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REVIEW

A review on technological and urban sustainability perspectives of advanced building-integrated photovoltaics

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Abstract

With the escalating urgency for sustainable energy alternatives, solar power in urban landscapes has gained prominence. Building-integrated photovoltaic (BIPV) systems are pivotal in this shift, blending efficient energy generation with architectural aesthetics. This review casts a spotlight on BIPV technologies, with a special emphasis on the less-explored semitransparent photovoltaics (PVs). These systems are not only energy generators but also natural light facilitators, setting them apart from their opaque PV counterparts. Advancements in both transparent and opaque PV, such as crystalline silicon, are discussed. However, the paper prioritizes semitransparent PV's unique benefits, including harmonious integration with building design and simultaneous energy and daylight management. An exhaustive examination of current literature and developments sketches BIPV's trajectory, highlighting applications, challenges, and technological strides. The narrative extols the aesthetic, financial, and efficiency merits of BIPV, particularly the semitransparent variants' blend of functionality and design. Performance optimization of BIPV systems is scrutinized across various environments and architectural styles. This meticulous discussion seeks to clarify the status quo, emerging research avenues, and future prospects of BIPV in fostering a greener energy transition. The review compares BIPV configurations with traditional solar PV systems, charting a path for enhanced energy production, cost efficiency, and aesthetic integration, with semitransparent PV as a key player. By exploring the interplay between architectural design, energy efficiency, and urban planning, this paper aims to solidify the groundwork for future research, reinforcing the sustainability narrative in urban energy infrastructure.

KEYWORDS

BIPV, electrical, energy, PV cells, thermal

1 | INTRODUCTION

Energy remains a rapidly expanding sector crucial for both development and economic growth. However, the escalating greenhouse gas (GHG) emissions from anthropogenic activities and machinery operations are exacerbating global warming. Astoundingly, about 1.4 billion individuals globally lack access to electricity, with only around 31% of the sub-Saharan African population enjoying this essential service.[1] The predominant reliance on fossil fuels for energy production, constituting approximately 80%, remains a significant contributor to climate change.[2] Annual global energy consumption is on an upward trajectory, increasing by around 8%–10%, and is projected to escalate by 40% by the year 2040 as depicted in Figure 1. Primarily, this surge is driven by economic development in advanced nations, anticipating a substantial rise in global energy demand by 2040. Consequently, renewable energy emerges as a potentially sustainable and clean energy source, expected to supply 14% of the primary energy by 2040,[3] as illustrated in Figure 1.

In dissecting the power sector, buildings, construction, industry, and transport systems (e.g., passenger road vehicles and road freight vehicles) are identified as the most energy-intensive sectors. Remarkably, the combined energy consumption of buildings and construction sectors accounts for over 30% of the global final energy consumption, thereby contributing nearly 40% of the CO_2 emissions.[4] The burgeoning global economy and resultant energy accessibility in developing nations, coupled with increased ownership of energy-consuming devices and a steady 3% annual growth in global buildings floor area, is forecasted to continually drive the energy demand from buildings and constructions upward.[5,6]

Transitioning to renewable energy sources, like, hydro, photovoltaic (PV), wind, and geothermal is highly advocated to accommodate the surging energy demands engendered by rapid population growth and economic expansion.[7] Among the solar technologies, building-integrated semitransparent photovoltaic (BISPV) modules for roofs and facades are spotlighted as clean and environmentally benign solutions, potentially mitigating climate change impacts through reduced CO_2 emissions.[8–10] Notably, a study conducted in India elucidated the feasibility of harnessing solar energy through advanced technologies, like, BISPV.[11] Embracing building-integrated photovoltaic (BIPV) technology transforms buildings from mere energy consumers to sustainable and clean energy producers, as emphasized in several studies.[12–14] The increasing adoption of BIPV, particularly crystalline silicon module cells accounting for approximately 85%–90% of the ongoing global market, is associated with economic growth observed over recent years.[15–17] PV systems, employing materials like polycrystalline silicon, amorphous silicon, or predominantly used crystalline silicon, are hailed as efficacious solutions for converting solar radiation into electricity.[18,19]

Buildings are noted to be voracious energy consumers, absorbing about 40% of energy, with commercial and residential buildings alone utilizing nearly 70% of a country's total electricity.[20] Contrarily, Tuncel and Pekmezci posited that around 60% of energy consumption in buildings is allocated to cooling, ventilating, or heating.[5] BIPV systems offer a myriad of benefits by replacing conventional construction materials, like, tiles, panels, and glazing, thus generating thermal energy sans electricity consumption.[21,22] The zero energy building concept embodies the

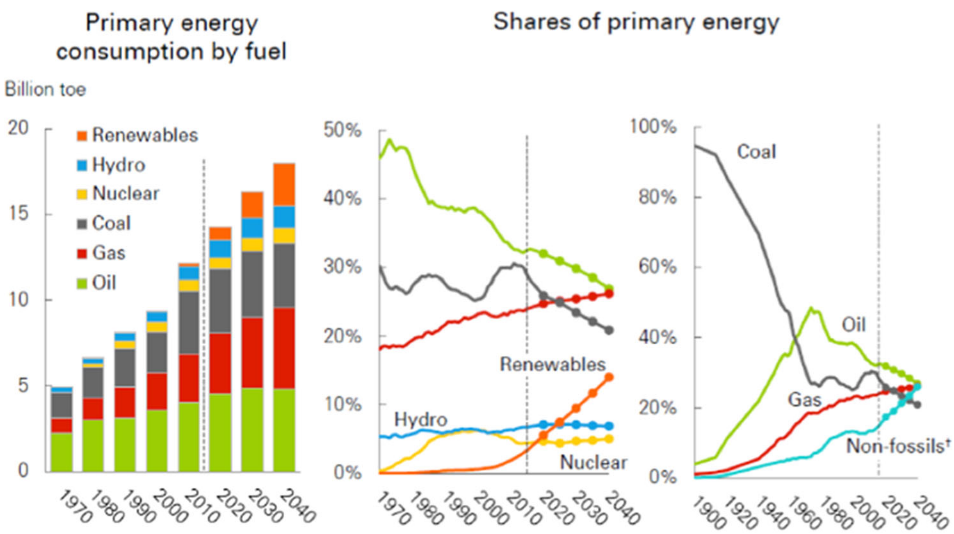

FIGURE 1 World energy consumption.[3]

aspiration of creating buildings capable of self-sustaining their electricity demand through renewable technologies without GHG emissions.[23,24] BIPVs are lauded for their versatility in replacing various building materials, promoting a seamless integration into facades, roofs, windows, balconies, thermal insulators, skylights, and shading devices.[12,13,21,24,25] Numerous reviews have been conducted on BIPV systems in the past, illustrating various technological advancements and applications. However, there is a discernible gap in the literature concerning the integration and advancements in semitransparent PVs specifically, as most reviews primarily focus on opaque PV technologies. For instance, Zhang et al.[25] and Park et al.[26] extensively reviewed crystalline silicon and other opaque PV technologies, with minimal emphasis on semitransparent variants. Furthermore, with the rapid innovation in the field, a current review capturing the latest developments, applications, and challenges is paramount to provide a fresh perspective and to guide future research endeavors. Unlike previous reviews, this work endeavors to provide a thorough understanding of semitransparent PVs within the BIPV context, extending the discourse to include aesthetic, economic, and energy-efficiency aspects. Additionally, this review incorporates a methodological framework to categorize and analyze the existing literature systematically, aiding in identifying research gaps and future potentials.[26]

In the realm of BIPV, semitransparent PV systems represent a revolutionary juncture that harmonizes energy production with architectural finesse. Unlike their opaque counterparts, semitransparent PV modules offer a dual benefit: they facilitate natural daylight within buildings while simultaneously generating clean energy, thereby eliminating the traditional compromise between structural aesthetics and functionality. This unique attribute makes them particularly valuable in urban landscapes, where the balance between built form and livable space is delicate. Semitransparent PV systems can transform facades and windows into active energy producers without sacrificing transparency, thus enabling buildings to meet energy demands without foregoing the architectural vision. Furthermore, their innate ability to modulate light and heat ingress enhances indoor environmental quality and potentially reduces reliance on artificial climate control systems. This aspect of BIPV technology is crucial in dense urban centers, where roof spaces are limited and facades offer untapped potential for energy harvesting. Our focus on semitransparent PV within this paper is driven by their potential to surpass traditional PV solutions by integrating energy efficiency with the aesthetic and practical needs of modern urban development.

By juxtaposing conventional energy solutions with BIPV, this paper aims to elucidate the potential of BIPV not only in reducing the energy deficit but also in curtailing greenhouse emissions significantly. A systematic review is conducted to provide a holistic understanding of the current state and potential trajectory of BIPV technologies. The categorization and analysis are geared toward establishing a concrete scientific foundation to fuel further research in this domain. The paper conducts a review of the recent developments and studies on particularly, semitransparent PVs integrated into buildings where technologies, applications topologies, and findings are discussed. The methodology has followed partially the framework of Agathokleous and Kalogirou.[27] A categorical methodology is developed to establish a scientific framework for the reviewed works.

Section 2 delineates an overview of PV systems structures for generation and buildings alongside their categories and installation types. Section 3 deliberates on different PV cell technologies and their potential for BIPV applications. Additionally, the technical details of various BIPV products, parameters affecting BIPV, and an analysis of the overall system performance of BIPV under diverse parameters, factors, and locations are expounded and tabulated in Section 4. Section 5 reviews the literature and classifies the contributions of various previous studies. Lastly, Section 6 elucidates the challenges and future research opportunities of BIPV.

2 | STRUCTURAL PV SYSTEMS IN BUILDING INTEGRATION

Solar PVs offer a versatile means of integrating renewable energy solutions within the architectural fabric of buildings. The seamless blend of PV systems into the structural design can be dictated by the construction specifics of the buildings, presenting a variety of applicable systems. This section delineates three prevalent systems: BIPVs, building-applied photovoltaics (BAPVs), and ground-mounted photovoltaics (GMPVs)–a shift from the earlier mentioned open rack-mounted photovoltaics (ORMPVs), to reflect a more precise terminology.

