Journal of Building Engineering 79 (2023) 107950

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Do Building Integrated Photovoltaic (BIPV) windows propose a promising solution for the transition toward zero energy buildings? A review

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ARTICLE INFO

Keywords:
BIPV
Windows
Conventional
Performance
Comparison
EV charging
Orientation
Koppen climates
Application
Limitations

ABSTRACT

BIPV windows are the most suitable alternative to conventional windows currently available today. They offer thermal insulation and can generate electricity from the embedded solar cells within their structure while also maintaining the practicality of conventional windows. Different types of BIPV windows will be reviewed in this paper, followed by an assessment of the energy-saving potential, optimal orientation, solar cell technology, Koppen climate impact, and application for each type of BIPV window. From the findings, it was evident that ventilated double BIPV windows had the highest energy-saving potential as well as being the BIPV system that can adapt the most to different Koppen climates. The optimal orientation was the south-facing façade which consumed the least amount of energy while also generating the highest amount of electricity from PV. Amorphous silicon is the most popular solar cell technology in BIPV studies due to its performance however they do have disadvantages. Application of BIPV windows includes BIPV-PCM systems and switchable glazing for smart window technology. Large-scale development integrated with BIPV windows can have a huge influence on meeting ZEB targets. Limitations in the study were observed by limited studies on vacuum BIPV glazing, and limited studies on a variety of Koppen climate classes.

1. Introduction

In 2015, the United Nations (UN) Sustainable Development Goals for 2030 were announced as a response to global sustainability issues [1]. For this, the UN set out 17 universal goals with guidelines on how they can be achieved by 2030 [2]. Goals 11 and 13 highlight the need to create sustainable cities and communities and to combat the impacts of climate change, which can be tackled by reducing global energy consumption rates [3,4]. There has been a growing incentive to reduce energy consumption in buildings as a result of the total contribution of buildings to global energy use [5,6], reported as 30 % by the International Energy Agency (IEA) [7], as revealed in Fig. 1. In buildings, 30 % of the total heat loss occurs from poor insulation within the building envelope and thermal bridges [8–10]. Windows are the weakest thermal insulative component within the building [11,12], and recent high-rise building designs have seen an increase in the window-to-wall ratios [13], alluding to the point that windows will continue to pose a threat to energy consumption and therefore the total greenhouse gas (GHG) emissions if it is not addressed [14–17].

Photovoltaic (PV) cells embedded in windows are a potential technique to reduce energy consumption by reducing the cooling demand while also generating power in buildings [18–20]. Building Integrated Photovoltaic (BIPV) windows can completely replace

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https://doi.org/10.1016/j.jobe.2023.107950
Received 26 July 2023; Received in revised form 3 October 2023; Accepted 13 October 2023

conventional windows as they are a combination of PV modules and conventional windows [21,22]. Compared to conventional windows, the introduction of BIPV windows can provide daylighting comfort by reducing glare within indoor environments [23,24].

BIPV windows' influence is generally measured using three categories: the amount of electricity it produces, the heat gain/loss within the window, and the optical characteristics [25,26]. Electrical generation is measured by the amount of power generated from the PV solar cell [27,28]. The thermal performance is measured by the overall heat transfer coefficient or thermal transmittance (*U*-value) which quantifies the heat loss that occurs from a window due to the difference in temperature between the internal and external environment [29,30]. And is also measured by the solar heat gain coefficient or solar energy transmittance (g-value) that quantifies the incident solar energy or energy gain through the window [31,32]. Hence, the terms solar heat gain coefficient (SHGC) and *U*-value are both considered when determining the impact on the energy use of the heating ventilation and air conditioning (HVAC) components [33,34]. The metrics for quantifying the daylight performance of PV windows include glare, useful daylight illuminance, illuminance uniform, colour rendering index (CRI), and Correlated colour temperature (CCT) which all have a key role to play in the views from interior to exterior [35–37].

Different approaches were taken by researchers to review the development, performance, and applications of BIPV windows. The electricity generation and the optical, and thermal characteristics of BIPV windows were reviewed by G. Yu et al. [38], along with a discussion on BIPV blinds, detailing the development and performance of these technologies. Singh D et al. [39] looked at a few parameters that influence the design and performance of building applied photovoltaics (BAPV)/BIPV systems. Performing an investigation into the performance of BIPV windows at different façade orientations regarding the incident solar radiation and energy demand. The ways for incorporating building-integrated/attached photovoltaics are discussed by Ghosh [40]. Regarding BIPV windows specifically, a review was performed of the impact that different solar cell technologies would have on the daylighting performance and commented on the ideal solar cells for high transmission results in BIPV window applications. While also examining the challenges and prospects of BIPV windows. The state of the BIPV/BAPV system in India is examined by Reddy P et al. [41]. Comparing the performance of different BIPV systems regarding their impact on reducing the overall energy consumption of the building, it was later realised that the incorporation of a BIPV window system is likely to be the best BIPV solution for reducing the building's HVAC load in the Indian environment.

Shukla A.K. et al. [42] introduced the properties, testing standards, and international guidelines of the industry-leading BIPV products, highlighting their use in roofs, façades, and windows. The evaluation provides a particular focus on solar PV efficiency, open circuit voltage (Voc), short circuit current (Isc), Pmax, and fill factor. A review of the BIPV module's life cycle also was made by looking at the energy payback period and GHG emissions. The review by Sun J. et al. [43]. gives an insight into the development of different types of semi-transparent solar cell technologies and the benefit that integrating these technologies would have as BIPV windows. The discussion considers the lighting load requirements and electricity savings of BIPV windows using semi-transparent solar cell technology under different building environments (office, residential, multi-zoned). Skandalos et al. [44] reviewed the achievements of semi-transparent PV windows in reducing a building's overall energy consumption and the impact these technologies had on human comfort regarding visual comfort and indoor environmental quality.

Chae et al. [45] assessed the overall energy performance of BIPV windows in a mid-sized commercial building under a range of

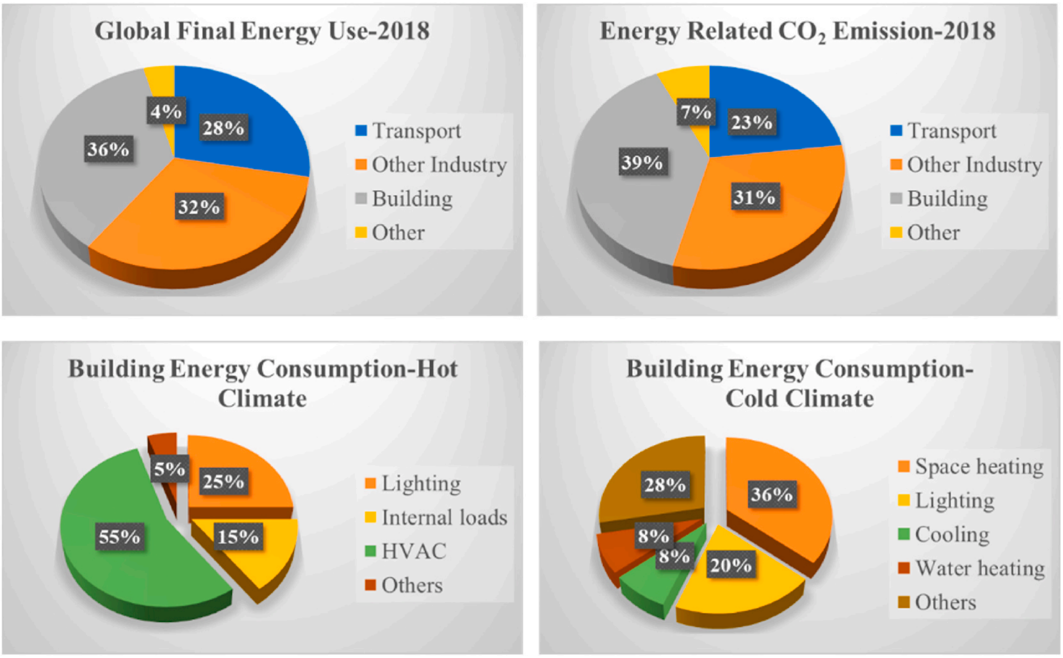


Fig. 1. a) Global final energy consumption by sector and building energy consumption in hot and cold climatic conditions. Redrawn from [7].

climate conditions. For each scenario, the study determined the optical, thermal, and electrical characteristics of the systems, as well as computing the heating/cooling demand, and GHG emission rates. Introducing Dye-Sensitized Solar Cells (DSSCs) as an alternative solar cell material in BIPV windows was reviewed by Chung et al. [46]. The study aimed to provide a clear indication of the building energy performance and the environmental conditions of DSSCs integrated into BIPV windows for architects looking to employ zero-energy buildings (ZEBs). The findings of the study revealed that compared to a conventional silicon solar cell, the power generation was significantly reduced due to the power conversion efficiency of DSSCs, however, DSSCs reduced the overall cooling demand as they performed well at blocking the penetration of sunlight. Likewise, the visual comfort of DSSCs was expressed owing to the reduction in glare. In another work, DSSC's performance after two years of ambient exposure showed potential application for BIPV integration [47].

