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Thermal, daylight, and energy potential of building-integrated photovoltaic (BIPV) systems: A comprehensive review of effects and developments

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ABSTRACT

According to energy consumption data of the European Union, buildings account for 40 % of overall energy consumption in all sectors. The rise in building energy demand seriously affects global warming. To reduce demand, buildings must be designed to be energy-efficient. As part of energy-efficiency initiatives, unique systems that employ renewable energy sources should be implemented in buildings. As a new technology, building-integrated photovoltaics is considered an essential technology to achieve this target. Several variables affect the thermal, daylight, and energy performance of building-integrated photovoltaic systems; related to environmental and photovoltaic-related parameters. Thus, the challenges and effects of these variables on the overall performance of these systems should be investigated. This research analyzes building-integrated photovoltaic implemented studies and presents a state-of-art review of recent developments. The study not only summarizes the existing studies developed in this field so far but also analyzes the variables and makes concrete generalizations and inferences. It enables finding gaps and deficiencies in the literature and provides a better understanding of all the variables that affect the performance of building-integrated photovoltaic systems by interpreting the results in detail and representing them graphically instead of only through textual analysis. Results show that building-integrated photovoltaics contribute to constructing a sustainable future for cities. Developments in this industry motivate researchers in this field, whose work will make it easier to cope with future ecological challenges. It helps to build a more sustainable future for society. With new developments, it will be possible to mitigate the effects of future environmental problems.

1. Introduction

According to the European Union (EU), the urban population will keep rising, and cities will account for 66 % of the World's population by 2050. As a result, cities will need to expand. The increased number of buildings will lead to an increase in total energy usage by buildings (Refat and Sajjad, 2020). Buildings with uncontrolled energy demand emit enormous amounts of CO_2. The rise in greenhouse gas emissions substantially impacts global warming (Giouri et al., 2020). As a result, buildings are expected to be developed in compliance with nearly zero-energy building (nZEB) approaches to meet the EU's 2050 climate change goals. A zero-energy building generates as much energy as it uses (Shin et al., 2019), while a nearly zero-energy building (nZEB) generates only a portion of the energy it consumes. To achieve a nearly zero energy building (nZEB), clean and renewable energy production must be implemented in buildings.

The EU seeks to lower total energy consumption by 20 % by 2020 through renewable energy generation. Photovoltaic (PV) system technology severely impacts the scope of renewable energy sources (Biyik et al., 2017). PV systems utilize solar energy to generate electricity. These were first created as PV panels that could not store energy for more than one day and were prohibitively expensive in energy storage and conversion (Knera et al., 2015). Building-integrated photovoltaics (BIPV) is a novel type recently brought to the market. BIPV is attached directly to the surface of the building to meet some of the building's energy needs, rather than a separate system remote from the building. As a result, they are considered as the potential to achieve nZEBs. BIPVs can be adapted to the roof, façade, floor, and shading of a building and can be used on various architectural surfaces. The performance of a PV system generally depends on the installation area and solar cell type. Also, environmental conditions, such as solar irradiation levels,

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Abbreviations

BIPV	Building-integrated Photovoltaic
BAPV	Building-attached Photovoltaic
EU	European Union
nZEB	Nearly Zero Energy Building
CDS	Amorphous Silicon
CdTe	Cadmium Sulphide
CIS	Copper Indium Selenide
PSC	Perovskite Solar Cell
OSC	Organic Solar Cell
CIGS	Copper Indium Gallium Diselenide

geographical region, and area climate, affect its performance. Additionally, certain variables effective on a PV system's overall energy performance during the design phase need to be investigated and studied. These variables are PV coverage area, incline angle, and solar cell type (Hamza et al., 2020), and each parameter should be investigated for an effective PV system. There are also recent material developments in the solar energy industry. For instance, a review study investigates the use of nanofluids due to their thermophysical properties to improve the energy performance of SE systems (Elsheikh et al., 2018). It is seen that nanofluids contribute to system performance due to transfer of heat and generation of energy. One study explores the potential of solar cell types by using meta-heuristics methods such as genetic algorithms, particle swarm optimization, wind-driven optimization, etc. (Oliva et al., 2019). The research addresses the problem of low energy conversion and efficiency of PV systems; thus, it aims to understand variables affecting the success of solar cells. It presents possible solar cell designs by comparing the methods mentioned above. Many studies in the literature investigate multi-objective optimization tools for optimum PV systems. A study uses multi-objective particle swarm optimization (MOPSO) to increase the energy generation capacity and efficiency of the system (Zayed et al., 2020). Linear programming technique for multidimensional analysis of preference (LINMAP) determines the possible solution of Pareto optimal frontier (POF). Results propose that the optimized model presents higher power output and system efficiency. Particle swarm optimization is seen as one of the promising methods to improve a PV's overall performance (Elsheikh and Abd Elaziz, 2018). In addition, artificial neural network (ANN) is often used in multi-objective optimization studies to achieve suitable performance parameters. A relative study reviews the studies that use ANN systems to enhance the performance of different solar energy systems (Elsheikh et al., 2019). Review results show that ANN is beneficial in estimating and optimizing the performance of different systems. Another optimization study forecasts the performance of the photovoltaic/thermal collector (PVTC) system based on energy generation and solar cell-based variables by using the mayfly-based optimization (MO) and random vector functional link (RVFL) algorithms (Abd Elaziz et al., 2021). Results indicate that the prediction model and experimental results correlate with each other. A similar study uses artificial intelligence to generate optimized models for a PV-integrated solar thermoelectric air-conditioning system (STEACS) (Almodfer et al., 2022). The performance of the system is tested under different cooling load conditions. Experimental results are used for the machine learning process. The model uses a jellyfish search algorithm (JFSA), sine cosine algorithm (SCA), artificial ecosystem-based optimization (AEO), and manta ray foraging optimization (MRFO). As mentioned, many variables affect the performance of PV systems. Thus, they are significant for enhancing the efficiency and success of the system.

This study aims to conduct a comprehensive analysis and comparison of BIPV research. The study differs from recent reviews in terms of the analysis type and the way of presenting the study results. The research reveals deficiencies in the literature and guides the researchers for future projections of BIPV systems. The study variables are environmental conditions, solar cell type, location, and methods of study. Although there is a wide range of research related to BIPVs, there is a need to understand the impact of these variables on overall energy performance. A comprehensive literature review is conducted in the study, and the analysis is presented in table form. The result of the study is represented with extensive graphics. A wide range of studies on BIPV systems is reviewed. Firstly, studies on PV glazing technology are reviewed and analyzed according to several categories, such as their aim, methodology, tools, findings, climatic region of the study, PV system type, etc. Each analysis related to studies is shown in Table 1.

2. Building-integrated photovoltaic (BIPV) systems

The first PV implementations were practiced in the 1980s. It was initially seen as high technology development, but the system's cost and technical-related problems emerged over time. Although the 1990s solved some problems, new technology is required for further solar industry developments. With the developments of ZEB strategies, BIPV systems have gained popularity.

2.1. Field of application

Due to lower cost and easy application, BIPVs started to be implemented on building roofs, façades, glazing, and shading systems (Taveres-Cachat, 2019). BIPV systems can generate electrical energy via the conversion of solar energy. Since they are attached to the building envelope, they also act as a thermal barrier between the building and the outdoor environment. They are beneficial since they reduce buildings' material, labor, and energy costs and provide an aesthetically pleasing view (Zhang et al., 2018).

2.1.1. Roof applications

For greater efficiency, PVs started to be first implemented on roofs (Knera, 2015). PVs can be integrated as both BIPV and building-attached photovoltaic (BAPV) systems. Although BAPV systems generate more electricity, BIPV systems provide a better overall building performance since they control the solar gain of the building. The available roof area for BIPV implementation is generally defined as 40 % of the ground floor area. Most of the solar cells available in the industry can be used for BIPV roof applications (Ghosh, 2020). However, as mentioned in Section 3.2, first-generation PV cells are used mainly in roof BIPV applications. These include monocrystalline and multicrystalline silicon PV cells. In BIPV roof applications, orientation and slope of the roof are the main parameters which affect performance, with south-facing and sloped roofs generally performing better. In first-generation PV cells, there is no airflow under PV modules, which can be a disadvantage. Product types like BIPV foil, BIPV tile, BIPV module, and solar cell glazing are suitable for roofs (Dim, 2017). Studies show residential buildings have great potential for roof BIPV implementations (Defaix et al., 2012).

2.1.2. Façade (Wall) applications

Since building facades cover more than roofs, façade BIPV implementations have gained popularity. Studies show that façade BIPV implementations significantly improve energy saving by 15 % and 35 % since they act as thermal barriers between indoor and outdoor environments (Jahanara, 2013). When thin-film and newly developed cells are used, the façade will allow daylight. If first-generation (i.e., silicon-based) cells are used, the façade will generally be opaque. BIPV façade systems contribute to the energy performance of the building and add an aesthetic appearance to the structure. One advantage of façade applications is their easy application process since they only require a mounting system with aluminum staples, brackets, and profiles (Chatzipanagi et al., 2016). There are two strategies for implementing PV on walls. PV can either be implemented by mounting on an existing wall as

Table 1
Comparative analysis of literature review.

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Yoo and Lee, 2002	Gyeonggi-Do, Korea	Cold	Commercial	PV Shading	monocrystalline and polycrystalline solar cell	Energy	Performance analysis of a PV shading by considering weather conditions, aesthetic, cost, etc.	Reference building, field measurements, monitoring	PV-WR 1800 = 1500 PV-DATA, measuring instruments	Periodical analysis	Depending on the weather, climate, and shading effects, the efficiency of the modules significantly varies.
Omer et al., 2003	Nottingham, UK	Cold	Education	BIPV	a-Si and monocrystalline silicon solar cell	Energy and cost	To compare two different PV systems in terms of design, installation, performance, and economics	Reference building, 3D modeling, simulation	PVSYST simulation model	Periodical analysis	Results compare amorphous silicon and crystalline PV in terms of design, installation, performance, and economics.
Fung and Yang, 2008	Hong Kong, China	Subtropical	–	PV Window	Polycrystalline silicon semi-transparent and opaque solar cells	thermal	To develop a one-dimensional heat transfer model for PV glazing to forecast heat gain under different variables	Reference building, numerical model, field tests, simulation	Calorimeter box, an adjustable solar simulator, mathematical formulas	Steady-state	It is proved that the solar cell's area in a PV module affects heat gain.
Ordenes et al., 2007	Natal, Brasília and Florianopolis, Brazil	Moderate	Residential	BIPV	a-Si, monocrystalline, polycrystalline silicon, CdTe, CID	Energy	To evaluate the energy performance of six different PV systems in 3 other cities of Brazil	Reference building, 3D modeling, simulation	Energy Plus	–	Results show that the energy-saving potential is directly associated with the climatic region of the city.
Li et al., 2009	Hong Kong, China	Subtropical	Office building	PV Window	a-Si solar cell	Daylight, thermal, energy and cost	To explore the capacity of a PV glazing for thermal, daylight, and energy performance	Reference building, field measurements	Measurement tools	Steady-state	PV glazing and shading devices can reduce lighting loads and electricity consumption.
Rüther and Braun, 2009	Florianopolis, Brazil	Moderate	Airport	BIPV	a-Si solar cell	Energy	To see the potential of a-Si PV modules on energy demand reduction	Reference building, simulation	Simulation model	Periodical analysis	Full coverage of PV on the façade can supply the whole electricity energy demand of the airport.
Cheng et al., 2009	20 cities	Varied	–	BIPV	monocrystalline and polycrystalline silicon solar cell	Energy	To investigate the relation between the incline angle of BIPV system on roof and latitude of a region	Mathematical model, simulation	Mathematical equations, PVSYST	Periodical analysis	Latitude angle needs to be used as tilt angle to provide a better thermal performance and comfort.
James et al., 2009	Southampton, UK	Oceanic	Education building	PV Shading	monocrystalline solar cell	Energy, thermal, daylight, cost	To assess different shading solutions for electricity generation, daylight, and thermal performance	Reference building, questionnaire, numerical model	Mathematical equations, survey	Periodical analysis	PV system has a significant effect on not only the overall performance of a building but also its cost and carbon footprint.
Han et al., 2010	Unspecified	Unspecified	–	PV Window	a-Si solar cell with Low-E coating	Thermal	To understand the convective heat transfer rate of double-pane window integrated with a-Si PV	Numerical method	Mathematical equations	Steady-state	Results proved that the Low-E coatings could help to reduce heat transfer via radiation.

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
							cells with Low-E coatings				
Sun and Yang, 2011	Hong Kong, China	Subtropical	–	PV Shading	Monocrystalline solar cell	Energy and thermal	To understand the effect of tilt angles of shading devices on the energy performance of the system	Numerical model	Mathematical equations	Periodical analysis	The proper tilt angle of the shading device is determined for better energy performance.
He et al., 2011	Hefei, China	Humid subtropical	Office building	PV Window	a-Si solar cell	Thermal and energy	To assess thermal and energy performance of thin-film a-Si PV window	Reference building, numerical model, field tests, simulation	Measuring tools CFD software tool FLUENT, GAMBIT	Periodical analysis	Results show that the numerical model performed parallel to field experimental data.
Yoon et al., 2011	Gyeonggi-Do, Korea	Cold	Office building	PV Window	a-Si solar cell	Energy	To compare the energy performance of a-Si PV glazing by monitoring and estimation	Reference building, field measurements	Monitoring	Periodical analysis	Estimated and actual energy production results of the PV window were found unrelated.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Yoo and Manz, 2011	Suwon-si, Korea	Moderate	Office building	PV shading	monocrystalline silicon	Thermal, daylight, and energy	To evaluate the performance of the BISTS system in terms of daylight, thermal, and energy performance	Reference building, 3D model and simulation, field measurement	SOLCEL	Steady-state	Outdoor air temperature increases when a remodeled system reaches higher flows. It results in reduced power generation and an increasing energy generation effect.
Liangliang, 2011	Hong Kong, China	Subtropical	Undefined	PV shading	Mono and polycrystalline silicon	Energy	To evaluate the use of PV more effective vertically on high rise building	Reference building, numerical model, 3D model, and simulation	Solar simulation lab of the Department of the Building Services Engineering, TRANSYS	Steady-state	Compared with traditional PV implementations, PV shadings provide more energy savings.
Yoo and Manz, 2011	Suwon, Korea	Humid continental	Commercial building	PV shading	monocrystalline	Energy, thermal comfort, and daylight	To develop a numerical, experimental, and simulation model of a BIPV shading device	Reference building, 3D model and simulation, numerical model	SOLCEL, mathematical equations and measuring instruments	Periodical analysis	SOLCEL may be applicable to develop a multi-functional BIPV shading device to improve overall building performance.
Peng et al., 2011	China	Varied	Varied	BIPV review	Varied	Function, cost, technology, aesthetics, maintenance, and replacement	To discuss the issues of BIPV on several criteria	Literature review	Undefined	–	BIPV-associated problems in China may occur due to a lack of maintenance and replacement structures.
Urbanetz et al., 2011	Florianópolis, Brazil	Warm humid subtropical	Education building and car park	Façade and roof	a-Si	Energy	To test the hypothesis of whether there is a satisfactory compromise between form and function	Reference building, 3D model, and simulation	Ecotect	Periodical analysis	The energy generation of the curve PV module is 12 % lower than the other one. However, in summer, it performed better.