In the realm of BIPV, PV modules find their utility as integral components of building structures, including roofs, facades, or windows, thus influencing the overall building functionality.[28] Additionally, a derivative of BIPV known as building-integrated photovoltaic thermal (BIPVT) system merits a mention. The BIPVT system exploits PV modules for the concurrent conversion of solar radiant energy into both electrical and thermal energy.[29] The incorporated PV panel in BIPVT facilitates heating of the indoor air, thereby generating thermal energy via the absorption process.[29,30] The use of BIPVT as a thermal insulation solution for heating has manifested a substantial reduction in electrical energy consumption across residential and commercial edifices.[22] Contrarily, BAPV employs PV modules that are attached directly to the building structures without substituting any existing component, thereby maintaining the original functionality of the structure.[6] These modules, arranged in multiple rows and columns on roofs, maintain a slight gap between the PV modules and the roof surface.[31] GMPVs, predominantly utilized in open areas, are affixed to the ground, sharing attributes with BAPV but possessing the potential for enhanced energy production when optimally aligned with the desired azimuth and tilt angles.[32] Figures 2–4 elucidate the differing attributes of BIPV, BAPV, and GMPV.

The allure of BIPV lies in its lightweight nature, durability, superior aerodynamic design, and flexibility, whereas BAPV, being heavyweight and more fragile, necessitates frequent maintenance albeit offering positional adjustments for optimizing solar capture.[37] The quintessence of BIPV is its capability to meld into the building's envelope, thereby catering to its electrical demands. In contrast, BAPV is primed for maximal energy production.[28,38] BAPV is broadly bifurcated into rack-mounted arrays and standoff arrays. The former are mounted on roofs with an alignment favoring sun exposure for enhanced efficiency, while the latter are placed above and parallel to the roof's tilt, adhering to the pitch of the roof.[39]

Recent advancements in PV technology are paving the way for more cost-effective and efficient BIPVs. The burgeoning interest in this domain stems from the high volume of existing buildings that could benefit from the easy installation of BIPVs. The proposition of solar cell glazing is being lauded for its potential in solar shading, daylight transmission, and augmented electricity production. Nonetheless, the adoption of BIPV in residential buildings remains less frequent due to the limited scope of roof upgrades, making BAPV a more appealing choice.[6,28] In Cyprus, the installed capacity of PV solar energy was around 85 MW in 2016, with aspirations to escalate to nearly 200 MW by 2020.[40] The conducive climate makes PV installations a viable venture, though the demographic constraints pose challenges in attaining significant strides in production and market expansion. Figure 5 delineates the market share for BIPV, BAPV, and GMPV in exemplary European PV markets, namely, Italy, Germany, France, and Spain. Notably, France led the BIPV market share with approximately 60%, trailed by Italy, Spain, and Germany with 30%, 2%, and 1%, respectively. Conversely, Germany dominated the BAPV market with an 82% share, with Italy, Spain, and France following suit. Lastly, the GMPV market was spearheaded by Spain with a 75% share, trailed by Italy, France, and Germany.[38]

3 | PV CELL TECHNOLOGY OVERVIEW

This section delves into the various PV cell technologies and categorizes them into three main types: silicon-based, thin-film, and nanomaterial cells.

Silicon-based cells encompass a sole category known as crystalline silicon, further divided into monocrystalline, polycrystalline, and ribbon cast solar cell modules. Thin-film cells branch into four categories: cadmium telluride (CdTe), copper indium gallium selenide (CIGS), copper indium selenide (CIS), and amorphous silicon (a-Si). Nanomaterial cells also

FIGURE 2 Building-integrated photovoltaics.[33,34]

FIGURE 3 Building-applied photovoltaics.[35]

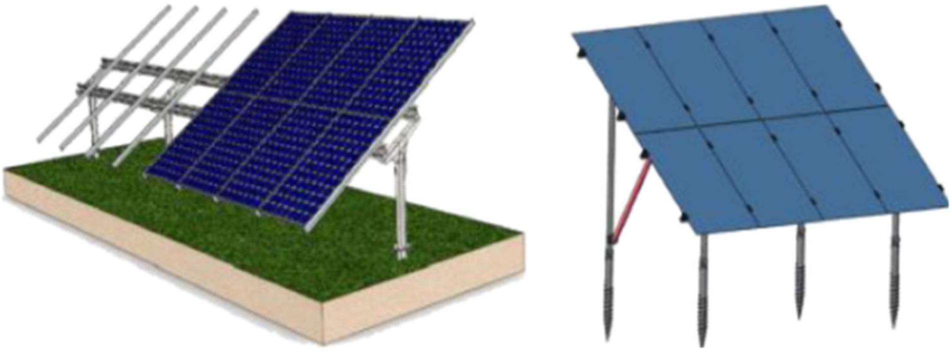

FIGURE 4 Open rack-mounted photovoltaics.[36]

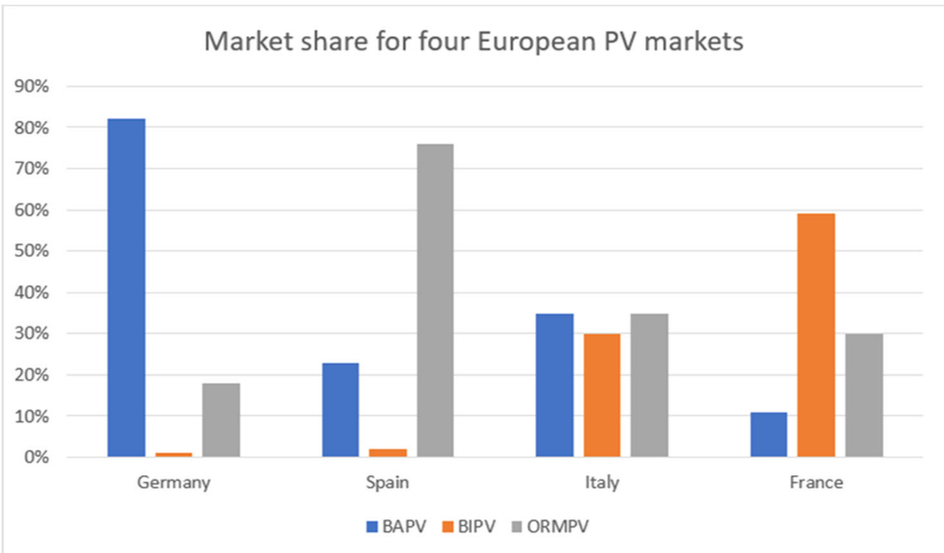

FIGURE 5 Market share for four European PV markets.[38] BAPV, building-applied photovoltaic; BIPV, building-integrated photovoltaic; ORMPV, open rack-mounted photovoltaic; PV, photovoltaic.

comprise four categories: organic PV cells, quantum dot-sensitized solar cells (QDSSCs), dye-sensitized solar cells (DSSCs), and hybrid solar cells (HSCs). Figure 6 illustrates the PV cell technology categorization.

3.1 | Silicon-based technology

Crystalline silicon (c-Si), a semiconductor technology, boasts an efficiency nearing 20% and is abundant, aiding in cost reduction and enhancing reliability over a

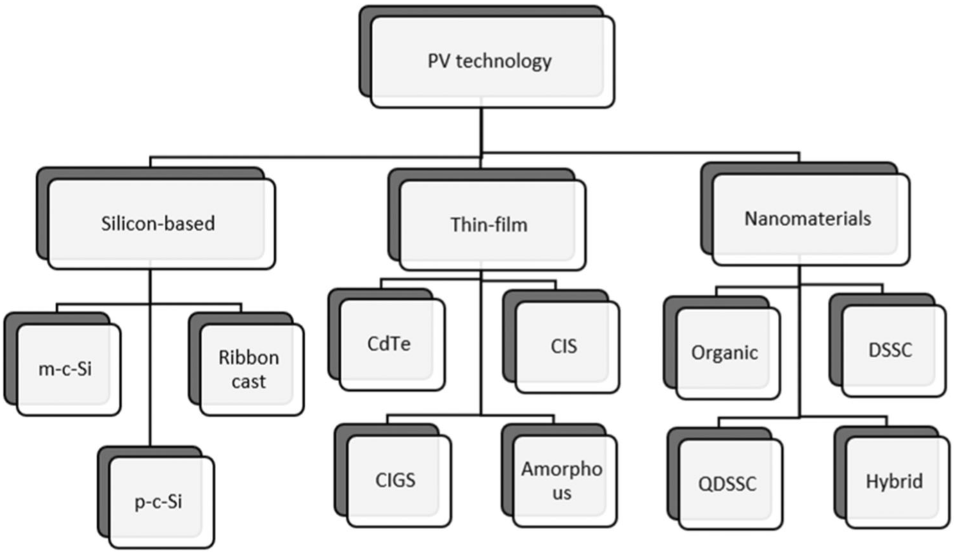

FIGURE 6 PV cell technology categorization.[14,15] a-Si, amorphous silicon; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; CIS, copper indium selenide; DSSC, dye-sensitized solar cell; m-c-Si, monocrystalline silicon; p-c-Si, polycrystalline silicon; PV, photovoltaic; QDSSC, quantum dot-sensitized solar cell.

prolonged module lifetime. In PV technology, solar cells are interconnected and encapsulated within a hardened glass, delivering weather-resistant and reliable PV modules.[14]

3.1.1 | Monocrystalline silicon

Monocrystalline silicon (m-c-Si), Figure 7, entails high-purity single-crystal Si rods, sliced into thin wafers through a wire-cutting method called the Czochralski process. Although it ranks as one of the pricier solar cell types with an efficiency of around 15%, its lower manufacturing costs somewhat offset the initial expense. However, the complex and time-consuming manufacturing process drives up the costs compared with other cells.[41,42]

3.1.2 | Polycrystalline silicon

Polycrystalline silicon (p-c-Si), Figure 8, comprises molten silicon crystals arranged to form a rectangular rod of multicrystalline silicon, which is subsequently sliced into blocks and thin wafers. Utilizing polycrystalline cells is a practical approach to diminishing PV development costs due to its functional material and cost-effectiveness, with an efficiency range of 13%–15%. Polycrystalline silicon emerges as a more feasible alternative to monocrystalline silicon.