Previous studies mainly include the building energy consumption, the application, and the development of BIPV windows, while there are no studies that identify whether BIPV windows are the solution for transitioning towards ZEBs. Thus, this paper looks to review the energy-saving potential of different BIPV window technologies and their influence under different Koppen climates, with a prospectus on how this energy-saving can be used to charge an electric vehicle (EV). This is then followed by a review of the application of BIPV windows in smart window technology and then the paper will conclude with the future of BIPV window technology, specifically highlighting the challenges and its future potential. Section 2 of this paper will provide a literature review of all the experiments on BIPV windows, specifically, studies that derived energy savings from a building energy performance assessment. Section 3 of the paper will then discuss these energy savings as to what they say about the performance of different BIPV types, the climatic impact,

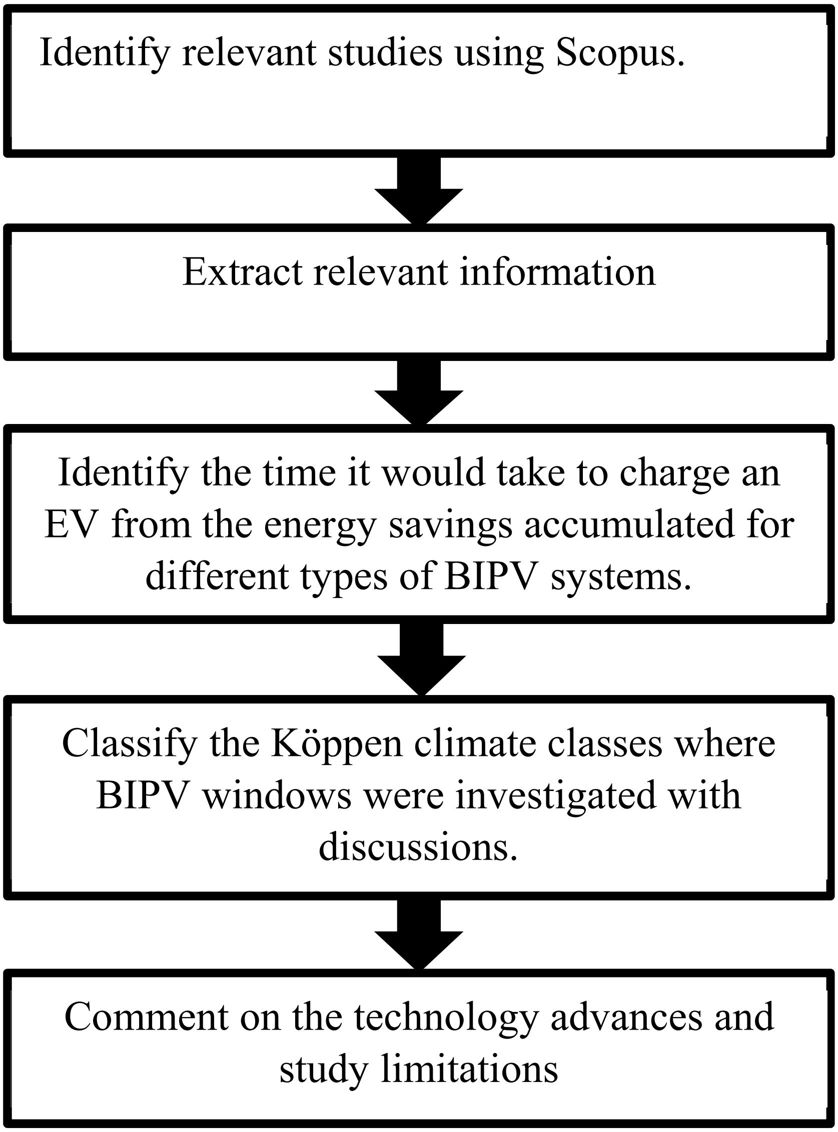


Fig. 2. Flow diagram of the process for the review paper.

Table 1
Summary of research findings from literature review.

Author	BIPV Window Type	Orientation	Climate	Solar cell technology	Building model	Energy savings
Alrashidi et al. [48]	Single glazing	S & SW	Penryn, UK	CdTe	University building	260 kWh/yr compared to conventional single glazing
Do et al. [49]	Single glazing	S, E, N & W	Houston, USA	Not specified	Residential buildings	6.25 kWh/yr to 16.08 kWh/yr compared to conventional double glazing
Olivieri et al. [50]	Single glazing	S	Madrid, Spain	a-Si	Typical office room	2940 kWh/yr compared to conventional glass
Ng et al. [51]	Single glazing	S, E, N & W	Singapore	μc-Si	Typical office room	3920 kWh/yr compared to single clear glazing, and 2940 kWh/yr compared to double clear glazing
Ng et al. [51]	Non-ventilated double glazing	S, E, N & W	Singapore	a-Si	Typical office room	7840 kWh/yr compared to single clear glazing, and 5880 kWh/yr compared to double clear glazing
Zhang et al. [52]	Single glazing	E, ESE, SE, SSE, S, SSW, SW, WSW, W	Hong Kong	a-Si	Typical office room	3920 kWh/yr compared to conventional double glazing
Chae et al. [45]	Single glazing	S, E, N & W	Miami, Phoenix, Los Angeles, Baltimore, Chicago, and Duluth	a-Si	Midsized commercial building	Cooling load energy savings occurred at all climates, however only Miami, Phoenix and Los Angeles incurred heating load savings
Lu and Law [53]	Single glazing	S, SW, SE, E, W	Hong Kong	Not specified	Typical office room	900 kWh/yr and 1300 kWh/yr for water-cooled and air-cooled air-conditioning systems were around
Liao and Xu [54]	Single glazing	Not specified	Central China	a-Si	Typical office room	3724 kWh/yr compared to single clear glazing, and 2881.2 kWh/yr compared to double clear glazing
Mesloub et al. [55]	Non-ventilated double glazing	S, E, N & W	Tebessa, Algeria	Not specified	Typical office room	17,640 kWh/yr for south-oriented BIPV window compared to base model
Cheng et al. [56]	Non-ventilated double glazing	N, NE, NW, SW, SE, S, E, W	Taiyuan University of Technology, China	a-Si	Typical office room	2861.6 kWh/yr compared to single clear glazing, and 1411.2 kWh/yr compared to double clear glazing
T.Miyazaki [57]	Non-ventilated double glazing	NW, NE, SW, SE	Tokyo, Japan	a-Si	Typical office room	1881.6 kWh/yr compared to single clear glazing, and 1352.4 kWh/yr compared to double clear glazing
Sun et al. [58]	Non-ventilated double glazing	S	Chengdu, Chongqing, Guiyang Location, Kunming, Lhasa	Thin film CdTe	Typical office room	Compared to conventional double glazing, the energy savings were 600, 532, 485, 889, and 984 kWh/yr in Chengdu, Chongqing, Guiyang Location, Kunming, and Lhasa, respectively.
Chow et al. [59]	Ventilated double glazing	S, SE, SW	Hong Kong	a-Si	Typical office room	725, 690 and 660 kWh/yr, for the south, southwest, and southeast orientations.
Chow et al. [60]	Ventilated double glazing	S, E, N, W and Central	Hong Kong	a-Si	Typical office room	25,087 kWh/yr compared to conventional single glazing
Barbosa et al. [61]	Ventilated double glazing	N, S	Piracicaba, Sao Paulo, Brasilia, Niteroi, Campo Grande, Cuiaba, Rio de Janeiro	a-Si	Typical office room	25,480, 19,600, 29,400, 30,380, 37,240, 29,400, and 31,360 kWh/yr for the seven tropical climates in Brazil compared to full air conditioning
Jia et al. [62]	Ventilated double glazing	S	Taiyuan, China	a-Si	University building	284.7 kWh/yr and 318.3 kWh/yr compared to the non-ventilated and internal circulation options.
Yang et al. [63]	Ventilated double glazing	N	Darwin, Sydney, and Canberra in Australia	a-Si, DSSC, Perovskite solar cells	Typical office room	34.1 %, 86 % and 106 % per year in Darwin, Sydney and Canberra, respectively compared to conventional technologies, also Perovskite solar cells achieved optimal energy savings.

(*continued on next page*)

Table 1 (*continued*)

Author	BIPV Window Type	Orientation	Climate	Solar cell technology	Building model	Energy savings
Guo et al. [64]	Ventilated double glazing	S, E, N & W	Harbin, Beijing, Shanghai, Shenzhen, and Lhasa	a-Si	Typical office room	75,000, 70,000, 35,000, 80,000, and 20,000 kWh/yr for the five climates compared to single clear glazing. And compared to double clear glazing, the energy savings were approximately 15,000, 30,000, 10,000, 50,000, and 15,000 kWh/yr, respectively.
Huang et al. [65]	Vacuum glazing	S, E, N & W	Hong Kong and Harbin	monocrystalline silicon	Typical office room	65,000 kWh/yr and 60,000 kWh/yr compared to NDP glazing for Hong Kong and Harbin climates
Qiu et al. [66]	Vacuum glazing	S, E, N & W	Hong Kong	a-Si	Typical office room	90,000 kWh/yr and 10,000 kWh/yr compared to traditional single and double clear glazing,

orientation, solar cell technology, application of BIPV, and the limitations in the study.

2. Method and literature review

This section will provide a literature review of all the studies detailing the impact of different BIPV windows on building energy performance. For different combinations of complimentary search phrases, the online database 'Scopus' is utilised to discover the literature. For the purpose of this paper, Scopus tracked 240 documents for 'BIPV window', and 104 documents for 'BIPV windows' and 'overall energy performance'. Out of the 104 documents, only 21 provided relevant information regarding the energy savings from the BIPV system, the remaining documents discussed the heat gain/loss in terms of SHGC and *U*-value or focused on the thermal comfort and indoor environment aspect. 2005 saw the first year where major publications related to BIPV windows started, the following review covers the period from 2005 to 2022. Fig. 2 highlights a flow diagram of what information is being extracted from the selected publications and how that information will be discussed in section 3.

The literature review is summarized in Table 1, which lists the literature review of previous work assessing the overall building energy performance for different types of BIPV glazing.

