https://doi.org/10.1016/j.rser.2021.111355

A review on developments and researches of building integrated photovoltaic (BIPV) windows and shading blinds

Guoqing Yu[1], Hongxing Yang[2], Daina Luo[1], Xu Cheng[1], Mark Kyeredey Ansah[2]

[1]University of Shanghai for Science and Technology, Shanghai 200093, China

[2]Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Abstract: BIPV windows integrate solar cells within window glazing and do not only retain the functionality of conventional windows but also provide other benefits such as electricity generation and thermal insulation. BIPV windows are categorized into single glazed BIPV windows, double glazed BIPV windows with/without ventilation and vacuum BIPV windows depending on the configurations of the glazing. The electricity generation, thermal performance and optics of BIPV windows are reviewed in this paper. The results of this study showed that the total heat gain through BIPV windows are less than conventional windows in summer and hence the electricity used by air-conditioning in summer would be reduced. In addition to the electricity produced by BIPV windows, there are great potentials to reduce building energy consumption significantly in hot climate areas. The development and performance of BIPV blinds which integrate solar cells with blinds are also reviewed. BIPV blinds are grouped into outdoor PV blinds, indoor PV blinds and middle PV blinds according to the position of blinds relative to the windows. Future research directions are also suggested for this research domain.

Keywords: BIPV windows, PV glazing, PV blinds, performance

1 Introduction

According to the report from International Energy Agency (IEA), more than 30% of global energy is consumed by buildings, which has become a great incentive to reduce building energy consumption [1]. During summer, the solar radiation entering rooms through windows significantly increases the energy consumption by air-conditioning systems, it is especially serious in new-built high-rise buildings with high window-to-wall ratios. Therefore, reducing the solar radiation through windows into rooms is an effective approach to reduce cooling loads and energy consumption for air conditioning.

Integrating photovoltaic (PV) cells within windows or shading devices is a promising way to cut down cooling loads and to generate electricity in buildings. Building Integrated Photovoltaic (BIPV) window is an integration of PV modules with traditional windows, which can replace traditional windows entirely [2]. Compared with traditional windows, BIPV windows can attenuate the solar radiation penetrating into rooms, thereby reducing the power consumption of air-conditioning systems. Meanwhile, BIPV windows may mitigate light glare from windows [3] [4].

The impact of BIPV windows is commonly analyzed in three dimensions: electricity generation, thermal performance and optical performance [5][6]. The electrical performance is expressed in terms of electrical efficiency and electricity production per square meter while the thermal performance is mainly expressed in terms of SHGC (solar heat gain coefficient) and U-value (heat transfer coefficient, indicates the thermal transmission per unit area of a material).

The value of SHGC determines the solar energy directly incident into the room through the window [7], and the U-value determines the heat gains/losses through the window due to temperature difference between indoors and outdoors environment [8]. Both SHGC and U-value significantly affects the heat gains/losses of the room, hence affects the energy used for HVAC systems [9] [10]. The optical performance includes visual light transmittance (VLT) and glare probability value, which affects the indoor visual effect and energy consumption of artificial illumination[11].

Fig. 1 illustrates how the BIPV adoption affects building energy consumption. The optical characteristics of BIPV windows affects indoor illumination and therefore artificial lighting in buildings, which consequently influences energy consumption for lighting. The SHGC and U values which express the thermal characteristics of BIPV windows directly affect indoor heat gain, and therefore energy consumption for air conditioning. BIPV windows can generate electricity which can be consumed in the buildings or connected to a grid. which has realized building energy conservation to a certain extent. Therefore, the impact of BIPV windows on building energy consumption is determined by the trade-off between lighting performance, electrical generation performance, and thermal performance [12].

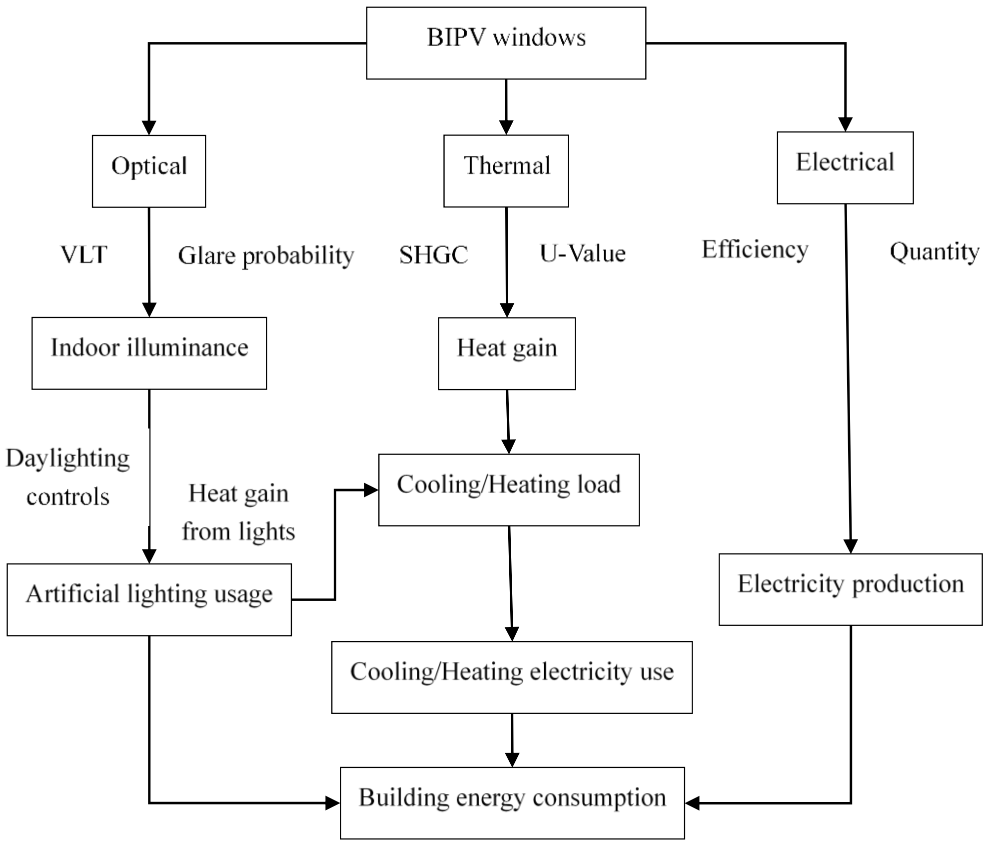


Fig. 1. Effects of BIPV adoption on building energy consumptions [12].

Some researchers have reviewed the applications and performances of BIPV systems in buildings from different perspectives. Baljit et al. [13] compared the installation methods, system performance and applications of BIPV and BIPV/T technologies. Agathokleous et al. [14] reviewed research progress on heat transfer of PV panels integrated with double skin facades with multiple integration modes. Yang et al. [1] conducted a review of BIPV/T systems and categorized them into air-based, water-based and other systems. Debbarma et al. [15] reviewed recent studies on BIPV and BIPV/T systems including thermal modeling and exergy analysis. Debbarma et al. [16] also compared the performance of various BIPV and BIPVT technologies as well as their functions, costs, appearance and installation applications. Sarkar et al. [17] carried out an investigation on development trends of the characteristics of BIPV system. Lucchino et al. [18] reviewed current effective tools for energy simulation of double skin facades and highlighted potentials for future development. Zhang et al. [19] reviewed photovoltaic integrated shading devices (PVSDs). Shukla et al. [20] reviewed the application of BIPV in South Asia and discussed its barrier, challenges and future directions. Saretta et al. [21] conducted a review on the use of BIPV in renovation of facades to improve their energy performance. Biyik et al. [22] reviewed BIPV and BIPV/T applications in the light of power generation, nominal power, efficiency, type and performance evaluation methods. In addition, several approaches to improve the efficiency of BIPV/T through ventilation or the use of integrated new thin film technology were identified. The application of BIPV and BAPV system, strengths and challenges and solutions were reviewed at length by Ghosh [23]. Tilmann et al. [24] reviewed a wide range of technical design options for BIPV systems and analyzed two basic module-level designs. This included using PV cells as the fundamental elements of patterns and using colors to hide PV cells in particular. Yu et al. [25] reviewed the development of BIPVT with a focus on the design of an integrated solar system with a building façade and its influences on power production, PV cell thermal performance, and building energy consumption for the cooling load.

Cannavale et al. [26] investigated the potential to reduce energy consumption of a case building in southern Italy by incorporating BIPV. The results showed that the overall annual energy use could be reduced by 18% if standard clear glass windows are replaced with BIPV windows and shadings. Chen et al. [27] presented a design optimization methods for BIPV systems to explore the influences of confounding factors and archetypes in urban high-rise commercial buildings. Chen et al. [28] also studied PV application and the design strategies of traditional passive buildings through a comprehensive design optimization process.

The review of BIPV window is illustrated in Table 1.

Table 1 Summary of researches of single glazed BIPV windows

Authors year	Research object	Main research contents	Locations
Baljit et al. 2016 [13]	1) BIPV 2) BIPV/T	1) Installation methods 2) Different heat transfer working fluids 3) Applications of BIPV and BIPV/T	Malaysia
Agathokleous et al. 2016 [14]	1) Double skin facades and PV facades	1) Air flow in double skin facades and PV facades 2) Heat transfer analysis	Cyprus Limassol
Yang et al. 2016 [1]	1) BIPV/T	1) Developments of various BIPV/T systems, 2) Building performance 3) Application of BIPV/T	Montreal Canada
Debbarma et al. 2016 [16]	1) BIPV 2) BIPV/T	1) Applications of BIPV and BIPV/T installations 2) Thermal performance	Bhopal India
Debbarma et al. 2017 [15]	1) BIPV 2) BIPV/T	1) Applications of BIPV and BIPV/T 2) Thermal modeling 3) Energy and exergy analysis	Bhopal India

Authors year	Research object	Main research contents	Locations
Sarkar et al. 2019 [17]	1) BIPV	1) current-voltage (I-V) and power-voltage (P-V) characteristics 2) Development and recent trends related to BIPV systems	Jharkhand India
Lucchino et al. 2019 [18]	1) double skin facades	1) Different approaches to modelling and simulating DSFs	Trondheim Norway
Zhang et al. 2018 [19]	1) PVSDs	2) PVSD types, PV material, orientations, tilt angles	Harbin China
Shukla et al. 2018 [20]	1) BIPV	1) Applications、barrier and challenges of BIPV system	Bhopal India
Saretta et al. [21]	1) BIPV	1) Energy performance	Italy
Cannavale et al. 2017 [26]	1) perovskite-based	1) Energy performance	Bari Italy
Biyik et al. 2017 [22]	1) BIPV 2) BIPV/T	1) BIPV and BIPVT applications 2) Power generation	Izmir Turkey
Aritra 2020 [23]	1) BIPV 2) BAPV	1) Application of BIPV and BAPV system 2) Advantages、challenges and solutions	UK
Tilmann et al. 2020 [24]	1) BIPV	1) Application of BIPV 2) PV cells as basic elements of patterns 3) The use of color to conceal the PV cells	Freiburg Germany
Yu et al. 2020 [25]	1) BIPVT	1) The designs and development of BIPVT 2) Power production, thermal performance of PV cell 3) Energy consumption	Shanghai China

Previous studies mainly include the application of BIPV windows in building components, or a single study on the performance of a certain type of BIPV windows while only few studies analyzed the impact of BIPV windows on building energy consumption. Thus advancement in BIPV windows has not been comprehensively addressed. Figure 1 shows the three main aspects of BIPV windows for building energy consumption.

There are many types of BIPV Windows and shading blinds. Thus, this paper classifies them according to their structure prior to studying their performance. First of all, the BIPV windows are classified into single-layer photovoltaic window, double-layer photovoltaic window and vacuum photovoltaic window. Furthermore，the double-layer photovoltaic windows are further categorized into double-layer photovoltaic window with closed air layer and double-layer photovoltaic window with ventilated air layer according to the presence or absence of air circulation in the cavity layer. With reference to the location of the louvers, BIPV shading blinds are divided into outdoor PV blinds, middle PV blinds and indoor PV blinds. When studying each type of photovoltaic window, its structure is introduced in detail at first. Thereafter its influence on building energy and indoor environment performances are analyzed. Furthermore, the energy savings from these windows are compared with that of traditional windows. The application of new solar cells to BIPV windows are also mentioned in this paper. Finally, data is extracted from the literature review to compare the performance of several types of BIPV Windows or shading louvers blinds.

This paper takes the approach of reviewing and analyzing the different BIPV windows and shading blinds. Therefore, the Section 2 of this paper presents a comprehensive review on recent developments and research of BIPV windows by evaluating their optical, thermal and electrical performance from the structure of the photovoltaic glass. At the end of the Section 2, the content of the whole chapter is analyzed from the PV type, research method, locations distribution researched, year distribution, the main focus on performance, and main findings. In Section 3, shading blinds also be reviewed since their designs and conditions of shading largely affect the performance of windows. Section 4 presents the research results of this article and the future direction of BIPV window research that needs rigorous studies and improvement. The study does not focus on the differences between BIPV and BIPVT since integrating both technologies with windows inevitably affects the cooling and heating loads of a building.

2 BIPV Windows

2.1 General description

BIPV windows in this study refer to semi-transparent PV (STPV) glazing integrated within windows applied to buildings. BIPV windows have a photovoltaic effect that transforms part of the incident solar irradiation into useful electricity, while reducing solar heat gain and indoor daylighting [5]. Since BIPV windows are usually semi-transparent, they are often referred to as semi-transparent PV in many literatures. Solar cells used in BIPV windows include c-Si, a-Si or CdTe solar cells, and other new solar cell technologies, such as poly-Si, dye-sensitized solar cells (DSSCs) and perovskite solar cells. BIPV windows have been utilized in some demonstration projects all over the world. In this study, BIPV windows are classified by their configurations into 4 groups as shown in Fig. 2.

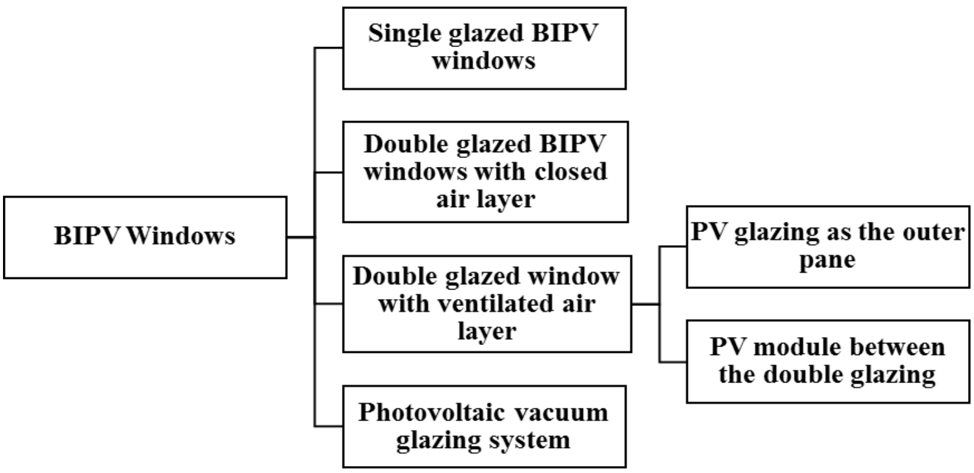


Fig. 2. BIPV Window classification.

2.2 Single glazed BIPV windows

(1) Configuration

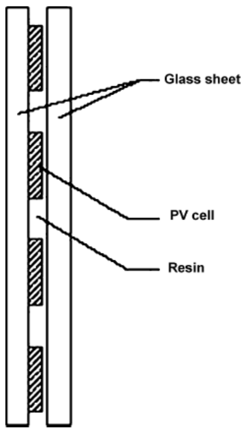


Fig. 3. Typical structure of a single glazed BIPV window [29].

A single glazed BIPV window refers to a window equipped with single semi-transparent PV glazing. As shown in Fig. 3, the single PV glazing consists of two layers of glass panes, and a series of thin-film solar cells which are enclosed between the two glass panes [29]. The thin-film solar cells are semi-transparent with a VLT ranging from 5 to 10%. In order to increase the VLT of the whole glazing, the glazing is usually not fully covered with solar cells. The ratio of the area covered with solar cells to the total area of the glazing is called cell coverage ratio. The single PV glazing is the basic type of PV glazing and all the other classes of PV glazing are based on it. The single PV glazing can be used as a common glass pane in a window. This class of BIPV windows can produce electricity and reduce indoor solar heat gain as it converts part of the incident radiation into electricity [11] [60].

(2) Performance of single glazed BIPV windows

Fung and Yang [29] investigated the heat transfer of the single glazed BIPV window by establishing a numerical transient heat transfer model and conducted an experiment in Hong Kong. Fig. 4 shows the schematic diagram of experimental device for measuring heat transfer through this module. The results indicated that the total heat gain mainly came from solar heat gain, while other factors such as PV efficiency had little effect on it.

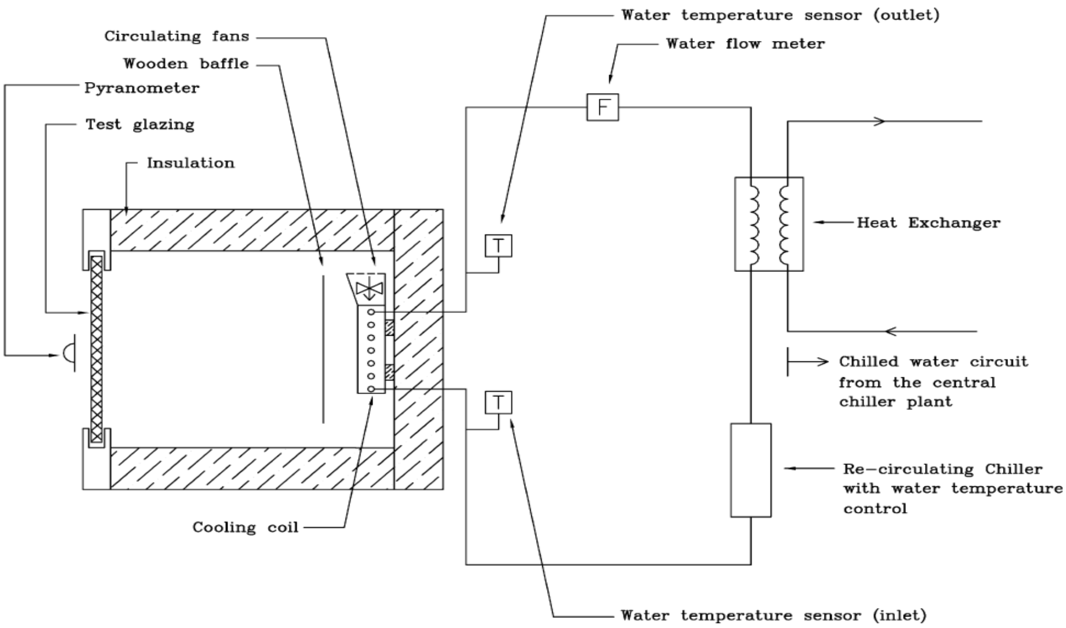


Fig. 4. Schematic diagram of device setting for measuring heat transfer [29].

