systems are very convenient and cost-effective for cooling of PV cells, heating and ventilation of spaces bound by the façade. Air-based BIPV systems provide a convenient way for space heating or ventilation for the room directly bounded by the façade, however it is inconvenient for rooms distant from façades. Also, the thermal energy can only be effectively used in winter. These significantly limits their applications.

Water (or refrigerant) based PVT collectors can be easily connected into hydronic heating systems and heat can be transported to distant rooms for space heating or water heating. For the water based BIPVT, PVT collectors are generally constructed as a separate unit and attached to façades. Hence water-based BIPVT can be easily dismantled from a building for replacement. Considering this advantage over air-based systems, water-based BIPVT systems are expected to be widely used in the future.

BIPV-PCM wall provide a new approach to integrate PCM into BIPV, however more research is needed to verify its cost-effectiveness and to improve its performance.

BIPV-TE radiant wall systems offer a novel way to used PV for both heating and cooling. Hence, it needs to be evaluated extensively to explore whether it is more efficient or cost-effective than ordinary heat pump systems driven by electricity from PV panels. Other concerns include the possibility of condensation on panel surface when used for cooling.

BIPV with heat pump provides a new approach to increase the performance of heat pump, however the systems becomes complex and the cost is significantly increased with the use of heat pump. Hence, detailed analysis are required to verify cost-effectiveness and also improve electrical and thermal performances. Considering the wide array of studies combining solar heating with heat pump for hot water or space heating, integrated applications of water-based BIPVT with heat pump is expected to increase.

The advantages and disadvantages of various BIPVT systems are outlined in Table 5.

Table 5 The advantages and disadvantages of various BIPVT systems.

Designs	Advantages	Disadvantages
Cooling of PV by air	1) Low cost 2) Convenient for installation	1) Total efficiency is low
PV Trombe wall for space heating and ventilation	1) Total efficiency is significantly increased than no use of heat. 2) The overheat during summer can be easily solved.	1) The heat is not convenient to conveyed to rooms distant from the façade.
BIPVT for water heating	1) High total efficiency 2) The heat can be delivered to places distant from the façade 3) Either for domestic water heating or space heating	1) Freezing in winter and overheat in summer may occur
BIPV-PCM	1) The temperature of PV is reduced by use of PCM	1) High cost of PCM
BIPV-TE wall	1) Heating in winter and cooling in summer	1) The COP is not high
BIPV-heat pump	1) The COP of the heat pump is higher than ordinary air source heat pump	1) Much higher cost of the whole system

10. Conclusions and outlooks

This review indicates that BIPVT systems provide a high total efficiency and potential to reduce the heating/cooling load of HVAC, therefore they are very promising to reduce building energy consumption towards the development of low energy buildings. From the literature review, the following future research directions are identified:

1) Due to the advantages of water-based BIPVT systems, their applications are expected increase significantly in the future. However, studies on water-based BIPVT are fewer than that of air-based BIPVT. Therefore, more researches are required to improve their performance and lower costs.

2) With regards to BIPVT for water heating applications or BIPVT including PCM, the integration of PVT collector within buildings will inevitably affect heat transfer through the façade, hence the heating and cooling load will be affected. However, there are very few studies in this regard.

3) Because the addition of PVT collectors change the boundary conditions of building envelope, moisture transport of BIPV wall is much different from ordinary building walls. At present, research on moisture transport within solar integrated structures are insufficient.

4) Compared with roofs, façades are much more easily shaded by peripheral buildings. The shading effects may reduce the electrical and thermal performance of façade-based BIPVT heavily. For buildings in urban context, shading by peripheral buildings is inevitable, however the shading effects of façade-based BIPVT have not been studied sufficiently. More research should therefore be conducted in this direction.

5) At present, many BIPVT systems use air as working fluid. Since it has a poor heat transfer coefficient, BIPVT using refrigerants should be researched for heat absorption or anti-freezing purposes.

6) Studies on LCCA of BIPVT systems are limited at present, hence studies should be conducted to accurately and holistically evaluate the economic performance of BIPVT systems.

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