2.1. Single-glazed BIPV

A single-glazed BIPV window consists of two glass sheets with a single PV glazing in between [67], as revealed in Fig. 3. The cell coverage ratio is the proportion of solar cells to the total area of the glazing [68,69]. The solar cells on the PV glazing don't cover the entire area of the window in order to maximise light transmission [70–72]. The PV solar cells within the glazing convert incident solar

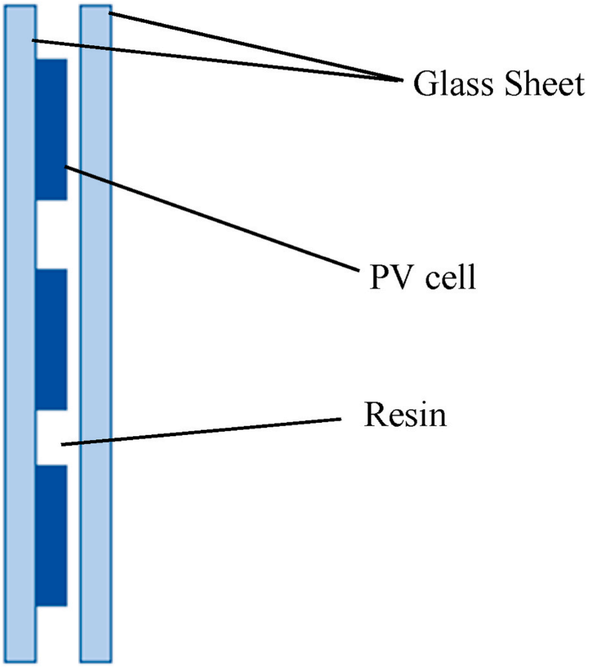


Fig. 3. single BIPV window structure [53].

radiation to electricity which can be beneficial for reducing solar heat gain while also reducing the impact of glare [73–75]. Single PV glazing is the first form of BIPV windows to be introduced and therefore, it serves as the foundation for all other PV glazing systems [76–78].

Alrashidi et al. [48] examined the impact of CdTe on the energy consumption of building facades. The study modelled 4 different scenarios during analysis using BIPV incorporating semi-transparent CdTe employed on the ESI building at the University of Exeter. Results showed that incorporating CdTe can reduce energy consumption up to 260 kWh/yr, which when compared to conventional single glazing, will have net energy savings of approximately 20 %.

Do et al. [49] performed an energy simulation of a residential building in Housten, USA. Using a DOE-2.1e single glazed BIPV window module with daylight-dimming systems to analyse the lighting and cooling demand in a hot climate, utilising three levels of transparency; 40 %, 20 %, and 10 %. Through modelling, it was discovered that south-facing windows had the greatest potential for power production and cooling load reduction, while the most reduction in the lighting load was seen in the east-facing windows. The BIPV window delivered significant energy savings compared to conventional double-glazing windows, ranging from 6.25 kWh/yr to 16.08 kWh/yr depending on the BIPV type and daylight-dimming system.

Olivieri et al. [50] investigated the global energy performance of BIPV single glazing in a middle-sized south oriented office building located in Madrid, Spain by utilising the Energy Balance Index. When compared to the reference glazing, the findings of experimentation and modelling suggested that using BIPV windows will reduce energy consumption by approximately 15 kWh/m^2, which amounts to an energy saving of 18 %, as shown in Fig. 4. It was also found that increasing the transparency degree of the material; increased the cooling demand, decreased the lighting demand, and decreased PV generation.

Ng et al. [51] evaluated the overall energy performance of six commercial BIPV windows in the tropical areas of Singapore using computer simulations and a newly formulated index. The annual net energy consumption which includes PV generation, cooling loads, and lighting loads were computed for a typical office room at the different window-to-wall ratios and orientations. Four single-glazed and two double-glazed BIPV modules were selected for analysis and compared to conventional window types such as single-glazing and double-glazing. Results showed that compared to conventional single glazing, the four single BIPV modules and two double BIPV modules produced energy savings of approximately 20 kWh/m^2/yr and 40 kWh/m^2/yr, respectively and compared to conventional double-glazing, the energy savings were 15 kWh/m^2/yr and 30 kWh/m^2/yr.

Zhang et al. [52] introduced 4 different types of glazing (single glazing, double glazing, low-E glazing, and semi-transparent photovoltaics (STPV) glazing) with solar transmittance values of 0.771, 0.607, 0.245, and 0.268 respectively and compared the net electricity consumption of each type at different orientations in Hong Kong using WINDOW [53] and EnergyPlus [54] for simulation, as highlighted in Fig. 5. The net electricity use includes the consumed and generated electricity of different windows. When compared to conventional windows, the BIPV window was determined to have significant energy savings of approximately 20 kWh/m^2/yr.

Chae et al. [45] assessed the overall energy performance of single BIPV glazing integrated into a midsized commercial building under six different US climates at different orientations. The six US climates were Miami, Phoenix, Los Angeles, Baltimore, Chicago, and Duluth. According to the findings, the south-facing window generated the highest annual electricity from the BIPV window, and the north orientation generated the lowest, across all climates. The study also investigated the cooling and heating energy requirements for each climate using the BIPV window and compared the findings to a base model of single clear glazing. The cooling energy load was reduced by approximately 15 % across all climates due to the integration of the BIPV window compared to the base case. The heating energy load was reduced by approximately 60 % for Miami, Phoenix, and Los Angeles climates only, however, more heating energy was required for Baltimore, Chicago, and Duluth.

Lu and Law [55] modelled a typical tall office building in Hong Kong to establish the overall energy performance of the building integrated with single BIPV windows and compare results to clear glazing. The study also assessed the energy performance at five orientations including southeast and southwest. Using a single BIPV window reduced the annual heat gain by 65 % in comparison to

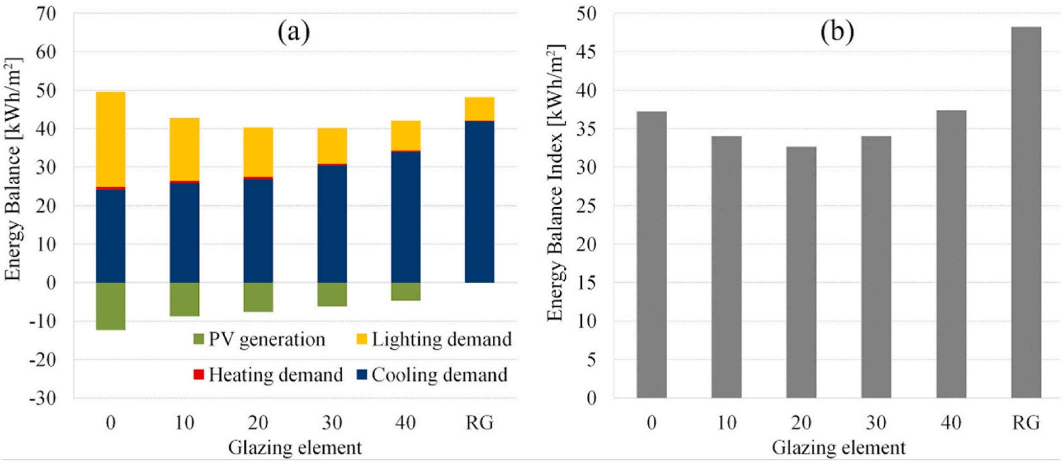


Fig. 4. a) annual energy balance for different glazing materials b) net energy balance index values [50].

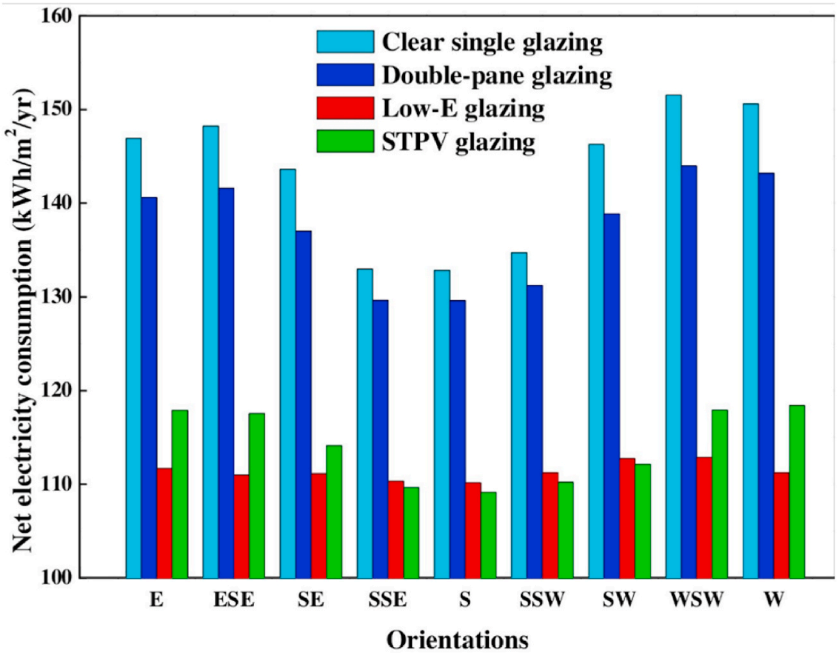


Fig. 5. Impact of 4 types of glazing on the net electricity consumption at different orientations [52].

clear glass. The annual energy savings for water-cooled and air-cooled air-conditioning systems were around 900 kWh and 1300 kWh, respectively. The southeast-facing windows were the optimal orientation with regard to the total energy performance compared to the other orientations.