Li et al. [30] studied the visual characteristics and economic performance (energy gains and costs) of BIPV windows used for typical office buildings in Hong Kong. The measured visible light transmittance and daily conversion efficiency was up to 11% and 6.0%, respectively. To elaborate the performance of this BIPV facade, case studies were conducted which indicated that the additional income from such systems can offset the initial construction cost.

Chen et al. [7] introduced a method to measure SHGC of BIPV glazing used in tropical areas. It was proved that the spectrum of the solar simulator had obvious effect on the SHGC measurement. When the incident angle of solar irradiation was above 45°, the SHGC was significantly reduced which results in higher PV efficiency. This resulted in a higher conversion efficiency in comparison to re-radiated heat. The measured results are shown in Fig. 5 and Fig. 6.

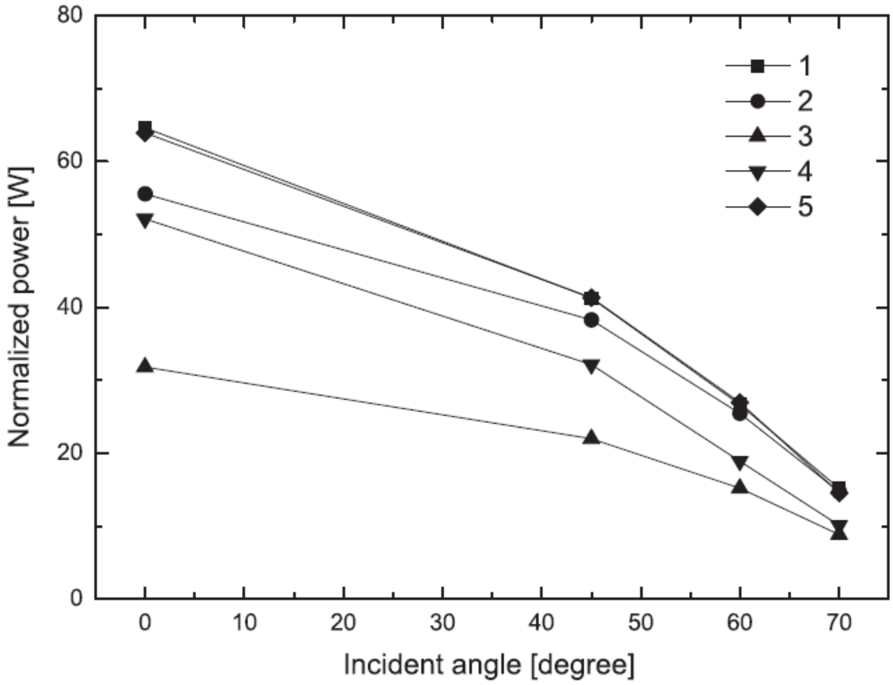


Fig. 5. The normalized power under different incident angles [7].

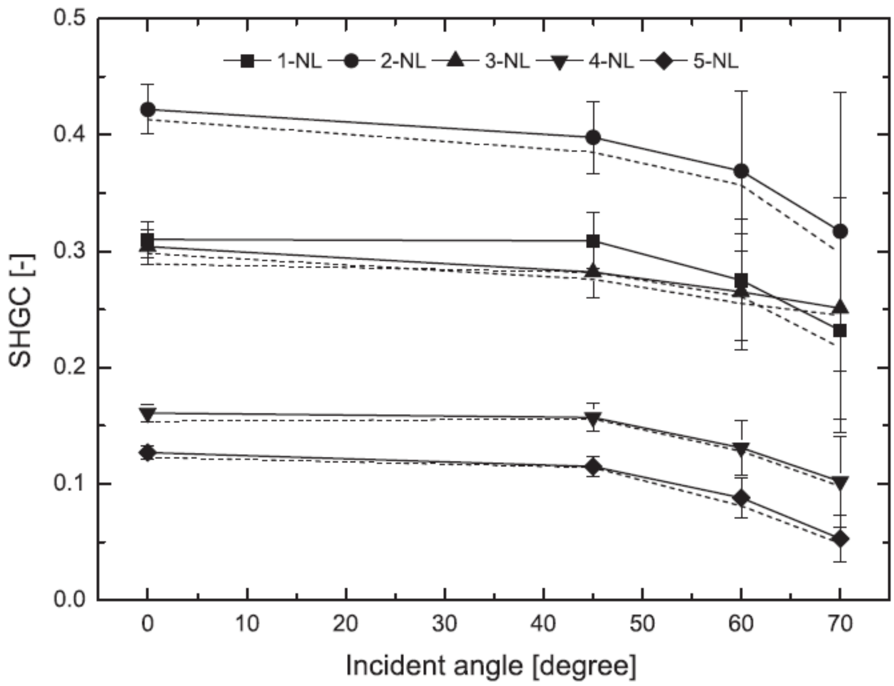


Fig. 6. The SHGC under different incident angles [7].

Karthick et al. [31] investigated and compared the energy performance of single glazed BIPV windows incorporating two different solar cell coverage ratios of 0.69 and 0.77 at an latitude of 9°10' N and 77°52' E. The orientation of the modules influenced the performances of the BIPV system. An east orientation was most desirable for maximum power generation, however a south orientation was recommended for other parameters. By integrating buildings with PV modules, the indoor heat gain was reduced. It was found that the system had better energy performance under the condition of a low cell coverage ratio. Furthermore, Karthick et al. [32] studied the performance of some BIPV skylights on the rooftop of a laboratory in India under actual outdoor environmental condition. From the results, a cell coverage ratio of 0.62 resulted in a maximum daylight factor and indoor illumination of 4% and 850 lux, respectively. Furthermore, the PV skylight reduced the cooling load to 248 kWh per year. If the cell coverage ratio is increased to 0.72, an overall annual maximum energy saving of about 450 kWh can be obtained at a unit cost of 0.0354 $ / kWh.

Peng et al. [33] developed a new single glazed BIPV window with c-Si cells. The technical procedures to develop this novel module are illustrated in Fig. 7. The power generation, heat transfer performance and daylighting performance of the module were investigated experimentally in Berkeley, California. The daily electrical efficiency in the solar cell active area was nearly 15% in sunny days. Compared with conventional glass windows, this single glazed BIPV window had a lower SHGC of 0.25 and could also reduce discomfort glare. The daily energy consumption for artificial lighting was nearly 431 Wh while the electricity output by BIPV was 1940 Wh/day. The peak power output decrease by 0.42% for every temperature rise of 1°C.

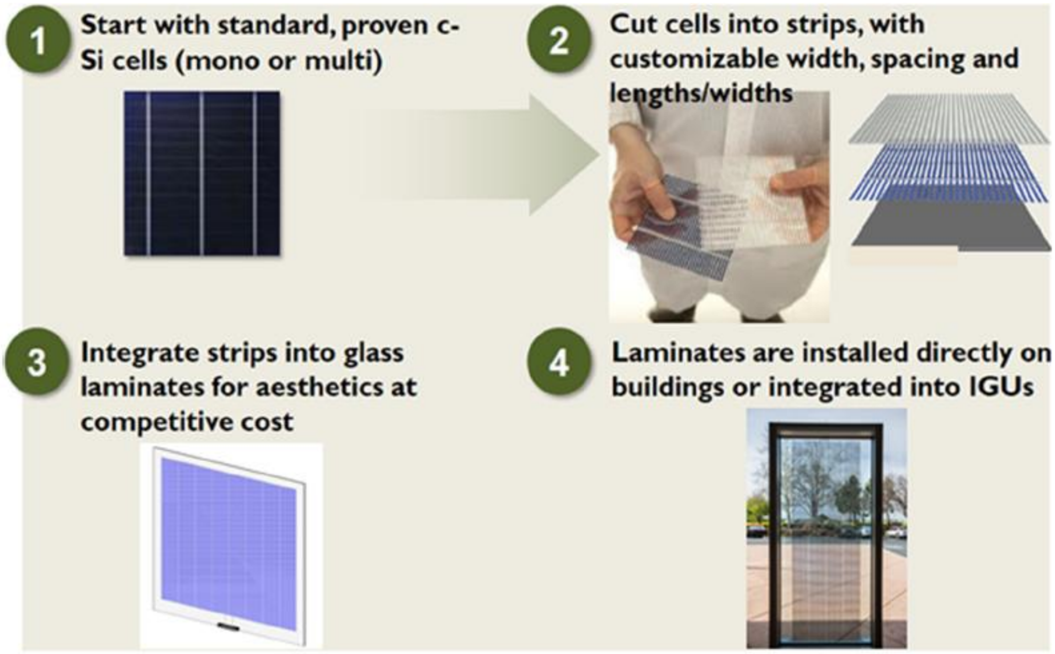


Fig. 7. Specific technical procedures of novel BIPV module based on c-Si [33].

Elghamry et al. [34] studied the influences of location of solar cells, the orientation and location of windows on the energy performances and CO_2 emissions of BIPV windows at New Borg El-Arab in Egypt. The results showed that south oriented BIPV windows installed on roof generates the maximum annual power whereas the north oriented BIPV yields the minimum.

Yang et al. [35] investigated the performance of façades with single glazed BIPV window affected by indoor air distribution by experiment in Taiyuan, China. The results showed that the influence of indoor air distribution on the operating temperature of PV modules was less impactful in comparison to the heat gain of single glazed BIPV facades. In contrast to a mixed ventilation (MV) system, the heat gain of the single glazed BIPV facades with the displacement ventilation (DV) system was reduced by 11.7%.

Alrashidi et al. [36] experimentally characterized BIPV incorporating semi-transparent cadmium telluride (CdTe) in the UK. The visible transmission and solar transmission were confirmed to be 25% and 12%, respectively through spectral measurements. Also, the U-value of the BIPV window was 2.7 W/m^2 K. Alrashidi et al. [37] also found that the net potential energy saving of CdTe based single-glazed BIPV window was 20% more than a common single glazed window.

Fan et al. [38] systematically studied the impact of thin film(TF) and crystalline silicon(C-Si) photovoltaic materials on the indoor lighting environment under different area coverage in different climate regions in China by using the

DAYSIM tool to carry out a simulation. The results show that the optimal coverage area ranges of TF and C-Si are: 50-60% for both TF and C-Si in the representative area of Xi 'an; 60-70% for TF and 50-70% for C-Si in Beijing; 50-60% for TF and 60-70% for C-Si in Shanghai area; 50-60% for TF and 50-70% for C-Si in Guangzhou area; 40-60% for both TF and C-Si in Harbin representative area; and 30-50% for both TF and C-Si in Chongqing area.

Yang et al. [39] investigated the effect of surface structure modification on the performance of solar cells in BIPV modules with metal oxide back coatings. The BIPV modules studied under different conditions included: transparent glass with black backing (G-BBS), coated glass with black backing (GC-BBS), etching glass with black backing (EG-BBS), and etching coated glass (EGC-BBS) with black backing. The results showed that by using the EGC-BBS structure, the photoelectric conversion efficiency (η) of the Si solar cell embedded in the BIPV module is 15.23%, and the fill factor (FF) value is 65.05%. Xuan et al. [40] introduced a new type of concentrator PV window (CPVW) system improve daylight uniformity through a concentrator. The daylighting performance of CPVW was analyzed and compared to a recent semi-transparent photovoltaic window system (STPVW). The research results show that the use of CPVW can significantly improve the uniformity of daylighting and also expand the effective illuminated area. The proportion of the effective illuminated area provided by CPVW is 6.69 times that of STPVW under the same conditions.

Toledo et al. [41]studied the operating cell temperature of PV modules by using two prediction models: NOCT and Sandia. The study also investigated the thermal performance of different photovoltaic technologies including polycrystalline silicon, CdTe, a-Si and organic PV. The results revealed how both models are strongly correlated to the amount and direction of incident solar irradiance.

(3) Influence on building energy consumption and indoor environment

BIPV windows absorb a portion of the incident solar radiation and convert it to generate electricity. Hence, this affects the indoor heat gains and natural daylight.

Chae et al. [42] evaluated and compared the performance of single glazed BIPV windows with three different types of solar cells in a typical midsized commercial building under 6 different US climate conditions. The results indicated that the thermal and optical performance of BIPV windows significantly affected the overall building energy consumption. The sun wavelength spectra sensitively varied because of the manufacturing conditions of the solar cells, hence the BIPV window characteristics should be customized with real optical data.

Do et al. [43] used the DOE-2.1e module to assess a single glazed BIPV windows adopting daylight-dimming systems in residential buildings in Houston, USA. It was found through simulation that the south-facing windows showed the highest potential for electricity generation and decrease of cooling load, while the east-facing windows saved the largest amount of lighting energy per year. In comparison to ordinary windows the BIPV window had huge energy saving potential.

(4) Comparison of BIPV windows and conventional glazing windows

Ng et al. [2] used computer simulations to analyze the energy performance of six commercial BIPV windows, including 4 single-glazed modules and 2 double-glazed modules in Singaporean office buildings. The study proved that these six different modules had a better energy saving potential than conventional windows. Ng et al. [44] further researched the lifetime performance of BIPV windows in tropical areas.

Lu and Law [45] established three simulation models to evaluate the energy performance of single-glazed BIPV windows located in Hong Kong. The case study indicated that the thermal performance of the BIPV windows was primary for energy saving considerations while artificial lighting consumption was secondary.

Liao and Xu [46] contrasted the overall energy performance of single-glazed a-Si based BIPV windows of two different transmittances to three traditional glazings in China. The study concluded that a-Si based PV glazing performed better than the traditional single glazed and double glazed windows in cooling dominated regions. In addition, the results revealed that BIPV glazing was more suitable than ordinary glazing for shallow rooms with large windows.

Zhang et al. [47] compared the overall performance (thermal, daylighting and energy) of BIPV windows with ordinary double-pane windows and Low-E windows in different orientations used in Hong Kong based through simulations. It was found that the BIPV window had great electricity saving potential when compared to single and double-pane windows. The results were illustrated in Fig. 8.

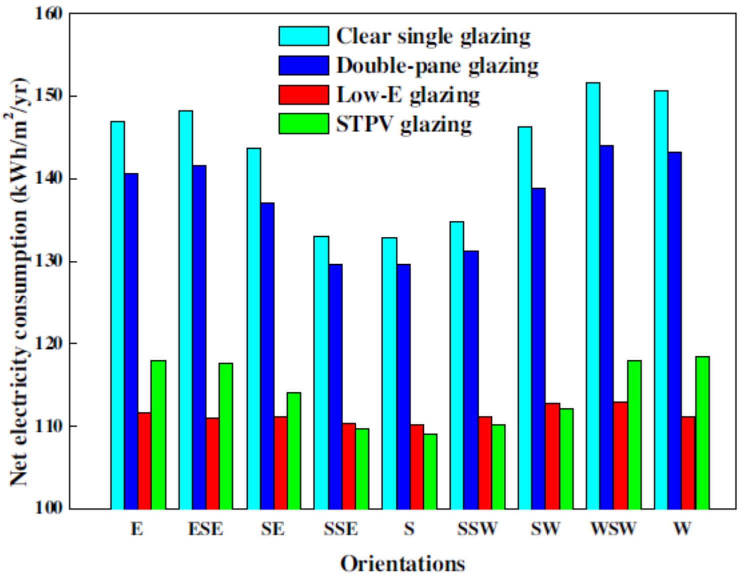


Fig. 8. The net electricity consumption of four types of glazing in different orientations [47].

As shown in Fig.8, in contrast to transparent single pane and double pane glazing, the net electricity consumption of single glazed BIPV window in Hong Kong was significantly reduced, indicating a much better energy performance. However, its net electricity consumption was higher than low-e glazing in east and west orientation, and was only a little lower than low-e glazing in south orientation. The overall energy performance and cost-effectiveness of single glazed BIPV windows should be investigated under more typical climates (such as hot, cold, temperate climates, strong or weak solar irradiation) and typical orientations (south, west, east, north), and compared with various typical glazing (single pane, double pane glazing, low-e glazing, vacuum glazing).

(5) New approaches for analysis

Olivieri et al. [48] introduced the Energy Balance Index to assess the global energy performance of the single-glazed BIPV windows in Madrid, Spain. The results from experimentation and simulation indicated that the adoption of BIPV windows could result in energy savings of at least 18% and even up to 50% when compared with the reference glazing. For the normal incidence of solar radiation, Baenas and Machado [49] developed a closed-analytical expression that simplified the calculation process of SHGC of BIPV modules.

He and Schnabel [50] developed a method for daylight analysis in an indoor environmental condition with BIPV window installations. The developed Calculation Model and Process for Daylight Illumination provided a relatively swifter approach to estimate the hourly indoor illumination.

(6) Researches of PV glazing based on new material

Cannavale et al. [51] found that the useful Daylight Illuminance value of semitransparent perovskite-based solar cell glass is significantly higher in comparison with transparent glass. Also, its performances are comparable to that of solar control glass, and the occurrence of high Daylight Glare Probability values could be reduced by 23%.

Yang et al. [52] developed a new BIPV window adopting penetration-type semi-transparent thin-film solar cells based on hydrogenated a-Si. The results showed an improved transmittance and efficiency.

Tsai [53] introduced key technologies for developing large-area (1.3m×1.1m) of tandem a/m-Si thin-film type solar modules for BIPV window applications and also explored its electrical and optical performances.

Ghosh et al. [54] developed and studied the application a new type of carbon counter electrode perovskite solar cells used for BIPV windows as shown in Fig. 9. The results of the study showed that the average solar and visible transmittance were 30% and 20%, respectively. The SHGC decreased from 0.33 to 0.14 when the incident angle increased from the lowest to the highest value. The visible transmission decreased from 30% to 10% when the incident angle increased from 10^{o} to 90^{o}. The U-value of this glazing was 5.6 W/m^2 K.

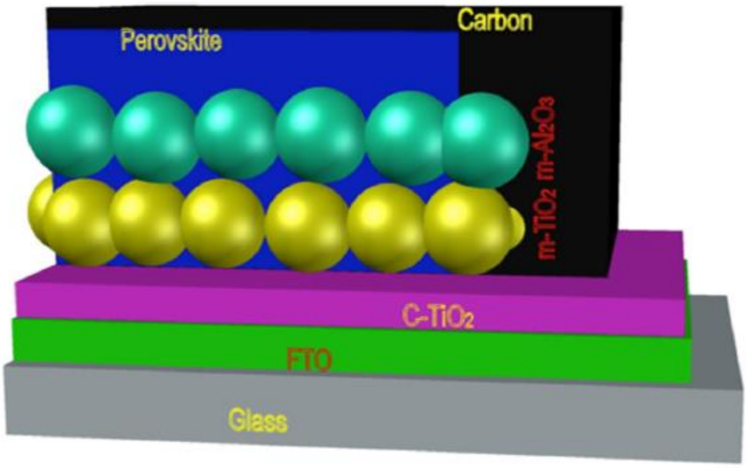


Fig. 9. Schematic structure of carbon counter electrode perovskite [54].

From the above review studies, it is found that there are few specific data studies on the heat transfer performance, visible light transmission performance and energy conversion efficiency of single-layer photovoltaic windows. Most studies explore the impact of integrated photovoltaic window applicationson building energy consumption. Presently the visual light transmittance is low and should be improved in future studies. Also, more efforts should be taken to increase the electrical efficiency and cut down the cost.