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Mandalaki et al., 2012	Athens, Chania, Greece	Mediterranean and temperate	Office building	PV shading	Undefined	Thermal, daylight, and energy	Thermal and daylight performance of 13 different configurations of BIPV shading devices	A reference building, 3D model, and simulation	Energy Plus, Autodesk Ecotect, Desktop Radiance	Steady-state	The authors develop 13 different energy and daylighting models for two other Greece cities.
Cronemberger et al., 2012	Brazil	Hot	–	BIPV	Undefined	Energy	To understand the relationship between solar irradiation, tilt angle, and orientation	Numerical model	Mathematical formulas	Periodical analysis	The optimal tilt angle is always above the latitude angle value or 9 °C.
Hwang et al., 2012	Gyeonggi-Do, Korea	Cold	Office building	BIPV	polycrystalline silicon	Energy	To propose an energy model to compare the base case and PV-integrated models.	Experimental measurements, reference building, 3D model, and simulation	PV-DesignPro, eQUEST, BEMS	Periodical analysis	BIPV can supply the electricity demand between 1-and 5 % when some variables are optimized.
Sun et al., 2012	Hong Kong, China	Subtropical	Undefined	BIPV	monocrystalline and polycrystalline silicon	Energy	To test the effect of BIPV shading systems' façade orientation and incline angle on building energy performance	Numerical model, reference building, 3D model, and simulation	Undefined	Periodical analysis	An optimum design for the BIPV shading system is proposed for different orientations.
Lu and Law, 2013	Hong Kong, China	Subtropical	Office building	PV window	Undefined	Thermal, daylight, and energy	To assess the PV window's daylight, thermal, and energy performance	Reference building, simulation	Undefined	Periodical analysis	The PV window system provided electricity and lighting, saving between 900 and 1300 kWh.
Leite Didoné et al., 2013	Fortaleza and Florianopolis, Brazil, Frankfurt, Germany	Subtropical/ continental	Office building	PV window	a-Si	Thermal, daylight, and energy	To create an energy and daylight model for an a-Si PV glass in various climate zones	Reference building, 3D model, and simulation	DAYSIM, Radiance, Energy Plus, Optics 6	Periodical analysis	PV glass can decrease the cooling and lighting loads of the building.
Ng et al., 2013	Singapore	Tropical	Office building	PV window	a-Si and micro-morph silicon PV modules	Thermal, daylight, and energy	Different PV windows are tested for energy and daylight performance.	Reference building, 3D model, and simulation	Energy Plus	Periodical analysis	Daylight and energy performance are affected by building orientation, solar cell choice, and window-to-wall ratio.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Bigot et al., 2013	Reunion Island, France	Subtropical	Undefined	BIPV	polycrystalline silicon	Energy	To present an optimization and validation model between simulation and field experiments	Experimental measurements, reference building, 3D model and simulation, numerical model	ISOLAB, GenOpt, MAT-LAB, ISOTEST	Steady-state	Results propose that PV application on roof can significantly reduce heat flux via roof.
Hwang et al., 2014	Chungbuk, Korea	Moderate	Office building	PV shading	Undefined	Energy	To assess the power generation capacity of PV light shelf	Reference building, scale model, field tests	The Solarlink photovoltaic monitoring system	Periodical analysis	The energy performance of PV shading elements is better when they are placed horizontally.
	Korea	Undefined		Facade		Energy					

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Kim et al., 2014			Office building		a-Si and monocrystalline		To develop a PV blind system together with daylight responsive dimming system for better energy performance	Experimental measurements, reference building	Power meter, illuminance meter, several measuring instruments, etc.	Periodical analysis	PV blind incline angle and artificial light fixture affect the overall performance of a PV system.
Lee et al., 2014	Incheon-si, Korea	Continental	Research center	Façade, roof, and window	Monocrystalline and a-Si	Energy	To evaluate the zero-energy potential of a building with various BIPV systems	Reference building, field experiments, numerical model	pyrheliometer, thermometer, hygrometer, etc., mathematical formulas	Periodical analysis	The building is classified as a zero-energy building with the contribution of a BIPV façade.
Chae et al., 2014	Varied	Varied (6 different zones)	Commercial building	PV window	a-Si solar cell	Energy	To develop a model for a BIPV window to assess its energy and daylight performance	Reference building, 3D model and simulation, field measurements, numerical model	Energy Plus, mathematical formulas,	Periodical analysis	It is suggested that window optical characteristics should be optimized according to climate.
Mandalaki et al., 2014	Chania, Athens/Greece	Warm and temperate/ Mediterranean	Office building	PV shading	Monocrystalline and polycrystalline	Energy	To compare the results of 3 different methods of PV energy performance calculation	Reference building, 3D model and simulation and field measurements	Energy Plus, Sketch Up, Open Studio	Periodical and steady-state	Simple and more complex energy models present similar results, and field measurement of PV systems provides more accurate results.
Peng et al., 2016	Hong Kong, China	Subtropical	Office building	PV window	a-Si	Thermal, daylight and energy	To evaluate capacity of a-Si based PV double-skin façade on energy and daylighting performance	Reference building, 3D model and simulation, field measurements	Energy Plus, spectrometer, OPTICS software, WINDOW	Periodical analysis/ steady-state	A simulation model that can predict the overall energy and daylight performance is presented for further design developments.
Kapsis et al., 2015	Toronto, Canada	semi-continental	Office building	PV window	a-Si	Daylight	To investigate the daylight performance potential of 3 different PV windows	Reference building, 3D model, and simulation	DAYSIM, Energy Plus	Periodical analysis	BIPV windows can provide optimum daylight performance and maximize daylight and outdoor view.
Li 2015	Los Angeles, USA	Moderate	Office building	PV shading	Undefined	Energy and daylight	To evaluate the performance of BISTS on energy and daylight performance	Reference building, 3D model and simulation, mathematical equations	Energy Plus, DAYSIM, TRNSYS	Periodical analysis	BISTS improves daylight performance and is efficient for hot water, space heating and cooling strategies.
Freitas and Brito, 2015	Geneva, Switzerland, Lisbon, Portugal	Continental, mild subtropical	Undefined	PV shading	Undefined	Energy	To analyze different BIPV shading system configurations to maximize solar irradiation	Reference building, 3D model and simulation, optimization	Rhino, Grasshopper, Diva, Galapagos, MatLab	Periodical analysis	A tilted louvre can produce 20–40 % more electric energy than a typical flat and vertical shading system.
Knera et al., 2015	Lodz, Poland	Moderate	Office building	BIPV	Undefined	Energy	To assess the capacity of BIPV to supply	Reference building, 3D model and	ESP-r, WATSUN, DAYSIM	Periodical analysis	Energy generated from BIPV cover most

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
							electricity demand and daylight	simulation, numerical model			of the lighting loads for the south façade.
Zhang and Du, 2015	Beijing, China and London, UK	Warm and temperate	Office building	Facade	Undefined	Daylight	To evaluate the daylight performance of a BIPV through a simulation model	Reference building, 3D model, and simulation	DAYSIM, EVALGLARE	Steady-state	Configuration of BIPV has a significant effect on daylight performance.
Zhang et al., 2016	Hong Kong, China	Subtropical	Office building	PV window	a-Si	Thermal, daylight and energy	To evaluate energy, daylighting, and thermal performance of PV window	Experimental measurements, Reference building, 3D model, and simulation	Energy Plus	Periodical analysis	When it is compared with single and double-pane glazing, a-Si PV window can reduce the heating and cooling loads differently on varying facades.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Göksu et al., 2016	Stuttgart, Germany	Temperate	Office building	PV shading	Undefined	Energy	To BIPV shading device's energy performance	Reference building, 3D model, and simulation	Ecotect, Energy Plus	Periodical analysis	Vertical multiple shading elements on the south façade provide the best thermal performance.
Stamatakis et al., 2016	Crete, Greece	Mediterranean	Office building	PV shading	Monocrystalline	Energy, Thermal, and Daylight performance	To analyze PV integration in buildings in a multipurpose way	Reference building, 3D model, and simulation	PROMETHEE	Periodical analysis	Brise soleil full facade performed best while canopy inclined double or louvers horizontal inwards inclined present worse.
Tripathy et al., 2016	Varied	Varied	Varied	BIPV review	Varied	Life cycle assessment	To conduct an analysis on BIPV for life cycle assessment	Literature review	Varied	Varied	BIPV orientation and shadow consideration affect the life cycle assessment of a BIPV system.
Wang et al., 2021	Harbin, Beijing, Changsha, Kunming, Hong Kong, China	Varied	Office building	PV window	a-Si	Thermal, daylight, and energy	To assess the energy performance of PV double skin façade (PV-DSF) and PV insulating glass unit (PV-IGU)	Reference building, 3D model and simulation, field measurement	Energy Plus, laboratory tests	Periodical analysis	The overall energy-saving potential of two glazing systems is defined as 28.4 % and 30 %.
Jayathissa et al., 2017	Zurich, Germany	Temperate	Office building	PV shading	CIGS	Thermal, daylight, and energy	To propose an adaptive and dynamic PV shading system for better energy performance	Reference building, 3D model, and simulation	Rhino, Grasshopper, Ladybug, Honeybee	Periodical analysis	The proposed dynamic model report 20–80 % energy saving.
Martellotta et al., 2017	Los Angeles, USA	Warm Mediterranean	Office building	PV window	a-Si and perovskite	Energy performance	To compare two different PV solar cells' energy performance	Reference building, 3D model, and simulation	Energy Plus	Periodical analysis	A-si PV module saves more energy than perovskite-based cells. PCs have a better daylight performance.
Zhang et al., 2017	Hong Kong, China	Subtropical	Office building	PV shading	Polycrystalline silicon	Thermal, daylight, and energy	To optimize the tilt angle of PV shading for	Reference building, 3D model and	Energy Plus	Periodical analysis	Optimized PV shading element on south

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
							better daylight and energy performance	simulation, field measurements			façade with 20° tilt angle is proposed.
Budhiyanto et al., 2017	Jakarta, Indonesia	Monsoon	Office building	PV shading	Undefined	Energy	To compare energy models of various PV shading devices	Reference building, 3D model, and simulation	Energy Plus, mathematical formulas	Periodical analysis	Fewer panel installation with greater distance provides better performance than more close-distance panels.
Shukla et al., 2017	Varied	Varied	Varied	BIPV review	Varied	Life cycle assessment, economically	To present a comprehensive review of BIPV technologies	Literature review	Varied	Varied	Large monocrystalline PV modules have the highest energy payback time compared to thin-film cells.
Nundy and Ghosh, 2020	Cornwall, UK	Temperate oceanic	–	PV window	Polycrystalline	Thermal and daylight	To offer hybrid smart glazing to control excessive solar gain, thermal and visual comfort	Numerical models, field experiments	UV–VIS-NIR spectrophotometer	Steady-state	Multicrystalline-based combined PV-vacuum glazing with different transparencies ranged between 35 %, and 42 % is produced.
Sun et al., 2018	Harbin, Beijing, Shanghai, Guangzhou, Kunming, China	Varied	Office building	PV window	CdTe	Daylight and energy	To understand the energy and daylight performance of thin-film CdTe PV glazing	Reference building, 3D model, and simulation	Energy Plus, RADIANCE	Periodical analysis	Thin-film CdTe PV glazing improves daylight performance and saves energy when the WWR is high.
Cheng et al., 2018	Taiyuan, China	Cold	Office building	PV window	a-Si	Daylight and energy	To assess daylight and energy performance of PV glazing considering variables as transmittance, orientation, window-to-wall ratio	Experimental measurements, reference building, 3D model and simulation, numerical model	DAYSIM, Energy Plus, Optics, field measurement equipment	Periodical analysis/ steady-state	Glazing transmittance and WWR should be 50–60 % and 40–50 %, respectively, to satisfy both energy and daylighting performance.
Gao et al., 2018	Shanghai, New York, Tokyo, Beijing, London, Los Angeles, Toronto, Paris, Berlin	Varied	Office building	PV window	monocrystalline silicon	Daylight and energy	To evaluate the daylight and energy performance of PV glazing integrated with shading elements	Reference building, 3D model, and simulation	MATLAB, MATLAB Simulink, Sketch-Up, Rhinoceros DIVA, and Grasshopper	Periodical analysis	Annual energy generation covers 27.4 % of the total energy demand of the building.
Gao et al., 2018	Undefined	Undefined	Office building	PV window	Undefined	Daylight and energy	To test the potential of PV windows with shading devices for maximum solar energy harvesting	Reference building, 3D model, and simulation	Rhinoceros DIVA and Grasshopper	Periodical analysis	Dynamic and static PV shading elements can reduce glare risks.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Asfour 2018	Saudi Arabia	Hot desert	Office building	PV shading	Undefined	Thermal and daylight	To assess the daylight and thermal performance of	Reference building, numerical	Design-Builder, Energy Plus, analysis programs such as IES	Periodical analysis	Horizontal BIPV shading device with 45° incline angle has