Liao and Xu [56] compared three conventional windows to the building energy performance of single-BIPV windows in Central China. Results showed that in cooling-dominated locations, a-Si-based BIPV glazing outperformed conventional single and double glass windows as shown in Table 2, reducing the annual energy consumption by 19 kWh/m^2 and 14.7 kWh/m^2, respectively with respective visible transmittances of 0.87 and 0.71.

From the studies above, it can be said that single-glazed BIPV windows have been explored extensively. Different climatic conditions have been explored, different building models were used, several solar cell technologies were investigated, and the impact on different orientations was considered. Energy savings from the single glazed BIPV windows compared to conventional glazing were apparent but were low owing to the low visible transmittance and the low electrical efficiency of the system, and thus, future studies should explore these aspects.

2.2. Non-ventilated double glazed BIPV

The structure of a double BIPV window includes a single PV glazing on one side and an ordinary glass panel on the other, with an air gap in between [79]. The term closed air layer refers to an enclosed double PV glazing similar to that of a conventional double-glazing window [80,81], but instead of there being two glass panels, one of them is replaced with a single PV glazing, as revealed in Fig. 6 below. Double BIPV windows often have lower *U*-values than single BIPV windows [82–84].

Mesloub et al. [57] identified the optimum design for a double-glazed BIPV window for an office room in Tebessa, Algeria through a series of EnergyPlus simulations to identify the overall energy performance at different orientations with a fixed transmittance of 20 %. Results showed that for the east, south, west and north orientations, the energy savings for the cooling load amounted to 108, 100, 86, and 29 kWh/m^2, respectively. The double-glazed south-oriented BIPV module yielded the highest overall energy savings of 90 kWh/m^2/yr, which is a 60 % reduction compared to the base model.

Table 2
Overall energy performance for each glazing [54].

Glazing	Energy consumption (kWh/m^2)			PV generation (kWh/m^2)	Overall energy performance (kWh/m^2)
	Lighting	Heating	Cooling		
Low transmittance a-Si PV glazing (no exterior shading)	20.9	10.7	45.2	4.7	72.1
High transmittance a-Si PV glazing (no exterior shading)	19.6	7.5	54.1	3.8	77.4
Single glazing (with shading slab)	18.3	4.3	68.5	/	91.1
Double glazing (with shading slab)	18.5	2.2	66.2	/	86.8
Low-E double glazing (with shading slab)	18.6	4.3	48.7	/	71.6

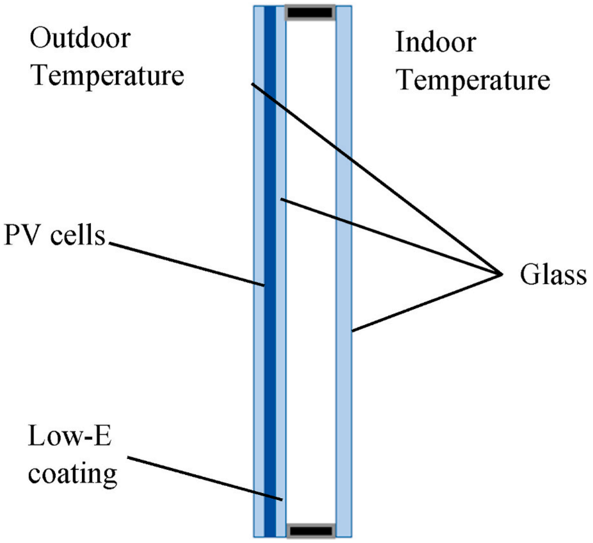


Fig. 6. Structure of a non-ventilated double BIPV window [80].

By using a novel metric defined as the ratio of N-Daylit area, Cheng et al. [58] investigated the overall energy performance and daylighting of double-glazed BIPV windows in the cold regions of China using an office room as the base model. According to the findings, when the N-Daylit area ratio reached 56 %, the net electricity consumption of the office room decreased by approximately 14.6 kWh/m^2/yr compared to single clear glazing, and 7.2 kWh/m^2/yr compared to conventional double glazing, as confirmed in Fig. 7.

T.Miyazaki [59] investigated the impact of a double-glazed semi-transparent PV window with 40 % transmittance on the heating and cooling demand of an office building in Tokyo, Japan at different WWRs. The study compared the results of the BIPV window to conventional double and single-glazed windows to characterise the optimal solar cell transmittance and WWR that would deliver the best energy savings. Using a standard office floor model (33 x 24 x 3.6 m) and the energy simulation software EnergyPlus, the annual energy performance of the office floor was characterised. Results from the study revealed that due to the energy efficiency and power generation of BIPV windows, the energy savings amounted to 9.6 kWh compared to single glazing (55 % reduction) and an energy

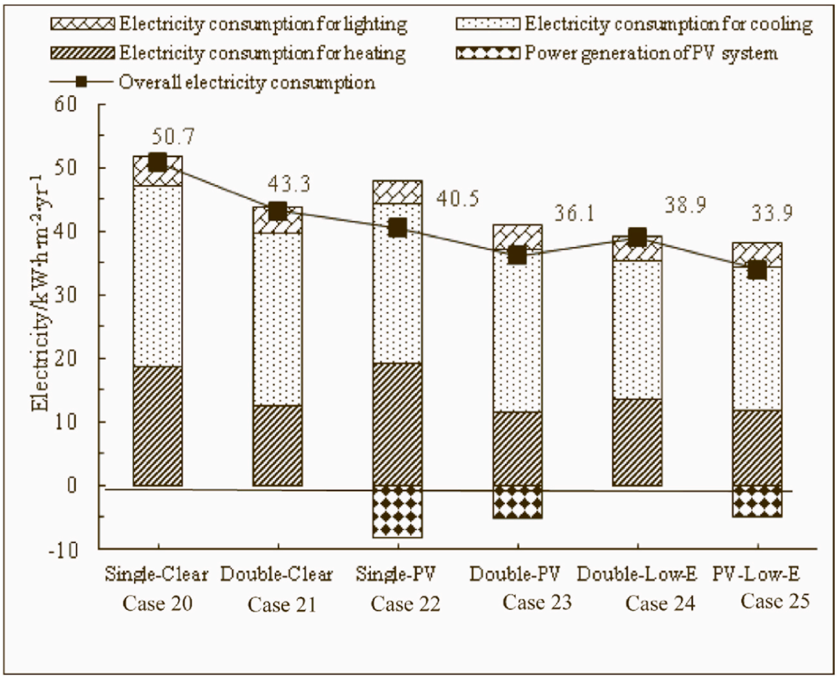


Fig. 7. Net electricity generation of an office room for different types of glazing [58].

saving of 6.9 kWh compared to double glazing (42.1 %) with WWR of 30 % and no lighting control, as revealed in Table 3 below.

Sun et al. studied the building energy performance of an office room integrated with non-ventilated double BIPV windows in different climates of China, using a novel metric [60]. Results showed significant increases in the energy savings of the BIPV windows compared to conventional windows. The reduction in the total energy consumption in Chengdu using double-glazed BIPV windows was 600 kWh/yr compared to conventional double glazing, while the energy savings in Chongqing were 532 kWh/yr, 485 kWh/yr in Guiyang Location, 889 kWh/yr in Kunming, and 984 kWh/yr in Lhasa. As revealed in Fig. 8.

Non-ventilated double-glazed BIPV windows modelled in these studies confirm that the use of amorphous silicon provides greater energy savings compared to thin-film technology. Compared with single-glazed BIPV windows, the energy savings are significantly higher when using non-ventilated double-glazed BIPV windows in hotter climates such as Algeria but in the cold and temperate climates such as Japan and China, the energy savings compared to single-glazed BIPV aren't significant. Future studies should explore the impact of other solar cell technologies such as crystalline silicon or perovskite solar cells. Also, more studies on non-ventilated double-glazed BIPV should be performed in hotter climates.

2.3. Ventilated double-glazed BIPV

As illustrated in Fig. 9, the structure of the ventilated double BIPV window consists of an exterior single PV glazing, an interior clear glass panel, an air cavity in between the two layers, and two openings at the top and bottom [85,86]. The temperature of the PV modules is reduced by the heat extracted due to airflow [87,88]. Incoming solar energy is shielded by the PV modules and reduced as it enters the indoor space due to outdoor airflow [89–91].

Chow et al. [61] evaluated the performance of an office building in Hong Kong that incorporated a ventilated double BIPV window on its building façade. An EnergyPlus simulation revealed that the annual electricity savings at the south, southwest, and southeast orientations were 725 kWh, 690 kWh, and 660 kWh, respectively. For the highest electricity savings, transmittance values in the range of 0.45–0.55 were identified. Chow et al. [62] also analysed a novel double BIPV glazing with natural ventilation and deduced that the reduction in the annual electricity consumption compared to conventional single glazing was 25,087 kWh, which amounts to 28 % in energy savings.

Barbosa et al. [63] evaluated the energy performance of an 11-story office building incorporating fan-assisted ventilated double BIPV windows in the bioclimatic regions of Brazil with a light transmittance of 0.75 for the glazing and 0.12 for the PV panel. Fig. 10 highlights the cooling load of seven different tropical regions using fan-assisted mixed-mode ventilation and air conditioning. For each climate listed below, the annual energy savings amounted to 130 kWh/m^2, 100 kWh/m^2, 150 kWh/m^2, 155 kWh/m^2, 190 kWh/m^2, 150 kWh/m^2, and 160 kWh/m^2. Overall, the simulated model increased power generation while conserving significantly more energy in the cold climate zones compared to the hot climate zones.