2.3 Double glazed BIPV windows with closed air layer

(1) Configuration

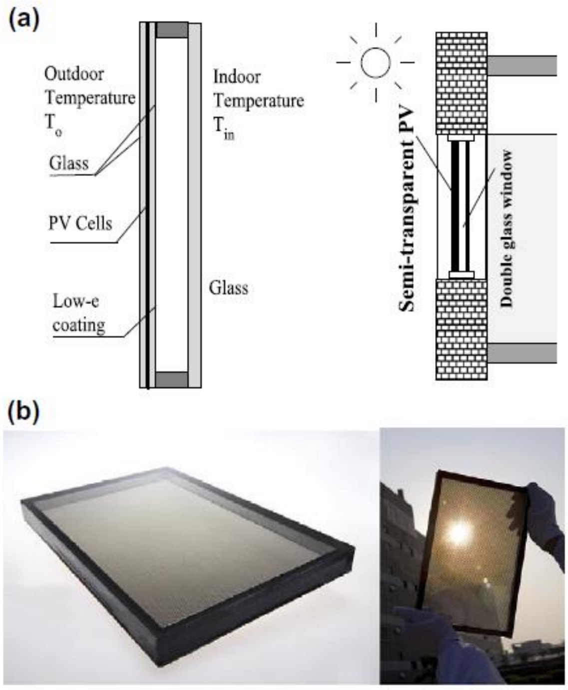


Fig. 10. Schematic diagram of double glazed BIPV (a), photo of the module (b) [55].

The double glazed BIPV windows with closed air layer refer to windows equipped with closed double PV glazing. The closed double PV glazing as shown in Fig. 10 is similar to a common double glazing except that its outer pane is a single PV glazing instead of a common glass pane. It consists of a single PV glazing, an ordinary single glass pane, and an air gap sealed between the two panes. Double glazed BIPV windows generally have lower U-values than single glazed BIPV windows [55].

(2) Performance of double glazed BIPV windows

Han et al. [55] conducted a numerical analysis of a closed double PV glazing with a-Si based solar cells equipped with low-e coatings. The study evaluated the heat transfer by radiation and convection, and the internal airflow patterns in the middle air gap.

Yoon et al. [56] used a mock-up test to analyze the important characteristic of the surface temperature of double glazed BIPV windows. By experiment, they found that the surface temperature of double glazed BIPV windows in summer daytime and winter night were 1 °C lower and 2 °C higher than that of ordinary window, respectively, due to the effect of thermal insulation.

Lee and Yoon [57] evaluated the long-term performance of a vertical and 30° inclined BIPV windows employing dye-sensitized solar cells (DSSC) in a mock-up facility with full-scale size (as shown in Fig. 11). The test data indicated that the vertical DSSC BIPV window had better energy performance than the 30° inclined variant.

Fig. 11. Experimental appearance of DSSC BIPV mock-up [57].

Chen et al. [58] developed a test unit to monitor and find ways to optimize the energy performance of closed double glazed BIPV windows. The study found that installing south-facing PV windows with cell coverage ratio of 87% and two glazing panes with air gap of 0.9 mm was the best design option in southwest China.

Mesloub et al. [59] conducted experiments and simulations on the optimum BIPV window design in Algeria. The highest energy savings obtained with double-glazed south orientated BIPV module was 60%.

Chung et al. [60] studied the applicability of Dye-sensitized solar cells (DSSC) prototype windows by analyzing indoor illumination and temperature, cooling, heating and lighting; performance. Research results show that DSSC prototype glass windows have a higher heat transfer rate (ie U value), but the visible light transmittance (VLT) is lower than low-e glass windows. Therefore, they reduce heating energy and increase cooling and lighting energy.

Khalid et al. [61] used two different methods to adjust the operating temperature of low-concentration photovoltaic solar cells: 1) using argon in the concentrating element; 2) bonding a polymer dispersed liquid crystal film to the top of the module. The research results show that there is greater potential for ameliorating operating condition and lowering the cells' temperature. When the temperature of the argon filled module and the polymer dispersed liquid crystal (PDLC) integrated module were reduced by 10°C and 4°C, respectively, the power improved by 37 mW-47 mW.

(3) Influence on building energy consumption

1) Vertical windows

Miyazaki et al. [62] investigated how solar cell light transmittance and the ratio of window area to wall area affects the energy saving capacities of a double glazed BIPV window in Japan. The results indicated up to 55% energy savings in comparison to an ordinary single glazed window.

Lee et al. [63] performed an analysis on the annual energy performance of vertical BIPV window applied to the south façade in an office building in Korea (shown in Fig. 12). The analysis indicated that the annual average yield was reduced to 1.52 h/day considering partial shading compared to 2.15 h/day for the reference without shading.

Fig. 12. Interior view of BIPV windows [63].

Sun et al. [64] developed an innovative model to evaluate both the energy and daylight performance of closed double glazed BIPV windows in office buildings under five typical climatic conditions in China. The results clearly showed that BIPV windows improved energy savings and daylight performance.

Cheng et al. [65] researched the energy and daylight performances of double glazed BIPV window incorporating different ratio of window area to wall area, cell coverage ratios and orientations in cold regions of China by adopting a new index defined as ratio of N-Daylit area. The research results showed that when the ratio of N-Daylit area rises to 56%, the annual net power consumption of the room space was reduced to about 36.1 kWh/m^2.

Ioannidis et al. [66] conducted an experimental analysis on Double Skin Facades (DSF) integrating semi-transparent photovoltaics (STPV). The study also developed the Nusselt number of the correlation coefficient and defined a heat recovery index which is distinguished from the thermal efficiency. The results showed that the heat loss of a typical building when compared with buildings integrated with DSF-STPV, may be 20% higher (8 W/m^2) in the facade area. Under different experimental conditions, the heat recovery index can increase by 30%, and the total utilization efficiency of solar energy can be between 30% and 77%.

2) Performance of applications on roof

Wong et al. [67] simulated the potential of energy saving by BIPV roof panels for residential applications under five climates of Japan. The results indicated significant reductions in cooling and heating energy demand.

Unlike previous studies, James et al. [68] evaluated semitransparent PV atrium connecting two administrative buildings at the University of Southampton, United Kingdom. Through a comparative analysis, it was found that an appropriate design of PV atrium could justify its cost and carbon footprint.

3) A special design of double glazed BIPV window

Cook and Al-Hallaj [69] developed a novel BIPV window system which applied optical elements with film as solar concentrator, in Chicago, USA. The system adapted micro-facets to induce the total internal reflection as shown in Fig. 13. Two kinds of films to PV-cell ratio were assessed and the maximum power increase was observed to be 35.1%.

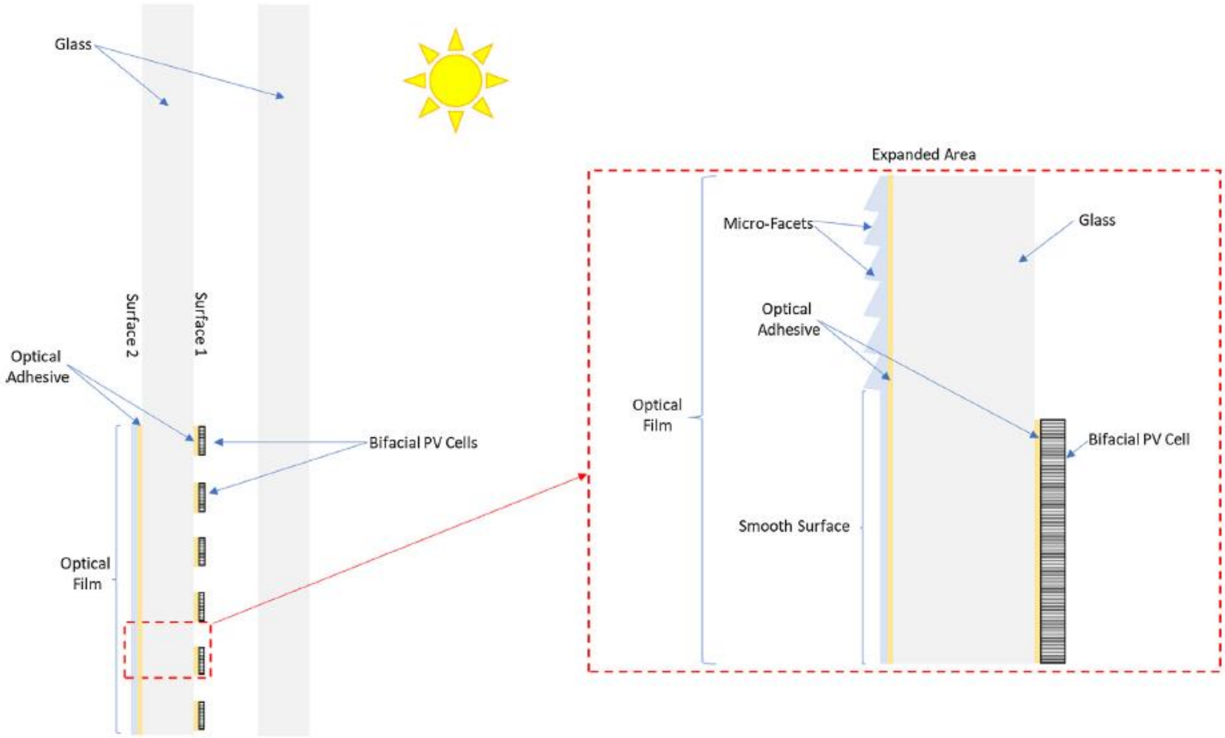


Fig. 13. Cross-sectional view of proposed BIPV window [69].

(4) Comparison with other types of glazing

Compared with single glazed BIPV windows, the U-values of the double glazed BIPV windows, hence the heat gains during summer and heat losses during winter due to temperature difference between indoors and outdoors are reduced. However, compared with ordinary double glazing windows, the solar energy directly incident into the room is usually reduced due to the existence of solar cell, hence the heating load of the room will be increased.

In addition, built-in louvered double pane glazing has been widely applied because of its satisfactory energy performance, flexibility and reasonable cost, the built-in louvers can be hung up during winter to allow more solar energy into the room while the built-in louvers can be dropped for shading to reduce cooling loads during summer, therefore the energy for heating and cooling can be cut down. Double pane glazing with low-e coating is also widely used for its excellent performance of thermal insulation. The overall energy performance and cost-effectiveness of double glazed BIPV windows should be compared with built-in louvered double pane glazing and low-e double pane glazing under typical climates and typical orientations, respectively.

2.4 Double glazed window with ventilated air layer

2.4.1 PV glazing as the outer pane

(1) Configuration

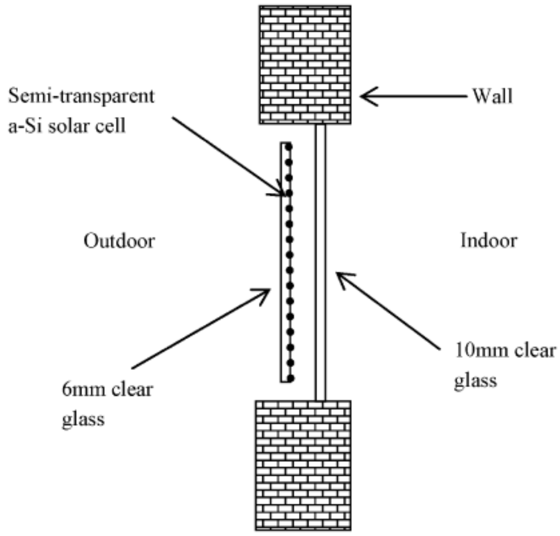


Fig. 14. Schematic of PV glazing as the outer pane of BIPV window [49].

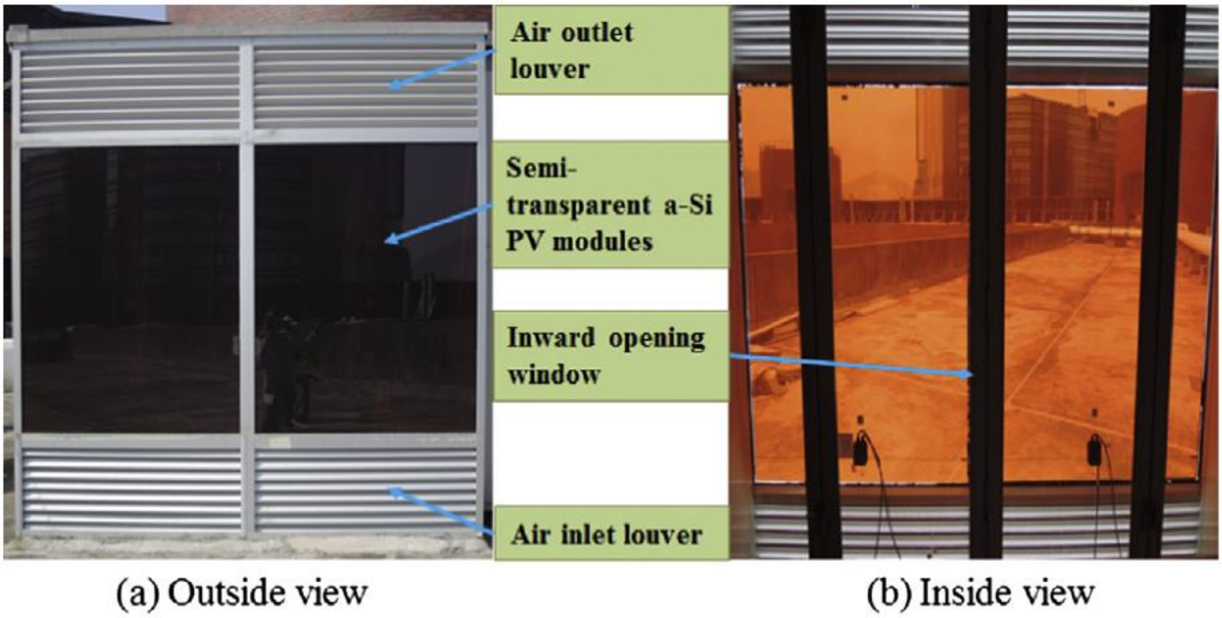


Fig. 15. Photograph of double-glazed BIPV window with ventilation [9].

This type of BIPV window consists of an external single PV glazing, middle air layer, internal glazing and two vents located at the top and bottom respectively, as shown in Figs. 14 and 15. The air flow extracts heat produced by PV modules, thus decreasing the PV temperature effectively. The shielding effect of PV and the outdoor air flowing into vents reduces the solar energy entering the indoor space.

(2) Performance

He et al. [71] experimentally and numerically studied the performance of BIPV window using a-Si PV cells in Hefei, China. The research results showed that this double glazed BIPV window had lower heat gain in comparison with single glazed BIPV window, hence a significant improvement in indoor predicted mean vote (PMV).

Peng et al. [10] conducted experiments on a novel double glazed BIPV façade including a-Si PV module in Hong Kong, China. The results revealed that SHGC could be reduced with a ventilated design. Peng et al. [9] also comparatively studied the thermal and energy performances of ventilated double glazed BIPV façades under several ventilation modes. The study found that the average SHGC of a ventilated BIPV window was the lowest while non-ventilated BIPV windows achieved the best thermal insulation effect. The electrical output of mechanical ventilation mode is greater than that of non-ventilation mode and natural ventilation mode by 3% and 1.9%, respectively.

Cipriano et al. [72] introduced a method to analyze the effective range of existing correlations associated with the convective coefficient of heat transfer and air flowrate within laminar flow regime and transitional flow to turbulent free convection. The study also evaluated the asymmetry of wall boundary conditions that affected free-ventilated double-skin PV facades.

Gaillard et al. [73] researched the annual energy performance of a prototype of naturally ventilated double glazed BIPV window, which was installed on the façade of a multi-story office building located in Toulouse, France.

Chatzipanagi et al. [74] conducted a study on a demonstrative BIPV project with five BIPV windows, different PV cells and orientations in Lugano, Switzerland. The results of one-year monitoring showed the ventilated a-Si PV module had a lower operating temperature at slope of 90°, whereas both a-Si and c-Si based modules had their highest operating temperature at a slope of 30°.

(3) Influence on building energy consumption and indoor environment

Chow et al. [70] used EnergyPlus program to simulate the performance of ventilated double glazed BIPV windows installed on the façade of a typical office building located in Hong Kong. The maximum energy saving was realized with an SHGC between 45%-55%. Chow et al. [4] also found that, when compared with traditional single-absorptive glazing window, the novel naturally ventilated double glazed BIPV window could decrease energy consumption for air conditioning by nearly 28%.

Han et al. [75] investigated the performance of naturally ventilated double glazed BIPV windows through experiments in Hong Kong and found that the maximum indoor air temperature of the double glazed BIPV window was nearly 29°C, which was about 5°C less than conventional façade.

Barbosa et al. [76] used computational simulations to assess the energy performance of fan-assisted ventilated double glazed BIPV windows in tropical climates. The proposed design yielded an increase in electricity output, with a considerable energy saving in 'cool' climate zones than 'hot' climate zones.

Yang et al. [11] used TRNSYS simulation tool to perform a comparative analysis for four different types of BIPV/T systems under climates of Australia. Both naturally ventilated and non-ventilated double glazed BIPV/T façade showed different performances in variable visible light transmittance (VLT) PV glazing. The study also found that naturally ventilated double glazed BIPV windows of lower VLT resulted in a more favorite indoor temperature in hot climates, however the non-ventilated double glazed BIPV window of higher VLT performed better for cold climates.

Jia et al. [77] conducted experimental and simulation studies on the power generation and surface temperature of double-skin semitransparent photovoltaic (DS-STPV) windows. The energy performance of DS-STPV windows with non-ventilation, internal circulation and air supply ventilation modes were analyzed in cold areas.The three ventilation modes are shown in Fig.16. The research results suggested that in comparison with the other two ventilation methods, air supply DS-STPV windows can reduce the net power consumption of the building by 18.5% and 20.2%, respectively.

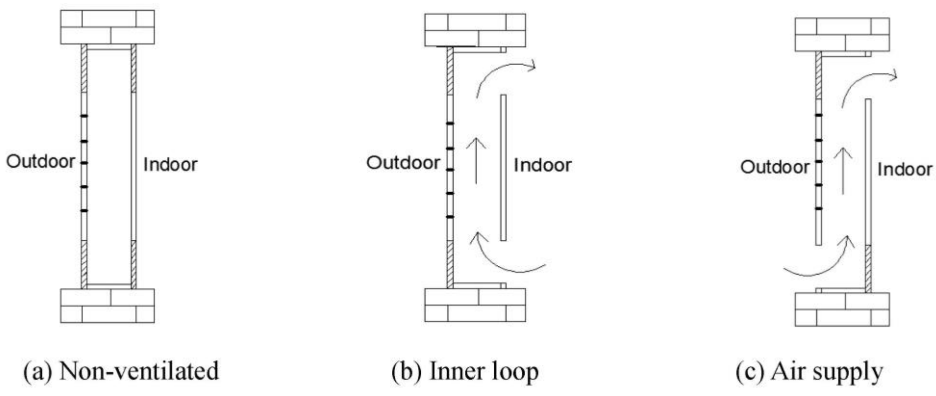


Fig. 16. DS-STPV window with different ventilation modes[77].