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
							various shading devices with different incline angles	model, simulation	VE and Ecotect Analysis 2011		the highest annual solar radiation by providing an effective shading of 96 %.
Piccoli and Dama , 2018	Athens/ Greece, Milan/ Italy, Copenhagen	Mediterranean	–	PV shading	Undefined	Daylight	To assess a BIPV shading device for better daylight and energy performance	Reference building, 3D model and simulation	Energy Plus, MATLAB, Window,	Periodical analysis	??
Agathokleous et al., 2018	Limassol, Cyprus	Coastal	–	Facade	Undefined	Energy	To analyze a BIPV system's energy performance theoretically and experimentally	Numerical and experimental model	Mathematical equations and measuring instruments	Periodical analysis	The system's energy saving potential varies between 26.5 and 33.5 %, while energy efficiency varies between 13 and 16 %.
Zhang et al., 2018	Varied	Varied	Varied	BIPV review	Varied	Energy	To review the evaluation and progress of recent developments in BIPV systems	Literature review	Undefined	–	Energy payback time and greenhouse-gas emissions are discussed.
He and Schnabel, 2018	Wuhan, China	Temperate	Undefined	Facade	Undefined	Daylight	To propose a daylight performance evaluation method for BIPV	Reference building, 3D model and simulation, numerical model	Rhino, Grasshopper, DIVA, Energy Plus	Steady-state	Results present similar values between simulation and numerical models.
Zhang et al., 2018	Varied	Varied	Varied	PV shading review	Varied	Energy, thermal, and daylight	To analyze PV shading implementations in terms of overall energy performance	Varied	Varied	Varied	Comprehensive literature is grouped according to PV materials, orientations, tilt angles, building types, and research approaches.
Sun et al., 2018	Harbin, Beijing, Shanghai, Hong Kong, Kunming, China	Varied	Office building	PV window	a-Si	Daylight and energy	To evaluate the energy and daylight performance of PV glass in different climates	Experimental measurements, reference building, 3D model, and simulation	Laser Comp FOX heat flow meter, OPTICS, Berkeley Lab WINDOW, Energy Plus	Periodical analysis	Although the glazing increases lighting loads, it still proposes better daylight performance due to reducing glare risks.
Mesloub et al., 2019	Algeria	Semi-arid	Office building	PV window	a-Si	Daylight and energy	To understand the energy and daylight performance of PV window	Experimental measurements, Reference building, 3D model, and simulation	Energy Plus, Open Studio, Integrated Environment Solution-Virtual environment (IES-VE)	Periodical analysis	Cooling load and glare reduction are minimized. PV window provided a uniform distribution of daylight by keeping illuminance levels between 300-and 700 lx.
Chinazzo et al., 2019	Geneva, Casablanca, Helsinki, Morocco	Temperate, hot-arid, cold	Office building	PV window	Undefined	Thermal, daylight, and energy	To explore thermal and visual comfort and overall energy performance	Reference building, 3D model and simulation, field measurements	Ladybug, Honeybee, Energy Plus, DAYSIM, RADIANCE, MATLAB	Periodical analysis	Results proposed the best design alternation for Geneva and Helsinki with 50 % transmittance

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
											and Casablanca with 20 % transmittance.
Alrashidi 2019	Penryn, UK	Cold	Office building	PV shading	CdTe	Thermal, daylight and energy	To investigate the thermal, daylight, and energy performance of different types of CdTe thin-film based PV glazing	Reference building, field measurements, data analysis, mathematical equations	Measuring tools	Periodical analysis/ steady-state	BISTS enhance daylight performance by reducing glare and increasing UDI. They provide 85 % of hot water and 20 % of heating and cooling demand.
Taveres-Cachat et al., 2019	Oslo, Norway	Nordic	Office building	PV shading	Undefined	Thermal, daylight and energy	To optimize the performance of shading elements for overall performance	Reference building, 3D model and simulation, optimization	Rhino with Grasshopper, plug-ins of Ladybug with Honeybee and Energy Plus, Octopus	Periodical analysis	The authors propose an optimized model for the building's daylight, thermal, and energy performance.
Lee 2019	Seoul, Korea	humid continental	Office building	PV shading	monocrystalline silicon	Daylight and energy	Developing a light shelf covers only some part of the shading element to evaluate daylighting and energy generation at the same time	Reference building, scale model, field tests	Scale model and field test	Steady-state	The optimum incline angle is different for light shelves with or without PV implementation. The uniform distribution of daylight decreases when the PV area changes.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Bennouna et al., 2019	Morocco	Varied	Undefined	PV window	a-Si, monocrystalline, and polycrystalline silicon	Energy	To evaluate the energy performance of different PV glazing systems on various sites	Reference building, field measurements	Measurement tools	Periodical analysis	There occurred a difference in energy performance between seaside and continental cities.
Piccoli and Dama, 2018	Milan, Italy	Temperate	Office building	PV shading	monocrystalline	Energy	To assess the energy performance of the BIPV shading device	Numerical and 3D simulation model	Window LBNL software, Energy Plus, mathematical formulas	Periodical analysis	BIPV shading device can improve glare risks with proper solar control performance.
Aelenei et al., 2019	Lisbon, Portugal	Temperate	Office building	Façade and roof	Polycrystalline and a-Si	Energy	To evaluate the energy performance of two BIPV systems on the roof and façade.	Using a reference building, 3D model and simulation, numerical model	Mathematical equations and measuring instruments	Periodical analysis	BESS's energy flexibility can improve metrics such as load matching and grid interaction.
Yoo 2019	Seoul, Korea	Humid continental	Community center	PV shading	Monocrystalline	Energy and thermal comfort	To assess the thermal and energy performance of a BIPV shading device	Using a reference building, 3D model and simulation	SolCel 19, TRNSYS 17	Periodical analysis	Parameters are optimized for better energy performance and thermal comfort.
Jakica et al., 2019	Varied	Varied	Varied	BIPV review	Varied	Energy, thermal, and daylight	To present tools and methods for BIPV design and performance modeling	Simulation	RET Screen, Homer Pro, Sunnulator, SAM, Polysun, PV Sol, PV-GIS, Skelion, Ladybug, PVsyst, PVwatts, Revit, PV-	Varied	The study comprehensively analyzes the tools used to make a BIPV performance analysis.

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Saretta et al., 2019	Varied	Varied	Varied	BIPV review	Varied	Varied	A comprehensive review of BIPV systems in terms of approaches, methods, tools, and characteristics	Literature review	GIS, Grasshopper Plug-ins Varied	Varied	BIPVs can develop the overall energy performance of a building in a significant manner.
Sarkar et al., 2020	Varied	Varied	Varied	BIPV review	Varied	Development and recent trends	To evaluate recent development and trends on BIPV energy generation	–	–	–	A systematic review is conducted on the recent technologies of BIPV.
Chan 2019	Varied	Varied	Commercial building	Façade	Varied	Energy	To assess the effect of shading on BIPV system's energy performance	Reference building, 3D model, and simulation	Energy Plus	Periodical analysis	Correlation between energy generation ratio and sky view factors is conducted.
Qiu et al., 2020	Beijing, Wuhan, Hong Kong, and Kunming, China	Varied	–	PV window	Undefined	Thermal, daylight, and energy	To see how PV vacuum glazing affects thermal, daylight, and energy performance in various climatic zones	Measurements, real-time tests, 3D modeling, and simulation	Spectrophotometer, Rhino, Ladybug with Honeybee and DAYSIM, Energy Plus	Periodical analysis/ steady-state	In four climatic zones, PV vacuum glazing reduces energy consumption by 43.4 %, 66.0 %, 48.8 %, and 35.0 %, respectively. In hot and temperate areas, they raise cooling demand.
Liu et al., 2020	Birmingham, UK	Temperate maritime climate	Office building	PV window	CdTe	Daylight	To test the effect of varied transmittance of CdTe on daylight performance	Field measurement, simulation	RADIANCE	Periodical analysis	CdTe PV glazing helped improve the uniform distribution of daylight and overall performance.
Mesloub et al., 2020	Riyadh, London, Kuala Lumpur, Algiers	Varied	Office building	PV window	a-Si	Energy and daylight	Assess double-glazing Low-E STPV glazing and double glazed Low-E argon filled a clear glass with interior light shelves for energy and daylight performance	Reference building, 3D model, and simulation	Energy Plus, Rhino with Grasshopper, Diva plug-in of Grasshopper	Periodical analysis	a-Si STPV glazing could not improve daylight performance for east and west, but it contributed to energy saving.
Qiu et al., 2020	Hong Kong, China	Subtropical	Office building	PV window	CdTe	Energy and daylight	To examine the energy and daylight performance of vacuum CdTe PV windows	Reference building, 3D model and simulation, field measurements	RADIANCE simulation, ANN model, spectrophotometer	Periodical analysis	The proposed model presents a more accurate daylight performance result for this hybrid glazing.
Sun et al., 2020	Harbin, Shanghai and Guangzhou, China	Varied	Office building	PV window	CdTe and monocrystalline silicon	Daylight	To explore the daylight performance of various PV glazing options under multiple circumstances and performance measures	Reference building, scale model, field tests, 3D model, and simulation	RADIANCE	Periodical analysis	If crystalline silicon cells and CCPC optics are used together, they can enhance daylight performance.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Alrashidi et al., 2020	UK	Temperate	Office building	PV window	CdTe	Energy	To understand the effect of PV window's orientation and transmittance on reducing cooling loads	Using a reference building, field tests, simulation	Measuring tools, data logger, AAA solar simulator	Steady-state	PV glazing achieved an energy saving of 20 % %.
Mesloub et al., 2020	Algeria	Semi-arid	Office building	PV window	a-Si	Daylight and energy	To assess PV window's daylight and energy performance	Reference building, 3D model and simulation, field measurements,	Energy Plus, Open Studio, Sketch-Up, RADIANCE, measuring instruments	Periodical analysis	Double-glazing PV modules with a 20 % window-to-wall ratio are considered optimal PV windows. They provide 60 % energy saving for the south façade.
Nundy et al., 2020	Undefined	Temperate	Undefined	PV window	undefined	Thermal and daylight	To evaluate thermal and visual comfort of SPD vacuum glazing	Reference building, field measurements	Outdoor test cell, non-calorimetric, PMV, and PPD methods	Periodical analysis	The opaque state did not provide proper daylighting on the overcast sky.
Mesloub et al., 2020	Ha'il, Saudi Arabia	Hot desert	Office building	PV shading	Undefined	Thermal, daylight, and energy	To understand the effects of light shelves' configurations on building performance	Reference building, 3D model, and simulation	Rhino, Diva, and DAYSIM plug-ins of Grasshopper	Periodical analysis	The best configuration for energy and daylight performance is proposed.
Megahed and Radwan, 2020	Mansoura, Egypt	Desert	Residential building	Roof	polycrystalline silicon	Energy, thermal, and cost	To develop a PV system for supplying some of the building's energy demand	Reference building, numerical and simulation model	Mathematical formulas, ANSYS Fluent 19.2	Periodical analysis	PV system with a coolant flow rate (2 L/min) module can produce the maximum electrical energy with satisfied thermal energy.
Ghosh 2020	Varied	Varied	Varied	BIPV review	Varied	Energy, thermal, daylight	To conduct a comprehensive review on BIPV and (BAPV)	Literature review	–	–	Obstacles that produce shading on PV systems may obstruct PV installation.
Li et al., 2020	Tianjin, China	Monsoon	Educational building	Facade	monocrystalline	Energy	To understand the effect of shading conditions on a BIPV system's overall performance	3D model and simulation, numerical model, field measurements	ANSYS, COMSOL Multiphysics, mathematical formulas, measuring instruments	Steady-state	Shading and masking conditions are effective in the performance of a PV.
Ramanan et al., 2020	Tamil Nadu, India	Hot and humid	Educational building	Facade	polycrystalline	Energy	To evaluate the effect of orientation and incline angle on the performance of the BIPV system	Field experiments, 3D model, and simulation	HOMER, mathematical formulas, measuring instruments	Periodical analysis	The East façade is the optimum orientation for BIPV implementation. South orientation is the best performed one for pitched roofs.
Paydar and Meysam, 2020	Tehran, Iran	Cold semi-arid	Undefined	PV shading	Undefined	Energy	To assess the energy performance of a BIPV shading device with different incline angles	Reference building	Energy Plus and MATLAB	Periodical analysis	The optimum PV system is proposed. Movable shading devices performed better than fixed ones in energy generation and thermal loads.
Jung et al., 2020	Michigan, USA	Continental	Office building	PV shading		Energy and daylight	To develop a BIPV shading device model	Reference building,		Periodical analysis	Results present a consistency between

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Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
					Undefined		to save energy and enhance visual comfort	numerical and experimental model	ANN model, scale model, measuring instruments		the ANN model and experiment results in energy and daylight performance.
Yadav and Panda, 2020	Delhi, India	Humid subtropical	Two stories small building	Roof	Undefined	Thermal	To evaluate the thermal performance of a semi-transparent BIPV on a building roof	Reference building, numerical and experimental model	Mathematical equations and measuring instruments	Periodical analysis	On the 15th of May, rooms have the highest indoor temperature values as 47.3 °C and 42.6 °C.
Alrashidi et al., 2020	Penryn, UK	Temperate	Education building	PV window	CdTe	Thermal	To develop an experimental model to test a PV system's thermal performance	Experimental measurements	UV–Vis-NIR, Class AAA+, AM 1.5, NI logging system, K-type thermocouple sensors, Pyrheliometer and Pyranometer	Steady-state	The overall heat transfer coefficient (U-value) of the PV module was found as 2.7 W/m^2K
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Yahya et al., 2020	Baghdad, Iraq	Hot desert	Office building	PV shading	Undefined	Energy	To evaluate the energy generation capacity of a PV shading device on façade	Reference building, 3D model and simulation, statistical data analysis	Autocad, Sketch-Up, ModelIT-IES, IES-VE, LBNL Window 7.5,	Periodical analysis	A systematic approach is needed for the further development of the BIPV system.
Tonui et al., 2018	Varied	Varied	Varied	BIPV review	Perovskite		To discuss challenges and current situation of perovskite-based cell technology in the industry	Literature review	–	Varied	Perovskite-based cell challenges, potential, current situation, and knowledge are discussed.
Saretta et al., 2020	Ticino, Switzerland	Warm humid	Residential	Façade	Undefined	Daylight	To present a calculation method for radiation estimation	Reference building, numerical model, 3D model, and simulation	Mathematical equations, Python, SwissALTI3D, DOM, SRTM, GIS tools, Radiance, DAYSIM		The proposed method can enhance current solar radiation prediction and implementation for solar city planning.
Gosh et al., 2021	Riyadh, Saudi Arabia	Hot desert	–	PV window	Perovskite	Daylight	To understand the effect of perovskite BIPV windows on visual comfort and proper daylight performance	Reference building, 3D model, and simulation	Rhino with Grasshopper, Diva plug-in of Grasshopper		For a south-facing façade, optimum glazing transmittance should be between 50- and 70 %. Transmittance should be around 90 % for improved color rendering, which may create glare problems.
Lee et al., 2021	Undefined	Undefined	Office building	PV shading	Polycrystalline silicon	Energy	To develop a scale model to estimate the BIPV shading elements' thermal and daylight performance	Reference building, scale model and field tests, numerical model	Monitoring by sensors, math formulas	Periodical analysis	Light shelve incline angle and PV module installation area effectively affect daylight uniformity and thermal performance.
Gholami and Nils, 2021	Stavanger/ Norway, Bern	Varied	Undefined	Facade	Varied	Energy and daylight	To understand the effect of climate and		Measurement tools	Periodical analysis	Solar radiation of whole façade is higher