Jia et al. [64] investigated the power generation of double BIPV glazing with light transmittance in the visible range equal to 0.1 at different ventilation modes on a university campus building in the cold regions of Taiyuan, China. The three ventilation options were non-ventilated, internal circulation, and air supply, as shown in Fig. 11. According to the findings, double BIPV glazing with the air supply ventilation mode contributed to significant energy savings in the building's net electricity consumption. Compared to the non-ventilated and internal circulation options, the energy savings were 284.7 kWh and 318.3 kWh, respectively.

Yang et al. [65] investigated the energy performance of a north-facing office building integrated with ventilated double BIPV windows in three Australian climates (Darwin, Sydney, and Canberra). The study evaluated different solar cell materials (amorphous silicon, dye-sensitized solar cell, and Perovskite-based solar cells) with visible light transmittances of 0.186, 0.335, and 0.332 respectively, as well as different options for ventilation (no ventilation, natural ventilation, and mechanical ventilation). From the findings, it was evident that the perovskite-based double BIPV window with natural ventilation achieved optimal energy savings when comparing different ventilation modes and BIPV technologies.

Guo et al. [66] studied the building energy performance of an office building integrated with four different BIPV windows under five climates in China at different orientations. The BIPV windows chosen were single PV glazing (SPV) with an effective visible light transmittance of 0.1, double PV glazing (DPV), and naturally ventilated double PV (NVDPV) in both winter and summer modes. In the climates of Harbin, Beijing, Shanghai, and Lhasa, south-facing windows consumed the least amount of electricity, whereas, in Shenzhen, a greater reduction in electricity consumption was observed in the east-facing windows.

The paper also compared the annual electricity consumption of the different BIPV options to that of single clear glazing (SC) and double clear glazing (DC) for each of the five climates, as illustrated in Fig. 12. For the five climates, Harbin, Beijing, Shanghai, Shenzhen, and Lhasa, the annual energy savings that resulted from the integration of NVDPV compared to SC were approximately 75,000 kWh, 70,000 kWh, 35,000 kWh, 80,000 kWh, and 20,000 kWh, respectively. And compared to DC, the energy savings were approximately 15,000 kWh, 30,000 kWh, 10,000 kWh, 60,000 kWh, and 15,000 kWh, respectively.

Table 3
Summary of heating and cooling loads at different WWR [59].

	Units	WWR 30 %			WWR 40 %			WWR 50 %		
		SG	DG	PV	SG	DG	PV	SG	DG	PV
Heating	(kWh/m^2)	5.2	3.4	4.5	5.8	3.4	4.7	6.6	3.6	5.1
Cooling	(kWh/m^2)	12.1	13.0	10.2	12.9	14.2	10.6	13.3	15.2	10.9
Lighting	(kWh/m^2)	38.6	38.6	38.6	38.6	38.6	38.6	38.6	38.6	38.6
PV output	(kWh/m^2)	0	0	5.2	0	0	6.9	0	0	8.6

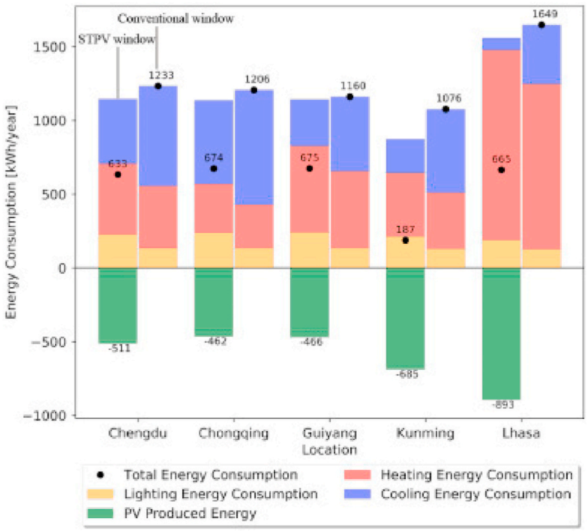


Fig. 8. Annual energy consumption for five cities in Southwest China [60].

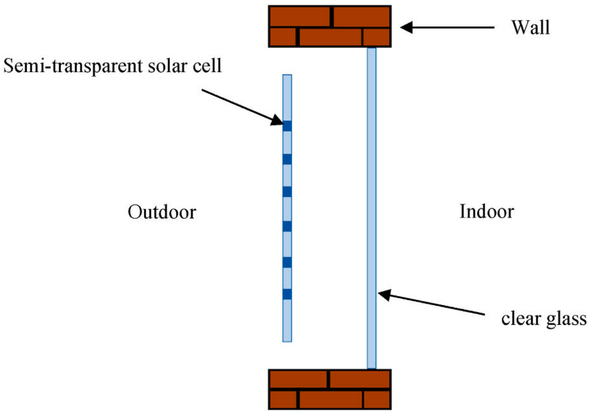


Fig. 9. Structure of a ventilated double BIPV window [91].

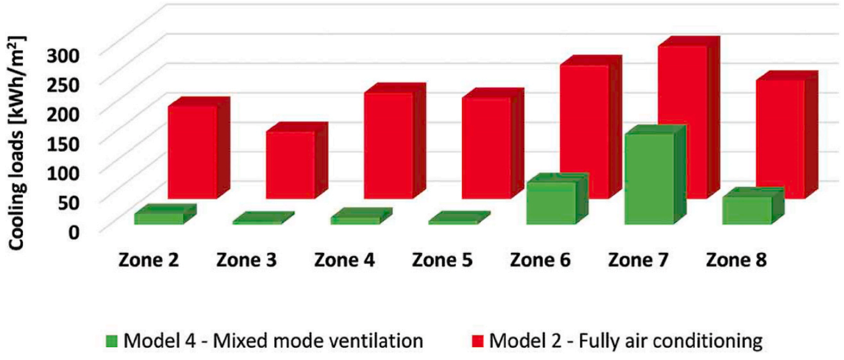
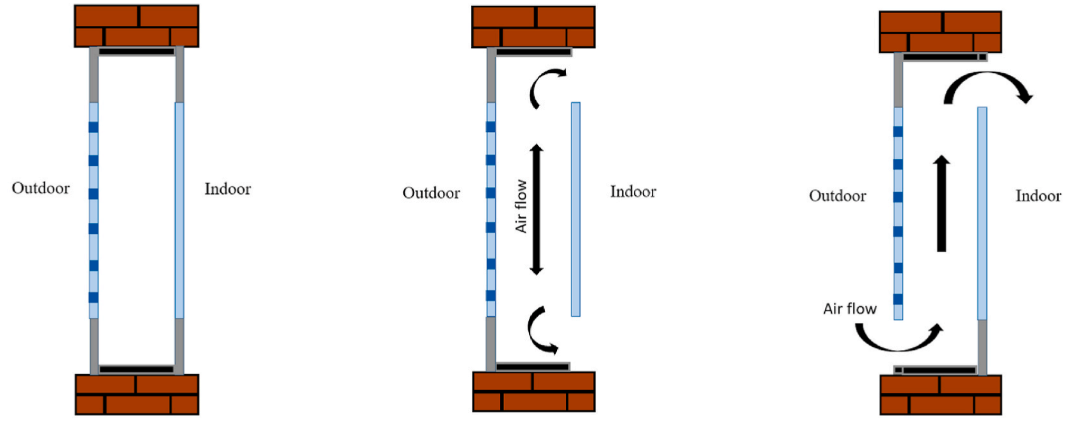


Fig. 10. Annual cooling loads of eight tropical climates in Brazil using fan-assisted mixed mode ventilation and fully air conditioning [63].

According to the studies mentioned above, the presence of an air layer in double-glazed BIPV windows enhances its thermal performance which as a result increases the energy savings compared to non-ventilated double-glazed BIPV windows. While non-ventilation offers higher insulation, ventilation provides greater electricity production.

Ventilated BIPV windows are more suitable for temperate and cold climates where space heating is predominant. The air gap allows



(a) Non-ventilated (b) Inner loop (c) Air supply

Fig. 11. Double BIPV glazing at different ventilation modes [64].

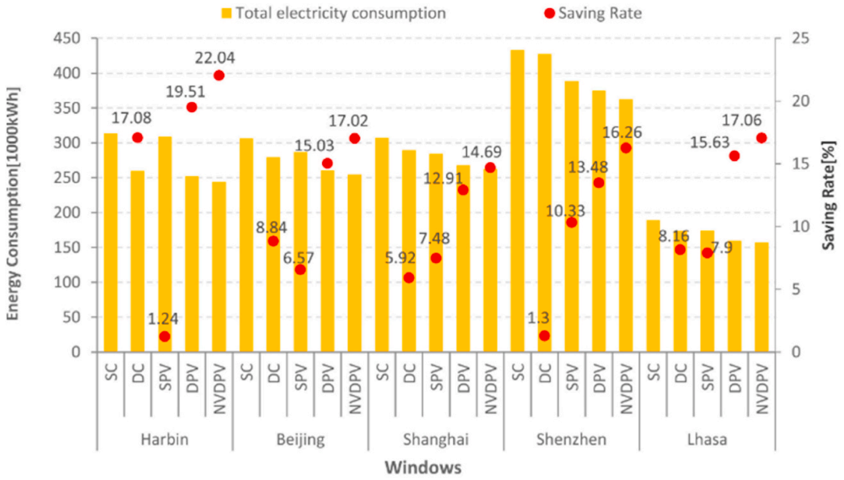


Fig. 12. The annual electricity consumption of an office building using five different glazing systems [66].

outside air to be heated from the heat generated from the PV panels as it enters the inside space, raising the fresh air temperature and greatly enhancing overall energy efficiency. Ventilated BIPV double glazing using perovskite solar cells demonstrates superior energy saving compared to other solar cell technologies and thus future studies should adopt perovskite solar cells in their analysis.