FIGURE 7 Monocrystalline silicon cell.[43]

3.1.3 | Ribbon cast silicon

Ribbon cast silicon has two subcategories: edge-defined film-fed growth (EFG) and string ribbon. EFG, a crystal growth technique, generates single crystals from liquid, achieving precise dimension control over extensive lengths with minimal speed control and temperature adjustment.[44,45] String ribbon technique produces Si ribbons approximately 100 and 300 μm thick. For the 100 μm variant, the ribbon remains flat with two high-temperature strings connecting to a silicon melt throughout. For the 300 μm variant, the strings embed within the ribbon, creating high-angle grain boundaries about 2 mm from the core, achieving a high efficiency of 17.8% through this methodology.[46]

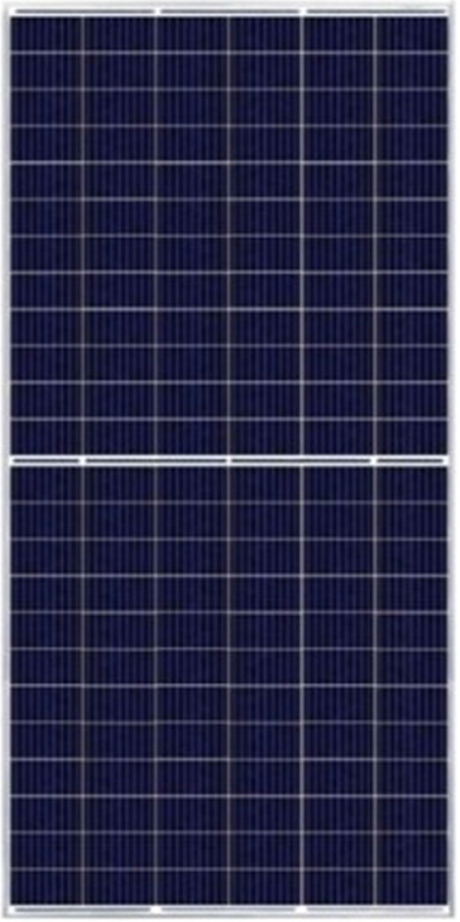

FIGURE 8 Polycrystalline silicon cell.[43]

3.2 | Thin-film cells

Thin-film solar cells, characterized by their thin layer of various materials like semiconductors, are grouped into four main categories: CdTe, CIGS, CIS, and a-Si.[47] Initially conceived in the 1970s by researchers at the Institute of Energy Conversion at the University of Delaware, USA, the market for thin-film solar cells has been growing at an impressive rate, with further growth anticipated.[48]

3.2.1 | Cadmium telluride

CdTe, Figure 9, holds the position as the second most common PV technology in the marketplace, trailing behind crystalline silicon. However, it stands as the prime candidate among all thin-film solar cells due to its efficient light-absorbing material. Although CdTe cells are less efficient than crystalline silicon cells, they are cheaper to produce and have the potential to surpass silicon-based cells in terms of cost per kW of installed capacity. Economic and manufacturing growth is anticipated for CdTe technology. CdTe has a direct bandgap with an optical bandgap of 1.44 eV, nearing the optimum for photoconversion, and exhibits an experimental efficiency of 22.1%; however, the overall displayed efficiency is 16.1%.[48–50]

FIGURE 9 Cadmium telluride.[51]

3.2.2 | Copper indium gallium selenide

CIGS, Figure 10, is an emerging technology with significant promise, owing to its impressive electronic and optical properties. It has achieved an efficiency of nearly 23% and boasts a production capacity of 1000 MW/year with a 15% module efficiency. The rising module production to €0.27/W makes CIGS an attractive option in PV technology. The material's absorption potential is enhanced by its direct bandgap of 1.04 eV, which can be extended to about 1.7 eV by substituting gallium (Ga) with indium (In).[49,52]

3.2.3 | Copper indium selenide

CIS cells consist of thin layers, sharing similarities with CIGS. They are considered to be less toxic and harmful to the environment. With an efficiency of 14%, CIS cells

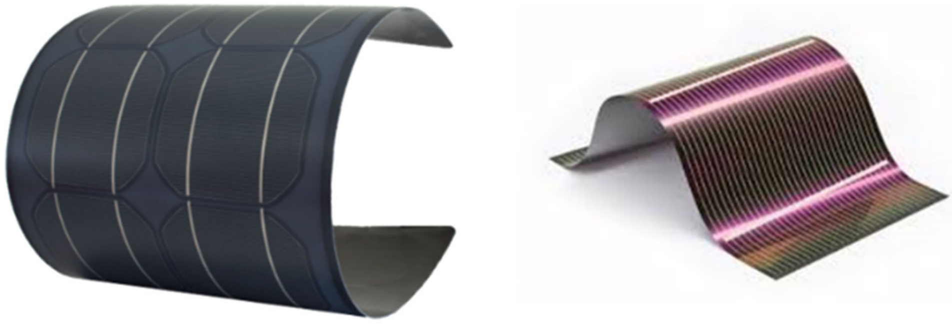

FIGURE 10 Copper indium gallium selenide.[49,53]

exhibit comparable characteristics and functionalities to silicon solar cells, such as durability.[48,50]

3.2.4 | Amorphous silicon

a-Si, Figure 11, is one of the earliest and most appealing PV cell technologies, credited for its lowest material cost in the industry. Unlike crystalline silicon, a-Si is composed of noncrystalline silicon, which leads to lower manufacturing costs. Additionally, a-Si is an abundant material characterized by nontoxic emissions, low deposition temperature, and low cost, albeit with a low efficiency of less than 10%.[54,55] It possesses a direct bandgap ranging from 1.7 to 1.9 eV, lacking a base crystal structure, which allows a fraction of light to be absorbed from a thin layer.[56] Moreover, a-Si can be deposited using various chemical vapor deposition (CVD) methods, such as plasma enhanced CVD, catalytic CVD process, or sputtering.[49]

3.3 | Nanomaterial cells

Nanomaterial cells encompass both inorganic and organic solar cells (OSCs), divided into four main categories: organic PV cells, QDSSCs, DSSCs, and polymers and molecules-based cells, which result in an HSC configuration. These cells are developed using chemicals that present opportunities for efficiency improvement through enhanced light trapping and photocarrier collection, without incurring additional fabrication costs.[58] Nanostructured materials have the potential to improve conventional solar cells through various methods and could foster the development of efficient materials with high conversion efficiencies using low-cost production methods.[59]

3.3.1 | Organic PV cells

Organic photovoltaic (OPV) cells or OSCs represent an emerging photovoltaic technology, gaining traction over the last two decades. These are categorized as third-generation solar cells featuring a light-absorbing layer. Notably, OSCs offer distinct advantages including diverse color and shape options, lightweight construction, mechanical flexibility, and new avenues for integrated solar power harvesting. Their low-cost production and material use result in high-volume production opportunities. Although the current conversion efficiency ranges between 9% and 10%, ongoing research aims to enhance this efficiency further.[60–62]

3.3.2 | Dye-sensitized solar cell

DSSCs emerged as a cost-effective and technically viable alternative within the PV industry, particularly effective under low-light conditions. They offer good overall performance, flexibility in colors and appearances, and potential low cost. Initially developed in the early 1990s with a breakthrough by O'Regan and Gratzel in 1991, DSSCs had an efficiency of 7%. Over the past two decades, research and experimentation have driven efficiency improvements, reaching at least 13%, with a single PV device achieving 33.8% at a 1.9-eV optical bandgap under 1000 W/m^2 illumination.[63–66] DSSCs comprise working electrodes imbued with a mesoporous layer of titanium oxide TiO_2 and redox electrolyte on glass, sealed adjacent to a counter electrode soaked and affixed to a transparent oxide.[60,67]

3.3.3 | Quantum dot-sensitized solar cell

QDSSCs, Figure 12, were introduced as potential replacements for DSSCs due to their advanced optoelectronic properties, albeit requiring more environmentally cautious experimentation for realization. Their structure and function resemble that of DSSCs, boasting a power conversion efficiency of 13% along with enhanced photostability and a broader absorption profile. QDSSCs present a promising avenue in solar cell

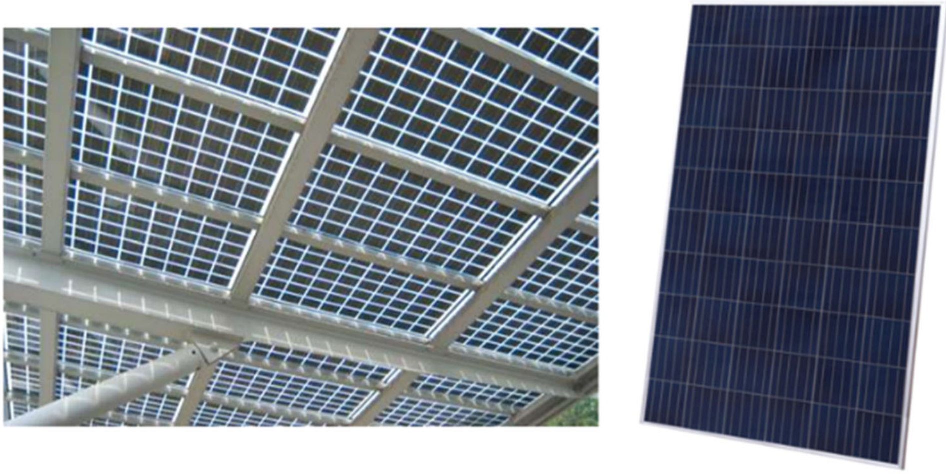

FIGURE 11 Amorphous silicon cell.[54,57]

technology for the upcoming decades, with foundational development traced back to 1991 by Gratzel (similar to DSSCs). They can be prepared through two distinct methods: in situ preparation and attachment of pre-synthesized colloidal quantum dots.[59,68–71]

3.3.4 | Hybrid solar cell

HSCs embody a fusion of two or more materials, such as conjugated polymers, nanoparticles, and organic or inorganic semiconductors to leverage the benefits of combined materials. For instance, electron provision can enhance cell performance without incurring high costs or environmental hazards, while the inorganic semiconductor can facilitate higher charge carrier mobility compared with *n*-type materials.[72] HSCs are subdivided into two groups: dye cells and organic/inorganic bulk heterojunctions. Their efficiency has been found to exceed 17%.[73,74] Figure 13 exemplifies another variant of hybrid PV known as solar PV-T, where solar PV–thermal panels convert solar energy into both electricity and hot water.