Guo et al. [78] studied the energy performance of three types of PV windows with transmittances and orientations under five climatic conditions in China. The types of PV windows are shown in Fig. 17. Under the climate of Harbin, Beijing, Shanghai and Shenzhen, , natural ventilated double PV (NVDPV) windows integrated photovoltaic glass with 10% light transmittance provides higher energy performance than a window with a transmittance of 5%. South facing windows also minimizes electricity consumption of the building under the climate of Harbin, Beijing, Shanghai and Lhasa, In the case of Shenzhen, east-facing windows use the least electricity.

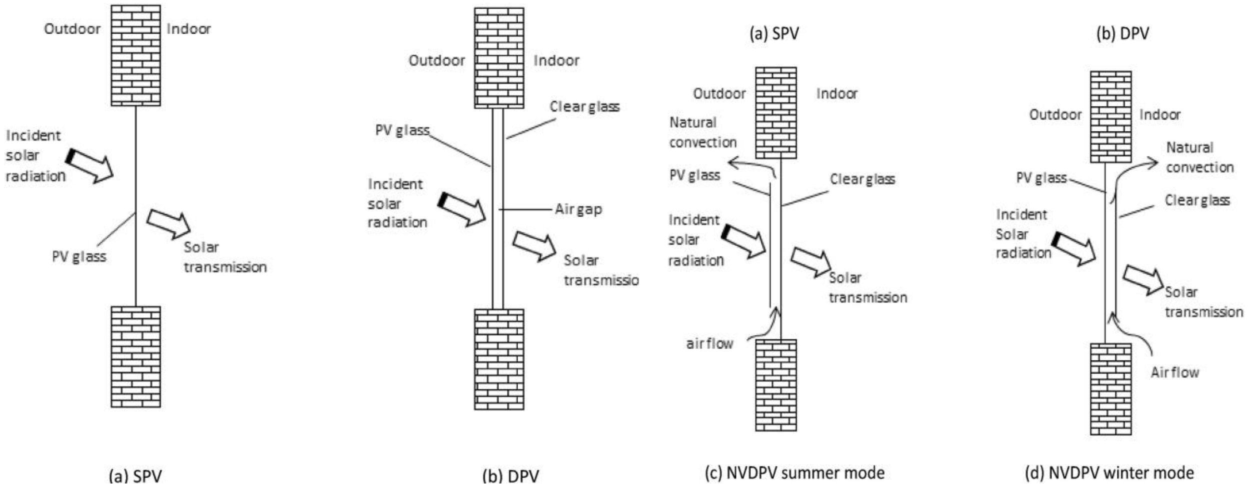


Fig. 17. Schematic configuration of PV windows [78].

Yang et al. [79] conducted a detailed evaluation of the energy performance of building integrated photovoltaic thermal double skin façade (BIPV/T-DSF) through numerical simulations. The study included PV glass windows and three types of air cavity ventilation methods (no ventilation, natural ventilation and mechanical ventilation). By comparing different working modes and BIPV technology, the results reveal that the natural ventilation DSF integrated with perovskite-based solar cells is the best configuration to achieve the highest energy savings.

Shakouri et al. [80] used thermodynamics and heat transfer phenomena to analyze and model the temperature and velocity distribution between the exterior and interior facades, and also analyzed the energy performance of the building integrated photovoltaic thermal double-layer facade (BIPVT-DSF). The study concluded that a photovoltaic system with a peak power of 10.6 kW: (a) can generate 18,064 kWh of grid-connected electricity per year, and (b) can increase the energy performance index of existing buildings by 34.3%.

Preet et al. [81] investigated the thermal and electrical performance of photovoltaic double-layer exterior walls under different ventilation methods (natural ventilation and forced ventilation) and air holes. The results suggest that for natural ventilation systems, increasing the pore size from 50 mm to 250 mm can reduce SHGC by 12%. Similarly, for a 200 mm air chamber with a wind speed of 5 m/s, the SHGC of the forced ventilation system is reduced by 19.24%. The SHGC of a 200 mm air cavity and a forced ventilation system with a flow rate of 5 m/s is lower than 36% of the natural ventilation of the same air cavity. Compared with natural ventilation, it is found that forced ventilation has a significant impact on energy performance.

Wang et al. [82] conducted a simulation and comprehensive analysis of the energy performance of DSF in the Yangtze River Area (YRA) which showed improved configurations, the use conditions of the blinds (up and down or slat angle) and the applicability of DSF within the studied area. The results showed that DSF (structure II, as shown in Fig.18) with internal double glazing is a more suitable configuration with better thermal performance in YRA. In summer, when the angle of the shutter is 45°, DSF has the best heat dissipation performance.

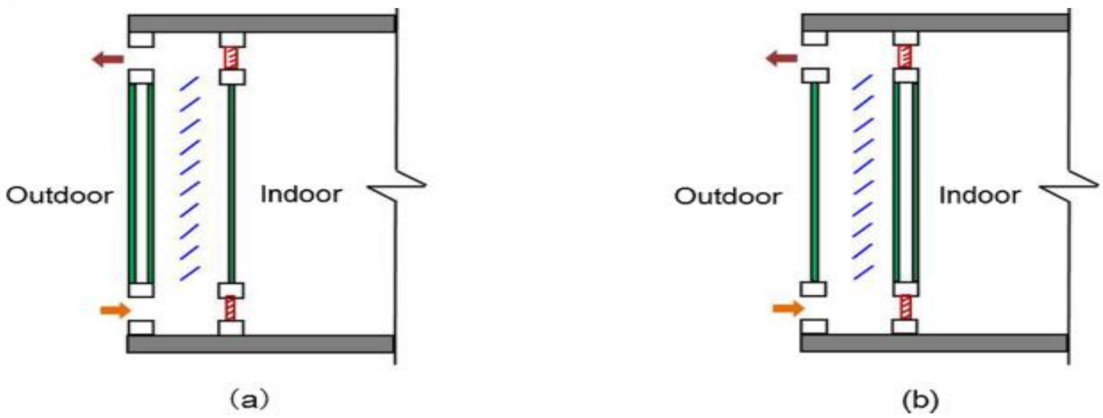


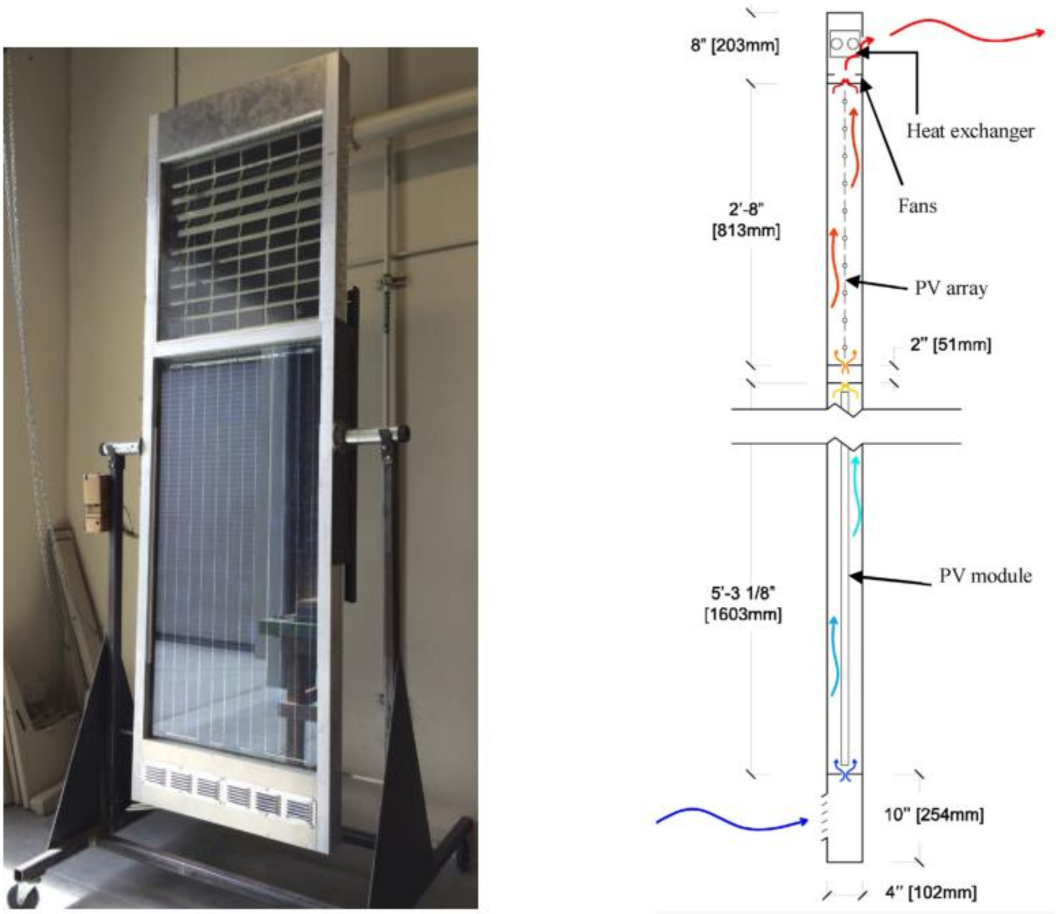
Fig. 18. Configurations of the DSF: (a) Structure I, (b) Structure II. [82]

A simulation framework combining global sensitivity analysis (SA) method and multi-physical field BIPV model was proposed by Juliana et al. [83]. The sensitivity of the BIPV Windows was analyzed by investigating the performance of the natural ventilation BIPV external wall elements and building performance indicators, such as the total heat flux inside the building and the temperature of the building wall. The results suggested that the SA results strongly rely on the various inputs selected. For narrow changes in weather conditions, the external convective heat transfer coefficient is determined to be the input that had the greatest influence on BIPV performance. The results also indicated that as the external convection heat transfer decreases, cavity ventilation plays a crucial role in energy saving.

With the help of ventilated air layer, a large part of the heat from PV panels is rejected to the ambient air, hence the heat gains into the room are reduced and the electrical efficiency can be improved. However, the addition of vents complicates the design of windows, increases their cost and reduces the area of net glazing. Actually, this type of BIPV window is a special kind of double skin façade and it is not a double PV glazing. The whole window should be designed and operated as one device. Moreover, the dust in the air inevitably enters the ventilated air gap, some dust accumulates on the internal surface of the glazing, which may makes cleaning the glazing difficult.

2.4.2 PV module between the double glazing

(1) Configuration



(a) Photograph of the prototype. (b) Schematic of cross section and airflow.

Fig. 19. PV module between the double glazing [84].

(2) Performance

Chialastri et al. [84] developed a prototype for a novel double glazed BIPV/T with airflow and conducted tests under three seasons in Salinas, California. As shown in Fig. 19, the developed prototype includes two double-glazed window components with a cavity in the middle where PV modules are located. It also featured two vents, one at the bottom of the external glazing for inflow of cold air, the other at the top used to extract hot air. The average thermal efficiency and the electrical efficiency were 31% and 7%, respectively.

Charron et al. [85] conducted a research to optimize the design of double-skins façade with blinds (upper part) and PV panels (lower part) placed in the middle air cavity, in Montreal, Canada. The optimization method resulted in an overall thermal-electric efficiency of more than 60%.

From the above research, it can be seen that the existence of air layer helps to improve the thermal performance of the double-layer photovoltaic window. The movement of air in the air gap takes away heat generated by the photovoltaic effect, thus reducing the operating temperature and increasing the power generation efficiency. Moreover, the solar heat gain coefficient decreases with the increase of air layer thickness. The photovoltaic modules mounted on the roof have a much higher power generation capacity than those mounted on the wall. Results show that the power generation potential of the south wall, east wall and west wall is basically the same, while the power generation of the unit roof photovoltaic modules is more than that of the wall-mounted modules. The ventilated PV roofs have higher power efficiency and lower cooling load. Therefore, it is more suitable for summer applications than ventilated photovoltaic roofs, which are more suitable for winter use because it helps to reduce the thermal load. The ventilation is better at increasing power generation and reducing solar heat gain, while non-ventilation provides better insulation.

For this kind of BIPV windows, a large part of the heat from PV panels is used to heat the outdoor air flowing into the room, hence the fresh air temperature provided for the room is increased and the total energy performance can be improved significantly. They are suitable for cold climates where space heating dominates.

2.5 Photovoltaic vacuum glazing system

(1) Configuration

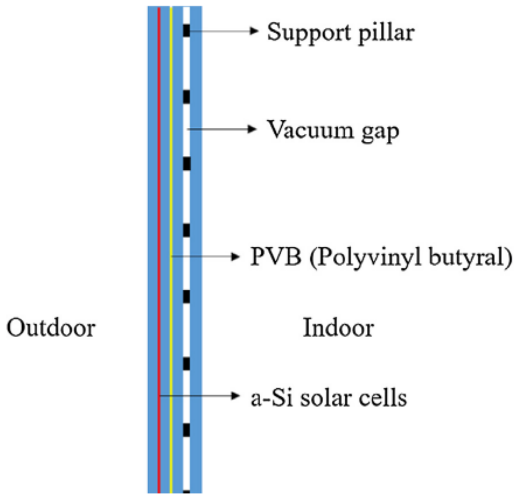


Fig. 20. The structure of photovoltaic vacuum glazing system [86].

As shown in Fig. 20, the photovoltaic vacuum glazing system is mainly composed of external PV glazing and internal vacuum glazing. The external PV glazing is similar to single BIPV glazing. The internal vacuum glazing includes two sealed panes and the gap between them is evacuated and small support pillars are used to resist the external environmental pressure. The external PV glazing and internal vacuum glazing are usually adhered together by transparent adhesive, such as polyvinyl butyral[86] .

(2) Performance

Huang et al. [86] conducted numerical experiment on the thermal and power generation of a new-developed vacuum PV (VPV) glazing under climate conditions of Hong Kong as well as Harbin. In comparison to ordinary double pane glazing, the VPV glazing reduced heat absorption by nearly 82% and heat loss by nearly 32% in Hong Kong while by nearly 75% and 32% in Harbin. Considering electricity production of BIPV windows and energy for lighting, heating and/or cooling, the purchased electricity consumption of building models using different windows were shown in Fig.21

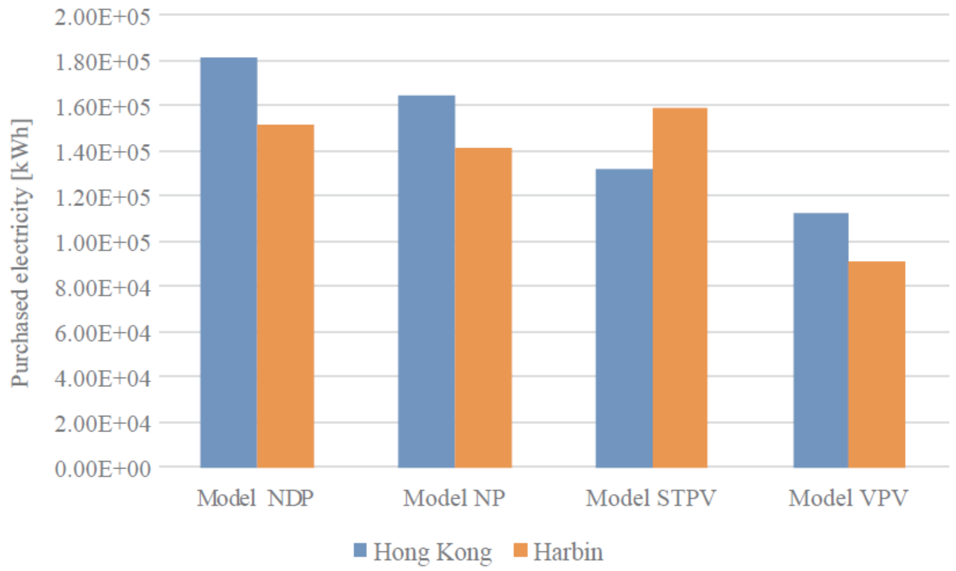


Fig.21 Purchased electricity consumption of building models using different windows [86]

Qiu et al. [87] conducted experiments and simulations on the potential to reduce cooling loads using an innovative photovoltaic vacuum glazing system located in Hong Kong. Their analysis showed it was beneficial to apply this innovative system because of its energy saving potential.

Ghosh et al. [88] researched the thermal performance of vacuum PV glazing and compared it with double pane PV glazing using a one-dimensional model. The comparisons indicated the BIPV vacuum glazing system results in higher room temperatures on sunny days in UK.

Jarimi et al. [89] developed a mathematical model for PV vacuum glazing which was validated through experiments. An optimal design produced a U-value of about 0.6 W/m^2 K, which was much lower than common glazing.

Huang et al. [90] proposed an integrated PV vacuum glass window unit and a calibrated modeling method to evaluate its heat transfer performance. Four configurations of PV vacuum glass windows were compared in terms of temperature distribution and total heat transfer coefficient. The simulation results suggested that the best performance of PV vacuum double glazing can be achieved in four configurations when both PV module temperature and U value are considered. Four types of photovoltaic vacuum glass window structures are shown in Fig 22.

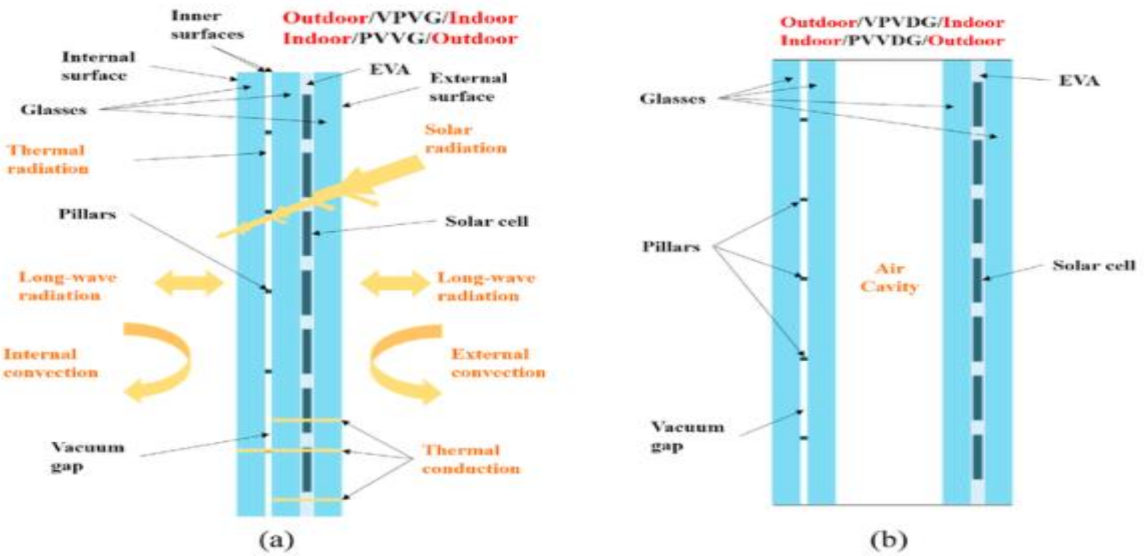


Fig.22. Different types of PV vacuum glazing and a sample heat transfer illustration. [90]

Experimental and theoretical studies on the thermal and electrical properties of six different glazing systems are reported by Radwan et al. [91]. Their performance were compared with that of single glazing (SG). The results showed that the U value obtained by the VGPV (semi-transparent PV with VG) system is lower than that of the VIPPV (semi-transparent PV with translucent vacuum insulation panel system). Moisture condensation can be eliminated by using VGPV or VG (photovoltaic glazing) systems. The study concluded that VGPV and VIPPV generate relatively less electricity, but supply higher thermal insulation.