2.4. Vacuum glazed BIPV

The structure of the vacuum-glazed BIPV mainly consists of a single PV glazing on the exterior and a vacuum glazing on the interior

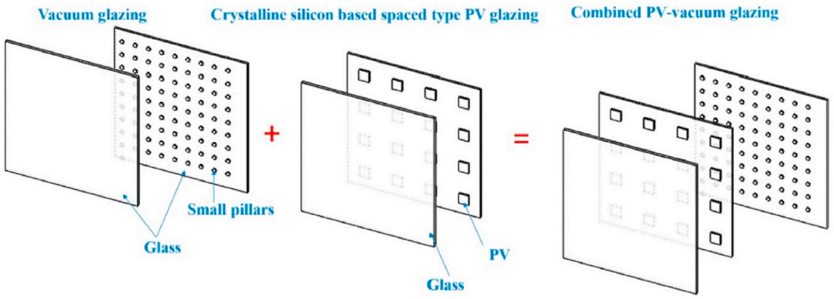


Fig. 13. PV vacuum glazing structure [42].

[92,93], as illustrated in Fig. 13. The vacuum glazing consists of two sealed panels with an evacuated space within and support pillars to withstand pressure from the external environment [94,95]. A transparent glue, such as polyvinyl butyral, is commonly used to join the single PV glazing with the vacuum glazing [96–98].

Huang et al. [67] performed a computational model to quantify the electricity generation of an office building integrated with a novel vacuum PV (VPV) glazing in Hong Kong and Harbin. The purchased electricity consumption of the office building utilising different glazing systems was displayed in Fig. 14 by taking into account the electricity output of BIPV windows as well as the lighting, heating, and cooling loads. The different windows that were analysed were without PV module and daylight control (NDP), without PV module and with daylight control (NP), STPV, and VPV with visible light transmittances of 0.786, 0.786, 0.153, and 0.120 respectively. For Hong Kong and Harbin climates, the annual energy savings that were observed as a result of integrating VPV glazing compared to NDP glazing were 65,000 kWh and 60,000 kWh, respectively.

Qiu et al. [68] modelled a typical office room at different orientations in Hong Kong that utilised a novel vacuum-glazed BIPV with a transmittance of 0.2 system with the aim of identifying the potential for minimising cooling demands. The observed energy-saving potential of this novel PV vacuum system confirmed that using this type of glazing was favourable. From the results, it was evident that the north-facing orientation required the least amount of energy for cooling, furthermore, the annual energy savings for a PV vacuum glazing compared to traditional single and double clear glazing were 90,000 kWh and 10,000 kWh, respectively.

Vacuum-glazed BIPV windows can be a promising alternative to modern BIPV technologies due to the significant energy savings it presents compared to other BIPV system types. Vacuum-glazed BIPV also presents a solution for significantly reducing heat gain/loss from a building under hot and cold climates as revealed in the studies on the Hong Kong and Harbin climates in China. However, studies on Vacuum-glazed BIPV windows are limited, future studies should investigate the impact under other Köppen Climates, as well as compare the overall energy performance of vacuum-glazed BIPV with vacuum glazing without PV.

3. Discussion & perspective

3.1. *EV charging from building energy savings*

The previous section reviewed the studies that assessed the energy-saving potential of different BIPV windows under different climates. Here, the energy savings for each study will be discussed to determine the performance of each BIPV type and to provide an insight into the potential to use these energy savings for charging an EV (as shown in Fig. 15), whether it's slow chargers for in-house use and parking areas or fast chargers for highway applications [99,100], assuming a typical EV battery (60 kWh) [101]. Studies [52–59,63] provided energy savings in kWh/m^2/yr. Assuming the area of a typical office room to be 196 m^2 allowed the tabulated energy savings in Table 1 to all be under kWh/yr [102].

To demonstrate an accurate scenario, the energy savings compared to conventional double-glazing systems were selected as the use of single clear glazing is limited [103], whereas conventional double-glazed windows are popular at present [104]. Thus, the range of yearly energy savings encountered for each BIPV type was approximately between 2800 and 4000 kWh for single PV glazing, 5000-14,000 kWh for double PV glazing with a closed air layer, and 10,000–50,000 kWh for double PV glazing with ventilated air layer. This is the case for the studies that modelled a typical office room and incorporated amorphous silicon as the solar cell technology for analysis. An estimate for the vacuum glazing energy savings was not made due to limited studies available. From these savings, it is clear that double PV glazing with a ventilated air layer performs better than other types of BIPV windows. This is because airflow through the vents provides a cooling effect that lowers the PV temperature which subsequently increases PV module efficiency and increases electricity generation from PV [105–107].

For the case of residential buildings, the only study mentioned in Table 1 that simulated a residential house was [51]. The energy

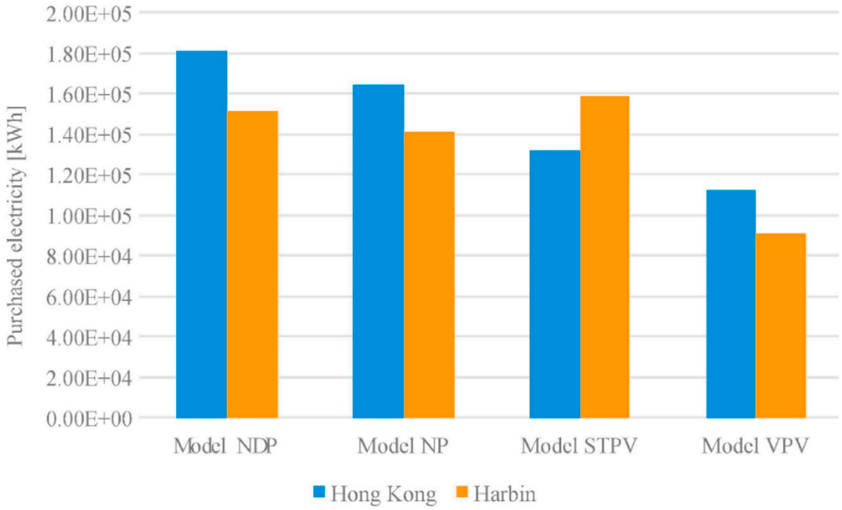


Fig. 14. Purchased electricity consumption for Hong Kong and Harbin building models using different glazing systems [67].

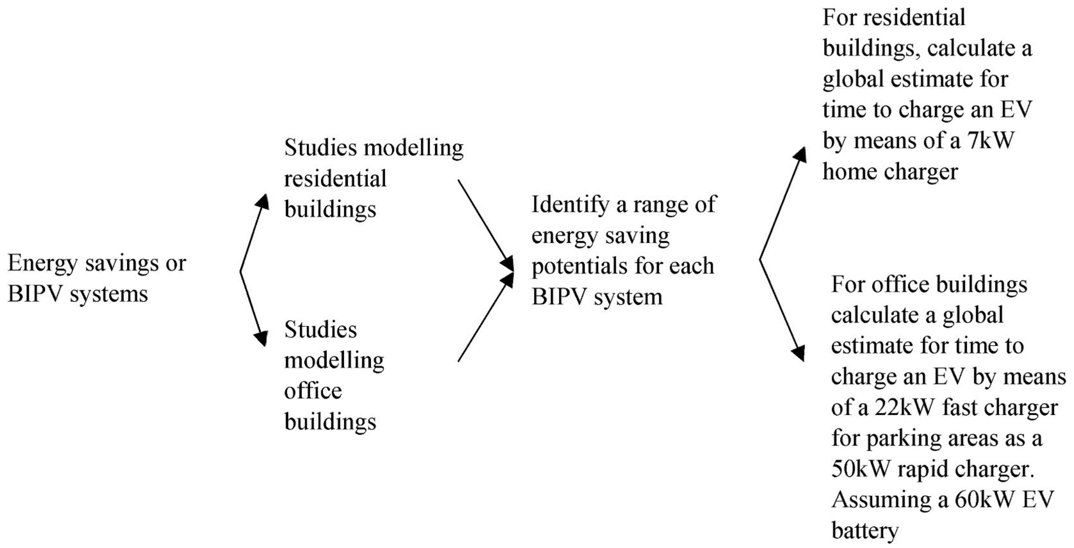


Fig. 15. Flow chart illustrating the method for analysing the energy saving potential of BIPV for EV charging.

savings for this study were between 6.25 kWh/yr to 16.08 kWh/yr for single PV glazing compared to conventional double glazing. Taking an average and converting to kW (11.165 kWh per year/8640hrs) would yield a power saving of 0.0013 kW. Using a 7 kW dedicated home charger can charge an EV to deliver 15–30 miles of range per hour of charge [108]. And it would take just under 8 h to charge the EV from empty to full [109], therefore, each EV would require 56 kWh of power to charge. The power savings produced by the study would be capable of charging an EV every 1806 days (56 kWh/(0.0013 kW x 24hrs)). This would be further improved if a double PV glazing system was introduced.

For office settings, the possible option for chargers is a 22 kW fast charger that can be used in parking areas outside the office building [110], and a 50 kW rapid charger that can be used for nearby highways [111]. The fast charger would provide up to 90 miles of range in approximately 30 min [108], and the rapid charger would provide 60–200 miles of range in approximately 20–30min [108]. For a typical EV (60 kWh battery), the fast charger would need around 5.5hrs to charge the EV to full and 1.5hrs for the rapid charger [109], and therefore would require 121 and 75 kWh of power to charge each EV, respectively. Taking an average and converting the energy savings for each BIPV type to kW would yield power savings of 0.39, 1.10, and 3.47 kW for single BIPV windows, non-ventilated double BIPV windows, and ventilated double BIPV windows, respectively. This ultimately means that for the 3 types of BIPV glazing, the power savings are capable of charging an EV every 13 days for single glazing, 5 days for non-ventilated glazing, and every 1.5 days for ventilated glazing, respectively for a parking area with 22 kW fast chargers. And would be capable of charging an EV every 8 days for single glazing, 3 days for non-ventilated glazing, and every 0.9 days for ventilated glazing, respectively for a highway with rapid 50 kW chargers. A summary of the findings is presented in Fig. 16 below.