FIGURE 12 Quantum dot-sensitized solar cell.[72]

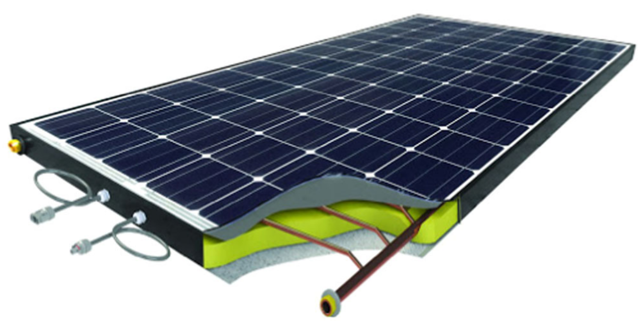

FIGURE 13 Hybrid solar cell.[75]

3.4 | Comparison of PV categories

In this section, the diverse PV cell categories are juxtaposed, with efficiencies delineated in Table 1. The first category encompasses silicon-based cells identifiable as crystalline, monocrystalline, and ribbon cast with efficiencies ranging from 22% to 26.7%. The second category encompasses thin-film cells subdivided into four types: CdTe, CIGS, CIS, and a-Si, with performance efficiencies between 12% and 24.2%. The third category consists of nanomaterial cells, including organic PV cells, QDSSCs, DSSCs, and HSCs. While m-c-Si cells exhibit higher efficiency compared with thin-film-based and nanomaterial cells, thin-film cells offer cheaper and

TABLE 1 Efficiencies of different PV cells.[76]

Type of PV cell	Recent cell efficiencies (%)
Monocrystalline silicon (m-c-Si)	22–26.7
Polycrystalline silicon (m-c-Si)	19–23.4
CdTe	16–23.3
CIGS	17–24.2
Amorphous silicon (a-Si)	12–14.2
Organic	7–18.2
DSSC	11.5–13
QDSSC	10–18.2

Abbreviations: CdTe, cadmium telluride; CIGS, copper indium gallium selenide; DSSC, dye-sensitized solar cell; PV, photovoltaic; QDSSC, quantum dot-sensitized solar cell.

quicker development alongside lower material and production costs. However, the third category is not often the primary choice due to its nascent stage of development and the consequent lack of extensive information and data for technology enhancement.

4 | TECHNICAL DETAILS

In this section, technical aspects of BIPVs are deliberated, drawing upon various studies. A comprehensive discussion surrounding the categorization, basic parameters, and factors influencing BIPV performance is provided.

4.1 | Categorization of BIPV

BIPV categorization, derived from diverse technology, application types, and market perspectives, is depicted in Figure 14. Under the technological dimension, PV technology bifurcates into silicon-based and nonsilicon-based subcategories. The silicon-based PV modules encompass monocrystalline, polycrystalline, ribbon cast, and amorphous types, whereas nonsilicon-based modules include CdTe, CIS, and CIGS.[6,77]

Additionally, a myriad of applications have emerged for BIPV systems, each serving unique functionalities and aesthetic appeals. A more nuanced classification of BIPV applications is illustrated in Figure 14, categorizing them into PV facade, PV window, PV roof, and PV sunshades photovoltaics integrated shading devices (PVSDs), aligning with the comprehensive review by Zhang et al.[78] on PVSDs. Semitransparent roofs predominantly comprise crystalline or thin-film panels, replacing traditional materials, thereby becoming an integral component of the building infrastructure.[79,80] On the other hand, semitransparent facade PV

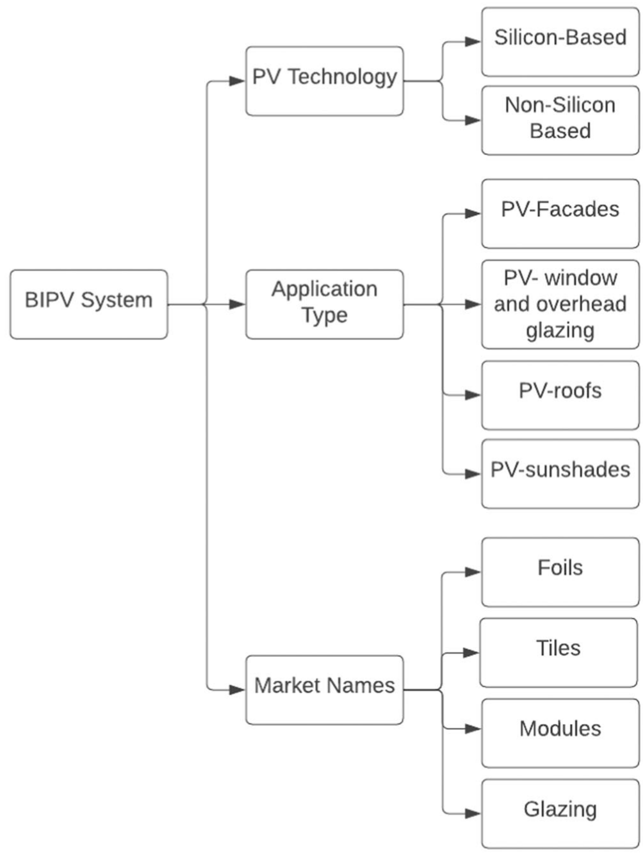

FIGURE 14 Categorization of BIPV.[78] BIPV, building-integrated photovoltaic; PV, photovoltaic.

modules substitute conventional glass, especially in storage houses, permitting natural daylight to permeate during the daytime. Their installation on walls or windows and within greenhouses is contingent upon mounting positions and climatic factors, such as solar irradiation, temperature, and tilt angle.[80,81] Figure 15 showcases various BIPV applications concerning roofs and facades.

Moreover, market-based categorization elucidates four BIPV product types, namely, foil, tile, module, and solar glazing products. Foil products, known for their lightweight and flexible attributes, necessitate straightforward installation, predominantly fabricated using thin-film cells. Tile products, either covering entire roofs or partial areas, emulate standard roof tiles' appearance and functionality while replacing a specific number of tiles. Contrarily, module products resemble conventional PV modules but feature weather skin solutions. Lastly, solar glazing products, integrable within roofs, facades, or window structures, are available in an array of aesthetic designs varying in color and transparency. Figures 16–19 illustrate these market-based products.[84–86]

FIGURE 15 Roof and facade applications.[82,83]

4.2 | Basic parameters and factors affecting the performance of BIPV

The performance of BIPV systems is contingent upon three principal parameters: electrical, thermal, and optical, as tabulated in Table 2. Electrical parameters encompass voltage and current, monitored using data loggers, facilitating the plotting of current–voltage (I–V) and power–voltage (P–V) curves, as illustrated in Figure 20.[88,89]

Figure 20 elucidates critical performance indicators, like, open circuit voltage (V_{OC}), short circuit current (I_{SC}), maximum power (P_{MAX}), current at maximum power (I_{MP}), and voltage at maximum power (V_{MP}). Using these parameters, computations for the fill factor (FF) and power conversion efficiency η are conducted as follows:

$$\mathrm{FF} = \frac{P_{\max}}{V_{OC} \times I_{SC}},$$

$$\eta = \frac{P_{\max}}{E_{tot} \times A} \times 100\%,$$

where E_{tot} is the total incidence irradiance (W/m^2), and A is the surface area (m^2).

Thermal performance factors encompass the solar heat gain coefficient (SHGC) and U value. The SHGC reflects the fraction of solar radiation either directly transmitted or absorbed and subsequently released inward through a window. The U value, indicative of a window or structure's nonsolar heat flow conductance, inversely correlates with insulation performance. The ensuing equations facilitate the computation of glass and window U values[90–92]:

$$U_g = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i} + \frac{L}{K}},$$

where U_g is the U value of a glass, h_o is the outdoor glass surface heat transfer coefficient (W/m^{2}K), h_i is the indoor glass surface heat transfer coefficient (W/m^{2}K), L is the glass thickness (m), and K is the thermal conductivity of the glass (W/m^{2}K). Also, the value of U value of the window can be calculated using the equation

$$U = \frac{U_g A_g + U_f A_f}{A_g + A_f},$$

where U_g and U_f are the U values of the glass and the frame, respectively; A_g and A_f are the areas of the glass and the frame, respectively, in m^2. The SHGC coefficient is calculated as

$$\mathrm{SHGC} = \tau + N\alpha,$$

where τ is the total solar transmittance of the PV, N is the inside flowing fraction of the absorbed radiation, and α is the solar absorption of the semitransparent PV.

Optical performance parameters include the window-to-wall ratio (WWR), light-to-solar gain ratio (LSGR), and visible light transmission (VLT). WWR, a critical determinant of a building's energy performance, entails the proportion of window area to wall area. VLT quantifies the visible light transmitted through PV modules, whereas LSGR represents the ratio of VLT to SHGC. The formulas below facilitate the computation of WWR, VLT, and LSHG:

$$\mathrm{WWR} = \frac{\Sigma\text{glazing area}}{\Sigma\text{gloss exterior wall area}},$$

where $\Sigma_{\text{glazing area}}$ is the area of the glass including the frames (total area of the window) (m^2) and $\Sigma_{\text{gloss exterior wall area}}$ is the total area of walls that separate the outside from the inside of the building (m^2). Then VLT is given by the equation

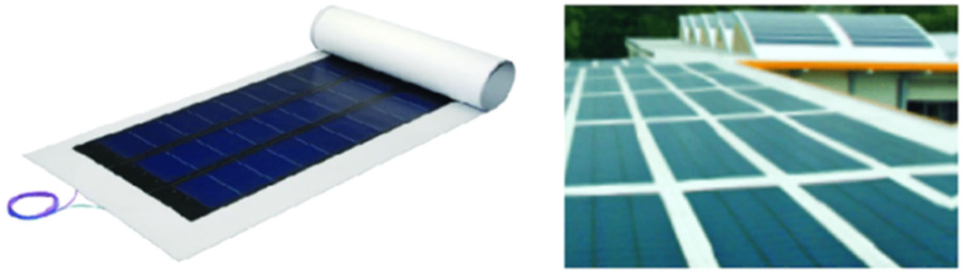

FIGURE 16 Foil products.[84,87]

FIGURE 17 Tile products.[84,87]

FIGURE 18 Module products.[84,87]

$$\tau = \Sigma\tau_i,$$

where τ is the total visible transmittance of semitransparent PV glazing and τ_i is the visible transmittance of the multiple layers from different days.[93] Thus, the equation of LSHG can be derived by the VLT and SHGC:

$$\mathrm{LSHG} = \frac{\mathrm{VLT}}{\mathrm{SHGC}}.$$

Subsequent studies ascertain other influential factors like module design, temperature, optical WWR, and orientation, significantly impacting a building's energy equilibrium concerning electricity generation, heating, cooling, and lighting.[94,95]

5 | STUDIES ON BIPV SYSTEM PERFORMANCE

In this section, the performance of semitransparent BIPV systems is reviewed, focusing on energy generation and saving, daylight saving, efficiency, and overall performance evaluation based on electrical, thermal, and optical properties. Tables 3 and 4 illustrate case studies and the

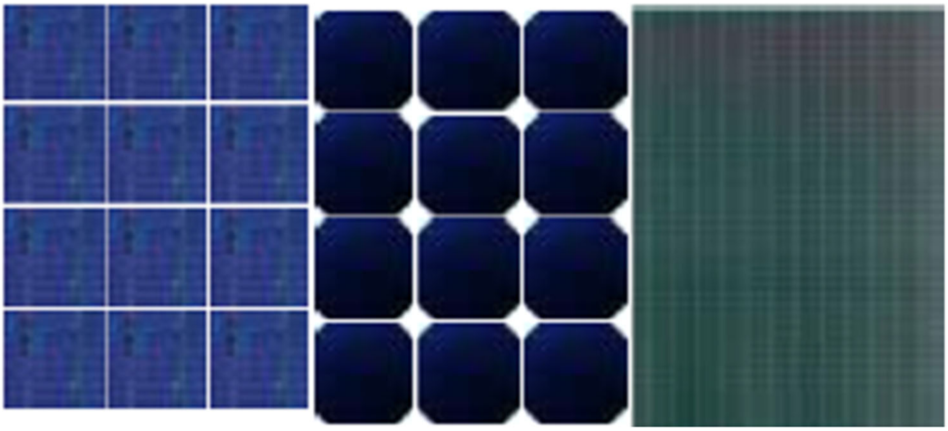

FIGURE 19 Solar glazing products.[84,87]

TABLE 2 Parameters that affect the building-integrated photovoltaic performance.