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Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
	/Switzerland, Rome/Italy, and Dubai/ UAE						weather on solar radiation, BIPV's performance	Reference building, field measurements			than average radiation on the east and west facades. Also, there found a correlation between the performance of solar cells and climate
Gonçalves et al., 2021	Leuven, Belgium	Temperate	Undefined	Facade	Undefined	Thermal	To propose a combination of CFD with a multi-physics BIPV model to assess its thermal performance	Reference building, 3D model and simulation, field measurement	openIDEAS/ Modelica mathematical formulas,	Steady-state	eCHTC variations may change cell temperatures up to 17 %. Also, near-edge zones have lower temperatures while bottom and center zones have higher.
Li et al., 2021	Chengdu, China	Temperate	Undefined	PV window	monocrystalline	Energy and daylight	To develop a BIPV and improve its daylight and energy performance	Reference building, field measurement, 3D model, and simulation	Scale model,	Steady-state and periodical	The daylight performance of a PV façade can be improved with good design. The highest energy saving of 26.5 % is achieved during the winter months.
Maghrabie et al., 2021	Varied	Varied	Varied	BIPV review	Varied	Varied	To conduct a comprehensive review on the application and challenges of BIPV systems	Literature review	–	Varied	Challenges and motivations with prospects of BIPV systems are presented due to the study.
Azami et al., 2021	Tabriz, Iran	Temperate climate	Office building	Facade	monocrystalline	Energy	To understand the role of building envelope for energy performance of BIPV systems with a parametric model	Using a reference building, numerical and 3D simulation model	DesignBuilder, mathematical formulas	Periodical analysis	Results imply a correlation between energy generation and form configuration with orientation.
Kuhn et al., 2021	Varied	Varied	Varied	BIPV review	Varied	Technology	To present widely analyzed BIPV systems in terms of technological opportunities	Literature review	–	Varied	The paper presents several design options for structural integration of the BIPV system on the building envelope.
Gulami et al., 2019	Varied	Varied	Non-domestic	BIPV review	Varied	Cost	To review the economic feasibility of BIPV systems in different regions	Literature review	–	Varied	Economic analysis of built projects shows that BIPV is economically feasible.
Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Syafaruddin and Said, 2021	Varied	Varied	Varied	BIPV review	Varied	Technology, cost, energy	To review the current technology and situation of BIPV systems	Literature review	–	Varied	New trends, opportunities, and challenges are discussed in the study.
Singh et al., 2021	Varied	Varied	Varied	BIPV review	Varied	Cost and thermal	To discuss the applicability and performance of phase-	Literature review	–	Varied	PSM decreases module and building

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
							change materials in BIPV				envelope temperatures.
Liu et al., 2021	Varied	Varied	Varied	BIPV review	Varied	Energy, aesthetic value	To review the feasibility of BIPV systems to increase their utilization in areas with high solar irradiation	Literature review	–	Varied	An optimum system is emphasized based on the factors that affect BIPV performance.
Rababah et al., 2021	Southeast Asia	Tropical	Varied	BIPV review	Varied	Overall performance and cost	To define the effects and challenges of BIPV application considering cost, climate, and government policy	Literature review	–	Varied	Climate and government policy substantially affect BIPV performance, efficiency, and technology improvement.
Rajoria et al., 2021	Varied	Varied	Varied	BIPV/T review	Varied	Energy and thermal	To review current developments of BIPV/T systems on building performance	Literature review	–	Varied	BIPV/T performance strongly depends on the climate and building design variables.
Martín-Chivelet et al., 2022	Varied	Varied	Varied	BIPV review	Varied	Thermal, energy, and daylight	To review thermal, solar, optical, and electrical aspects of BIPV systems	Literature review	–	Varied	The study presented knowledge of BIPV's thermal, solar, optical, and electrical aspects.
Bloem et al., 2012	Varied	Varied	Varied	BIPV review	Varied	Technology, life cycle assessment, and outdoor testing	To analyze outdoor test systems, technological improvement, and life cycle assessment of BIPV	Literature review	–	Varied	Different test systems are reviewed and presented for future improvements in the BIPV industry.
Chen et al., 2019	Phoenix, USA	Hot desert	High rise residential tower	PV window	a-Si	Thermal, daylight, and energy	To investigate building parameters and urban landscape's effect on PV window performance	Monitoring, numerical model	BEM-SLUCM model, mathematical equations,	Steady-state and periodical	The optical and thermal aspects of PW windows do not significantly affect urban microclimate.
Alrashidi et al., 2022	Penryn, UK	Temperate	Office building	PV window	CdTe	Thermal and energy	To understand window-based variables' effect on thermal and energy performance	Reference building, outdoor experiment, numerical model	Class AAA+, AM 1.5, mathematical equations	Steady-state and periodical	The relationship between window-based variables and building thermal and energy performance are discussed.
Wijeratne et al., 2022	Melbourne, Australia	Subtropical	Commercial	Roof and skylight	Varied	Energy and cost	To optimize BIPV envelope parameters, high energy generation and low life cycle cost	Reference building, 3D model and simulation, optimization	NSGA II, mathematical equations, Revit	Steady-state and periodical	Results present optimum roof sheet and skylight solutions for higher energy generation and lower life cycle costs.
Samarasinghalage 2022	Australia	Subtropical	Undefined	Roof, canopy, and cladding	Undefined	Energy and cost	To optimize BIPV energy generation and life cycle cost together with building envelope parameters and BIPV application type	Reference building, 3D model and simulation, optimization	Revit, NSGA II, Python, PyCharm IDE	Steady-state and periodical	In the early design stage, multi-objective optimization is effective.

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Table 1 (*continued*)

Reference	Location	Climate	Building function	Field of Application	Cell type	Performance Criteria	Aim	Methodology	Tools	Analysis Type	Results
Singh and Chaudhary, 2022	Indore, India	Tropical	Education building	Roof	Polycrystalline silicon	Thermal	To compare the thermal performance of insulated and non-insulated BIPV roofs	Reference building, scale model, numerical model	K-type thermocouple, datalogger, mathematical formula	Steady-state and periodical	Heat gain, heat loss and module temperature changes due to different insulation materials applied on BIPV.
Zhang et al., 2022	Hefei, China	Humid subtropical	Undefined	PV window	CdTe	Thermal and energy	Compare different PV glazing types' thermal and energy performance	Reference building, numerical model	Dataloggers, thermocouples, mathematical formula	Steady-state and periodical	Vacuum glazing improves the thermal performance of PV double-skin windows due to a lower U-value.
Kirimtat et al., 2022	Varied	Varied	Varied	PV shading	Varied	Cost and energy	To conduct comprehensive research on PV integrated shading devices and their cost and energy behavior	Literature review	–	Varied	A detailed analysis of current literature is presented regarding PV integrated shading devices.
Wang et al., 2022	Hefei, China	Humid subtropical	Undefined	PV window	CdTe	Thermal, energy, and daylight	To analyze thermal, daylight, and energy performance of CdTe-based PV window	Reference building, 3D model and simulation, numerical model, outdoor test	EnergyPlus, Sketch-Up, WINDOW, mathematical formula, measuring tools	Steady-state and periodical	CdTe window can improve thermal, energy, and daylight performance by providing better color rendering.

a BAPV system or directly integrated into a building wall by replacing the wall with the PV as a BIPV system. BAPV systems include a gap between the building envelope and PV to enhance performance (Ghosh, 2020). Although second generation cells are now being used in façade applications, silicon-based cells still account for 34 % of applications (Pierluigi et al., 2015). Third-generation cells are rarely used. The main reason for the continued use of silicon-based cells is their high energy generation capacity and efficiency.

2.1.3. Glazing applications

The integration of PV technology into windows increases the potential of fenestration systems. In today's technology, semi-transparent thin-film solar cells are implemented on windows. This newly emerged technology contributes to the energy generation capacity and improves daylight and thermal performance (Sun et al., 2020). BIPVs can be implemented on facades, and their optical properties may vary according to the energy demand of the building (Heinstein et al., 2017). A PV window's type, performance, and efficiency depend on its solar cell characteristics. With the newly emerged types, silicon-based and non-silicon-based cells are available in the industry. The silicon-based ones are monocrystalline, multi-crystalline, and amorphous silicon (a-Si). The non-silicon-based ones are cadmium sulphide (CdS), cadmium telluride (CdTe), copper indium selenide (CIS), and perovskite thin-film. There are also other non-silicon-based solar cells still in the experimental stage in the laboratory (Jelle et al., 2012).

According to the type of solar cell, there may be variations in the color and transmittance properties of the façade. Energy production efficiency may decrease for additional color and shading properties. Also, solar cells on the façade can be combined with double or triple glass panes, enhancing the system's thermal and acoustical insulation capacity (Cannavale et al., 2017). BIPV windows can control daylight penetration through the building and solar gain due to the amount of daylight entering, reducing the heat flow between indoor and outdoor environments. Solar gain and daylight performance of the building are also related to the PV coverage area of glazing. Studies show that the PV coverage area is more effective in thermal and daylight performance than in system efficiency. Efficiency and thickness directly affect power generation capacity; transmittance generally increases with thinner systems, but power generation decreases (Ghosh, 2020).

2.1.4. Shading system applications

As a capability of shading systems, these improve the daylight performance of an environment (Cesari et al., 2018). Also, they contribute the thermal performance by blocking excessive solar radiation (Jayathissa et al., 2017). Lately, PV systems have started to be implemented on shading elements due to their great potential (Fig. 1). Studies show

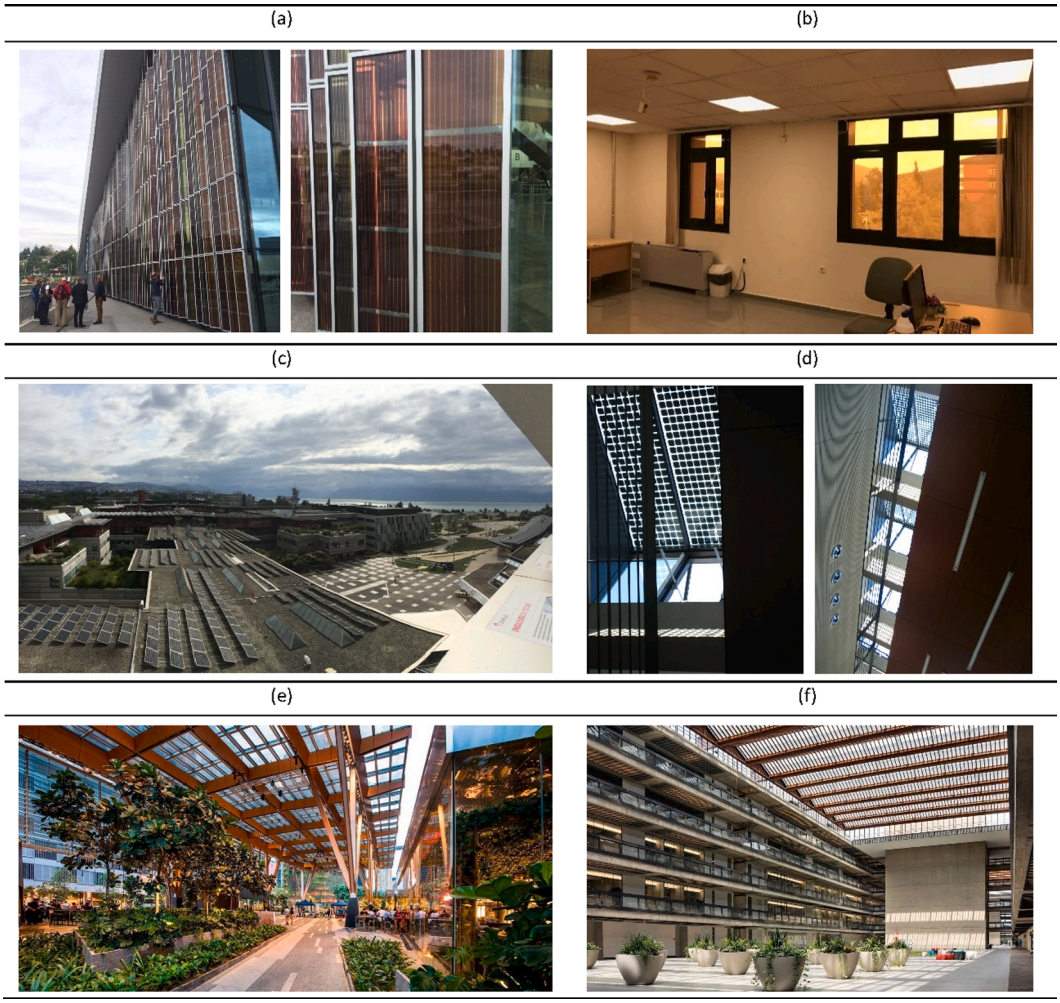

Fig. 1. (a) PV glass implementation on SwissTech Convention Center in Lausanne, Switzerland (Photo by Dr. Berk Ekici) (b) PV window application on the south façade of an education building in IZTECH Campus (c) PV implementation on the roof of EPFL building in Lausanne, Switzerland (Photo by Dr. Berk Ekici) (d) PV implementation on the roof of Schüco in Bielefeld, Germany (Photo by Dr. Onurcan Çakır) (e) PV canopy implementation on Tanjong Pagar Center by SOM Architects in Singapore by Solar Company ONYX SOLAR ENERGY S.L. (ONYX SOLAR ENERGY S.L., 2022) (f) PV skylight implementation on Bell Works building in Holmdel, NJ (Solar Company: ONYX SOLAR ENERGY S.L.) (ONYX SOLAR ENERGY S.L., 2022).

that PV-integrated shading elements effectively improve daylight uniformity while reducing the building's heating and cooling loads (Heangwoo et al., 2021a, 2021b). Some considerations must be studied during the design phase of PV-integrated shading systems since they affect their overall performance. The key ones are orientation, tilt angle, and a film type of shading element (Jayathissa et al., 2017). For instance, a study showed that the power performance of PV shading elements is better when placed horizontally, which results in more energy generation (Hwang et al., 2014). Also, one study shows that the optimum incline angle is different for a light shelf with and without PV implementation, and the uniform distribution of daylight decreases when the PV attachment area changes (Lee, 2019). Therefore, it is important to investigate these variables to optimize performance. PV-integrated shading devices can be either movable or fixed systems and can be designed in any size and shape. However, since these systems will obstruct the view and create shade, their daylight performance should be well investigated. BIPV systems can be implemented on a wide range of building components. As explained so far, these components are the roof, wall, window, and shading elements. However, BIPV systems may also be implemented on even slabs and skylights with new developments. This is generally preferred in public buildings and open areas. According to the solar cell, the system can be opaque and semi-transparent (ONYX SOLAR ENERGY S.L., 2021). The following variables for PV panels are significant for their overall energy performance: orientation, tilt angle, outdoor temperature, climate, geographical region, and cell type (Knera et al., 2015). Fig. 1 shows different BIPV implementations for various building facades.