3.2. Climatic impact

Various Köppen climates have been used to investigate the energy performance of BIPV windows. The Köppen climate classification

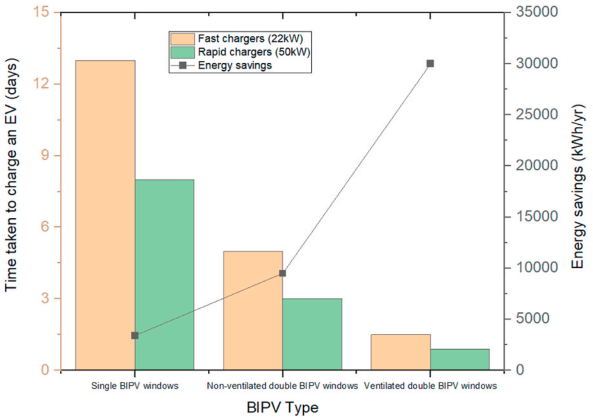


Fig. 16. Energy saving potential of different BIPV windows utilised for EV charging in office settings (the energy savings for each BIPV system was an average taken from the ranges of energy savings specified above).

is one of the most commonly used climate classification methods [110]. The classification is based on its fitting between climate and vegetation types which endows the method with a strong physical meaning and ease of understanding [111,112]. Table 4 elaborates on the specific Köppen climate class that each region relates to. Regions that fall under the tropical climates are Miami, Singapore, Darwin, Cuiaba, Brasilia, Niteroi, Sao Paulo, Rio de Janeiro, Campo Grande, and Piracicaba. Climates that fall under the Arid Köppen class are Phoenix and Tebessa. The regions that fall into the temperate climate category are LA, Houston, Penryn, Madrid, Sydney, Canberra, Hong Kong, Guiyang, Shenzhen, Shanghai, Chongqing, and Chengdu. And finally, the regions that are considered cold climates are Duluth, Chicago, Baltimore, Tokyo, Harbin, Beijing, Taiyuan, Kunming, and Lhasa. Table 1 shows the performance of different types of BIPV windows under various climatic conditions, classified by the köppen climate classification. The results show energy savings for all BIPV window types, in all climate types studied. However, it can be seen that the benefits of the BIPV windows are larger for certain types of technology in specific climates, showing that there is no one-size-fits all solution for BIPV windows, and it must be tailored to the environment in which the system is situated. Considering this information, we can notice several trends in the data. Double-glazed ventilated BIPV systems have performed better than other systems such as double-glazed non-ventilated systems in hotter climates due to the increased shading of the PV panel from incident radiation reducing the cooling load [113–115], as well as the flow of air through ventilation gaps the is able to ensure hot air does not stay trapped in the window, reducing the solar cell temperature thus increasing efficiency [114,115] and also decreasing the cooling load of the building [116–118]. The ventilation layer can also be optimised according to different climates by altering the arrangement of the vents for optimisation as shown in Figs. 9 and 10. While double-glazed ventilated BIPV looks to be an optimal solution for hot climates, double glazed non ventilated BIPV looks to be ideal for cold climates due to the characteristically low U-value, thus overall heat loss from the building can be reduced, consequently reducing the heating load [119–123]. Given the previously mentioned information, it can be concluded that hotter climates such as BWh, and Csa from the Köppen climate classification are more suited to ventilated double-glazed BIPV systems. Likewise, it can be seen that for colder climates such as Dwc and Dwd, closed-gap double-glazed BIPV systems are beneficial. This information gives conclusive information for the optimisation of BIPV systems for hot and cold climates. However, in the case of arid köppen climates, not many studies have been conducted. Thus, more work in the area is needed to assess the potential impact of the technology in these conditions.

3.3. *Orientation and solar cell technology*

Most of the compiled studies have assessed the influence of the orientation of BIPV windows on the electricity consumption of the building. The studies selected in Table 1 confirm BIPV windows positioned on the south orientation yielded the greatest energy savings from the reduction in cooling loads, while also generating maximum PV output, whereas the north-facing installation produces the least amount of power from PV [124–126]. It should also be noted that for some studies [51,66], positioning the BIPV windows in the east orientation yielded greater energy savings due to the reduction in the artificial lighting load.

Fig. 17 illustrates the solar cell technologies that were incorporated in each of the studies mentioned in Table 1. From this, it is evident that the use of amorphous silicon is superior to other technologies when selecting the primary solar cell material for analysis [127–129]. This is because the energy savings were greater when amorphous silicon was integrated compared to other technologies, for instance, studies [58,60] in Table 1, both assessed the building energy performance of double PV glazing with a closed layer in similar Koppen climates (Taiyuan & Lhasa), however, the former study used a-Si and the latter study used CdTe for their analysis, and from the findings, the energy savings for each study amounted to 1411.2 & 984 kWh/yr, respectively. Likewise, study [67] used c-Si in its analysis and achieved 65,000 kWh/yr of energy savings, while paper [68] used a-Si and achieved 90,000 kWh/yr of energy savings, with both studies assessing the building energy performance of vacuum PV glazing.

Nevertheless, amorphous silicon solar cells have low cell conversion efficiencies, and they degrade quite rapidly, which limits their service life to 2–3 years [130–132]. Yang et al. [65] investigated three different solar cell materials when modelling the building energy performance (a-Si, DSSC, and Perovskite solar cell), as displayed in Table 1. It was found that Perovskite solar cells incurred the highest energy savings compared to the other solar cell materials. Following this, many researchers have recently studied Perovskite solar cells as an alternative to commercial solar cell materials [133–135], and it is said that this new concept is considered to be the closest technology to commercialisation due to its efficiencies and cost reduction potential [136,137], and therefore, it is important that future studies on BIPV windows consider this material when modelling building energy efficiency. It should be noted in the case of perovskite solar cells however that this is a relatively novel technology, and while the efficiency of the cells was deemed to warrant the highest energy savings, it is also true that there are significant drawbacks involving the use of perovskite solar cells, such as poor stability at the outdoor conditions [138].

3.4. *Advanced application of BIPV (smart window and urban scale development)*

Although BIPV windows are at the forefront of replacing conventional windows compared to other window technologies, there are still ongoing innovations to formulate optimal design configurations. The BIPV-PCM system is an example of innovation, presented in Fig. 18. The basic function of the phase change material (PCM) involves an isothermal process, where heat is charged and discharged at constant temperatures [139–143]. When incorporated into a PV module, the solar cell temperature of the PV is reduced by the absorption of huge quantities of heat at a constant temperature [144–146]. In practice, it can reduce temperatures up to 10 °C for monocrystalline silicon solar cells in temperate climates, and up to 16–21 °C under hot climates [147,148]. Different forms of PCM utilised for PV temperature regulation include fatty acids, paraffin waxes, eutectic organic/non-organic substances, and salt hydrates [149–151].

Another innovative design involving BIPV technology is smart switchable windows powered by BIPV. BIPV windows present a suitable alternative to conventional windows with regard to thermal insulation, however, the transparency of these windows cannot be

Table 4
Köppen-Geiger climate classes [123].

1st letter	2nd letter	3rd letter	Description
A			**Tropical**
	f		- Rainforest
	m		- Monsoon
	w		- Savannah
B			**Arid**
	W		- Desert
	S		- Steppe
		h	- Hot
		k	- Cold
C			**Temperate**
	s		- Dry summer
	w		- Dry winter
	f		- Without dry season
		a	- Hot summer
		b	- Warm summer
		c	- Cold summer
D			**Cold**
	s		- Dry summer
	w		- Dry winter
	f		- Without dry season
		a	- Hot summer
		b	- Warm summer
		c	- Cold summer
		d	- Very cold winter
E			**Polar**
	T		- Tundra
	F		- Frost

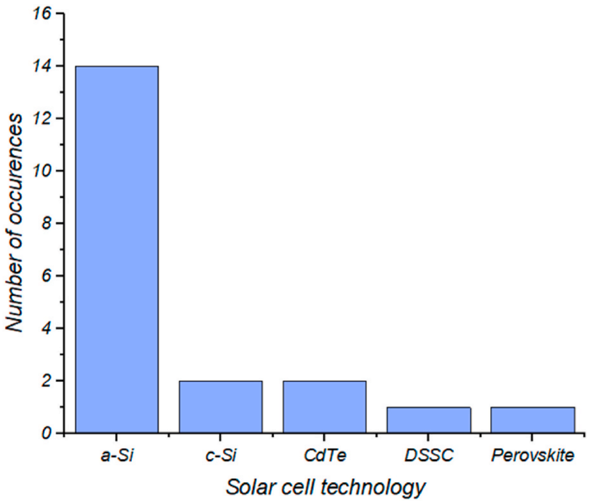


Fig. 17. Solar cell technology used in studies.

adjusted to control the amount of daylight penetration. Switchable glazing acts as a shading device by modulating the transparency of the window and thus can be combined with BIPV to create a thermally insulative window with shading control [153–155]. Switchable windows can be stimulated electrically and non-electrically [156]. But, for the purpose of building applications, the electrically stimulated switchable windows are favoured as the transmission can be manipulated [157]. Figure below illustrates two types of electrically switchable glazing, polymer-dispersed liquid crystal (PDLC) highlighted in Fig. 19(a) [158–160], and suspended particle device (SPD), highlighted in Fig. 19(b) [161–163].