Electrical	Thermal	Optical
Open circuit voltage (V_{OC})	Solar heat gain coefficient (SHGC)	Window-to-wall ratio (WWR)
Short circuit current (I_{SC})	U value	Light-to-solar gain ratio (LSGR)
Maximum power (P_{MAX})		Visible light transmission (VLT)
Current at maximum power (I_{MP})		
Voltage at maximum power (V_{MP})		
Fill factor (FF)		
Power conversion efficiency (η)		

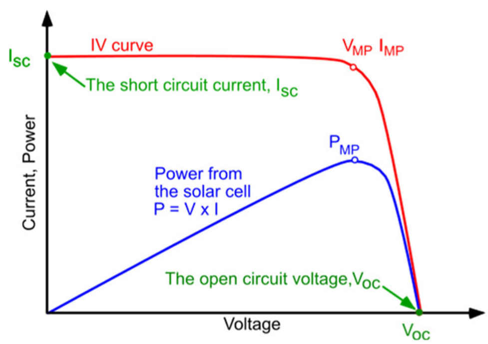

FIGURE 20 I–V and P–V curves.[88]

software utilized for system simulation and modeling, respectively.

5.1 | BIPV systems: Development, performance, and integration

In a study by Omer et al.,[96] two different BIPV systems are examined. The first one is a thin-film PV facade with a 58° tilt angle, showcasing an average annual efficiency of 2%. The second system, a monocrystalline PV roof module with a 52° tilt angle, displayed an efficiency of 3.6%. The total installation costs were £34,650 and £17,550 for the first and second PV systems, respectively, with annual energy costs of 34.01 and 3.69 £/kWh, respectively. Chen et al. in their study,[97] delve into an air-based BIPVT system, combined with a ventilated concrete slab system for additional solar heating within a solar house. The annual electricity generation was noted to be 3265 kWh. Employing a state-space model, it was inferred that the BIPVT system could lower the operating PV temperature, thereby generating more thermal energy. On sunny days, a temperature rise between 30°C and 35°C, which translates to a thermal energy gain of 8.5–10 kW, was observed. A different configuration was explored in Koyunbaba et al.,[98] where a BIPV system was installed adjacent to a wall, maintaining a 0.5-m air gap. The wall featured two air vents measuring 0.8 m^2 each to facilitate winter heating. Data collected in early February showed that the electrical and thermal efficiencies were 4.5% and 20.3%, respectively, with irradiations of 638.6 and 750.88 W/m^2, respectively. Further, Kundakci Koyunbaba and Yilmaz[99] discuss a BIPV setup connected to a wall and employing single, double, and a-Si semitransparent PV panels. Installed

TABLE 3 Summary and examination of the BIPV systems studies.

Reference	Location	Brief Summary	Results
[96]	Nottingham (UK)	Two BIPV systems to evaluate renewable energy and energy efficiency.	Average annual system efficiency, total capital installation costs, and annual energy costs were 2%, £34,650, and 34.01 £/kWh, respectively; and 3.6%, £17,550, and 3.69 £/kWh, respectively, for each system.
[91]	Penryn (UK)	Indoor and outdoor testing for semitransparent PV integrated into a facade building.	Compared with a single glazing case as a reference, the application CdTe achieved a net energy saving to be as high as 20%.
[97]	Quebec (Canada)	Air-based BIPVT system of a solar house was modeled by thermal properties.	Annual electricity generation of 3265 kWh. Temperature rise on a sunny day was between 30–35°C with a thermal energy gain of 8.5–10 kW.
[98]	Izmir (Turkey)	BIPV system connected to a wall to obtain electrical and thermal properties.	Electrical and thermal efficiencies of 4.5% and 20.3%, respectively, with irradiations of 638.6 and 750.88 W/m^2, respectively.
[98]	Izmir (Turkey)	Experimental measurements taken place to obtain the thermal characteristics of 3 BIPV system.	Nominal power of 27 W with a maximum electrical power rate of 35.79 W/m^2 and an electrical efficiency of 4.27%–4.65%.
[99]	Hong Kong (China)	Overall energy performance of semitransparent BIPV in an office.	A reduction heat of 65% was evaluated with a solar cell area ratio of 80%.
[100]	Beirut (Lebanon)	A 17.6-kW/hour BIPV system was simulated under parameters, such as tilt angle, type of cells, and climate in terms of energy generation.	Results showed an energy production of about 27 MWh/year at a tilt angle of 20°–30°. Also, placing the system in a vertical position produces less than 61% of energy. For 27 MWh/year, monocrystalline and polycrystalline need the same area but amorphous need more.
[101] (Contd)	Barcelona (Spain), Rome (Italy), and Cairo (Egypt)	The second experiment was taken to investigate energy production at different locations.	For Beirut, Rome, Barcelona, and Cairo, energy production was found to be 27.098, 25.207, 25.604, and 30.071 MWh/year, respectively.
[101]	Hong Kong (China)	The performance of a BIPV system was analyzed under the shading factor and reduced energy use in terms of electricity generation and consumption.	At smaller tilt angles, the system was producing more electricity. The maximum electricity generation was 598.26 kWh with a tilt angle of 70°.
[102]	Yaoundé (Cameroun)	A semitransparent BIPV was thermal modeled.	Maximum annual thermal energy was 76.6 kWh with a thermal efficiency of 56.04%. Also, the maximum value of heat received and extracted from fins was 28.485 Wh/year and kW/year, respectively.
[103]	Nice, Paris, and Lyon (France)	Examination and analysis of a semitransparent BIPV system in terms of electricity production during the four different seasons.	Nice had the highest electricity production in all seasons followed by Lyon in second place and at last Paris.
[89]	Singapore (Asia)	Evaluation of the performance of a semitransparent BIPV window system.	The net energy of the BIPV is dependent on the WWR and is the most efficient system in terms of energy saving with good energy-saving potential toward natural light.
[104]	Florianopolis, Fortaleza (Brazil)	Investigation of semitransparent BIPV window system in potential energy savings and generation.	Florianopolis had a higher energy-saving percentage than Fortaleza, but both almost had the same energy production.

TABLE 3 (Continued)

Reference	Location	Brief Summary	Results
[105]	Korea	Two buildings were compared in theoretical and simulation results in electricity usage per year.	As the theoretical values were too high, they were not considered while simulation results were more sensible and accurate, thus 5% of the annual power consumption on each building was accounted for.
[22]	Toronto (Canada)	Investigation of local residents' BIPVT energy productions.	A minimal monthly electricity cost while selling excess electricity to local grids, mostly in summer.
[106]	Almeria (Spain)	Evaluation of a PV plant system in terms of electricity production and efficiency, in experimental and simulation.	Estimation of the overall electricity production and efficiency was 8.25 kWh/m^2 and 4.7%, respectively, while simulation showed that these results had a minimal error.
[107]	Toronto (Canada)	Comparison of a BIPVT model in two simulation software.	Different electricity production because of the different thermal parameters, weather data, and electrical models; 4.96 and 5.15 kWh, for TRANSYS and EnergyPlus, respectively.
[108]	Shenyang (China)	An integrated BIPVT system was simulated to observe the thermal and transient thermal efficiency throughout different velocities.	Both factors were almost close to each other, but the optimal velocity was found to be 4 m/s.
[109]	Bangalore, Srinagar (India)	A semitransparent BIPV system was experimented with on two roofs and then simulated.	The system is preferable for both moderate and cold climates in terms of yearly electrical energy and exergy production amounts compared with a conventional BIPV system.
[110]	Sidney (Australia)	A PVT air system was designed to maximize energy output.	Thermal and electrical efficiency was 28%–55% and 10.6%–12.2%, respectively.
[111]	Lyon (France), Sydney (Australia)	Numerical and experimental investigation of natural convection with application to BIPV systems.	Different inputs result in an increase of convective heat transfer at lower wall temperatures and an increase in the chimney effect. Two inputs with 233 W power and temperature reduction of about 10°C.
[112]	Europe	An estimation of the potential of BIPV in electricity generation.	Average efficiency and performance of 17.9% and 0.8, respectively; with a potential of 951 GWp and annual energy generation potential of 840 TW.
[113]	UK	Observation in temperature rise of a BIPV system.	Three experiments with three ambient temperature values: 65°C, 44°C, and 34°C. Using simulation, the numerical error was by 1°C.
[114]	China	Evaluation for BIPV power generation during 2000, 2007, and 2009.	Output power at 3, 1088, and 4381 MW, respectively, with a 191.3% increase. The ideal position for placing a PV module is vertical.
[115]	Singapore (Asia)	Energy generation modeling of BIPV system in an office.	Install capacity of 142.5 kWp, average monthly performance, and energy generation of 0.81 and 12.1 MWh, respectively.
[116]	China	A new design BIPV system was thermally modeled.	Output power was 65 W/unit area and thermal conductivity coefficient was 0.021 W/m^2k.