Due to the absence of air inside the vacuum photovoltaic window, there is no gas conduction and convection heat transfer. Hence the vacuum photovoltaic window has excellent thermal insulation performance and can effectively block the transmission of sound. Also, the original photovoltaic glass can also play a protective role by reducing oxygen moisture erosion of photovoltaic modules.

Compared to ordinary double pane glazing, the VPV glazing could heavily reduce heat gain and/or heat loss both in hot climates such as Hong Kong and very cold climates such as Harbin, China. However, further studies are needed to study the separate contribution of PV glazing and vacuum glazing to energy saving. Furthermore, the overall energy performance and benefits of VPV should be compared with vacuum glazing without PV under typical climates, such as cold climates, hot climates and temperate climates. The cost-effectiveness of addition of PV glazing to vacuum glazing are also required to be evaluated under various weather conditions in the future studies.

2.6 Summary and statistics of researches on BIPV windows

(1) Year distribution

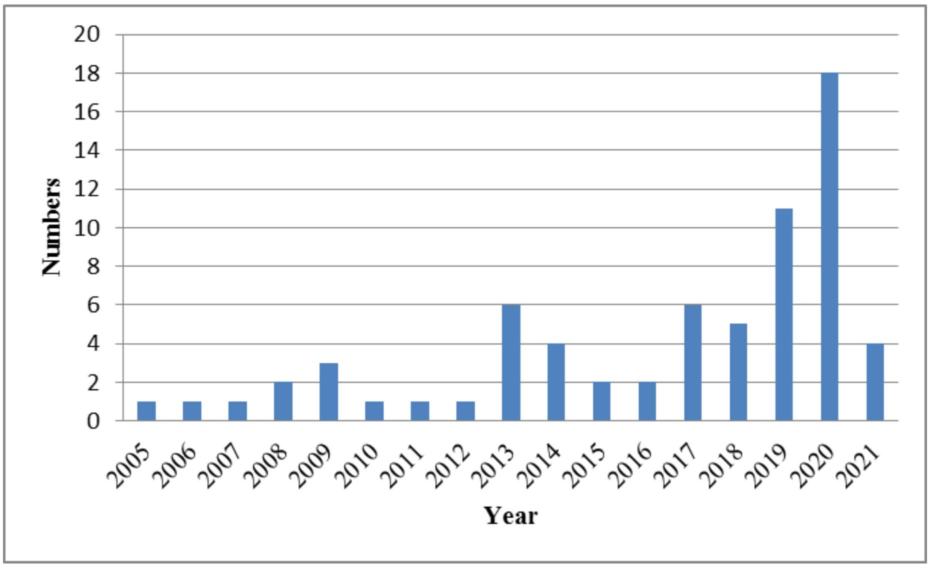


Fig. 23. Summary of year distribution

The yearly distribution of BIPV papers reviewed is shown in Fig. 23. In general, the researches on BIPV windows have increased in recent years. It is interesting that there are some peak years, such as 2009, 2013 and 2019, which are much higher than the other years.

(2) Locations distribution researched

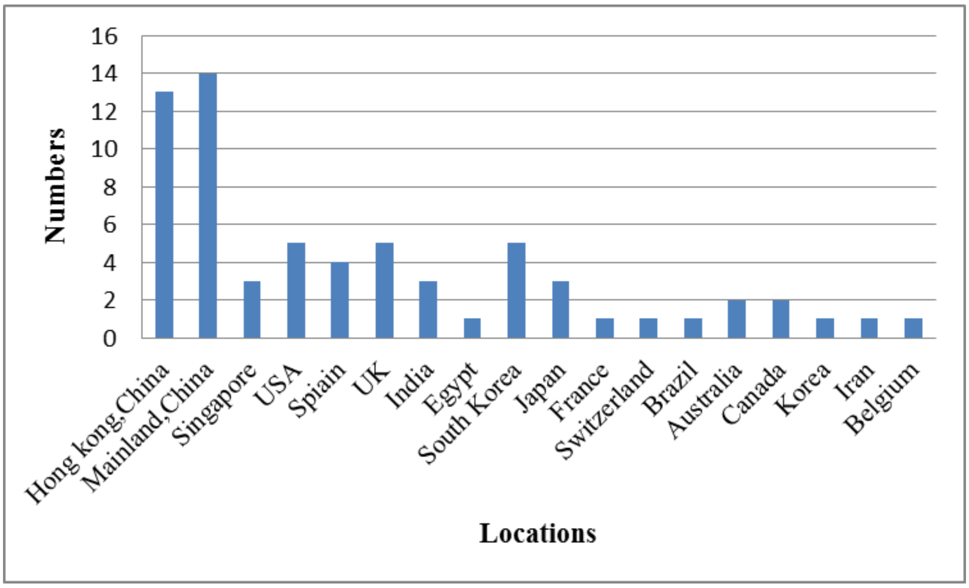


Fig. 24. Distribution of locations researched

Since the performance of BIPV windows are closely connected with local weather and climates. The distribution of locations where the BIPV windows were researched are shown in Fig. 24. It can be observed that the reviewed studies are widely spread around the world although Hong Kong is the most comprehensively researched region. Also, studies under weather condition of China, USA, UK and South Korea are more than other regions.

(3) PV types

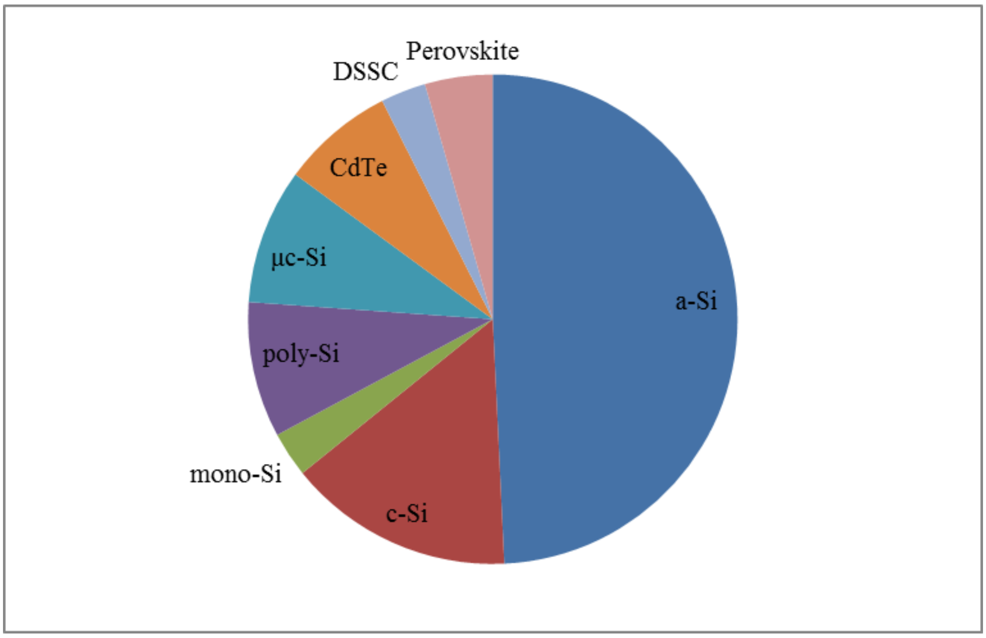


Fig. 25. Statistics of PV type

The types of PV cells affect the performance of BIPV windows significantly. A distribution of PV cells identified in the review is shown in Fig. 25. It can be seen that a-Si is the most widely researched cell followed by poly-Si and c-Si. Only a few cases CdTe of DSSC and perovskite were observed in the reviewed studies.

(4) Types of BIPV windows

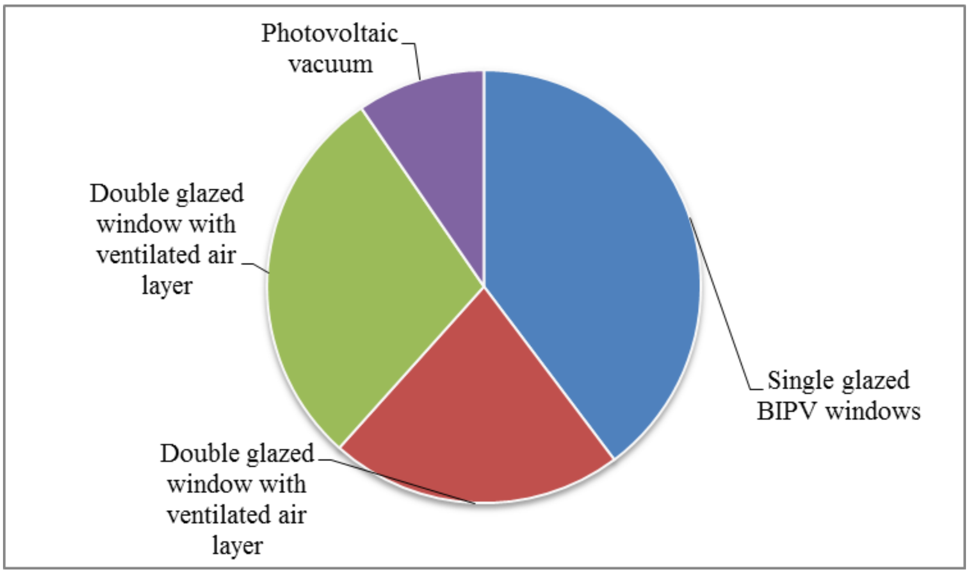


Fig. 26 Statistics of BIPV windows

The distribution of BIPV window types is illustrated in Fig. 26. It can be observed that single glazed BIPV windows are the most widely studied because of its basic role in BIPV windows. Double glazed BIPV windows with closed air layer and ventilated air layer are also extensively researched. Photovoltaic vacuum photovoltaic windows also have great research potential in the future.

(6) Factors

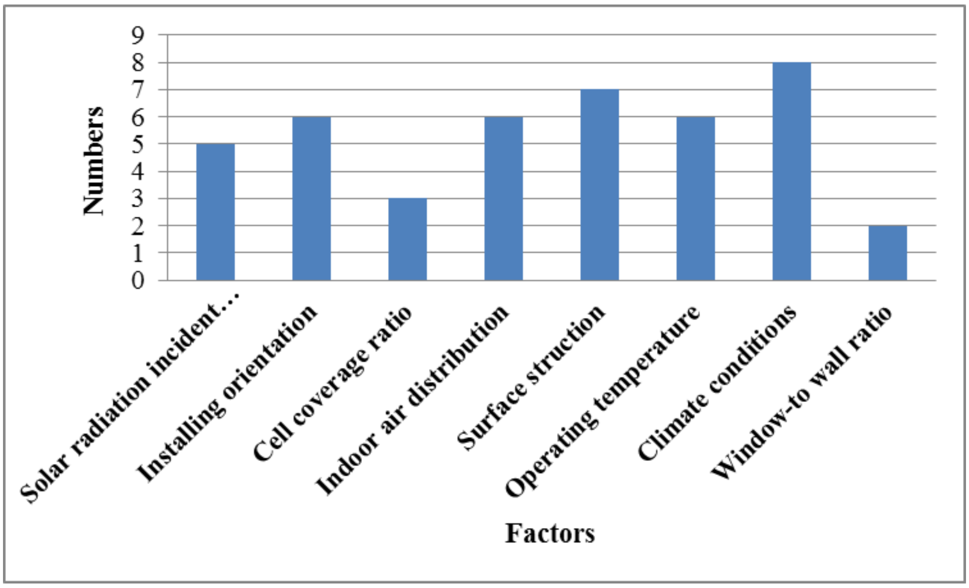


Fig.27. Statistics of factors

The performance of a BIPV window is affected by many factors, such as solar radiation angle, installation direction, battery coverage, indoor air distribution, etc. The influencing factors reviewed in this study are shown in Fig. 27. The angle of solar radiation has an important effect on the heat transfer performance of BIPV windows, particularly the solar heat gain coefficient. In addition, the installation angle of the photovoltaic window also affects its power generation capacity to a large extent, and improper installation may lead to a sharp decrease in power generation. There are many literatures on the influence of the orientation of photovoltaic windows on its performance. The studies shows that a south facing installation can yields the maximum potential for power generation, whereas a north facing installation yields the minimum. There are relatively few studies on battery coverage and window-wall ratio but these two factors are directly related to power generation. The surface structure of the photovoltaic window directly affects its heat transfer performance, and the operating temperature also directly affects its power generation performance.The aforementioned photovoltaic windows with closed/circulating/vacuum windows are designed to improve the operating temperature of photovoltaic cells. Illustrating with silicon cells, it is observed that for every 1 degree increase in the temperature of photovoltaic cells, the power decreases by about 0.48%. It is also necessary to study the influence of climate conditions on the performance of photovoltaic windows because each region receives different solar radiation illumination, and photovoltaic windows have different wavelength absorption capacities in different ranges.

(7) Summary table of data performance on BIPV windows

Table 2 Summary of data performance on BIPV windows

Window type	U-value (W/m^2 K)	SHGC	VLT	Power generation	Configurational features	Reference
Single glazed	5.08	0.289	9.17%	8.02%	a-si based with clear glass	[12]
	4.80	0.413	5.19%	5.90%	μc-Si based with clear glass	
	5.08	0.298	1.84%	3.32%	μc-Si based with clear glass	
	5.10	0.387	4.87%	4.43%	μc-Si based with clear glass	
Single glazed	/	10%	11.7%	6.3%	a-si based with clear glass	[30]
Single glazed	/	/	/	8% - 8.5%	1)Poly-Si based with clear glass 2)Poly-Si based with rear tinted glazing;	[32]
Single glazed	3.5	0.25	/	1)sunny days; 15% 2)cloudy days: less than 12%	c-Si based with clear glass	[33]
Single glazed	2.7	0.12	25%	12%	CdTe based with clear glass	[36]
Single glazed	/	/	/	1):16.33%; 2): 12.63% 3): 17.02% 4): 15.23%	Mono-Si based under four different conditions: 1) Front glass with Clear glass 2) Front glass with Coating glass 3) Front glass with Etching glass 4) Front glass with Etching Coating glass	[39]
Single glazed	/	/	30.1%	4.8%	A flat solar cell with 120-nm-thick intrinsic a-Si	[42]
			14%	5.3%	A flat solar cell with 180-nm-thick intrinsic a-Si	
			6%	6.3%	A textured solar cell with an 180-nm a-Si	
Single glazed	2.783	0.145	0	/	a-si based with different visible transmittance	[48]
		0.216	10%	/		
		0.253	20%	/		
		0.316	30%	/		
		0.367	40%	/		
Single glazed	2.603	0.367	40%	6.65%	Single glazed based on different visible transmittance	[43]
	2.412	0.220	20%	8.82%		
	2.308	0.158	10%	9.91%		
Single glazed	5.18	0.26	20%	4.9%	a-si based with clear glass	[46]
		0.41	32%	4.1%		
Single glazed	5.497	0.471	15.3%	/	a-si based with clear glass	[47]

Window type	U-value (W/m^2 K)	SHGC	VLT	Power generation	Configurational features	Reference
Single glazed	/	/	42.4%	6.64%	Perovskite with clear glass	[51]
Single glazed	5.6	0.14 -0.33	20%	8.13%	Perovskite with clear glass	[54]
Single glazed	6.1	/	/	/	CdTe based with clear glass	[91]
Single glazed	5.254	0.489	15.3%	/	a-si based with clear glass	[87]
Double glazed	1.67	0.154	6.91%	5.01%	a-si based with clear glass	[12]
	2.14	0.123	7.34%	4.75%	μc-Si based with clear glass	
Double glazed	0.8	/	8.83%	/	a-Si based with 6 mm air gap	[56]
dDouble glazed	0.883	/	22.5%	/	c-Si based with 9 mm air gap	[58]
Double glazed	/	/	10%	6.3%	a-si based with clear glass	[63]
Double glazed	2.584	0.354	13.6%	/	a-Si based with clear glass	[87]
Vacuum glazed	0.557	0.143	12%	/	a-Si based with clear glass and vacuum gap	[87]
Vacuum glazed	0.60	/	/	/	μc-Si / a-Si based with a 4 mm hard low-E coated glass and a 0.3 mm vacuum gap	[89]
Vacuum glazed	1.2	/	/	/	CdTe based with clear glass and vacuum gap	[91]

(5) Summary table of researches on BIPV windows

Table 3 Summary of researches of single glazed BIPV windows

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Fung and Yang 2008 [29]	Poly c-Si	Simulation and Experiment	1) Total heat gain	1）The total heat gain mainly came from solar heat gain	A whole year	Hong Kong China
Li et al. 2009 [30]	a-Si*	Experiment	1) Thermal and visual properties 2) Electricity generation	1）The visible light transmittance was up to 11% 2）The conversion efficiency was up to 6.0%	July 2007	Hong Kong China
Chen et al. 2012 [7]	a-Si* μc-Si*	Experiment	1) Solar heat gain coefficient	1) The incident angle of solar irradiation had effect on SHGC	Standard test conditions	Singapore
Lu and Law 2013 [45]	Not specified	Simulation	1) Total heat gain 2) Output power 3) Daylight illuminance	1) The thermal performance was primary for energy saving considerations	From 2003 to 2007	Hong Kong China

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Ng et al. 2013 [2]	a-Si, μc-Si*	Simulation	1) SHGC and U-value 2) Electricity generation	1) BIPV windows had a better energy saving potential	A whole year	Singapore
Chae et al. 2014 [42]	a-Si*	Simulation and Experiment	1) U-value and SHGC 2) Visible transmittance	1)The thermal and optical performance affected the overall building energy consumption	A whole year	Miami et al. USA
Ng and Mithraratne 2014 [44]	a-Si* μc-Si*	Simulation	1) Economic performance 2) Environmental performance namely carbon emissions	1) The EPBT and EROEI for the modules ranged from 0.68 to 1.98 and 11.72 to 34.49,respectively	Life cycle	Singapore
Olivieri et al. 2014 [48]	a-Si*	Simulation and Experiment	1) U-value 2) Glare and daylighting analysis 3) Electrical generation	1) Energy savings of at least 18% and even up to 50%	Assumed conditions	Madrid Spain
Liao and Xu 2015 [46]	a-Si*	Simulation and Experiment	1) Electricity generation 2) SHGC and U-value	1)the PV electricity yield is relatively small 2) a-Si based PV glazing performed better in cooling dominant regions 3) BIPV glazing was more suitable for shallow rooms with large windows.	A whole year	Wuhan China
Zhang et al. 2016 [47]	a-Si*	Simulation and Experiment	1) U-value and solar heat gain 2) Power generation 3) Daylighting illuminance	1) The U-value and solar heat gain of window was reduced 2)The BIPV window had great electricity saving potential	A whole year	Hong Kong China
Cannavale et al. 2017 [51]	Perovskite*	Experiment and Simulation	1) Yearly energy yield 2) Visual comfort	1) The useful Daylight Illuminance values of semitransparent perovskite-based solar cells glass is significantly higher	A whole year	Worldwide locations
Do et al. 2017 [43]	Not specified	Simulation	1) Electricity production 2) Energy saving potential	1) The south-facing windows showed the highest potential of electricity generation and decrease of cooling load 2) The east-facing windows saved the largest amount of lighting energy	A whole year	Houston USA