Many studies on BIPV windows are case-specific, meaning that the building model that is used in the analysis is a single building or room. In order to accurately assess the impact that BIPV window technology would have on achieving ZEBs, the building energy performance of BIPV glazing for a district or major city should be investigated [164]. Boccalatte et al. [165] investigated the energy performance of an entire district in Rome, Italy by modelling 11 residential blocks using OpenStudio and an Urban Weather Generator

Fig. 18. *BIPV–PCM* system [152].

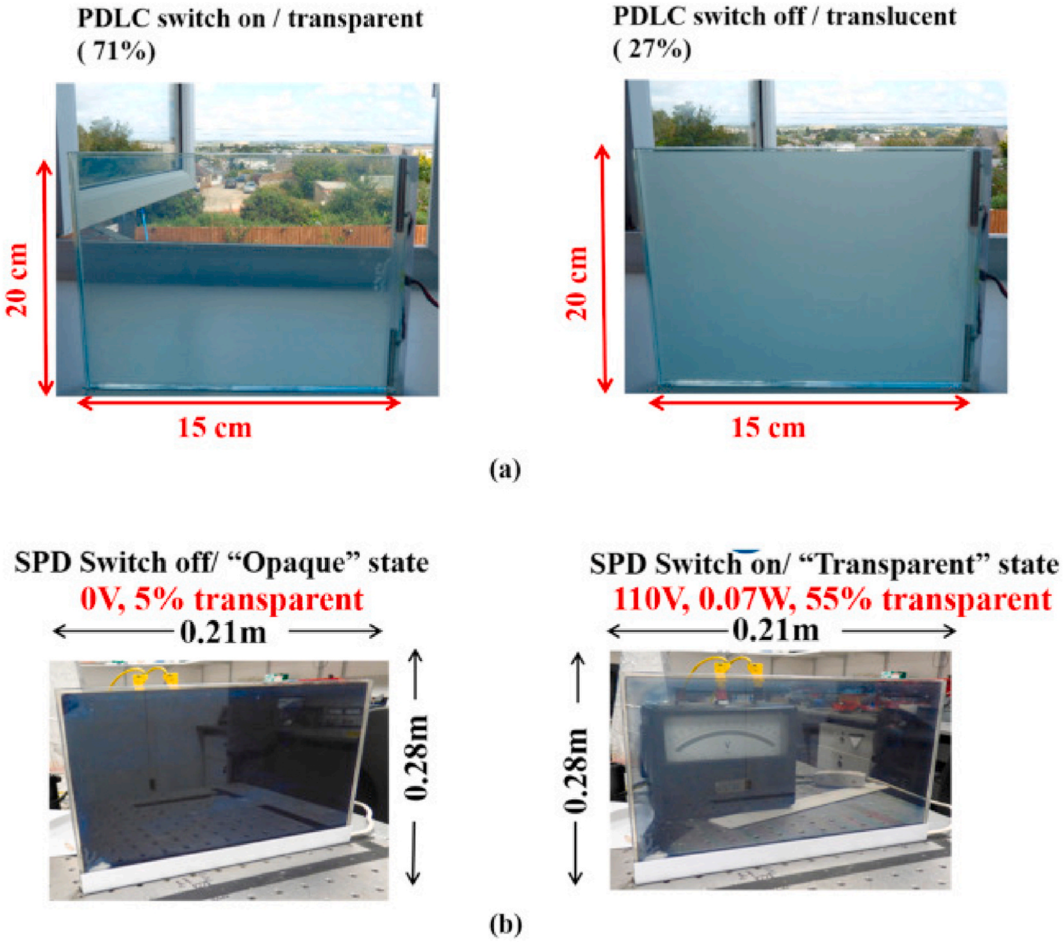


Fig. 19. a) Photograph of polymer dispersed liquid crystal (PDLC) smart switchable glazing b) Photograph of suspended particle (SPD) smart switchable glazing [42].

tool to predict the urban climatic conditions, as shown in Fig. 20. The power generation from the PV modules was estimated for the whole district using hourly simulations and postprocessing analyses. From the findings, it was evident that placing PV glazing on 60 % of the façade area generated 451 MWh of annual electricity across the 11 buildings, which reduced the annual electric energy demand of the buildings by 39 % which was enough to meet the nearly zero energy target of the district.

Urban climates such as capital cities contain many tall commercial buildings that feature large area facades. Esclapes et al. [166] confirmed that facades contribute to 60–80 % of all urban available surfaces. And therefore, facades in urban environments are likely to contribute significantly to the building energy gain from direct and indirect solar radiation which ultimately means it would have a significant impact on the energy consumption of the building [167,168]. BIPV windows are more suited for commercial buildings which makes them an ideal choice of technology in large-scale development [169], and therefore, future studies should consider investigating these concepts.

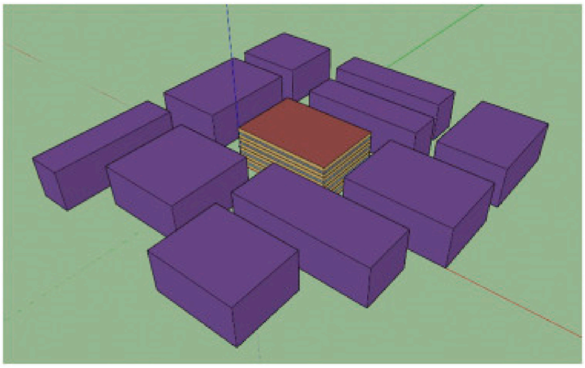


Fig. 20. OpenStudio model of 11 residential buildings in Rome, Italy [165].

3.5. *Life cycle analysis*

PV systems were first integrated into building facades and rooftops in the 1990's. As a result, many BIPV systems have not run what will be expected to be their full useful life, however, some work has been done analysing the lifecycle of BIPV systems [170]. analyses 6 semi-transparent BIPV systems in Singapore, considering electricity generation, the effect on cooling load, as well as artificial lighting requirements. An interesting finding was that while the energy payback period of the systems was as little as 2 years, the energy return on investment could be up to 35 times [171]. looks at a BIPV façade system in Drammen, Norway, analysing the performance after four years of operation. With a discount payback period of 22 years, and an internal rate of return of 6 %. It advises BIPV as a viable option for building skins in Norway [172]. Reviews BIPV studies from around the world analysing their viability and performance. It summarises that although it offers the benefit of onsite electricity generation, there are many improvements still necessary for the technology such as; improved lifecycle analysis studies, improved electricity generation, and lowered initial investment.

3.6. *Limitations*

Previous sections have highlighted the influence that the integration of BIPV windows has on energy savings and the overall building energy performance and how the energy savings produced can be utilised for other applications to accelerate the transition towards ZEBs. However, there are a few limitations in this study that should be addressed.

Many of the previous experiments on BIPV windows have focused more on office buildings as their building model for simulation and less on the impact on residential buildings. Residential buildings contribute 22 % of the global energy consumption and therefore the transition towards ZEBs significantly relies on improving the energy efficiency of conventional windows for residential applications [173,174]. The only experiment mentioned in this study that modelled a residential building for its analysis was based upon single BIPV glazing.

Another limitation is realised by the number of studies that have assessed the impact of vacuum PV glazing on the building's energy performance. From Tables 1 and it was evident that the energy savings encountered in vacuum PV glazing were significant when compared to conventional windows. Vacuum glazing does present as a promising glazing system to integrate for ZEBs as they can reduce the heat flow from indoor to the outdoor environment [175,176], due to the presence of a vacuum which can reduce the convective and conductive heat flow [177,178]. However, more studies should be performed to identify its behaviour at different Koppen climate classifications, as of now it has only been assessed in Hong Kong.

4. Conclusion

To conclude, BIPV windows do present as a promising solution for transitioning towards ZEBs in the future, however, work is still being done to improve the performance of BIPV windows so that they can adapt to different Koppen climates and provide higher transmissions. From the studies reviewed it became apparent that vacuum and ventilated BIPV windows produced significant energy savings compared to other BIPV technologies and conventional windows owing to the minimal energy losses as a result of the vacuum and the optimal PV performance from the ventilation. This then helped quantify the potential for these technologies for other applications such as EV charging, with key conclusions illustrated below.

- Using a global estimate for the potential energy savings of the BIPV technologies, single-glazed BIPV windows could power an EV every 1806 days for residential homes. However, for office settings, it can power an EV every 13 days and 8 days for fast 22 kW and rapid 50 kW chargers, assuming a 60 kWh battery capacity.
- Using a global estimate for the potential energy savings of the BIPV technologies, non-ventilated double-glazed BIPV windows could power an EV every 5 days using fast 22 kW chargers for parking areas, and every 1.5 days using rapid 50 kW chargers for highway road use.
- Using a global estimate for the potential energy savings of the BIPV technologies, ventilated double-glazed BIPV windows could power an EV every 3 days using fast 22 kW chargers for parking areas, and every 0.9 days using rapid 50 kW chargers for highway road use.

- Amorphous silicon is the most common type of solar cell technology used in studies related to BIPV windows.
- Ventilated double-glazed BIPV windows performed better than other systems in hot climates, and non-ventilated double BIPV windows performed better in cold climates.
- Energy consumption and electricity generation from PV were found to be optimal in the south-facing orientation, however, in some cases the east orientation consumed the least energy due to the reduced lighting load.
- Urban cities with a high percentage of façade areas are suitable for BIPV integration.

Declaration of competing interest

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

Data availability

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

Acknowledgement

The author declares no conflict of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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