(Continues)

TABLE 3 (Continued)

Reference	Location	Brief Summary	Results
[117]	Kastoria (Greece)	Analysis and simulation of a grid-connected BIPV system.	An installed power of 2.25 kWp and contributed 50% of the annual energy demand with an energy production of 4000 kWh/year, building annual energy demand of 8000 kWh/year, and overall cost of €24,000.
[118]	Suwon (Korea)	Analysis and simulation of a BIPV system as a shading device.	In winter, power generation for estimation and simulation was 221.5 and 217.8 kWh, respectively. Also, as power generation is reduced, the energy conversion effect is increased.
[119]	USA	A BIPVT system was integrated into a roof and simulated.	Temperature, output electricity, and PV efficiency decreased while solar irradiance increased due to flow rate increase.
[120]	Hong Kong (China)	Investigation of grid-connected BIPV system in terms of power and efficiency.	Maximum power output was observed on the roof while annual energy output and efficiency were 6878 kWh and 9%, respectively.

Abbreviations: BIPV, building-integrated photovoltaic; BIPVT, building-integrated photovoltaic thermal; CdTe, cadmium telluride; PV, photovoltaic; PVT, photovoltaic thermal.

TABLE 4 Software used in simulation studies.

Ref	Software	Description
[105–107, 110]	TRANSYS	Thermal analysis and simulation of BIPV/BIPVT
[97, 107, 108]	EnergyPlus	Analysis and simulation of BIPV
[114–117]	MATLAB	Equations and algorithms solution
[7, 110, 111]	PVsyst	Simulation, modeling, and data analysis of PV
[109]	ESP-r	Power output calculations
[121]	FLUENT	CFD analysis and electrical energy simulation
[122]	THERM	Power and energy simulation
[113]	MOSEK	Equation and algorithms solution
[119]	eQuest	Yearly electricity usage calculations
[16]	RETscreen	Annual energy generation
[117]	PROTEUS	Equations and algorithms solution
[22]	FORTRAN	Equation and algorithms solution
[118]	VR4PV	Shadow factor
[108]	Green Building XML	Analysis and simulation of BIPV

Abbreviations: BIPV, building-integrated photovoltaic; BIPVT, building-integrated photovoltaic thermal; CFD, computational fluid mechanics; PV, photovoltaic.

within an insulated room, the nominal power of the PV panel was recorded as 27 W. Subsequently, vents were positioned at both the upper and lower sections of the system, and the resultant maximum electrical power rate and efficiency were 35.79 W/m^2 and between 4.27% and 4.65%, respectively.

Lu and Law[121] have performed an exhaustive analysis of the energy performance of a semitransparent BIPV module, investigating parameters, such as total heat gain, power generation, and daylight consumption across five different PV orientations. A significant reduction of total heat gain, around 65%, was noted across all orientations due to the higher transmittance of the BIPV modules compared with clear glass. Additionally, the total heat gain was translated into electricity consumption of the air-conditioning system, revealing coefficients of performance (COP) for water-cooled and air-cooled systems to be 2.8 and 4.8, respectively. Salem and Kinab[100] embarked on evaluating a BIPV system of 17.6 kW/hour under varying parameters, such as tilt angle, type of cells, and climate, in terms of energy generation, revealing that a tilt angle between 20° and 30° yielded an energy production close to 27 MWh/year. Moreover, it was found that using polycrystalline technology was more cost-effective in comparison to monocrystalline while achieving nearly the same area requirement.

A study by Sun et al.[101] evaluated the performance of BIPV systems under varying shading factors to mitigate energy consumption in terms of electricity generation and consumption. The investigation was hinged on three parameters: WWR, tilt angle, and overhang length. It was observed that BIPV systems were more productive at smaller tilt angles. For instance, at a 40° tilt angle, the annual power output declined, and at an 80° tilt angle, the output measured 106.8 kWh/m^2—a 27% decrease compared with the peak value of 146.4 kWh/m^2. Interestingly, as both tilt angle and overhang length were incremented to 70° and 0.4 m, respectively, the electricity generation surged to 598.26 kWh. Martial et al.[102] explored and scrutinized a semitransparent BIPV system equipped with 30 multicrystalline PV modules. This assembly, boasting an area of 36.45 m^2 and a peak power of 5.4 kW, was oriented against the wind to optimize natural convection. By augmenting the contact surface between the fluid traversing the duct and the fin surface on the back sheet of the PV module of BISPVT, a heightened heat exchange via convection was achieved. This, in turn, reduced the cell temperature while amplifying the thermal energy extricated from the system. It was recorded that the maximum annual thermal energy attained was 76.6 kWh, rendering a thermal efficiency of 56.04%. Furthermore, the maximum value of heat transferred from the fin surface to the air coursing in the duct was 28.485 Wh/year, and heat drawn by the air from the fin surface totaled 55.4 kWh/year. Thus, it was deduced that the decline in cell temperature augments the electrical efficiency of the PV module.

In Saadon et al.,[103] an analysis of three varying degrees of facade transparency in semitransparent BIPV was conducted, namely, 0%, 30%, and 50%. The evaluation spanned three distinct French cities—Nice, Paris, and Lyon—across all four seasonal quadrants. Notable disparities in electricity production were registered among the cities and seasons. For instance, during summer, the electricity yields for Nice, Paris, and Lyon ranged from 3.8 to 7.5, 3.4 to 6.6, and 3.6 to 7.1 MWh, respectively. The autumnal output spanned from 4.5 to 8.8, 3 to 5.8, and 3.2 to 6.4 MWh, respectively, among the cities. Conversely, winter production witnessed a decline, measuring 4.1–8.1, 1.9–3.8, and 2.3–4.5 MWh, respectively, whereas spring yielded a range of 4.1–8.1, 3.3–6.5, and 3.6–7.1 MWh, respectively. Poh Khai[89] carried out in Singapore an appraisal of the performance of semitransparent BIPV windows. Six semitransparent BIPV modules were deployed to gauge the overall energy performance by tabulating the net electrical benefits (NEBs), which encompassed electricity generation, artificial lighting energy, and cooling energy reduction, parsed through parameters, like, thermal, electrical, and optical properties. It emerged that the NEB of BIPV was contingent on the WWR; and in juxtaposition with other glazing systems, semitransparent BIPV windows emerged superior in overall energy-saving performance. Furthermore, these windows displayed commendable energy-saving potential in harnessing natural light.

In a study by Leite Didoné and Wagner,[104] the investigation delved into the potential energy savings and energy generation capacities of semitransparent BIPV windows in two Brazilian cities: Florianopolis and Fortaleza. In Florianopolis, a remarkable energy-saving rate of about 43% was realized, alongside an energy production range of 591.8–750.3 kWh/year. In contrast, Fortaleza registered a lower energy-saving rate of about 19%, albeit a closely comparable energy production range of 493.6–798.6 kWh/year. The comparative analysis revealed that Florianopolis exhibited a higher propensity for energy savings while maintaining near-equivalent energy generation levels to Fortaleza. Furthermore, it was inferred that a reduction in energy consumption for cooling utilization and natural lighting, paired with enhanced energy production using semitransparent PV panels in windows, could engender optimal control frameworks. Hwang et al.[105] incorporated a BIPV system in two distinct edifices, dubbed Building A and Building B, where the annual electricity consumption was evaluated in two phases. Initially, Buildings A and B recorded electricity usage approximating 25,550 and 41,100 MWh/year, respectively. Subsequently, a simulation and analysis with eQuest demonstrated that Buildings A and B achieved a peak electricity production of 1.875 and 2.785 MWh/year, respectively. Additionally, the total electricity consumption for Buildings A and B was curtailed to 6.65% and 5.92%, respectively. In Kamel and Fung,[22] a TRNSYS model was conceived for a BIPVT system amalgamated with an air source heat pump (ASHP). It was discerned that the preheated air emanating from the BIPVT system when channeled into the ASHP slashed the electricity demand requisite to operate the heat pump. Consequently, a reduction in GHG emissions approximating 225 kg of CO_2 was observed. Additionally, an examination of the electricity cost and energy production among residents of Toronto was conducted. The electricity expenditure was tabulated at \$24/month, whereas the local energy production was derived from renewable resources, with surplus electricity being offloaded to the grid, amassing a revenue of \$97/year.

Pérez-Alonso et al.[106] showed a flexible thin-film PV system (with 24 PV modules) integrated into a 1.024-m^2 greenhouse and it was divided into two identical zones: T1 and T2, where both are a set of opaque flexible thin-film PV modules connected to the grid by an inverter and a surface area of about 192 m^2. The results showed that each module strip had a peak power of 92 W and the electricity production of the whole system was 8.25 kWh/m^2. Also, the overall efficiency was found to be around 4.7% but these results were found using estimations so modeling and simulations were taken using artificial neural networks. Results showed that this model is suitable for the real PV plant and shows minimal errors in terms of PV production. In Vuong et al.,[107] a BIPVT system was designed and simulated in software called EnergyPlus and TRNSYS. The system consisted of a single row of five PV panels (1 m × 1.2 m) and connected in series with an air channel and tilt angle of 45°. Both software used the same thermal equations but there were some differences in terms of temperature, thermal, and electrical outputs. The electricity production was found to be different between the two software because of the different thermal parameters, weather data, and electrical models. For TRANSYS and EnergyPlus, the electricity production was found to be 4.96 and 5.15 kWh, respectively.

In Li et al.,[108] an integrated BIPVT system is simulated and analyzed in EnergyPlus. To control the internal airflow distribution characteristics of the PVT collector on ASHP system heating performance, computational fluid mechanics (CFD) was used. Using CFD, the RNG $k-\varepsilon$ turbulence model was applied for numerical simulation of the system and was studied at different velocities: 2, 3, 4, 5, and 6 m/s, to evaluate thermal efficiency and transient thermal efficiency. For thermal efficiency, it was found to be 10.67%, 14.94%, 18.42%, 20.24%, and 21.02%, respectively; while transient thermal efficiency was 10.13%, 14.15%, 17.23%, 18.68%, and 19.13%, respectively. Therefore, it was assumed that the optimal velocity was 4 m/s, and the COP of the ASHP system was found to be 4.6.

Agrawal and Tiwari[109] integrated a BIPV into the roofs of two laboratories in India: Bangalore and Srinagar, for experimental work to forecast solar cell temperatures, duct air, and room air. Fans of 12 W were used to flow the air in the duct of the system for fresh air inlet. Theoretically, it was found that thermal energy, electrical output, and net energy for Bangalore were 7.4, 7, and 8 kWh, respectively; and for Srinagar were 7.6, 6.6, and 8.0 kWh, respectively. Also, it was found that cell efficiency and overall thermal efficiency were 12.5% and 53.1%, respectively, for Bangalore and 14.3% and 51.3%, respectively, for Srinagar. Then it was simulated to analyze the energy, exergy, and electrical energy at different weather conditions; for a mass flow rate of 0.2 kg/s, the system produced 629 exergy and 1.571 kWh of electrical energy. However, using the BIPVT is a more suitable choice because of the higher exergy and electrical energy of 633 and 1560 kWh, respectively.