2.2. Production technologies

The cells in the PV module are between a weatherproof backing and a transparent cover to protect the system from outdoor exposure. The cells are laminated with tempered and low iron-content glass on the front face. Glass protects from water, moisture, and contaminant gases. On the back part, there is a thin polymer sheet or glass. To supply adhesion, there is also a layer called ethyl vinyl acetate (EVA) on each side of the cell. An aluminum frame strengthens the system (Petter Jelle et al., 2012). According to their production technologies, there are several types of solar cells. First-generation PV cells were first introduced in the industry and remain the best-known and most-used ones in the PV sector. Monocrystalline and multi-crystalline silicon solar cells are included in First generation cells. With the development of technology, second-generation cells were introduced, generally known as thin-film solar cells. These have different materials and systems inside. The most used ones are a-Si, CdS, CdTe, and CIS solar cells. Other thin-film PV technologies are still under development, such as perovskite thin-films. Lastly, organic solar cells (OSC) are also being developed and introduced into the industry (Ghosh, 2020). Fig. 2 shows the scheme of production techniques of BIPV technology.

2.2.1. First-Generation PV cells

There are two main types of first-generation PV cells, called "first-generation crystalline silicon PV cells," monocrystalline and multi-crystalline silicon PV cells. Both cells are durable and healthy, posing no risk to indoor air quality since they are not toxic (Battaglia et al., 2016). They gained popularity between 2000 and 2008, resulting in higher prices and lower affordability. However, their costs decreased significantly in the last decade (Ran et al., 2015). Their energy payback time varies between three and four years (Luo et al., 2018).

2.2.1.1. Monocrystalline silicon PV cell. Monocrystalline silicon PV cells are produced with the Czochralski method, generated from single silicon crystals. Their manufacturing process is quite expensive since they require a specific processing period. Their energy pay-back time is around 3–4 years (Ghosh, 2020). Their efficiency varies between 16 and 24 %. They generally have dark colors, such as black and grey. Monocrystalline silicon cells' power per unit area varies between 75 and 155 Wp/m^2 (Petter Jelle et al., 2012). They have a more circular cell shape than multi-crystalline cells (Tripathy et al., 2016).

2.2.1.2. Multicrystalline silicon PV cell. The solidification of molten silicon material produces polycrystalline silicon PV cells. These have a lower efficiency than monocrystalline ones but have a similar energy payback time (Ghosh, 2020). Their efficiency varies between 14 and 18 %. They are less expensive due to their relatively straightforward manufacturing process. They generally are a shiny blue color because of the tiny crystals. Monocrystalline silicon cells' power per unit area varies between 75 and 155 Wp/m^2 (Petter Jelle et al., 2012). They have a square cell shape and are similar in size to monocrystalline cells. Multicrystalline cells have many reflective facets, while monocrystalline cells are more uniform (Tripathy et al., 2016).

2.2.2. Second generation PV cells (Thin-film solar Cells)

Thin-film solar cells mainly consist of thin layers of semiconductor materials implemented on an opaque backing material. According to the use of material, there are several types of thin-film solar cells: a-Si, CdS, CdTe, and CIS thin-film cells. First- and second-generation cells differ in materiality, but their structure and functioning are similar. Structurally, they consist of multiple, very thin layers. The arrangement of these layers is flexible (Tripathy et al., 2016). They can be combined with other smart window systems, such as Low-E coating.

Called "second generation," they were produced after first-generation silicon PV cells. In terms of cost, they are more affordable, but their efficiency is generally lower than silicon solar cells, and their

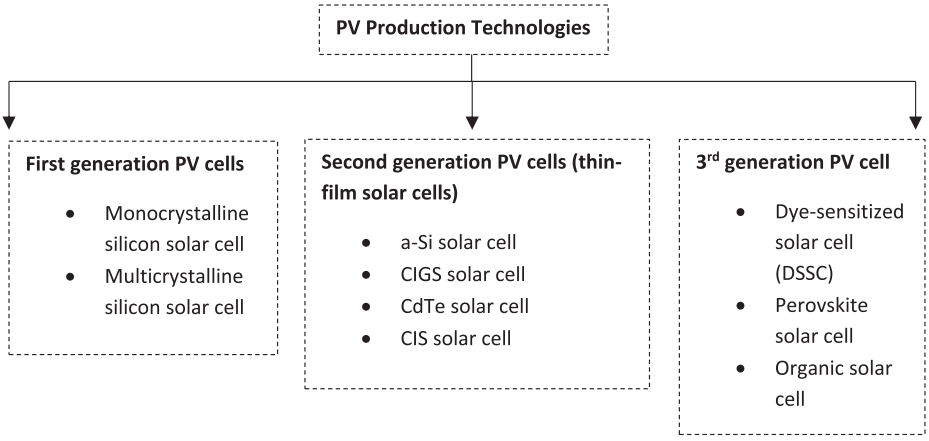

Fig. 2. PV production technologies.

performance may decrease after prolonged exposure to the outside environment. Despite such obstacles, thin-film solar cells are becoming popular. Radiation, incidence angle, outside temperature, and wind speed influence thin-film cells' performance and efficiency. In comparison, thin-film PV cells capture the solar spectrum more efficiently than first-generation PV cells (Ghosh, 2020). Thin-film solar cells have the advantage of a wide range of application areas and can be implemented on windows and vehicles (Tripathy et al., 2016).

2.2.2.1. Amorphous silicon (a-Si) Thin-film. a-Si solar cells' efficiency is lower than silicon-based cells, generally between 4 and 10 %. However, they perform better in higher and lower temperatures. The spectral changes of the ground radiation in summer and winter significantly affect the efficiency of a-Si solar cells (Ghosh, 2020). Their thickness, size, and used areas may vary. a-Si solar cells have three advantages: Firstly, structurally, they are more flexible than conventional silicon-based cells; secondly, despite being less efficient, they are cheaper to produce (Tripathy et al., 2016); and finally, they can have different transparencies between fully opaque and transparent. As shown in Fig. 3, different colors can be produced according to the user's preference, designer, etc. Their energy payback time varies between 2 and 3 years (Ghosh, 2020).

2.2.2.2. Copper indium gallium diselenide (CIGS) Thin-film. It is understood from its name that copper indium gallium diselenide (CIGS) thin-film solar cells consist of copper, indium, gallium, and selenium materials (Liu and Chuang, 2012). Their costs are less than silicon-based cells but more expensive than other thin-film cells. Compared with other technologies, their efficiency is moderate, between 12 % and 15 %. However, higher efficiency values are reached in a laboratory environment (Buecheler et al., 2011). They can generally keep their initial power, even after 20 years, as an advantage. Their energy payback time varies between 1.2 and 2.4 years. Additionally, their operational lifetime is 20 years (Ghosh, 2020).

2.2.2.3. Cadmium telluride (CdTe) Thin-film. CdTe thin films are emerging technologies in the thin-film cell industry, being more cost-effective than other technologies. They are produced on a substrate glass with transparent conducting oxide (TCO). TCO is generally made from fluorinated tin oxide (FTO) material. Their color is reflective, primarily dark green or black. Their efficiency varies between 9.4 and 13.8 % (Petter Jelle et al., 2012). They have a short energy payback time and 20 years of operational lifetime (Ghosh, 2020).

2.2.2.4. Copper indium selenide (CIS) Thin-film. CIS cells are the industry's most efficient types of thin-film cells. Generally, their efficiency varies between 11 and 18.7 %. Like CdTe thin-films, their color is usually dark gray or black (Buecheler et al., 2011).

2.2.3. Third generation PV cells

Although first- and second-generation PV cells are seen as technologically groundbreaking systems, their electricity generation capacity is limited. Not all solar energy can be transformed into electrical energy, as some energy turns into heat. The main advantage of third-generation PV cells is that they are highly efficient and can convert most of the collected solar energy into electrical energy. Additionally, they are low-cost (Dupré et al., 2015).

2.2.3.1. Dye-sensitized solar cell (DSSC). Dye-sensitized solar cells consist of three components: organic dye, electrolyte, and semiconductor layer sheets. Unlike conventional solar cells, these can be implemented on windows, terraces, facades, etc. Unlike the other cells mentioned above, natural elements can produce dye-sensitized solar cells, making them more affordable (Varga and Racz, 2021). They are flexible in shape, color, transmittance, and size. Their efficiency reaches 11.9 %, and they have a short energy payback time. Their operation time is similar to that of other cells, i.e., an average 20-year lifetime. (Ghosh, 2020). They can work under overcast sky conditions (Gong et al., 2017). Their energy payback time varies between 2 and 2.63 years for different cell efficiencies (Greijer et al., 2001). Their performance is dependent mainly on the system's photoanode material properties. Generally, TiO_2 is used for photoanodes since it has a large energy gap, chemical stability, is non-toxic, and low cost (Nien et al., 2021).

2.2.3.2. Perovskite solar cell (PSC). PSCs' power efficiency varies between 3 % and 22 % (Ghosh, 2020). In terms of efficiency, it reaches higher values than other cells (Zardetto et al., 2014). Perovskite has a formula of ABX_3. A is the cation, and B is the anion. Generally, they use methyl-ammonium-lead-iodide ($MAPbI_3$/ $CH_3NH_3PbI_3$) in their system. PSCs are suitable for windows because they provide sufficient transparency and power efficiency (Cannavale et al., 2017). The optical properties of PSCs are different than other cells, with a high absorption coefficient and low reflection (Hossain et al., 2020). In this sense, these are different than silicon-based solar cells. However, it is similar to DSSCs (Fig. 7). Energy pay-back time is not very well studied, but some studies suggest that it can vary between 0.2 and 5 years, depending on the material used (Espinosa et al., 2011; Gong et al., 2017).

2.2.3.3. Organic solar cell (OSC). OSCs are more efficient and cost-effective than conventional silicon-based solar cells. They can absorb light and produce electricity through conductive organic materials (Mime et al., 2021). Their efficiency is reportedly between 5 and 14 % due to organic material's high absorption coefficient (Ameri et al., 2013). As a disadvantage, excitons diffusion length is smaller than inorganic cells, and they are not appropriate for areas lacking light since this affects photons' energy levels (Sajjad et al., 2020). Their thermal coefficient is low, and they are not resistant to outdoor exposure. Their energy pay-back time is relatively shorter than other cell types, although



Fig. 3. (a) Colored (orange) PV glass application in Block E, IZTECH Campus (b) Colored (blue) PV glass application in Block E, IZTECH Campus *Glazings are supplied by ONYX SOLAR ENERGY S.L. to be used for a Doctoral Thesis supported by TUBITAK. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

their efficiency is not very high. Pay-back time varies between 0.79 and 2.02 years (Ghosh, 2020). Their transparency varies between 16 and 41 %, but increased transparency can be achieved at the cost of efficiency (Petter Jelle et al., 2012).

Fig. 4 shows implementation examples of varied solar cells in different parts of the building facades. As shown in Table 2, each solar cell has different properties, advantages, and disadvantages. Thus, their properties should be well understood, and their selection process is significant.

Studies have shown that BIPV systems have developed considerably in the process. The developments in the industry have identified the deficiencies in these systems and tried to eliminate them. The first-generation solar cells' opaque appearance turned transparent in the second and third generations. While higher-efficiency solar cells are being produced, BIPV systems have started to be integrated into different parts of buildings.

3. Results & discussion

Studies are reviewed and analyzed, as indicated in Table 1. Most studies can be divided into three categories based on their implementation areas: roof, façade, window, and shading device implementations of BIPV systems. Recently, BIPV systems have started to be implemented on different building elements, such as windows and shading devices.

Previously, these systems were more integrated with vertical facades and roofs. While reviewing the literature in online databases, the following keywords were used *BIPV, PV, PV shading device, PV window*, etc. The significant studies in the literature were reviewed and investigated in terms of publication years, locations, climate, building function, field of application, cell type, performance criteria, aim, methodology, tools used in the study, analysis type, and results. The review result is analyzed in this section based on these criteria. As shown in Fig. 5, the studies were conducted from 2002 to 2022. 60 % of the papers in the literature review were published in the last five years. There has been an increase in published articles related to BIPVs in recent years, and the graph suggests that this trend may continue soon.

BIPV implementation depends on the following factors: country population, government policies, geographical location, and climatic characteristics (Fig. 6). BIPV systems have begun to be implemented in some countries in Europe and China. The spread of its usage is due to its great potential. Fig. 7 displays the 27 countries that implement BIPV technology. The most important countries are China, Korea, the UK, Brazil, and the USA, perhaps due to these countries' populations and government policies. For example, China and Brazil have seen dramatic increases in population in recent years. The increase in population also increases construction and energy consumption in cities. Therefore, BIPVs gained importance in saving energy in China and Brazil due to the

Building name	Visual	Location	Manufacturer	Field of application	Solar cell type
Bilbao Kukullaga Station	 (ONYX SOLAR ENERGY S.L., 2022)	Bilbao, Spain	ONYX SOLAR ENERGY S.L.	Skylight	a-Si
Corison Winery	 (ONYX SOLAR ENERGY S.L., 2022)	California, USA	ONYX SOLAR ENERGY S.L.	Roof	Crystalline silicon
Autonomous Office	 (ONYX SOLAR ENERGY S.L., 2022)	Asturias, Spain	ONYX SOLAR ENERGY S.L.	Façade	CIGS
Solstex, Solar facade system integrated with ACM and Granite for the reclad of the EllisDon offices	 (Elemex®, 2022)	London, ON	Elemex®	Façade	CdTe
College of Pierre Mendes	 (©Heliatek/LaRochelle, 2022)	La Rochelle, France	©Heliatek/ LaRochelle	Roof	OSC

Fig. 4. Varied solar cell implementation on buildings.