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Baenas and Machado 2017 [49]	Poly c-Si	Modelling	1) Solar heat gain coefficient	1) A closed-analytical expression was developed to simplify the calculation process of SHGC of BIPV modules.	Assumed conditions	Alicante Spain
Karthick et al. 2017 [31]	Poly c-Si	Experiment	1) Power generation 2) Solar heat gain 3) Cells temperature	1) The system had better energy performance under the condition of a low cell coverage ratio	Several days	Kovilpatti India
He and Schnabel 2018 [50]	Not specified	Simulation and Experiment	1) Daylight calculation method	1)A Calculation Model and Process for Daylight Illumination was developed	A whole year	Wuhan China
Karthick et al. 2018 [32]	Poly c-Si*	Experiment	1) Daylight factor 2) Energy saving potential	1) A cell coverage ratio of 0.62 resulted in a maximum daylight factor 2) The PV skylight reduced the cooling load to 248 kWh per year	From January to December 2016	Kovilpatti India
Peng et al. 2019 [33]	c-Si	Experiment	1) SHGC 2) Daylight illuminance 3) Electricity production	1) Single glazed BIPV window had a lower SHGC of 0.25 2) The daily electrical efficiency was nearly 15% ;	From September to November 2015	California USA
Elghamry et al. 2019 [34]	c-Si	Simulation and Experiment	1) Power generation 2) Energy consumption 3) Comfort condition 4) CO_2 emissions	1)The south oriented BIPV windows generates the maximum annual power 2）The north oriented BIPV yields the minimum	A whole year	Alexandria Egypt
Yang et al. 2019 [52]	μc-Si*	Experiment	1) Optoelectronic performance	1)Improving transmittance and efficiency	Assumed conditions	Changwon South Korea
Yang et al. 2019 [35]	a-Si	Simulation	1) PV operating temperature 2) Power generation 3) Heat gain of façade	1) The influence of indoor air distribution on the operating temperature of PV modules was less impactful	In summer	Taiyuan China
Tsai 2020 [53]	a-Si/ μc-Si*	Experiment	1) Electricity production 2) Daylight transmittance	1）Specifications and performance are often limited by their associated technologies and manufacturing processes 2)Demonstrating and Discussing the potential and versatility of these silicon thin-film modules in BIPV applications	A whole year	Kaohsiung China

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Ghosh et al. 2020 [54]	Perovskite	Experiment	1) SHGC and U-value 2) Daylight glare control potential	1）The average solar and visible transmittance were 30% and 20%, respectively 2) The SHGC range from 0.33 to 0.14 3) The U-value was 5.6 W/m^2 K	Assumed conditions	Penryn UK
Alrashidi et al. 2020 [36]	CdTe*	Experiment	1) SHGC and U-value	1) The U-value was 2.7 W/m^2 K 2) The visible transmission and solar transmission were confirmed to be 25% and 12%, respectively	Assumed conditions	Penryn UK
Alrashidi et al. 2020 [37]	CdTe	Experiment	1) Energy generation 2) U-value and SHGC	1) The net potential energy saving was 20% more than a common single glazed window	Sample days over the year	Exeter UK
Yang, et al. 2020 [39]	mono-Si:	Experiment	1) power conversion efficiency (η) 2) fill factor (FF)	1)Using the EGC-BBS structure, η of the Si solar cell is 15.23%,the FF value is 65.05%	Assumed conditions	Suwon Korea
Toledo et al. 2020 [41]	c-Si/ CdTe/ a-Si/ organic PV	Experiment	1) Thermal performance 2) Comfort condition 3) Module temperature	1）How the two models strongly attached to the amount and direction of incident solar irradiance	A whole year	Murcia Spain
Fan et al. 2021 [38]	c-Si/ a-Si	Simulation	1) Daylight transmittance	1）In Xi 'an, 50-60% of TF and C-Si 2) In Beijing, TF was 60-70% and C-Si was 50-70% 3) In Shanghai, TF is 50-60% and C-Si is 60-70% 4）In Guangzhou，TF was 50-60% and C-Si was 50-70% 5) The TF and C-Si of Harbin area are 40-60% and 40-60% 6) The content of TF and C-Si in Chongqing area is 30-50%.	Assumed conditions	Xi’an Beijing Shanghai Guangzhou Harbin Chongqing China

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Xuan et al. 2021 [40]	Not specified	Simulation and Experiment	1) Daylighting performance	1) the use of CPVW can improve the uniformity of daylighting 2) The proportion of the effective illuminated area provided by CPVW is 6.69 times	October 31, 2018	Hefei China

(*) Indicates that this paper introduces BIPV window specifications and performance data.

Table4Summary of designs and performance of double glazed BIPV windows with closed air layer

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Miyazaki et al. 2005 [62]	a-Si	Simulation	1) Electricity production	1) Energy savings of up to 55%	In winter and summer	Tokyo Japan
Wong et al. 2008 [67]	Poly c-Si	Simulation	1) Power generation 2) PV temperature 3) Indoor daylight illuminance	1) Power generation deteriorates with increased panel temperature 2) BIPV roof panels obtain significant reductions in cooling and heating energy demand.	2 January and 2 August	Sapporo et al. Japan
James et al. 2009 [68]	Mono c-Si	Experiment	1) CO_2 emission 2) Electricity generation	1）An appropriate design of PV atrium could justify its cost and carbon footprint.	From June 2005 to May 2008	Southampton UK
Han et al. 2010 [55]	a-Si	Simulation	1) U-value 2) Convective heat transfer mechanism	1) Having lower U-values than single glazed BIPV windows	Assumed conditions	Hong Kong China
Yoon et al. 2013 [56]	a-Si	Experiment	1) Annual surface temperature	1) The surface temperature in summer daytime and winter night were 1 °C lower and 2 °C higher	A whole year	Gyeonggi-Do South Korea
Lee et al. 2017 [63]	a-Si	Simulation and Experiment	1) Power efficiency	1)The annual average yield was reduced to 1.52 h/day	From Sep 2012 to Aug 2013	Daegu South Korea
Lee and Yoon 2018 [57]	DSSC	Experiment	1) Power generation efficiency	1) The vertical DSSC BIPV window had better energy performance than the 30°inclined variant.	From 1st Jan. 2015 to 31st Dec. 2016	Daejeon South Korea
Sun et al. 2018 [64]	CdTe	Simulation	1) Electricity generation 2) Useful Daylight Illuminance and glare comfort	1) BIPV windows improved energy savings and daylight performance.	A whole year	Five cities China

Authors year	**PV type**	**Approach**	**Performance focused**	**Main findings**	**Conditions**	**Locations**
Cook and Al-Hallaj 2019 [69]	bifacial PV cell	Simulation and Experiment	1) Power output	1) The maximum power increase was observed to be 35.1%.	A whole year	Chicago USA
Cheng et al. 2019 [65]	a-Si	Simulation and Experiment	1) Daylighting quality 2) Energy efficiency	1）When the ratio of N-Daylit area rises to 56%，the annual net power consumption of the room space was reduced to about 36.1 kWh/m^2	From 1st to 31st May 2017	Taiyuan China
Chen et al. 2019 [58]	c-Si	Simulation and Experiment	1) Electricity generation 2) Heat transfer	1）Installing south-facing PV windows with cell coverage ratio of 87% and air gap of 0.9 mm was the best design option in southwest China	September 2018	Southwest China
Mesloub et al. 2020 [59]	a-Si	Simulation and Experiment	1) Energy output 2) U-value and SHGC 3) Visible light transmittance	1) Energy savings can up to 60%	E	Tebessa Algeria
Ioannidis et al. 2020 [66]	bifacial PV cell	Experiment	1) Thermal performance 2) Heat recovery index 3) Electrical efficiency	1) The heat loss of a typical building may be 20% higher 2) The heat recovery index can come up to more than 30% 3) The total utilization efficiency of solar energy can be between 30% and 77%.	20th of September	Montrea Canada
Chung et al. 2020 [60]	DSSC	Simulation	1) SHGC and U-value 2) visible-light transmission (VLT) 3) Power conversion efficiency	1) Having a higher heat transfer rate (ie U value) 2) The visible light transmittance (VL T) is lower	A whole year	Seoul South Korea
Khalid et al. 2021 [61]	c-Si	Experiment	1) Thermal and visual properties 2) Electrical performance	1) Ameliorating operating condition and lowering the cells' temperature	Several days	Penryn UK

Table 5 Summary of designs and performance of double glazed window with ventilated air layer

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Charron and Athienitis 2006 [85]	Not specified	Simulation	1) Electricity generation 2) Heat transfer coefficients	1) The overall thermal electric efficiency reached more than 60%.	Assumed conditions	Montreal Canada
Chow et al. 2007 [70]	a-Si	Simulation	1) Electricity output 2) Overall heat transfer	1) Energy saving was obtained when the SHGC was between 45%-55%.	A whole year	Hong Kong China

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Chow et al. 2009 [4]	a-Si	Simulation and Experiment	1) SHGC and U-value 2) Electricity generation	1）The energy consumption for air conditioning nearly decreased by 28%.	A whole year	Hong Kong China
He et al. 2011 [71]	a-Si	Simulation and Experiment	1) Electric efficiency 2) Temperature distribution and indoor heat gain	1) The electric efficiencies are about 3.65%; 2) The indoor heat gain is reduced to 46.5%;	In summer 2009	Hefei China
Han et al. 2013 [75]	a-Si	Experiment	1) Indoor air temperature and heat gain 2) Electricity generation	1）The maximum indoor air temperature was nearly 29°C	In summer	Hong Kong China
Peng et al. 2013 [10]	a-Si	Experiment	1) Solar heat gain coefficient	1）The average SHGC of a ventilated BIPV window was lowest 2) The electrical output of mechanical ventilation mode is the highest	From Jan. to Feb. 2013	Hong Kong China
Cipriano et al. 2013 [72]	Not specified	Simulation	1) Convective heat transfer coefficient 2) Air mass flow rate	1) Evaluated the asymmetry of wall boundary conditions	Assumed conditions	Terrassa Spain
Gaillard et al. 2014 [73]	c-Si	Experiment	1) Thermal efficiency 2) Electrical output	1) Improving the thermal performance of the building with PV components	A whole year	Toulouse France
Peng et al. 2015 [9]	a-Si	Experiment	1) SHGC and thermal insulation 2) Energy output	1)Reducing the heat gain of PV-DSF 2)Improve the energy conversion efficiency of PV modules	In winter 2012	Hong Kong China
Chatzipanagi et al. 2016 [74]	a-Si, c-Si	Experiment	1) Energy production	1) The ventilated a-Si PV module experienced a lower operating temperature at slope of 90° 2)Both a-Si and c-Si based modules had their highest operating temperature at a slope of 30°	A whole year	Lugano Switzerland
Chialastri and Isaacson 2017 [84]	Si	Simulation and Experiment	1) Thermal efficiency 2) Electrical generation	1) The average thermal efficiency was 31% 2) The electrical efficiency was 7%.	Several days in 2014 and 2015	California USA
Barbosa et al. 2019 [76]	a-Si	Simulation	1) Electricity generation 2) Thermal comfort acceptability	1)An increase in electricity output 2) A considerable energy saving	A whole year	Rio de Janeiro et al. Brazil

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Yang et al. 2019 [11]	a-Si	Simulation	1) Visible light transmittance 2) U-value	1) Different performances in variable VLT PV glazing 2) For naturally ventilated model, lower VL T resulted in a more favorite indoor temperature in hot climates	A whole year	Darwin, Sydney and Canberra Australia
Jia et al. 2020 [77]	a-Si	Simulation and Experiment	1) Power generation 2) Surface temperature	1) Air supply DS-STPV windows can reduce the net power consumption of the building	In winter (from No-vember to the following March	Taiyuan China
Guo et al. 2020 [78]	Not specified	Simulation and Experiment	1) Power generation 2) Energy performance 3) Thermal performance	1) NVDPV windows with 10% light transmittance provide higher energy performance 2) The windows facing south minimize the electricity consumption of the building	In summer	Harbin、Beijing, Shanghai 、Lhasa、Shenzhen China
Yang et al. 2020 [79]	a-Si/ DSS/ perovskite	Simulation	1) Energy consumption.	1) BIPV/T-DSF can achieve the highest energy savings.	A whole year	Darwin, Sydney and Canberra Australia
Shakouri et al. 2020 [80]	a-Si	Simulation	1) electricity generation 2) PV layers temperature 3) energy saving	1) A photovoltaic system with a peak power of 10.6 (kW) (a) can generate 18,064 (kWh) of grid-connected electricity per year 2) Increasing the energy performance index of existing buildings by 34.3%	A whole year	Tehran Iran
Preet et al. 2020 [81]	CdTe	Experiment	1) SHGC 2) Thermal performance 3) Power generation 4) energy performance	1) For natural ventilation systems, SHGC can reduce by 12% with the variable pore size 2）Forced ventilation has a significant impact on energy performance.	In summer	Jaipur India
Wang et al. 2020 [82]	c-Si	Simulation and Experiment	1) Thermal performance 2) heat gains/losses	1) DSF with internal double glazing have better thermal performance 2)In summer, the shutter angle of the shutter is 45° , DSF has the best heat dissipation performance	December 1 to February 28; June 15 to September 15	Changsha Shanghai Nanjing Wuhan Chongqing Chengdu China

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Juliana et al. 2020 [83]	c-Si	Simulation and Experiment	1) Power generation 2) Thermal performance 3) Sensitivity analysis	1) Cavity ventilation plays a crucial role in energy saving 2) SA results are strongly relying on the various selected for the input	Weather input data	Leuven Belgium

Table 6Summary of designs and performance of photovoltaic vacuum glazing system

Authors year	**PV type**	**Approach**	**Performance focused**	**Main findings**	**Conditions**	**Locations**
Huang et al. 2018 [86]	Not specified	Simulation	1) Thermal insulating performance 2) PV electricity generation	1) The VPV glazing reduced heat absorption by nearly 82% and heat loss by nearly 32% in Hong Kong	A whole year	Hong Kong, Harbin China
Ghosh et al. 2019 [88]	Poly c-Si	Experiment	1) Thermal comfort	1) BIPV vacuum glazing system ensues in higher room temperatures on sunny days	Some days in summer and winter	Penryn et al. UK
Qiu et al. 2019 [87]	a-Si	Simulation and Experiment	1) Electricity generation 2) U-value and SHGC	1) Having higher energy saving potential	A whole year	Hong Kong China
Jarimi et al. 2020 [89]	μc-Si/ a-Si	Simulation and Experiment	1) U-value	1) U-value of about 0.6 W/m^2 K	21st June 2019	Nottingham UK
Radwan et al. 2020 [91]	CdTe	Simulation and Experiment	1) U-value 2) Thermal performances 3) electrical performance	1) The U value of VGPV is lower than VIPPV 2) VGPV and VIPPV generate relatively less electricity	In winter	Hokkaido Japan
Huang et al. 2021 [90]	Not specified	Simulation and Experiment	1) The overall heat transfer coefficient) 2) PV module temperature.	1）The best performance of PV vacuum double glazing can be achieved	Assumed conditions	Hong Kong China

3 BIPV shading blinds

3.1 General description

BIPV shading devices integrate PV modules with shading devices to generate electricity while reducing indoor cooling demands through their shading effect. Shading devices can be classified into fixed shading panels and shading blinds. Whereas fixed shading panels are usually independent building components, shading blinds are often installed as an integral component of windows. Therefore, only BIPV shading blinds are included in this paper. According to the position of blinds, the classification of BIPV shading blinds is shown in Fig.28.

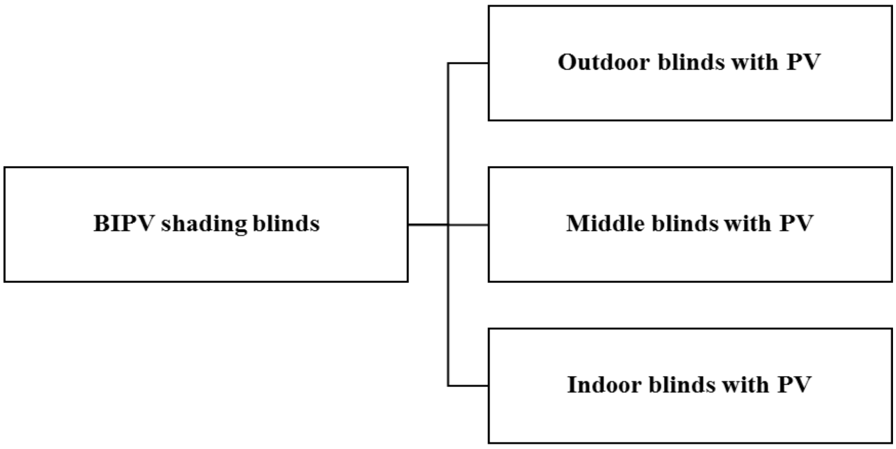


Fig. 28. Classification of BIPV shading blinds.

3.2 Outdoor PV blinds

(1) PV blinds

As showed in Fig. 29, PV blinds are often installed on the exterior surfaces of building façade. BIPV shading blinds attach PV panels onto the upper surfaces of external shading blinds and have the advantages of solar shading and energy generation.

Fig. 29. Photograph of an outdoor PV blinds [92].

The design of PV blinds needs to consider the cooling loads, heating loads and daylight of the building in addition to the electrical performance of PV panels. Bahr [93] introduced a systematic method to find the optimal parameters in the design of PV blinds.

Park et al. [94] presented a finite element model which was validated by simulation results. The model could be utilized to investigate and assess the technical as well as economic performance of the BIPV blinds and to determine an optimal strategy to maximize the investment returns.

Taveres-Cachat et al. [92] presented a method to optimize the design parameters of BIPV shading devices installed on the south façade of an office building in Norway. The optimization results showed that the designs with smaller louvres numbers were more desirable for this case study.

Gao et al. [95] studied the application of BIPV shading blinds to maximize power generation and minimize glare during daylighting. They obtained the best rotation angles using variable-pivot and 3-DOF (degree-of-freedom) to achieve sun tracking.

Meysam [96] studied the energy efficiency of a movable BIPV sun-shading system installed on windows. Compared with the BIPV that is fixedly installed at a distance and hung on a window, the thermal load of a building equipped with this system is reduced by 12%, 15%, and 16 respectively, and the power generation is 70% higher.

The design of outdoor PV blinds provides an effective way for electricity production, shading as well as reduction of cooling loads. Compared with vertical PV glazing, the PV blinds receive more solar radiation and hence produce more electricity. Generally speaking, outdoor PV blinds are applicable for places where external shading blinds are suitable. However, due to the high cost of outdoor shading blinds, their applications are limited for the present.

(2) PVT blinds

Vadiee et al. [97] developed a solar blind system incorporating PV/T collector for a greenhouse in Shiraz, Iran (as shown in Fig.30). The results indicated it is beneficial to install a solar blind system above the greenhouse roof since excess solar radiation will be absorbed and converted into useful heat and electricity. The highest thermal and electrical performance was realized at 18°C in a TRNSYS simulation. By using this same temperature set point, the cooling needs of the greenhouse were fully met while electrical demand was reduced by almost 73%.