In Bambrook and Sproul,[110] an experimental PVT air system is designed to maximize energy output in Sidney with experimental results, such as thermal, electrical, and overall system performance. To perform such an experiment, the input power range was between 4 and 89 W, and the air mass flow rate was between 0.02 and 0.1 kg/s to minimize the friction loss of the fluid in the system. But when the experiment took place, results changed in terms of thermal and electrical efficiency. Both parameters increased when the mass flow rate increased, thus thermal and electrical efficiencies were found to be 28%–55% and 10.6%–12.2%, respectively, for midday. In Timchenko et al.,[111] numerical and experimental studies were taken off the nonconstant flow and wall heat flux open-ended channel formed by the double-skin facade and then applied to the passive cooling of the BIPV system. This system was analyzed with specifications of 1.5 m height, 0.7 m depth, and 0.1 m length. The analysis consisted of three-dimensional calculation and natural convection between two walls for three different configurations: uniform, staggered, and nonuniform. The results showed that a variety of inputs (different cases) should be opened at different zones, such as heated and unheated, therefore conducting, at a steady pace, and increasing convective heat transfer at the lower wall temperature as well as the chimney effect. In both inputs, V1 and V2, it was observed that power was 233 W and a reduction in temperature of 10°C with a 9%–12% increase in mass flow rate.

In Defaix et al.,[112] European data (EU-27) were used to estimate the potential of BIPV, such as electricity generation. To estimate the potential of BIPV, floor area is calculated and then estimated for the number of floors, the ground floor area of the building, suitable roof, and facade surfaces, thus the final step is to combine these parameters with irradiation. An average efficiency and average performance of 17.9% and 0.8 were found, respectively, and the potential was 951 GWp while the annual energy generation potential was 840 TW, which consists of more than 22% of the European electricity demand. Using the results, it shows that Germany has the highest potential followed by Hungary, Denmark, and Cyprus.

Huang et al.[113] used a phase change material (PCM) to control the temperature rise of the BIPV system. Three experiments were taken and compared in terms of thermal behavior. The first experiment was a single flat aluminum plate system, and the ambient temperature was about 65°C. The second experiment was a PV/PCM system without internal fins and the ambient temperature was approximately 44°C. The third experiment was a PV/PCM system with internal fins and the ambient temperature was about 34°C. Then, the system was simulated, and results showed that the temperatures in each case varied by 1°C. In Peng et al.,[114] data were collected from China for PV power generation. Multiple periods are selected across this study: 2000, 2007, and 2009 where output power was 3, 1088, and 4382 MW, respectively, thus an increase is observed throughout the years, approximately 191.3%. Then, it was found that the best position for placing a PV module was vertical with the assistance of simulation and analysis. In Wittkopf et al.,[115] an office building in Singapore had an integrated BIPV system simulated and analyzed. The system consisted of 750 PV modules mounted on the roof of the building with a 0.3-m gap for air ventilation and grouped into 22 arrays with different orientations and tilt angles. The PV modules were made of polycrystalline and with a given open circuit voltage and short circuit current of 30.8 V and 8.23 A, respectively, thus having an installed capacity of 142.5 kWp. The simulation was conducted by MATLAB to analyze the performance of the system, with an average monthly performance ratio of about 0.81 and an average monthly energy generation of 12.1 MWh. Other parameters were presented to show the effects on the system, such as tilt angle, PV module temperature, partial shading, and irradiance fluctuations.

5.2 | Innovations and case studies in BIPV applications

Yu et al.[116] introduced a new design of the BIPV module in China where the "sandwich" structure is integrated with three different types of PV modules, such as thin films, polyurethane, and color organic-coated plates. Using these materials, a new type of PV module was formed and tested through different experiments. Results showed that the BIPV module generated an output power of 65 W/unit area and a thermal conductivity coefficient of 0.021 W/m^2 K. In Bakos et al.,[117] a grid-connected BIPV system in Greece was analyzed using a computerized renewable energy technologies (RETs) assessment tool. It is 2.25 kWp installed power and was connected in a three-phase mode to the electricity grid while it consists of 30 PV generators. Also, it contributes 50% of the annual energy demand with an energy production of approximately 4000 kWh/year, building annual energy demand of 8000 kWh/year, and an overall cost of €24,000. RETs were used to develop a model flow diagram using collected data, such as solar radiation, latitude of project location, annual average temperature, and system characteristics. Also, software was used for financial purposes and cost analysis, both initial and annual. In Yoo and Manz,[118] a BIPV system in Korea was used as a shading device and it was applied in a simulation called SOLCEL for analysis. The system was a monocrystalline silicon type and consisted of 114 units while each panel was built of 230 solar cells with an efficiency of 14.4%. According to the results, the power generation on a winter day was 221.5 and 217.8 kWh for the experiment and simulation, respectively. Also, it was assumed that for the remodeled system the air temperature increases as it reaches higher flows. This leads to two different cases where on the one hand the power generation is reduced and, on the other, the energy conservation effect is increased.

A BIPVT system was integrated by Chen and Yin[119] into the roof of a building in the USA and simulated using a solar simulator. The system was designed to heat the liquid that was water by cooling the solar energy and the PV was an aluminum high-density polyethylene functionally graded material panel, which consists of aluminum water tubes, thus the temperature was reduced by easily transferring heat from panels to the water tubes. The test results showed that the temperature increased at 37.5°C with a flow rate of 30 mL/min but at 150 mL/min the temperature decreased at 32°C. Also, at 150 mL/min water flow rate, the output electricity reached 32.96 and 44.91 W, and PV efficiency was 14.51% and 15.82% at solar irradiance of 800 and 1000 W/m^2, respectively. Finally, using an initial value for the water flow rate (150 mL/min), the total energy efficiency for the system was 79.8%, 77.3%, and 75.2% under solar irradiance of 620, 800, and 1000 W/m^2, respectively. In Yang et al.,[120] an experimental study was investigated regarding the first grid-connected BIPV system in Hong Kong. This system was contributed with 100 PV panels, integrated on three walls and the roof of a plant room on a building with an air gap for air ventilation and a total PV power capacity of 8 kWp. Then, the experimental results were compared with simulations to investigate in detail the effects. The results showed that maximum power output happened mostly on the roof and an annual energy output and efficiency of 6878 kWh and 9%, respectively. Also, it was analyzed in terms of cost where the power price of the system was HK$1.5–2.0/kWh. These prices were compared with electricity supplied by the local companies and it was found that the system's power price was higher than the local companies.

5.3 | Design, analysis, and optimization of BIPV systems

The performance and efficiency of BIPV systems are fundamental to their integration in urban landscapes. Taşer et al.[123] proffer a comprehensive review of the variables influencing the thermal, daylight, and energy performance of BIPV systems. The elucidation of these variables is instrumental in bolstering the efficacy and acceptability of BIPV systems, which, in turn, holds the promise of attenuating building energy demand, thereby curtailing global warming.

Additionally, a bespoke examination of the thermal impact of BIPV systems in a tropical climate is presented by Jhumka et al.[124] Through meticulous simulation modeling, the authors unveil the relative effectiveness of different BIPV installation scenarios in reducing overheating and energy consumption in a typical office building in Mauritius. Such context-specific analyses are pivotal in fine-tuning the deployment strategies of BIPV systems to cater to localized climatic and architectural nuances.

The advent of new design frameworks and methodologies for BIPV systems, as expounded by Yang et al.[125] and Chen et al.,[126] epitomizes the burgeoning innovation in this domain. Yang et al.[125] propose a comprehensive design framework to facilitate the conceptual design phase of BIPV systems in Australia,[126] delves into the design of a prefabricated unitized BIPV wall system.

5.4 | Economic analysis and policy context for BIPV

The quest for energy independence and sustainability drives the emergence of prosumer and sustainable community models, especially in mature markets with established PV infrastructures. A study centered in Italy explores the economic viability of a PV plant under a collective self-consumption scheme, employing net present value analysis amidst varying political and market contexts. The findings underline the significant economic returns with modest risk levels, emphasizing the pivotal role of self-consumption share and energy cost dynamics in fostering sustainable communities.[127] Concurrently, the implementation of BIPVs is gaining traction for its dual advantage of energy generation and building aesthetics. However, a cross-country comparison reveals a critical concern surrounding the fire safety standards of BIPV applications. The distinct normative frameworks across countries necessitate stringent fire safety regulations to ensure the well-being of building occupants and overall structural integrity. This comparative study not only elucidates the prevailing fire safety regulations applicable to BIPV modules but also hints at the necessity of harmonized global strategies to address fire safety concerns in BIPV implementations.[128] These discussions extend the narrative of our review on semitransparent PVs within BIPV systems, underscoring the broader socioeconomic and safety considerations imperative for the global adoption and advancement of BIPV technologies.

5.5 | Environmental impacts and sustainable integration of BIPV

The incorporation of BIPV systems into urban infrastructure is a burgeoning area of interest among researchers and policy-makers, given the pressing imperative to transition to cleaner energy sources. These studies collectively underscore a spectrum of considerations pertaining to the integration of BIPV systems in urban environments.

First, a notable concern surrounding BIPV systems is their potential contribution to the urban heat island (UHI) effect, as elaborated in the review by Elhabodi et al.[129] The authors conducted a meticulous literature survey to ascertain whether BIPV systems aggravate the UHI effect. Their findings divulged both direct and indirect impacts, driven principally by factors, such as the albedo effect and heat dispersion. This intricate relationship between BIPV systems and UHI underscores the necessity for careful planning and design to mitigate potential negative externalities.

Moreover, the study by Čurpek et al.[130] delineates a novel exploration into the dynamic thermal response of BIPV/PCM facades, shedding light on the potential of PCMs in enhancing the thermal performance of BIPV systems. This venture into uncharted territories exemplifies the inexhaustible avenues for augmenting the performance and appeal of BIPV systems.

The pivotal role of BIPV technology in the ambit of net-zero energy buildings (NZEBs) is accentuated by Kong et al.[131] Through a meticulous review and case studies, the authors highlight the indispensable considerations, such as building surface area to volume ratio, window–wall ratio, and glass solar heating gain coefficient in actualizing the NZEB standards. The entwinement of BIPV systems and NZEBs standards epitomizes the symbiotic relationship between clean energy technologies and sustainable building designs.