Table 2
Comparison of different cell types in terms of materials, efficiency, and appearance.

Item no	Solar cell type	Efficiency (%)	Appearance	Material type	Transparency	Energy payback time (year)	Advantages	Disadvantages
1	Monocrystalline silicon	16–24	dark grey, black	single silicon crystals	opaque	3–4	High efficiency, high durability	High manufacturing process
2	Polycrystalline silicon	14–18	shiny blue	molten silicon	opaque	3–4	Easy manufacturing process, high durability, high efficiency	Less expensive than monocrystalline silicon cells, more expansive than thin-films
3	a-Si	4–10	Varied	non-crystalline silicon	Varied transparency	2–3	More flexibility in size, shape, color, transparency, and implementation areas, cheaper, low-temperature processing, short energy payback time	Less efficiency
4	CIGS	12–15	Varied	copper, indium, gallium, and selenium	Varied transparency	1.2–2.4	Short energy payback time, long operational lifetime	More expansive than other thin-film cells
5	CdTe	9.4–13.8	Varied	cadmium and tellurium	Varied transparency	0.75–2	Cost-effective, short energy payback time	Low efficiency compared to other thin films has toxic effects on human health, complicated recycling, and disposal process
6	CIS	11–18.7	Dark gray and black	Copper, indium, and selenide	Varied transparency	–	Most efficient thin-film cell, short energy payback time	–
7	Dye-sensitized	Up to 11.9	Varied		Varied transparency	2–2.63	Affordable, flexible in terms of shape, color, transmittance, and size, short energy payback time, ability to work under overcast sky conditions, non-toxic	Low efficiency
8	Perovskite	3–22		methyl-ammonium-lead-iodide			High efficiency, long diffusion lengths, high mobility, tunable bandgaps, low cost,	require a large area for module fabrication, stabile system device
9	OSC	5–14	Varied	carbon-based conductive organic molecules	Varied transparency	0.79–2.02	Low cost, short energy payback time	Small excitons diffusion length, not appropriate for areas which lack light, low thermal coefficient, low resistance to outdoor exposure

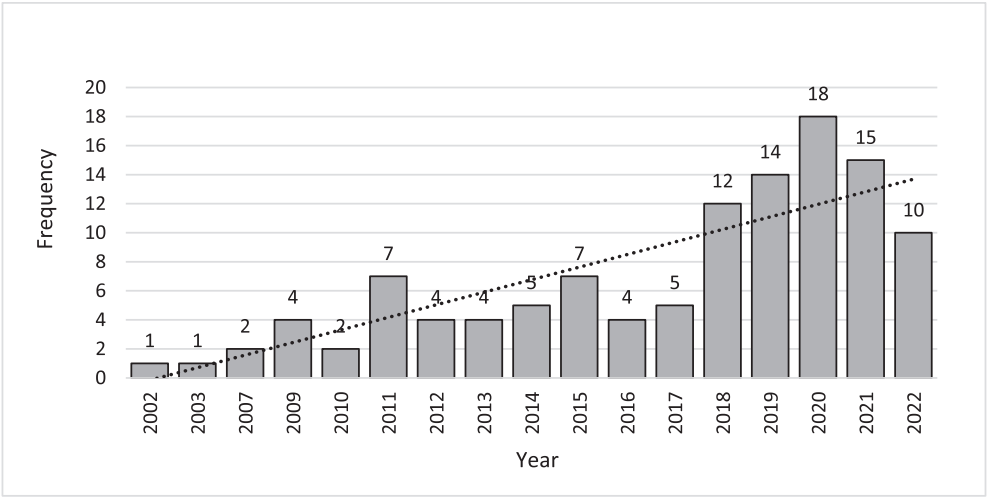

Fig. 5. The number of annually published papers in 2002–2022 on BIPVs.

large population. Although the population is lower in Korea, the UK, and Germany, these countries' governments strongly support BIPV investments (Osseweijer et al., 2018). Therefore, this may reflect the BIPV industry and literature. Additionally, BIPV implementation is related to the geographical conditions of countries.

BIPV systems are more beneficial in low-latitude regions where the sun angle is more direct. Results show that BIPVs are more implemented in temperate, subtropical, cold, moderate, and Mediterranean climates. BIPV implementation is stronger in some countries with cold temperatures, despite relatively low solar gain due to government policies.

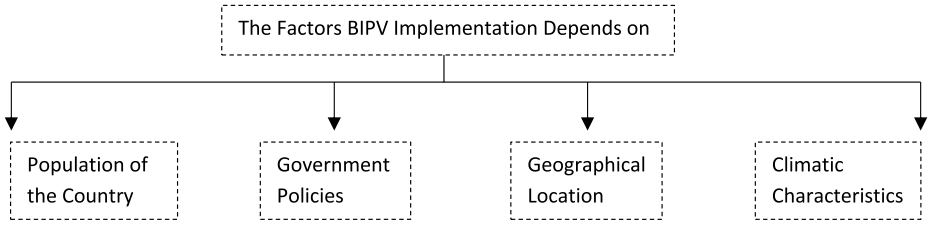

Fig. 6. The factors BIPV implementation depends on.

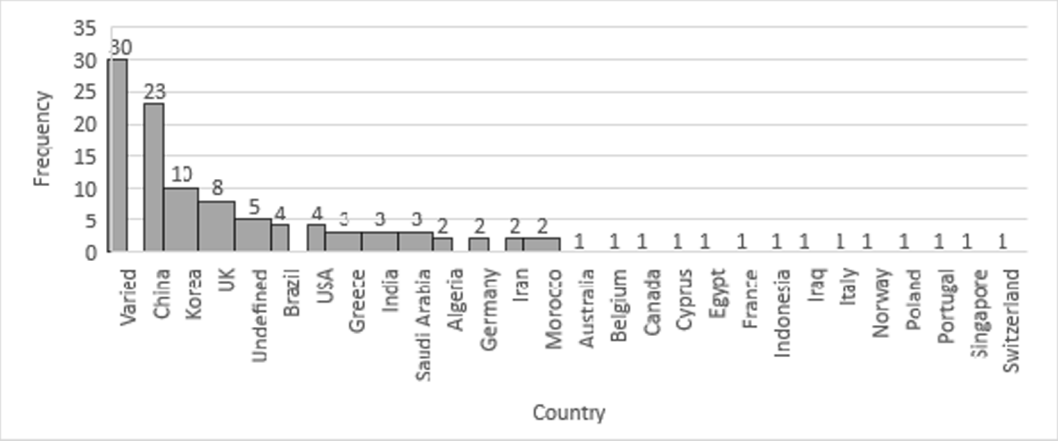

Fig. 7. BIPV systems implemented in countries.

However, it is seen in Fig. 8 below that with very high solar gain in hot countries, BIPVs are less popular in hot and hot desert climates compared to cold climate regions. This may be because BIPVs –mainly applied on vertical surfaces- may increase the temperature of the interior environment since they store all the heat and convert only some portion of it to energy.

One of the literature review's most significant aspects is comparing selected cell types used in studies. Cell type selection is crucial because it affects a BIPV's overall performance, cost, appearance, and payback time. In the literature review, seven different cell types are used. The most used cells are a-Si, monocrystalline, and multi-crystalline solar cells, with 25 %, 23 %, and 17 % (Fig. 8). These are the most popular, being the industry's most efficient, flexible, and cheapest cells. Other cells used in studies are CdTe, CIGS, CID, and perovskite-based cells, but they are less common due to their recent emergence in the industry. Therefore, their performance is still being tested in labs.

The studies were conducted with different methods and materials. Some use experimental procedures, and others simulation methods. Each study and its method and tools used are described in Table 1, and a summary is presented in Fig. 9. There are many digital and manual tools for assessing a BIPV's performance. Some studies use mathematical formulas, monitoring, and real experiment methods, while others use only digital techniques, and yet others, use both (Fig. 10). In terms of monitoring tools, many devices assess a building's energy, thermal, and daylight performance when a PV system is applied to the building envelope. The literature analysis of experimental studies shows that most of them implemented PV as a glazing or shading element. Thus, they mainly use a-Si and crystalline-based solar cells. Many of them used office type of buildings as references. This may be due to the fact that office buildings are usually high rises and have larger surface areas to

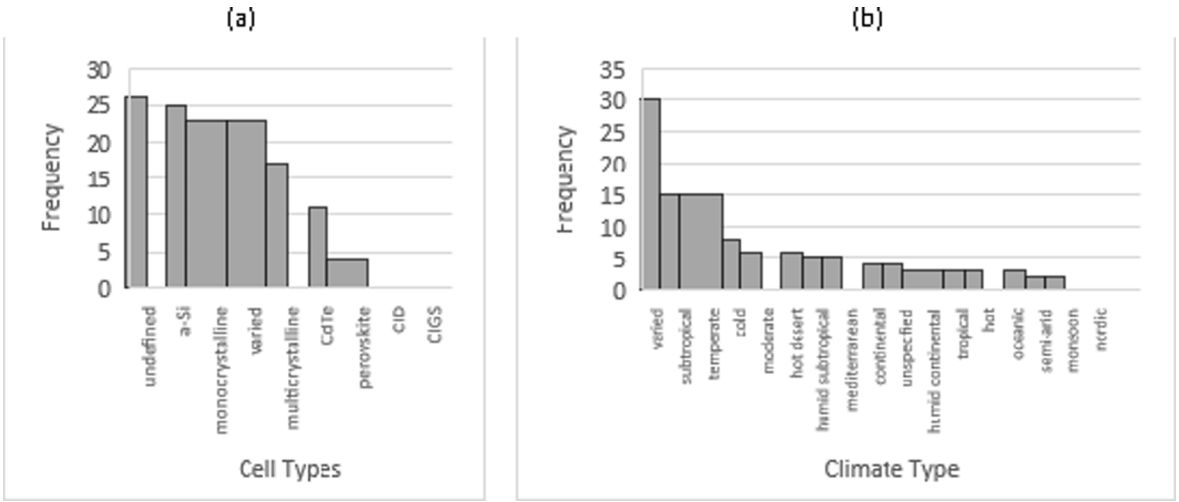

Fig. 8. (a) Solar cell types used in studies (b) Climate types in studies.

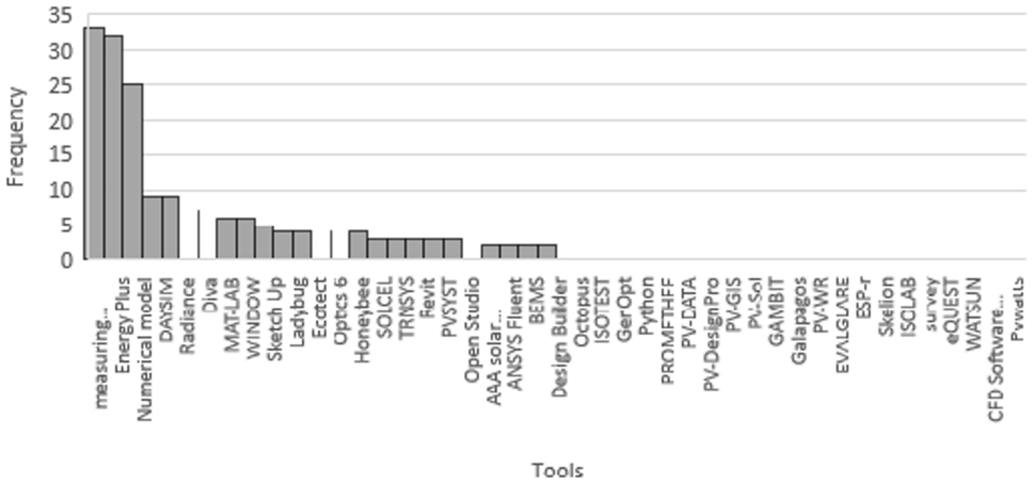

Fig. 9. Tools used in the studies.

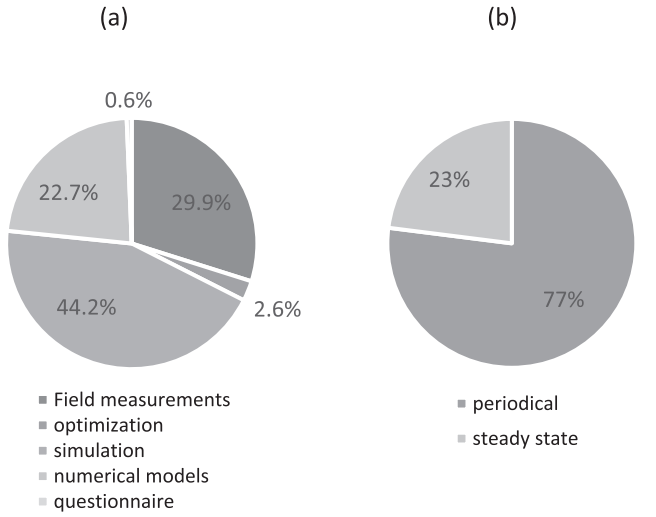

Fig. 10. (a) Experimental conditions (b) Analysis type of the studies.

implement PV on their vertical surfaces. The climatic conditions of the studies are mostly subtropical and temperate climates. The performance criteria are primarily assessing the energy generation capacity of the PV system and the daylight performance of the selected room or building. In terms of digital methods, a wide range of software is used to assess a BIPV's energy performance. They are as follows: Energy Plus, Open Studio, Design Builder, Skelion, etc. These are the most prominent ones in the studies in the literature, 43.4 % of which investigate energy performance. DIVA, Radiance, DAYSIM, and Honeybee are generally used to evaluate the daylight performance of BIPVs (Food4Rhino, 2021; Radiance, 2021; DAYSIM, 2021). PW-WR, PV-DATA, PVSYST, SOLCEL, TRNSYS, MATLAB, etc. are generally used to evaluate a BIPV's electrical properties and energy generation ability. However, these are not very user-friendly and require expertise. Lastly, optimization studies are presented in Table 3. Studies use different algorithms, variables, objectives, and tools. Galapagos and Octopus are Grasshopper plug-ins to conduct multi and single-objective optimization (Food4Rhino, 2021).