Fig. 30. The configuration of the PVT collector in the solar blind [97].

The design of outdoor PVT blinds provides an effective way for electricity production, hot water heating and shading as well as reduction of cooling load. The total energy efficiency is significantly increased. However, this kind of applications is very limited, because the requirement of water heating is limited than electricity production and the addition of water heating device makes the shading blinds much heavier and increases cost of the supporting system.

3.3 Middle PV blinds

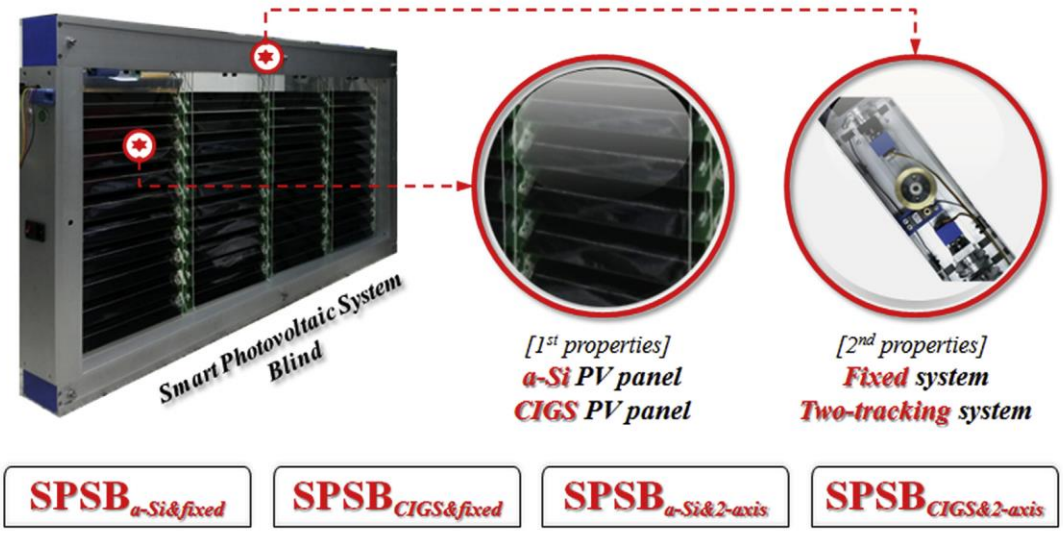


Fig. 31. Prototype models of middle PV blinds [98].

Fig. 31 shows a prototype model of a window with middle PV blinds. This window includes blind slats, a solar tracking device, a drive unit, and a circuit panel. The distinct feature of this window is that the upper surfaces of all the blind slats are integrated with PV panels.

Kang et al. [99] conducted theoretical analysis on the effect of ventilation on the cooling of PV modules in double glazed BIPV shading blinds. The ventilation measure reduced the maximum temperature of PV modules and improved its electrical efficiency.

Jeong et al. [100] introduced a novel smart PV blinds called Smart Photovoltaic System Blind (SPSB), which consist of PV panels, a monitoring device and tracking system, as shown in Fig.30. Koo et al. [98] investigated the technical, economic and political impacts of the SPSB on solar buildings towards net-zero energy in South Korea. The results showed that SPSB using CIGS-based PV panel and special two-axis tracking devices were superior to other systems in both technical and economic aspects. Hong et al. [101] conducted a nonlinearity analysis on the technical and economical performances of BIPV blinds incorporating shading effect.

Luo et al. [102] proposed a novel double skin window with PV blinds which was applied on building façade in Changsha, China. The results indicated an efficient realization of electricity generation and reduction in sunlight penetration as well as flexible daylight control, as shown in Fig. 32. The results of an experimental study demonstrated that the potential of energy saving of double skin windows with PV blinds can be approximately 12.2% and 25.6% when compared with traditional double-glazed window with or without blinds. Luo et al. [103] contrasted the performance of a double glazed BIPV shading blinds to a traditional brick wall (opaque façade) and double glazing (semi-transparent façade) in winter climates. It was found that double glazed BIPV shading blinds could reach a higher SHGC and lower U-value in non-ventilation mode.

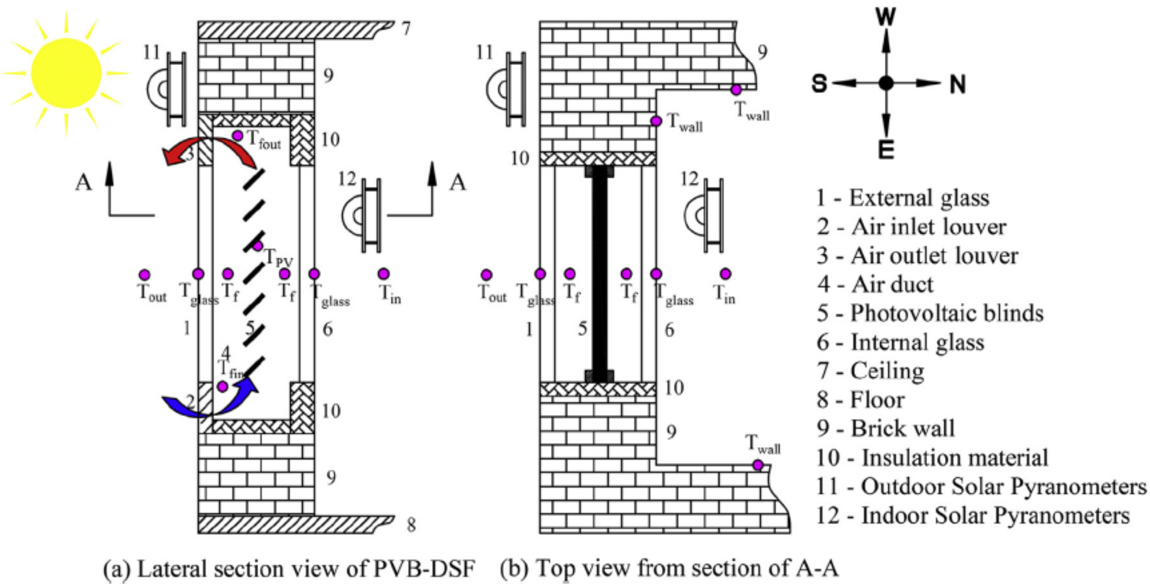


Fig. 32. Schematic of vertical section of PVB-DSF system [102].

The windows with middle PV blinds are promising to meet the requirement of electricity production, shading and daylight control due to the flexibility of the usage of the blinds. However, these windows are much more complicated and expensive than conventional windows. More researches are required to investigate their energy performance and economic performance under various climates. In addition, the advantages of PV blinds over ordinary blinds placed between two glazing should be verified both from perspective of energy production and cost-effectiveness for different climates.

3.4 Indoor blinds with PV

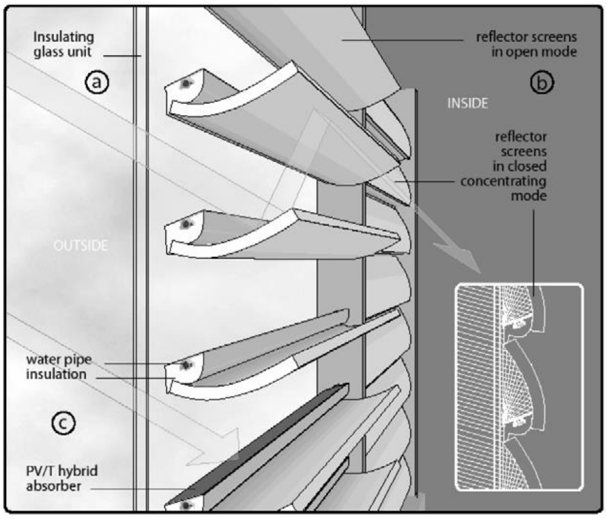


Fig. 33. Rendering of the parabolic reflector and absorber [77].

Davidsson et al. [104] developed a new multifunctional BIPV/T design of solar window in Sweden, as shown in Fig. 33. The solar window consisted of solar thermal absorbers laminated with PV cells. The absorbers were built inside a common window while reflectors were placed behind the absorber to minimize the area of PV cell. They further developed annual energy performance simulation model, the simulations by this model showed that in contrast with a vertically installed flat PV panel, this design of solar window generated approximately 35% more electricity for same cell area. In comparison to a system with a single solar collector and PV modules, the solar window required more auxiliary energy, but the required auxiliary energy was less than an ordinary heating system without a solar collector [105].

This design of solar window brought a new way of integration of PV/T collector and shading device. However, there are limitations to its wide application due to the complicated structure and dissatisfactory visual perception from occupants. Since large fraction of solar energy enters into the indoor space, this design is more suitable for very cold climates where space heating is dominating.

3.5 Summery of researches on BIPV blinds

In general, studies on outdoor PV blinds and middle PV blinds exceed the number of studies on indoor blinds. The studies reviewed are shown in Table 6, Table 7, and Table 8.

Table 7 Summary of researches of outdoor PV blinds

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Bahr 2014 [93]	c-Si a-Si	Simulation	1) Thermal comfort 2) Visual comfort 3) Electricity generation	1）Introduced a systematic method to find the optimal parameters in the design of PV blinds.	A whole year	Abu Dhabi
Park et al. 2016 [94]	CIGS	Simulation	1) Techno-economic performance	1）Presenting a finite element model	A whole year	Seoul South Korea

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Vadiee et al. 2016 [97]	Not specified	Simulation and Experiment	1) Thermal energy performance 2) Electrical energy gain	1) The highest thermal and electrical performance was realized at 18° C in a TRNSYS simulation 2)Installing a solar blind system above the greenhouse roof is economic	A whole year	Shiraz Iran
Gao et al. 2018 [95]	Thin film Si	Simulation	1) Power generation 2) Non-glare daylighting	1) Maximize power generation and minimize glare during daylighting by obtaining the best rotation angles	A whole year	Shanghai et al. China
Taveres-Cachat et al. 2019 [92]	CIGS	Simulation	1) Thermal properties 2) Optical properties 3) Electric generation	1) The designs with smaller louvres numbers were more desirable 2) The energy converted could be improved by up to 10%	A whole year	Nordic
Meysam 2020[96]	Not specified	Simulation	1) thermal load 2) electricity generatio	1)The thermal load is reduced 2) The power generation is 70% higher.	A whole year	Iran

Table 8Summary of researches of middle PV blinds

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Kang et al. 2012 [99]	c-Si	Simulation	1) Electric harvesting efficiency	1) Improving electrical efficiency 2) Reducing the maximum temperature of PV modules	A whole year	Seoul South Korea
Koo et al. Jeong et al. 2017 [98] [100]	a-Si CIGS	Simulation	1) Energy self-sufficiency rate 2) Electricity generation	1) SPSB using CIGS-based PV panel and special two-axis tracking devices were superior to other systems	Assumed conditions; 6 August 2015	South Korea
Hong et al. 2017 [101]	CIGS	Simulation	1) Technical–economic performance	1) As the width of the PV panel increases, the AE Gunit from the BIPV tends to decrease	A whole year	Pusan South Korea
Luo et al. 2017, 2018 [102] [103]	a-Si, c-Si	Simulation and Experiment	1) SHGC and U-value 2) Power generation efficiency	1) Double glazed BIPV shading blinds could reach a higher SHGC and lower U-value in non-ventilation mode 2)The potential of energy saving of double skin windows with PV blinds could be higher	From Jun. to Sep. 2016; From Dec. 2015 to Feb. 2016	Changsha China

Table 9 Summary of researches of indoor PV blinds

Authors year	PV type	Approach	Performance focused	Main findings	Conditions	Locations
Davidsson et al. 2010, 2012 [104] [105]	Not specified	Simulation and Experiment	1) Electrical energy production 2) U-value	1) Generated approximately 35% more electricity for same cell area	From 2006 to 2008; A whole year	Lund Sweden

4 Conclusion and outlook

BIPV windows/shading blinds are promising technologies to have the function of conventional windows while providing other benefits such as shading and electricity generation. The electrical, thermal and optical performances of BIPV windows/shading blinds have received great attention in recent studies. Many studies have proved that the energy performance BIPV windows are excellent in summer and winter, hence the net electricity consumed in buildings can be reduced significantly. It is concluded that, in general, the photovoltaic window using silicon-based-solar cells have been widely studied due to mature and rapid technology advances. Hence they have high reliability, long lifespan, readily available raw materials and many other advantages. In recent years, thin film solar cells (such as cadmium telluride (CdTe), gallium arsenide (GaAs), and copper indium gallium selenium compounds (CIGS)) and new solar cells (such as dye sensitized solar cells (DSSCs), perovskite solar cells (PSCs), quantum dot solar cells (QDSCs), etc.) have been developed rapidly. The growing interest in BIPV systems has enhanced the overall development of photovoltaic cell technology, which has led to cost reductions that increase the feasibility of BIPV investments.

This paper analyzes the performance and applicability of BIPV components and systems with regards to the three performance indicators: heat transfer, lighting and power generation. The electrical performance of BIPV windows is influenced by a number of important factors such as shadow effect, ambient temperature, building orientation, as well as PV slope and climatic conditions. Researchers take many measures to reduce the operating temperature of the photovoltaic window (such as ventilation, shading, vacuum). The performance of single-layer photovoltaic window, double-layer photovoltaic window, vacuum photovoltaic window and louver photovoltaic window is reviewed. The BIPV system can be tailored to a variety of building projects and contribute to renewable energy systems.

As seen in the summary tables, experiment and simulation have been an important method of research in recent years. The advantage of the experiment is that a more intuitive and more accurate experimental data is obtained, which provides a more accurate data basis for the research and analysis of the BIPV window's heat transfer performance, lighting capacity and power output. Simulation software on the other hand can overcome the limitation of the traditional experiment and easily change the configuration of the system and the choice of the region. TRNSYS, CFD and EnergyPlus are currently the most commonly used software to study the BIPV window

However, some limitations have been identified through this literature review. The following issues are proposed for future research:

1) The total area of façades is usually much larger compared to roofs, which provides a chance to install more PV panels hence to produce more electricity. However, the solar irradiance on the vertical façades is usually only a half or even less than a half of the solar irradiance on the roof, which will significantly reduce the electricity output for unit cell

area. In addition, vertical windows are more likely to be shaded by peripheral buildings, which further affects the electrical and thermal performance of BIPV windows. For buildings in urban environments, shading by peripheral buildings are inevitable, hence shading impact must be taken into account in evaluation the energy performance and cost-effectiveness of BIPV windows.

2) Presently, the cover ratios of the BIPV windows are usually low in order to retain the necessary visual light transmittance. This further reduces the total electricity production per square meter. The visual perception of BIPV windows yet does not meet the aesthetic requirements of many architects and occupants. High visual light transmittance is the basic requirement of windows. Therefore, much more efforts should be taken to increase the visual light transmittance in future developments.

3) Many studies have investigated by experiments and/or simulations the energy performance of various BIPV windows in buildings located in hot climate whereas fewer studies have been conducted for buildings in other climates. The overall energy performance and influence on building energy consumption in various typical climates (hot, cold, temperate, strong or weak solar irradiation) for all types of BIPV windows/blinds should be further studied.

4) The optical, electrical and thermal performance of various individual BIPV windows has not been sufficiently studied. Particularly the dependence of VLT, SHGC and electrical efficiency on angle and spectrum of solar radiation coupled with the aging problems require further research.

5) Because the electricity output is low due to low solar irradiation and low cover ratio, many researches indicate that the major contribution of BIPV windows is reduction of energy consumption for heating/cooling and daylighting. However, there are many widely-used advanced glazing technologies, such as low-e coating, built-in louvers double pane glazing, vacuum double glazing and so on. The overall energy performance and cost-effectiveness of BIPV windows should be compared with these advanced glazing technologies in various typical climates (hot, cold, temperate, strong or weak solar irradiation) for all types of BIPV windows. The electricity production of BIPV window is the distinguished feature from other window technologies. Without sufficient electricity production, BIPV windows are difficult to compete with other advanced window technologies. High electrical efficiency and low cost are the keys to the success and wide application of BIPV windows. Therefore, much more efforts should be taken to improve the electrical efficiency and reduce cost in future developments.

6) Compared to BIPV windows, the BIPV blinds provide more flexibility to adjust the visual effect, hence a variation in the energy generation and solar heat gains is expected. The influence of occupants' behavior should be considered in future evaluation models of the electrical, thermal and optical performance of BIPV blinds.

Acknowledgments

The research is supported by the National Natural Science Foundation of China (Nos. 71974129).

References

[1] Yang T, Athienitis A. A review of research and developments of building-integrated photovoltaic-thermal (BIPVT) systems. Renewable and Sustainable Energy Reviews 2016; 66: 886-912.

[2] Skandalos N, Karamanis D. PV glazing technologies. Renewable and Sustainable Energy Reviews 2015; 49:306-322.

[3] Olivieri L, Caama ~no-Martín E. Energy saving potential of semi-transparent photovoltaic elements for building integration. Energy 2014; 76: 52-583.

[4] Chow T, Qiu Z, Li C. Potential application of "see-through" solar cells in ventilated glazing in Hong Kong. Solar Energy Materials & Solar Cells 2009; 93: 230-238.

[5] Danny H, Tony N, Wilco W. Energy and cost analysis of semi-transparent photovoltaic in office buildings. Applied Energy2009; 86:722-729.

[6] Lu L, Law M. Overall energy performance of semi-transparent single-glazed photovoltaic (PV) window for a typical office in Hong Kong2013; 49:250-254

[7] Chen F, Wittkopf S, Ng P, Du H. Solar heat gain coefficient measurement of semi-transparent photovoltaic modules with indoor calorimetric hot box and solar simulator. Energy and Buildings 2012; 53: 74-84.

[8] Cuce E, Young C, Riffat S. Thermal performance investigation of heat insulation solar glass: A comparative experimental study. Energy and Buildings2015;86:595-600.

[9] Peng J, Lu L, Yang H, Ma T. Comparative study of the thermal and power performances of a semi-transparent photovoltaic façade under different ventilation modes. Applied Energy 2015; 138: 572-583.

[10] Peng J, Lu L, Yang H. An experimental study of the thermal performance of a novel photovoltaic double-skin facade in Hong Kong. Solar Energy 2013;97: 293-304.

[11] Yang S, Cannavale A, Prasad D, Sproul A, Fiorito F. Numerical simulation study of BIPV/T double-skin facade for various climate zones in Australia: Effects on indoor thermal comfort. Building Simulation 2019; 12(1): 51-67.

[12] Ng P, Mithraratne N, Kua H. Energy analysis of semi-transparent BIPV in Singapore buildings. Energy and Buildings 2013; 66: 274-281.

[13] Baljit S, Chan H, Sopian K. Review of building integrated applications of photovoltaic and solar thermal systems. Journal of Cleaner Production 2016; 137: 677-689.

[14] Agathokleous R, Kalogirou S. Double skin facades (DSF) and building integrated photovoltaics (BIPV): A review of configurations and heat transfer characteristics. Renewable Energy 2016; 89: 743-756.

[15] Debbarma M, Sudhakar K, Baredar P. Thermal modeling, exergy analysis, performance of BIPV and BIPVT: A review. Renewable and Sustainable Energy Reviews 2017; 73: 1276-1288.