BIPV systems can be implemented on various building types. 44 % of the studies focus on office buildings (Fig. 11). Recently, extreme urbanization in cities resulted in the construction of high-rise buildings. Office buildings are defined as target buildings for energy reduction since these are the most prominent types in city centers, and most studies were conducted on office-type high-rise buildings. The application of BIPVs in residential buildings is significantly less, despite the more significant numbers of these buildings.

Table 3
Review of the optimization studies.

Variables	Objectives	Tools	Algorithms and methods
Solar cell-based variables (i.e., transparency, temperature, coefficient, etc.)	Energy conversion efficiency	Octopus, Galapagos, GenOpt, Python, ANN-based tools	Genetic optimization, particle swarm, wind-driven, ANN, MOPSO, LINMAP, POF, MO, RVFL, JFSA, SCA, AEO, MRFO,
Weather conditions	Power output		
BIPV geometry	Solar irradiation		
Daylight performance	Life cycle cost		
Building geometry			

4. Conclusion

This paper provides a comprehensive review of BIPV technologies and their development. In this study, BIPV systems are explained in terms of theoretical background. First, the motivation of the research was clearly defined, and objectives were identified. Later on, previously conducted studies were summarized as a literature review. The main conclusions of this paper, considering the results, may be listed as follows:

- PV systems emerged in the 1990s. In the 2000s, they gained popularity and a wide range of use. However, due to their high costs, they were gradually replaced by BIPV systems in the 2000s. BIPV systems have great potential for lower cost, easier manufacturing, and implementation, greater structural flexibility, etc. Therefore, it is forecasted that there will be an important development in these systems.
- Previously, BIPV systems were more often integrated on walls and roofs. More recently, these tended to be implemented on different building components, such as windows and shading elements. New implementation areas of BIPVs bring both new opportunities and new technologies.
- The solar cell type changes as the integration area changes, leading to new solar cells (second and third generation). In previous studies, mono and multi-crystalline solar cells were the most common cells in the industry and literature. Still, recently a-Si and other thin-film cells have appeared more frequently.



Fig. 11. (a) Building types that BIPVs are implemented in studies (b) Evaluation criteria in studies.

- BIPVs are generally evaluated in terms of their overall performance. This includes their thermal, daylight, and energy performance. However, the key aspect for assessment is their energetic properties, which consist of their energy production and energy-saving capacity. This capacity is primarily related to the solar cell included in PV panels.
- In studies, it is generally mentioned that certain parameters affect the overall performance of BIPV systems. These are building orientation, panel slope, solar cell type, ambient temperature, shadowing effect, and site geographical location. Most studies aimed to investigate the impact of these variables on the overall performance of BIPV systems. It is found that when a developed country is overpopulated, its government tends to give more importance to preserving energy due to the increase in the population of the cities. Even though the country is not overpopulated, the BIPV industry is pretty developed in some countries due to the government policy and support for this sector.
- Some of the study results indicate that BIPV performance significantly differs according to the climate and geographical region. It is found that their performance is directly related to how much the building exposes to the sun. BIPV systems are generally more effective in low latitude regions since the sun comes with a more direct angle and increases the solar gain of panels. However, due to different policies and considerations of governments, they are popularly applied in even cold climatic regions such as Germany. In very hot climatic such areas as hot desert climates, BIPV applications are not very beneficial since they increase indoor air temperature more than usual. They are generally more helpful in moderate, temperate, and subtropical regions. Also, if the surrounding obstacles do not shade the building and PV-implemented area, the system is more likely to generate electrical energy. In addition, building orientation is one variable that impacts energy generation performance. A BIPV system is mostly implemented on the south facade in the northern hemisphere. It is the north façade for the regions in the southern hemisphere. Similarly, the panel slope is a decisive factor in the system's efficiency. If the panel is installed at an incline, it can generate more energy than those installed vertically or horizontally.
- Also, solar cell type is one of the most prominent variables among these studies. Although recently emerged third-generation solar cells are promising, their application in the literature is rare. In industry, silicon-based cells are the most prominent ones. These are monocrystalline, polycrystalline, and a-Si solar cells. They have low cost, excellent efficiency, and easy implementation procedure. However, recently, third-generation PV cells started to gain importance in literature and the market. For instance, CdTe, CIGS, and perovskite-based ones are started to be implemented in several studies. Therefore, it is possible to see various studies on BIPVs in the future. The efficiency of a solar cell directly influences the system's energy generation capacity. If the aim is to generate more energy, then highly efficient solar cells (i.e., monocrystalline) are preferred. However, other solar cell types need to be tested to evaluate the building's overall energy, thermal, and daylight performance.
- Studies have shown that BIPVs performed more efficiently on high-rise buildings since the application area is the largest in these types of buildings.
- Among the variables examined so far, environmental-based ones (i.e., building orientation, panel slope, shadowing effect, and building location) are directly related to the success of a BIPV system. On the other hand, system-based variables (i.e., solar cell type, implementation area and location, and BIPV type) still influence the performance of the system; however, they do not seem as the determinant and vital variables for a system's overall success.
- Tools used in studies are divided into two categories: digital and manual. Manual tools mainly include measurement instruments and scale models. Although these tools were common in early studies, digital tools gained popularity due to their lower cost and effortless analysis procedure. Digital tools mainly consist of simulation software such as TRNSYS and Energy Plus. Simulation studies are generally conducted for energy performance assessment of BIPV systems.
- BIPV contributes to constructing a sustainable future for our cities. Developments in the BIPV industry will assist researchers in this field. With the overall developments, we can cope with the ecological challenges in the future.
- The study allows researchers to find gaps and deficiencies in the literature according to the analysis of many variables. It is the aim of future works to benefit from this work and improve BIPV-implemented studies. The authors hope that those researching BIPV systems will find this review paper useful in BIPV design principles, performance assessment, and future developments.

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.

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References

Refat, K.H., Sajjad, R.N., 2020. Prospect of Achieving Net-Zero Energy Building with Semi-Transparent Photovoltaics: A Device to System Level Perspective. Appl. Energy 279.

Giouri, Evangelia Despoina, Tenpierik, Martin, Turrin, Michela, 2020. Zero Energy Potential of a High-Rise Office Building in a Mediterranean Climate: Using Multi-Objective Optimization to Understand the Impact of Design Decisions Towards Zero-Energy High-Rise Buildings. Energy Build. 209.

Shin, M., Baltazar, J.-C., Haberl, J.S., Frazier, E., Lynn, B., 2019. Evaluation of the Energy Performance of a Net Zero Energy Building in a Hot and Humid Climate. Energy Build. 204.

Biyik, Emrah, Mustafa Araz, Arif Hepbasli, Mehdi Shahrestani, Runming Yao, Li Shao, Emmanuel Essah, et al., 2017. "A Key Review of Building-integrated Photovoltaic (Bipv) Systems." Eng. Sci. Technol. Int. J. 20, no. 3 (2017): 833-58.

Knera, Dominika, Szczepańska-Rosiak, Eliza, Dariusz, Heim, 2015. Potential of Pv Façade for Supplementary Lighting in Winter. Article Energy Procedia 78, 2651–2656.

Hamza, H., Ashour, A.M., Sabry, H., Ismail, R.M., 2020. Identifying the Influence of Design Variations on the Performance of PV Systems for Net-Plus Energy Residential Buildings in Egypt. Int. J. Eng. Res. Technol. 13 (3), 528–539.

Elsheikh, A.H., Sharshir, S.W., Mostafa, M.E., Essa, F.A., Ahmed Ali, M.K., 2018. Applications of nanofluids in solar energy: A review of recent advances. Renew. Sustain. Energy Rev. 82, 3483–3502. https://doi.org/10.1016/j.rser.2017.10.108.

Oliva, D., Abd Elaziz, M., Elsheikh, A.H., Ewees, A.A., 2019. A review on meta-heuristics methods for estimating parameters of solar cells. J. Power Sources 435. https://doi.org/10.1016/j.jpowsour.2019.05.089.

Zayed, Mohamed E., Zhao, Jun, Elsheikh, Ammar H., Li, Wenjia, Elaziz, Mohamed Abd, 2020. Optimal design parameters and performance optimization of thermodynamically balanced dish/Stirling concentrated solar power system using multi-objective particle swarm optimization. Appl. Therm. Eng. 178 https://doi.org/10.1016/j.applthermaleng.2020.115539.

Elsheikh, A.H., Abd Elaziz, M., 2018. Review on applications of particle swarm optimization in solar energy systems. Int. J. Environ. Sci. Technol. 16, 1159–1170. https://doi.org/10.1007/s13762-018-1970-x.

Elsheikh, A.H., Sharshir, S.W., Abd Elaziz, M., Kabeel, A.E., Guilan, W., Haiou, Z., 2019. Modeling of solar energy systems using artificial neural network: A comprehensive review. Solar Energy 180, 622–639. https://doi.org/10.1016/j.solener.2019.01.037.

Abd Elaziz, M., Senthilraja, S., Zayed, M.E., Elsheikh, A.H., Mostafa, R.R., Lu, S., 2021. A new random vector functional link integrated with mayfly optimization algorithm for performance prediction of solar photovoltaic thermal collector combined with electrolytic hydrogen production system. Appl. Therm. Eng. 193 https://doi.org/10.1016/j.applthermaleng.2021.117055.

Almodfer, Rolla, Zayed, Mohamed E., Elaziz, Mohamed Abd, Aboelmaaref, Moustafa M., Mudhsh, Mohammed, Elsheikh, Ammar H., 2022. Modeling of a Solar-Powered Thermoelectric Air-Conditioning System Using a Random Vector Functional Link Network Integrated with Jellyfish Search Algorithm. Case Stud. Therm. Eng. 31 (101797) https://doi.org/10.1016/j.csite.2022.101797.

Taveres-Cachat, E., Lobaccaro, G., Goia, F., Chaudhary, G., 2019. A Methodology to Improve the Performance of Pv Integrated Shading Devices Using Multi-Objective Optimization. Appl. Energy 247, 731–744.

Zhang, Tiantian, Wang, Meng, Hongxing, Yang, 2018. A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. Energies 11 (11), 31–57. https://doi.org/10.3390/en11113157.

Knera, Dominika, Szczepańska-Rosiak, Eliza, Dariusz, Heim, 2015. Potential of Pv Façade for Supplementary Lighting in Winter. Article Energy Proc. 78, 2651–2656.

Ghosh, A., 2020. Potential of Building-integrated and Attached/Applied Photovoltaic (Bipv/Bapv) for Adaptive Less Energy-Hungry Building's Skin: A Comprehensive Review. J. Clean. Prod. 276.

Defaix, P. R., W. G. J. H. M. van Sark, E. Worrell, E. de Visser. "Technical Potential for Photovoltaics on Buildings in the Eu-27." Solar Energy 86, no. 9 (09/01/September 20122012): 2644-53.

Jahanara, A., 2013. 'Strategy towards Solar Architecture by Photovoltaic for Building Integration'. Eastern Mediterranean University (EMU), Famagusta, Turkey Ph.D. Thesis.

Chatzipanagi, A., Frontini, F., Virtuani, A., 2016. Bipv-Temp: A Demonstrative Building-integrated Photovoltaic Installation. Appl. Energy 173, 1–12.

Pierluigi, Bonomo, Chatzipanagi Anatoli, Frontini Francesco. "Overview and Analysis of Current Bipv Products: New Criteria for Supporting the Technological Transfer in the Building Sector." Vitruvio: Int. J. Archit. Technol. Sustain., no. 1 (2015): 67-85.

Sun, Y., Liu, D., Flor, J.-F., Shank, K., Baig, H., Wilson, R., Liu, H., et al., 2020. Analysis of the Daylight Performance of Window Integrated Photovoltaics Systems. Renew. Energy 145, 153–163.

Heinstein, Patrick, Ballif, Christophe, Perret-Aebi, Laure-Emmanuelle, 2017. Building Integrated Photovoltaics (BIPV): Review. Potentials, Barriers and Myths.

Jelle, P., Bjørn, C.B., Røkenes, H.D., 2012. "Building-integrated Photovoltaic Products: A State-of-the-Art Review and Future Research Opportunities. Sol. Energy Mater. Sol. Cells 100, 69–96.

Cannavale, A., Hörantner, M., Eperon, G.E., Snaith, H.J., Fiorito, F., Ayr, U., Martellotta, F., 2017. Building integration of semitransparent perovskite-based solar cells: Energy performance and visual comfort assessment. Appl. Energy 194, 94–107.

Martellotta, F., Cannavale, A., Ayr, U., 2017. Comparing Energy Performance of Different Semi-Transparent, Building-Integrated Photovoltaic Cells Applied to "Reference" Buildings. Energy Procedia 126, 219–226.

Cesari, S., Valdiserri, P., Coccagna, M., Mazzacane, S., 2018. Energy Savings in Hospital Patient Rooms: The Role of Windows Size and Glazing Properties. Energy Proc. 148, 1151–2118.

Jayathissa, P., Luzzatto, M., Schmidli, J., Hofer, J., Nagy, Z., Schlueter, A., 2017. Optimising Building Net Energy Demand with Dynamic Bipv Shading. Appl. Energy 202, 726–735.

Heangwoo, L., Xiaolong, Z., Janghoo, S., 2021a. "A Study of Optimal Specifications for Light Shelves with Photovoltaic Modules to Improve Indoor Comfort and Save Building Energy. Int. J. Environ. Res. Public Health 18 (2574), 2574–2674.

Heangwoo, L., Xiaolong, Z., Janghoo, S., 2021b. A Study of Optimal Specifications for Light Shelves with Photovoltaic Modules to Improve Indoor Comfort and Save Building Energy. Int. J. Environ. Res. Public Health 18 (2574), 2574–2674.

Hwang, T., Kim, J.T., Chung, Y., 2014. Power Performance of Photovoltaic-Integrated Lightshelf Systems. Indoor Built Environ. 23 (1), 180–218.

Lee, Heangwoo, 2019. "Performance Evaluation of a Light Shelf with a Solar Module Based on the Solar Module Attachment Area." Building and Environment 159 (July). doi:10.1016/j.buildenv.2019.106161.

OnyxSolar, n.d. Accessed June 2021. https://www.onyxsolar.com/.

Knera, Dominika, Szczepańska-Rosiak, Eliza, Dariusz, Heim, 2015. Potential of Pv Façade for Supplementary Lighting in Winter." Article. Energy Procedia 78, 2651–2656.

OnyxSolar, n.d. Accessed June 2022. https://www.onyxsolar.com/.

Battaglia, C., Cuevas, A., De Wolf, S., 2016. High-Efficiency Crystalline Silicon Solar Cells: Status and Perspectives. Energy Environ. Sci. 9 (5), 1552–1576.

Ran, Fu, James, T.L., Woodhouse, M., 2015. Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness. Periodical IEEE J. Photovoltaics 5 (2), 515–524.

Luo, W., Khoo, Y.S., Kumar, A., Low, J.S.C., Li, Y., Tan, Y.S., Wang, Y., Aberle, A.G., Ramakrishna, S., 2018. A Comparative Life-Cycle Assessment of Photovoltaic Electricity Generation in Singapore by Multicrystalline Silicon Technologies. Solar Energy Mater. Solar Cells 174, 157–162.

Tripathy, M., Sadhu, P.K., Panda, S.K., 2016. A Critical Review on Building-integrated Photovoltaic Products and Their Applications. Renew. Sustain. Energy Rev. 61, 451–465.

Liu, C.P., Chuang, C.L., 2012. Fabrication of copper–indium–gallium–diselenide absorber layer by quaternary-alloy nanoparticles for solar cell applications. Solar Energy 86 (9), 2795–2801. https://doi.org/10.1016/j.solener.2012.06.018.

Buecheler, S., Chirila, A., Perrenoud, J., Kranz, L., Gretener, C., Blösch, P., Pianezzi, F., Seyrling, S., Tiwari, A.N., 2011. Flexible and Lightweight Solar Modules for New Concepts in Building-integrated Photovoltaics. Article.

Dupré, O., Vaillon, R., Green, M.A., 2015. Physics of the Temperature Coefficients of Solar Cells. Sol. Energy Mater. Sol. Cells 140, 92–100.

Varga, Zoltan, Ervin Racz, 2021. "Influence of the Cell Temperature on the Performance of a Dye Sensitized Solar Cell." 2021 IEEE 19th World Symposium on Applied Machine Intelligence and Informatics (SAMI), Applied Machine Intelligence and Informatics (SAMI), 2021 IEEE 19th World Symposium On, January, 000175–80. doi:10.1109/SAMI50585.2021.9378631.

Gong, Jiawei, Sumathy, K., Qiao, Qiquan, Zhou, Zhengping, 2017. Review on Dye-Sensitized Solar Cells (Dsscs): Advanced Techniques and Research Trends. Renew. Sustain. Energy Rev. 68 (Part 1), 234–246.

Greijer, H., Karlson, L., Lindquist, S.-E., Anders, H., 2001. Environmental Aspects of Electricity Generation from a Nanocrystalline Dye Sensitized Solar Cell System. Renew. Energy 23 (1), 27–39.

Nien, Y.-H., Hsu, H.-H., Yong, Z.-R., Geng-Ming, H.u., Chen, H.-H., Rangasamy, M., Chou, J.-C., et al., 2021. The Characterization of Dye-Sensitized Solar Cell Modified by Reduced Graphene Oxide- and Zro2-Doped Tio2 Nanofibers at Low Light Intensities. IEEE Trans. Electron Devices 68 (3), 1155–1161.

Zardetto, V., F. Di Giacomo, T. M. Brown, A. Di Carlo, A. D'Epifanio, S. Licoccia, W. M. M. Kessels, and M. Creatore. "Dye-Sensitized and Perovskite Solar Cells : Interface Engineering by Atomic Layer Deposition." 2014.

Hossain, M.I., Hossain, Mohammad I., Jahid Anowar, J., Anowar, Safayet Ahmed, Ahmed, S., Saleque, Ahmed M., et al., 2020. Optics of Perovskite-Based Highly Efficient Tandem Solar Cells. In: 2020 IEEE Region 10 Symposium (TENSYMP), Region 10 Symposium (TENSYMP). https://doi.org/10.1109/TENSYMP50017.2020.9230870.

Espinosa, N., García-Valverde, R., Urbina, A., Krebs, F.C., 2011. A Life Cycle Analysis of Polymer Solar Cell Modules Prepared Using Roll-to-Roll Methods under Ambient Conditions. Sol. Energy Mater. Sol. Cells 95 (5), 1293–1302.

Gong, Jiawei, Sumathy, K., Qiao, Qiquan, Zhou, Zhengping, 2017. Review on Dye-Sensitized Solar Cells (Dsscs): Advanced Techniques and Research Trends. Renew. Sustain. Energy Rev. 68 (Part 1), 234–246.

Mime, F.I., Islam, M.R., Hossain, E., Mehedi, I.M., Hasan, M.T., 2021. Design and Performance Analysis of Tandem Organic Solar Cells: Effect of Cell Parameter. Periodical. IEEE Access, Access, IEEE 9, 40665–40680.

Ameri, T., Li, N., Brabec, C.J., 2013. Highly Efficient Organic Tandem Solar Cells: A Follow up Review. Energy Environ. Sci. 6 (8), 2390–2413.

Sajjad, M.T., Ruseckas, A., Samuel, I.D.W., 2020. Enhancing Exciton Diffusion Length Provides New Opportunities for Organic Photovoltaics. Matter 3 (2), 341–354. https://doi.org/10.1016/j.matt.2020.06.028.

Osseweijer, Floor J.W., van den Hurk, Linda B.P., Teunissen, Erik J.H.M., van Sark, Wilfried G.J.H.M., 2018. A Comparative Review of Building Integrated Photovoltaics Ecosystems in Selected European Countries. Renew. Sustain. Energy Rev. 90 (July), 1027–1040. https://doi.org/10.1016/j.rser.2018.03.001.

food4Rhino, n.d. Accessed June 2021. https://www.food4rhino.com/en.

Radiance, n.d.. Accessed June 2021. https://www.radiance-online.org/.

DAYSIM, n.d. Accessed June 2021. https://daysim.software.informer.com/4.0/.

Ordenes, M., Marinoski, D.L., Braun, P., Rüther, R., 2007. The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil. Energy Build. 39 (6) https://doi.org/10.1016/j.enbuild.2006.10.006, 629–642–642.
Peng, J., Curcija, D.C., Lu, L., Selkowitz, S.E., Yang, H., Zhang, W., 2016. Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate. Appl. Energy 165, 345–356. https://doi.org/10.1016/j.apenergy.2015.12.074.
Zhang, Xin, Du, Jiangtao, 2015. "Lighting Performance in Office Buildings with BIPV Facades: Visual and Non-Visual Effects." Solar World Congress, 2015. Conference.
Nundy, S., Ghosh, A., 2020. Thermal and visual comfort analysis of adaptive vacuum integrated switchable suspended particle device window for temperate climate. Renew. Energy 156, 1361–1372. https://doi.org/10.1016/j.renene.2019.12.004.
Sun, Y., Shanks, K., Baig, H., Zhang, W., Hao, X., Li, Y., He, Bo, et al., 2018. Integrated Semi-Transparent Cadmium Telluride Photovoltaic Glazing into Windows: Energy and Daylight Performance for Different Architecture Designs. Appl. Energy 231, 972–984.
Piccoli, Emanuele, Dama, Alessandro. "Shading Device with Extensible Louvres for BIPV and Daylight Control." 2018. Conference.
Jakica, Nebojsa, Kragh, Mikkel K., Yang, Rebecca J., Pabasara, W.M., Wijeratne, U., Eric Too, Ron Wakefield, et al. 2019. "BIPV Design and Performance Modelling: Tools and Methods," January. doi:10.13140/rg.2.2.26359.16806.
Abdelhakim, Mesloub, Albaqawy Ghazy Abdullah, and Kandar Mohd Zin. "The Optimum Performance of Building Integrated Photovoltaic (Bipv) Windows under a Semi-Arid Climate in Algerian Office Buildings." article. Sustainability, no. 4 (2020): 1.
Megahed, Tamer F., Radwan, Ali, 2020. Performance Investigation of Zero-Building-Integrated Photovoltaic Roof System: A Case Study in Egypt. Alexan. Eng. J. 59 (6), 5053–5067.
Tonui, Patrick, Oseni, Saheed O., Sharma, Gaurav, Yan, Qingfenq, Mola, Genene Tessema, 2018. Perovskites Photovoltaic Solar Cells: An Overview of Current Status. Renew. Sustain. Energy Reviews 91 (August), 1025–1044. https://doi.org/10.1016/j.rser.2018.04.069.
Saretta, Erika, Caputo, Paola, Frontini, Francesco, 2019. A Review Study About Energy Renovation of Building Facades with Bipv in Urban Environment. Sustain. Cities Soc. 44, 343–355.
Gholami, Hassan, Nils, Røstvik Harald, 2021. "The Effect of Climate on the Solar Radiation Components on Building Skins and Building Integrated Photovoltaics (Bipv). Materials." article. Energies 14 (1847), 1847–1947.
Syafaruddin, Sari, Said, S.M., 2021. A Review of Building Integrated Photovoltaic-Thermal (BIPV/T) Systems: Current and Potential Technology Development. J. Eng. Sci. Technol. Review 14 (4). https://doi.org/10.25103/jestr.144.24, 197–206–206.
Singh, D., Kumar Gautam, A., Chaudhary, R., 2021. Application of phase change material in building integrated photovoltaics: A review. Mater. Today: Proc. 45 (Part 6), 4624–4628. https://doi.org/10.1016/j.matpr.2021.01.021.
Liu, Z., Zhang, Y., Yuan, X., Liu, Y., Xu, J., Zhang, S., He, B., 2021. A comprehensive study of feasibility and applicability of building integrated photovoltaic (BIPV) systems in regions with high solar irradiance. J. Cleane. Prod. 307 https://doi.org/10.1016/j.jclepro.2021.127240.
Rababah, Haitham Esam, Ghazali, Azhar, Isa, Mohd Hafizal Mohd, 2021. "Building Integrated Photovoltaic (BIPV) in Southeast Asian Countries. Review of Effects and Challenges" Sustainability 13 (23), 12952. https://doi.org/10.3390/su132312952.
Rajoria, C.S., Kumar, R., Sharma, A., Singh, D., Suhag, S., 2021. Development of flat-plate building integrated photovoltaic/thermal (BIPV/T) system: A review. Mater. Today: Proc. 46 (Part 11), 5342–5352. https://doi.org/10.1016/j.matpr.2020.08.790.
Martín-Chivelet, N., Kapsis, K., Wilson, H. R., Delisle, V., Yang, R., Olivieri, L., Polo, J., Eisenlohr, J., Roy, B., Maturi, L., Otnes, G., Dallapiccola, M., & Upalakshi Wijeratne, W. M. P. (2022). Building-Integrated Photovoltaic (BIPV) products and systems: A review of energy-related behavior. Energy & Buildings, 262. https://doi.org/10.1016/j.enbuild.2022.111998.
Bloem, J.J., Lodi, C., Cipriano, J., Chemisana, D., 2012. An Outdoor Test Reference Environment for Double Skin Applications of Building Integrated PhotoVoltaic Systems. Energy Build. 50 (July), 63. https://doi.org/10.1016/j.enbuild.2012.03.023.
Chen, Mo, Zhang, Wei, Xie, Lingzhi, Ni, Zhichun, Wei, Qingzhu, Wang, Wei, Tian, Hao, 2019. Experimental and Numerical Evaluation of the Crystalline Silicon PV Window under the Climatic Conditions in Southwest China. Energy 183 (September), 584–598. https://doi.org/10.1016/j.energy.2019.06.146.
Alrashidi, Hameed, Walid Issa, Nazmi Sellami, Aritra Ghosh, Tapas K. Mallick, and Senthilarasu Sundaram, 2020. "Performance Assessment of Cadmium Telluride-Based Semi-Transparent Glazing for Power Saving in Façade Buildings." Energy Build 215 (2020): N.PAG-N.PAG.
Wijeratne, W.M.P.U., Samarasinghalage, T.I., Yang, R.J., Wakefield, R., 2022. Multi-objective optimisation for building integrated photovoltaics (BIPV) roof projects in early design phase. Appl. Energy 309. https://doi.org/10.1016/j.apenergy.2021.118476.
Singh, D., Chaudhary, R., 2022. Performance evaluation of thermally insulated building integrated photovoltaic roof. Materials Today: Proc. 52 https://doi.org/10.1016/j.matpr.2021.10.294, 888–892–892.
Kirimtat, A., Tasgetiren, M.F., Brida, P., Krejcar, O., 2022. Control of PV integrated shading devices in buildings: A review. Build. Environ. 214 https://doi.org/10.1016/j.buildenv.2022.108961.
Wang, C., Ji, J., Uddin, M.M., Yu, B., Song, Z., 2021. The study of a double-skin ventilated window integrated with CdTe cells in a rural building. Energy 215 (Part A). https://doi.org/10.1016/j.energy.2020.119043.

Further reading

Azami, Ahadollah, Sevinç, Harun, 2021. The Energy Performance of Building Integrated Photovoltaics (BIPV) by Determination of Optimal Building Envelope. In: Building and Environment 199 (July). https://doi.org/10.1016/j.buildenv.2021.107856.
Marek Kryszak, Lai Wang Wang, 2020. "The Value of Aesthetics in the BIPV Roof Products Segment: A Multiperspective Study under European Market Conditions." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, August, 1–22.
Sun, Liangliang., 2011. Simulation and Experimental Investigation on Optimum Applications of the Shading-Type Bipv and Bipvt Systems on Vertical Building Facades."Ph.D. Kong Polytechnic University (Hong Kong, Hong.
Mesloub, Abdelhakim, Ghosh, Aritra, 2020. Daylighting Performance of Light Shelf Photovoltaics (LSPV) for Office Buildings in Hot Desert-Like Regions. Appl. Sci. 10 (7959), 7959. https://doi.org/10.3390/app10227959.
Heangwoo, Lee, Xiaolong, Zhao, Janghoo, Seo, 2021. A Study of Optimal Specifications for Light Shelves with Photovoltaic Modules to Improve Indoor Comfort and Save Building Energy. Int. J. Environ. Res. Public Health 18 (2574), 2574–2674.
Huang, J., Chen, X., Peng, J., Yang, H., 2021. Modelling analyses of the thermal property and heat transfer performance of a novel compositive PV vacuum glazing. Renewable Energy 163, 1238–1252. https://doi.org/10.1016/j.renene.2020.09.027.
Røstvik, Harald N., Müller-Eie, Daniela, Gholami, Hassan, 2019. Holistic Economic Analysis of Building Integrated Photovoltaics (BIPV) System: Case Studies Evaluation. Energy Build 203 (September).

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