[16] Debbarma M, Sudhakar K, Baredar P. Comparison of BIPV and BIPVT: A review. Resource-Efficient Technologies 2017;3:263-271.

[17] Sarkar D, Kumar A, Sadhu P. A Survey on Development and Recent Trends of Renewable Energy Generation from BIPV Systems. IETE Technical Review 2019; DOI: 10.1080/02564602.2019.1598294.

[18] Lucchino E, Goia F, Lobaccaro G, Chaudhary G. Modelling of Double Skin Facades. Building Simulation 2019; 12(1): 3-27.

[19] Zhang X, Lau S, Lau S, Zhao Y. Photovoltaic integrated shading devices (PVSDs): A review. Solar Energy 2018; 170: 947-968.

[20] Shukla A, Sudhakar K, Baredar P, Mamat R. BIPV based sustainable building in South Asian countries. Solar Energy 2018 170: 1162-1170.

[21] Saretta E, Caputo P, Frontini F. A review study about energy renovation of building facades with BIPV in urban environment. Sustainable Cities and Society 2019; 44: 343-355.

[22] Biyik E, Araz M, Hepbasli A. A key review of building integrated photovoltaic (BIPV) systems. Engineering Science and Technology, an International Journal 2017;20:833-858.

[23] Ghosh A. Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building’s skin: A comprehensive review. Journal of Cleaner Production 2020;276:123343.

[24] Tilmann E, Erban C, Heinrich M. Review of technological design options for building integrated photovoltaics (BIPV). Energy & Buildings 2021;231:110381.

[25] Yu G, Yang H, Yan Z. A review of designs and performance of façade-based building integrated photovoltaic-thermal (BIPVT) systems. Applied Thermal Engineering 2021;182:116081.

[26] Cannavale A, Ierardi L, Hörantner M, Eperon G, Snaith H, Ayr U, Martellotta F. Improving energy and visual performance in offices using building integrated perovskite-based solar cells- A case study in Southern Italy. Applied Energy 2017;

205: 834-846.

[27] Chen X, Yang H, Peng J. Energy optimization of high-rise commercial buildings integrated with photovoltaic facades in urban context. Energy 2019; 172: 1-17.

[28] Chen X, Huang J, Yang H, Peng J. Approaching low-energy high-rise building by integrating passive architectural design with photovoltaic application. Journal of Cleaner Production 2019; 22: 313-330.

[29] Fung T, Yang H. Study on thermal performance of semi-transparent building-integrated photovoltaic glazings. Energy and Buildings 2008; 40(3): 341-350.

[30] Li D, Lam T, Chan W, Mak. A. Energy and cost analysis of semi-transparent photovoltaic in office buildings. Applied Energy 2009; 86(5): 722-729.

[31] Karthick A, Murugavel K, Kalaivani L, Babu U. Performance study of building integrated photovoltaic modules. Advances in Building Energy Research 2017; 12(2): 178-194.

[32] Karthick A, Murugavel K, Kalaivani L. Performance analysis of semitransparent photovoltaic module for skylights. Energy 2018; 162: 798-812.

[33] Peng J, Curcija D, Thanachareonkit A, Lee E, Goudey H, Selkowitz S. Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window. Applied Energy 2019; 242: 854-872.

[34] Elghamry R, Hassan H, Hawwash A. A parametric study on the impact of integrating solar cell panel at building envelope on its power, energy consumption, comfort conditions, and CO_2 emissions. Journal of Cleaner Production 2019:1-15.

[35] Yang J, Cheng Y, Jia J, Du Z, Shi Z, Han J. The impact of indoor air distributions on the thermal performance of a single layer semi-transparent photovoltaic facade. Building Simulation 2019; 12(1): 69-77.

[36] Alrashidi H, Ghosh A, Issa W, Sellami N, Mallick T, Sundaram S. Thermal performance of semitransparent CdTe BIPV window at temperate climate. Solar Energy 2020; 195: 536-543.

[37] Alrashidi H, Issa W, Sellami N, Ghosh A, Mallick T, Sundaram S. Performance assessment of cadmium telluride-based semi-transparent glazing for power saving in façade buildings. Energy ＆ Buildings 2020; 215: 109585.

[38] Fan Z, Yang Z, Yang L. Daylight performance assessment of atrium skylight with integrated semi-transparent photovoltaic for different climate zones in China. Building and Environment 2021;190:170299.

[39] Yang K, Lee W, Jeon J. Controlling the visibility of embedded silicon solar cells in building-integrated photovoltaic windows using surface structure modification and metal-oxide back coating. Solar Energy 2020;197:99-104.

[40] Xuan Q, Li G, Lu Y. Daylighting utilization and uniformity comparison for a concentrator-photovoltaic window in energy saving application on the building. Energy 2021;214:118932.

[41] Toledo C, Vicente R, Abad J. Thermal performance of PV modules as building elements: Analysis under real operating conditions of different technologies. Energy & Buildings 2020;223:110087.

[42] Chae Y, Kim J, Park H, Shin B. Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells. Applied Energy 2014; 129: 217-227.

[43] Do S, Shin M, Baltazar J, Kim J. Energy benefits from semi-transparent BIPV window and daylight-dimming systems for IECC code-compliance residential buildings in hot and humid climates. Solar Energy 2017; 155: 291-303.

[44] Ng P, Mithraratne N. Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics. Renewable and Sustainable Energy Reviews 2014; 31: 736-745.

[45] Lu L, Law K. Overall energy performance of semi-transparent single-glazed photovoltaic (PV) window for a typical office in Hong Kong. Renewable Energy 2013; 49: 250-254.

[46] Liao W, Xu S. Energy performance comparison among see-through amorphous-silicon PV (photovoltaic) glazings and traditional glazings under different architectural conditions in China. Energy 2015; 83: 267-275.

[47] Zhang W, Lu L, Peng J, Song A. Comparison of the overall energy performance of semi-transparent photovoltaic windows and common energy-efficient windows in Hong Kong. Energy and Buildings 2016; 128: 511-518.

[48] Olivieri L, Caamaño-Martín E, Moralejo-Vázquez F, Martín-Chivelet N, Olivieri F, Neila-Gonzalez F. Energy saving potential of semi-transparent photovoltaic elements for building integration. Energy 2014; 76: 572-583.

[49] Baenas T, Machado M. On the analytical calculation of the solar heat gain coefficient of a BIPV module. Energy and Buildings 2017; 151: 146-156.

[50] He Y, Schnabel M. An approach for daylight calculation of a building integrated photovoltaic (BIPV) Façade. Architectural Science Review 2018; 61(4): 226-233.

[51] Cannavale A, Hörantner M, Eperon G, Snaith H, Fiorito F, Ayr U, Martellotta F. Building integration of semitransparent perovskite-based solar cells: Energy performance and visual comfort assessment. Applied Energy 2017; 194: 94-107.

[52] Yang J, Jo H, Choi S, Kang D, Kwon J. Adoption of wide-bandgap microcrystalline silicon oxide and dual buffers for semitransparent solar cells in building-integrated photovoltaic window system. Journal of Materials Science & Technology 2019; 35(8): 1563-1569.

[53] Tsai C, Tsai C. See-through, light-through, and color modules for large-area tandem amorphous/microcrystalline silicon thin-film solar modules: Technology development and practical considerations for building-integrated photovoltaic applications. Renewable Energy 2020; 145: 2637-2646.

[54] Ghosh A, Bhandari S, Sundaram S, Mallick T. Carbon counter electrode mesoscopic ambient processed & characterised perovskite for adaptive BIPV fenestration. Renewable Energy 2020; 145: 2151-2158.

[55] Han J, Lu L, Yang H. Numerical evaluation of the mixed convective heat transfer in a double-pane window integrated with see-through a-Si PV cells with low-e coatings. Applied Energy 2010; 87: 3431-3437.

[56] Yoon J, Shim S, An Y, Lee K. An experimental study on the annual surface temperature characteristics of amorphous silicon BIPV window. Energy and Buildings 2013; 62: 166-175.

[57] Lee H, Yoon J. Power performance analysis of a transparent DSSC BIPV window based on 2 year measurement data in a full-scale mock-up. Applied Energy 2018; 225: 1013-1021.

[58] Chen M, Zhang W, Xie L, Ni Z, Wei Q, Wang W, Tian H. Experimental and numerical evaluation of the crystalline silicon PVwindow under the climatic conditions in southwest China. Energy 2019; 183: 584-598.

[59] Mesloub A, Albaqawy G, Kandar M. The Optimum Performance of Building Integrated Photovoltaic (BIPV) Windows Under a Semi-Arid Climate in Algerian Office Buildings. Sustainability 2020; 12, 1654; doi:10.3390/su12041654.

[60] Chung M, Park B, Choi E. Performance level criteria for semi-transparent photovoltaic windows based on dye-sensitized solar cells. Solar Energy Materials and Solar Cells 2020;217:110683.

[61] Khalid M, Shanks V, Ghosh A. Temperature regulation of concentrating photovoltaic window using argon gas and polymer dispersed liquid crystal films. Renewable Energy 2021;164:96-108.

[62] Miyazaki T, Akisawa A, Kashiwagi T. Energy savings of office buildings by the use of semi-transparent solar cells for windows. Renewable Energy 2005; 30: 281-304.

[63] Lee H, Yoon J, Kim S, Shin U. Operational power performance of south-facing vertical BIPV window system applied in office building. Solar Energy 2017; 145: 66-77.

[64] Sun Y, Shanks K, Baig H, Zhang W, Hao X, Li Y, He B, Wilson R, Liu H, Sundaram S, Zhang J, Xie L, Mallick T, Wu Y. Integrated semi-transparent cadmium telluride photovoltaic glazing into windows- Energy and daylight performance for different architecture designs. Applied Energy 2018; 231: 972-984

[65] Cheng Y, Gao M, Jia J, Sun Y, Fan Y, Yu M. An optimal and comparison study on daylight and overall energy performance of double-glazed photovoltaics windows in cold region of China. Energy 2019; 170: 356-366.

[66] Ioannidis Z, Rounis E, Athienitis A. Double skin façade integrating semi-transparent photovoltaics: Experimental study on forced convection and heat recovery. Applied Energy 2020;278:115647

[67] Wong P, Shimoda Y, Nonaka M, Inoue M, Mizuno M. Semi-transparent PV- Thermal performance, power generation, daylight modelling and energy saving potential in a residential application. Renewable Energy 2008; 33: 1024-1036.

[68] James P, Jentsch M, Bahaj A. Quantifying the added value of BiPV as a shading solution in atria. Solar Energy 2009; 83: 220-231.

[69] Cook M, Al-Hallaj S. Film-based optical elements for passive solar concentration in a BIPV window application. Solar Energy 2019; 180: 226-242.

[70] Chow T, Fong K, Lin W, Chan A. Performance evaluation of a PV ventilated window applying to office building of Hong Kong. Energy and Buildings 2007; 39: 643-650.

[71] He W, Zhang Y, Sun W, Hou J, Jiang Q, Ji, J. Experimental and numerical investigation on the performance of amorphous silicon photovoltaics window in East China. Building and Environment 2011; 46: 363-369.

[72] Cipriano J, Houzeaux G, Chemisana D, Lodi C, Martí-Herrero J. Numerical analysis of the most appropriate heat transfer correlations for free ventilated double skin photovoltaic façades. Applied Thermal Engineering 2013; 57: 57-68.

[73] Gaillard L, Giroux-Julien S, Me´ne´zo C, Pabiou H. Experimental evaluation of a naturally ventilated PV double-skin building envelope in real operating conditions. Solar Energy 2014;103: 223-241.

[74] Chatzipanagi A, Frontini F, Virtuani A. A demonstrative Building Integrated Photovoltaic installation. Applied Energy 2016; 173: 1-12.

[75] Han J, Lu L, Peng P, Yang H. Performance of ventilated double-sided PV façade compared with conventional clear glass façade. Energy and Buildings 2013; 56: 204-209.

[76] Barbosa S, Carlo J, Ip K. Energy performance of PV integrated office buildings with fan-assisted double skin façades under tropical climates. International Journal of Green Energy 2019; 16(13): 1061-1072.

[77] Jia J, Gao F, Cheng Y. A comparative study on thermoelectric performances and energy savings of double-skin photovoltaic windows in cold regions of China. Solar Energy 2020;206:464-472.

[78] Guo W, Kong L, Chow T. Energy performance of photovoltaic (PV) windows under typical climates of China in terms of transmittance and orientation. Energy 2020;213:118794

[79] Yang S, Cannavale A, Carlo A. Performance assessment of BIPV/T double-skin façade for various climate zones in Australia: Effects on energy consumption. Solar Energy 2020;199:377-399.

[80] Shakouri M, Ghadamian H, Noorpoor A. Quasi-dynamic energy performance analysis of building integrated photovoltaic thermal double skin façade for middle eastern climate case. Applied Thermal Engineering 2020;179:115724

[81] Preet S, Sharma M, Mathur J. Performance evaluation of photovoltaic double-skin facade with forced ventilation in the composite climate. Journal of Building Engineering 2020;32:101733

[82] Wang Y, Chen Y, Li C. Energy performance and applicability of naturally ventilated double skin façade with Venetian blinds in Yangtze River Area. Sustainable Cities and Society 2020;61:102348.

[83] Juliana E, Hooff T, Saelens D. Understanding the behaviour of naturally-ventilated BIPV modules: A sensitivity analysis. Renewable Energy 2020;161:133-148.

[84] Chialastri A, Isaacson M. Performance and optimization of a BIPVT solar air collector for building fenestration applications. Energy and Buildings 2017; 150: 200-210.

[85] Charron R, Athienitis A. Optimization of the performance of double-façades with integrated photovoltaic panels and motorized blinds. Solar Energy 2006; 80: 482-491.

[86] Huang J, Chen X, Yang H, Zhang W. Numerical investigation of a novel vacuum photovoltaic curtain wall and integrated

optimization of photovoltaic envelope systems. Applied Energy 2018; 229: 1048-1060.
[87] Qiu C, Yang H, Zhang W. Investigation on the energy performance of a novel semi-transparent BIPV system integrated with vacuum glazing. Building Simulation 2019; 12: 29-39.
[88] Ghosh A, Sarmah N, Sundaram S, Mallick T. Numerical studies of thermal comfort for semi-transparent building integrated photovoltaic (BIPV)-vacuum glazing system. Solar Energy 2019; 190: 608-616.
[89] Jarimi H, Lv Q, Omar R, Zhang S, Riffat S. Design, mathematical modelling and experimental investigation of vacuum insulated semi-transparent thin-film photovoltaic (PV) glazing. Journal of Building Engineering 2020; 31: 101430.
[90] Huang J, Chen X, Peng J. Modelling analyses of the thermal property and heat transfer performance of a novel compositive PV vacuum glazing. Renewable Energy 2021;163:1238-1252.
[91] Radwan A, Katsura T, Memon S. Thermal and electrical performances of semi-transparent photovoltaic glazing integrated with translucent vacuum insulation panel and vacuum glazing. Energy Conversion and Management 2020;215:112920.
[92] Taveres-Cachat E, Lobaccaro G, Goia F, Chaudhary G. A methodology to improve the performance of PV integrated shading devices using multi-objective optimization. Applied Energy 2019; 247: 731-744.
[93] Bahr W. A comprehensive assessment methodology of the building integrated photovoltaic blind system. Energy and Buildings 2014; 82: 703-708.
[94] Park H, Koo C, Hong T, Oh J, Jeong K. A finite element model for estimating the techno-economic performance of the building-integrated photovoltaic blind. Applied Energy 2016; 179: 211-227.
[95] Gao Y, Dong J, Isabella O, Santbergen R, Tan H, Zeman M, Zhang G. A photovoltaic window with sun-tracking shading elements towards maximum power generation and non-glare daylighting. Applied Energy 2018; 228: 1454-1472.
[96] Meysam A. Optimum design of building integrated PV module as a movable shading device. Sustainable Cities and Society 2020;62:102368.
[97] Vadiee A, Yaghoubi M, Martin V, Bazargan-Lari Y. Energy analysis of solar blind system concept using energy system modelling. Solar Energy 2016; 139: 297-308.
[98] Koo C, Hong T, Jeong K, Ban C, Oh J. Development of the smart photovoltaic system blind and its impact on net-zero energy solar buildings using technical-economic-political analyses. Energy 2017; 124: 382-396.
[99] Kang S, Hwang T, Kim J. Theoretical analysis of the blinds integrated photovoltaic modules. Energy and Buildings 2012; 46: 86-91.
[100] Jeong K, Hong T, Koo C, Oh J, Lee M, Kim J. A Prototype Design and Development of the Smart Photovoltaic System Blind Considering the Photovoltaic Panel, Tracking System, and Monitoring System. Applied Sciences 2017; 7(10).
[101] Hong T, Koo C, Oh J, Jeong K. Nonlinearity analysis of the shading effect on the technical-economic performance of the building-integrated photovoltaic blind. Applied Energy 2017; 194: 467-480.
[102] Luo Y, Zhang L, Wang X, Xie L, Liu Z, Wu J, Zhang Y, He X. A comparative study on thermal performance evaluation of a new double skin façade system integrated with photovoltaic blinds. Applied Energy 2017; 199: 281-293.
[103] Luo Y, Zhang L, Liu Z, Xie L, Wang X, Wu J. Experimental study and performance evaluation of a PV-blind embedded double skin façade in winter season. Energy 2018; 165: 326-342.
[104] Davidsson H, Perers B, Karlsson B. Performance of a multifunctional PVT hybrid solar window. Solar Energy 2010; 84: 365-372.
[105] Davidsson H, Perers B, Karlsson B. System analysis of a multifunctional PVT hybrid solar window. Solar Energy 2012; 86: 903-910.

Abbreviations	
BIPV building integrated photovoltaic	SHGC solar heat gain coefficient
U heat transfer coefficient(W/m^2 K)	VLT visual light transmittance
PVSDs photovoltaic integrated shading devices	STPV semi-transparent photovoltaic
DSSCs dye-sensitized solar cells	MV mixed ventilation

DV displacement ventilation	c-Si crystalline silicon
TF thin film	G-BBS glass with black backing
GC-BBS coated glass with black backing	EG-BBS etching glass with black backing
EGC-BBS etching coated glass with black backing	
CPVW concentrator PV window	STPVW semi-transparent photovoltaic window
PDLC polymer dispersed liquid crystal	DSF double skin facades
DS-STPV double-skin semitransparent photovoltaic	
NVDPV natural ventilated double photovoltaic	
BIPV/T-DSF building integrated photovoltaic thermal double skin façade	
GPV photovoltaic glazing	VG vacuum glazing
GVIP translucent vacuum insulation panel	SG single glazing
VGPV semi-transparent photovoltaic with vacuum glazing	
VIPPV semi-transparent photovoltaic with translucent vacuum insulation panel	
a- Si amorphous silicon	VPV vacuum photovoltaic
mono-Si monocrystalline silicon	poly-Si polycrystalline silicon
CIGS copper indium gallium selenide	CdTe cadmium telluride
μc-Si micromorph silicon	DSSC dyesensitized solar cell
SPSB Smart Photovoltaic System Blind	DSF double skin facades

993