5.6 | Innovative BIPV applications and user-centric designs

These advancements are instrumental in overcoming the technical and operational hurdles often associated with BIPV systems, thereby accelerating their mainstream adoption. The allure of OPVs for BIPV applications, especially due to their semitransparency, flexibility, and lightweight, is articulated by Feroze et al.[132] The study delineates the comparative advantage of OPV modules, particularly in vertical mounting scenarios, which is a salient consideration for facade-integrated BIPV designs.

The innovative approach to harnessing solar energy through solar photovoltaic blinds (SPBs), as depicted by Nicoletti et al.,[133] is a testament to the inexorable march of innovation in the realm of BIPV systems. This simplistic yet effective method of evaluating the electrical power generated by SPB illuminates the potential for integrating PV technology into everyday architectural elements. The integration of aesthetics and functionality in BIPV systems is another layer of the dialog, explored exhaustively by Pelle et al.[134] Tackling the societal acceptance of colored BIPV systems, the paper delves into the impact of colored layers on the power generation of these modules. The economic viability and the technical intricacies of colored BIPV systems are dissected, underscoring the hindrances in market uptake despite the larger decarbonization agenda. By proposing a fusion of detailed optical modeling and mathematical elaborations, the paper underscores the necessity for accurate assessments of the influence of colored layers on power generation. This inquiry not only alleviates the hurdles in custom manufacturing but also advances the dialog on optimizing product performance, thereby contributing significantly to the broader discussion of BIPV systems' market integration.

5.7 | Practical considerations and real-world applications

In a noteworthy endeavor, the study by Fu et al.[135] dives into the intricacies of thermal estimation within BIPV facade systems, shedding light on the significant thermal energy that can be harnessed for building utilization through air channel heat. The crux of the issue, as identified, revolves around the challenges posed by imprecise air channel heat transfer models under actual operating conditions. By proposing a novel method for accurate thermal estimation, substantiated by long-term outdoor experimental tests, the study makes strides toward bridging this knowledge gap. The unveiling of temperature gradient and the chimney effect within the air channels, particularly when solar radiation surpasses 100 W/m^2, offers a nuanced understanding. Moreover, the establishment of a new air channel heat transfer model, which showcased a promising percentage relative error of less than 7.49%, paves the way for better design strategies in BIPV facade systems. This advances the narrative on the potential of BIPV systems in contributing to building energy-saving goals, a critical conversation in the discourse of sustainable urban development.

On a related note, the spatial constraints in urban locales and their impact on renewable energy utilization, particularly solar energy systems, are comprehensively examined by Şirin et al.[136] The paper underlines the gargantuan energy demands of buildings, which account for a substantial chunk of global energy consumption and GHG emissions. The potential of BIPV/T systems in navigating these challenges is explored, emphasizing the dual benefit of electrical and thermal energy production. By delving into the operational dynamics, classification, and utilization benefits of BIPV/T systems, along with performance improvement techniques, the paper elucidates the significant strides that can be made toward energy-efficient buildings. The discourse extends an invitation to new users and researchers, providing a rich reservoir of information on the technological advancements in BIPV/T systems. This exploration not only enriches the understanding of BIPV/T systems but also propels the discussion on energy-efficient architectural solutions forward, aligning with the broader narrative of sustainable urban development.

The cross-examination of these studies offers a well-rounded view of the various dimensions of BIPV and BIPV/T systems, emphasizing the critical role they play in steering urban development toward energy efficiency and sustainability. Each study, with its unique focus, contributes a piece to the larger puzzle of how best to integrate solar energy systems within building architectures while navigating the technical, societal, and spatial hurdles.

6 | CHALLENGES AND FUTURE RESEARCH OPPORTUNITIES

The integration and utilization of solar energy through BIPVs present a significant stride toward sustainable energy production. However, the data and information amassed underscore that BIPV has not yet reached its zenith due to a plethora of challenges and barriers. Addressing these hurdles through novel materials and technological advancements could markedly improve efficiency and broader adoption of BIPV.

6.1 | Challenges of BIPV

Currently, BIPV accounts for a mere 1% of the total PV installations globally, a statistic significantly impacted by various barriers and challenges inherent in BIPV technology. Various studies delineate a multitude of challenges faced by BIPV.

In Shukla et al.[16] and Goh et al.,[137] challenges and barriers are categorized into five main domains: human resource, information, technical, economic, and policy. The human resource domain indicates a shortage of technically adept and marketing-savvy professionals leading to suboptimal data collection, analysis, project management, operation, and maintenance. The information domain reveals a paucity of quality information regarding PV technologies, BIPV, and equipment suppliers, compounded by inadequate training and skill development. Additionally, a lack of information hampers policy-making and mobilizes civil society. Technical challenges stem from a lack of standardized technology, limited local manufacturing of specialized equipment, and a dearth of technological advancements in PV products for efficient power generation. Economically, some BIPV systems bear high installation costs due to expensive materials and production, exacerbated in economies with long payback periods and high initial capital costs. Lastly, policy challenges emanate from weak energy policies, low prioritization in planning, and ineffective implementation structures. Furthermore, the implementation of BIPV projects is envisioned in three stages: enablers, drivers, and barriers, with each stage intricately interdependent. Barriers impede BIPV project progression while drivers provide solutions to these barriers. Although enablers are a crucial facet of this process, their impact on the project is not profound.

In Mousa[138] and Baljit et al.,[139] interviews reveal numerous barriers, the most salient being cost. This primarily arises from an industry-wide lack of education leading to long payback periods, high initial costs, permitting costs, and insurance hiccups. Following closely is the barrier of government policies and financial support mechanisms, which have a substantial bearing on investment and adoption. A significant number of participants were oblivious to any financial support mechanisms, attributable to either a lack of such programs or awareness thereof. The grid-connection administrative process, a critical step in connecting PV systems to local grids, was identified as a major barrier due to its lengthy and cumbersome nature. Additionally, the rush to install high volumes of PV systems led to excessive output transmitted to local grids, creating a myriad of problems precipitated by a lack of planning.

Education, particularly in solar design, emerged as another barrier. A considerable lack of practical experience and information among architects regarding the awareness and practical application of PV technologies leads to inadequate preparation for customer engagements. Various recommendations were proffered to ameliorate these barriers, key among them being the provision and expansion of financial support mechanisms, investment in educational and marketing tools for PV promotion among architects, and the formulation of more inclusive policies promoting the adoption of renewable energy sources.

In Defaix et al.,[112] challenges encompassing aesthetic, technical, economic, and social domains are outlined. Aesthetic challenges pose a significant hurdle as the integration of PV modules into current architectural designs proves to be a herculean task given the space requirements for PV installations. Social challenges arise from the nascent nature of this technology, causing skepticism and reservations among stakeholders regarding the reliability of this technology. Consequently, there is an imperative need for a paradigm shift in stakeholder engagement and training methodologies to foster BIPV systems promotion. The economic challenge is underpinned by the high costs associated with BIPV system installation and implementation compared with the system itself.

Moreover, while the potential of BIPV is being increasingly recognized, there are notable barriers to its widespread implementation. A recent study conducted in Singapore elucidated some of these challenges using an interpretive structural modeling approach. Among the identified barriers were the lack of professionals knowledgeable in BIPV systems and the absence of cost-effective BIPV products and design tools, which are crucial for fostering broader adoption and implementation.[140]

In light of addressing these barriers, innovative design approaches are emerging to bolster the feasibility and appeal of BIPV systems in contemporary architecture. A study introduced a novel design approach focusing on prefabricated BIPV walls for multistorey buildings. This approach not only expedites the construction process but also enhances the aesthetic and functional integration of PVs into the building envelope, consequently promoting a more sustainable and energy-efficient architectural paradigm.[126]

Furthermore, this prefabricated design approach significantly simplifies the integration of BIPV, making it a more accessible and attractive option for both new constructions and retrofitting projects. By leveraging prefabrication, the associated costs and technical challenges of BIPV integration can be considerably mitigated, thus addressing some of the primary barriers to BIPV adoption. These advancements underscore the evolving nature of BIPV design, showcasing a promising trajectory toward more user-friendly, cost-effective, and aesthetically pleasing BIPV solutions.

Figure 21 encapsulates the challenges expounded in this subsection, underscoring a consensus across the studies regarding the under-promotion and engagement of PV technology.

6.2 | Future research opportunities in BIPV

Various studies elucidate the promising horizon of BIPV technology, brimming with innovative PV technologies potentially igniting a wave of novel integrations into buildings. These encompass fields like ultra-low-cost and efficiency, avant-garde design and simulation methodologies, and enhanced energy production capabilities.

In Shaikh et al.,[122] a future outlook in BIPV technology is posited. A critical objective is honing systems to adeptly predict and adapt to energy demands of both the infrastructure and occupants, while also understanding occupancy behavior and expectations. It suggests leveraging artificial intelligence (AI) techniques, such as fish swarm algorithms, Type-2 fuzzy set modeling, and differential evolution, among others, for enhanced system optimization. Future technologies ought to incorporate smart appliances, safety, security, and monitoring integrations for seamless access to information. Moreover, the development of comprehensive databases is essential for more precise data collection under varying conditions, subsequently leading to more accurate results.

In Shukla et al.,[16] the Indian government's ambitious goal of achieving a 100-GW installed capacity of PV panels by 2022 is highlighted. This vision is underscored

FIGURE 21 Summary of BIPV challenges and barriers. BIPV, building-integrated photovoltaic; PV, photovoltaic.

by a firm stance against imported solar PV and BIPV modules, focusing instead on nurturing local projects, like, solar farms and parks. Furthermore, an emphasis on rooftop installations, enhancing power evacuation infrastructure, and improving policy implementation processes is stressed.

Yang[141] lays down several recommendations geared toward ameliorating BIPV technology. New designs aiming at mitigating heat and noise factors, reducing corrosion, and fostering a deeper understanding of lifecycle cost analysis could significantly influence clients' decisions on PV panel selection, utilization, and maintenance. Future research should delve into a comprehensive analysis of system lifecycle costs, encompassing all process costs. Engendering a well-informed customer base regarding the benefits and risks of BIPV systems is vital, achievable through shared risks in BIPV lifecycles, and engaging stakeholders in technology diffusion discussions to surmount prevailing barriers and challenges. Technologically, the development of building information modeling is essential to minimize risks in installation and maintenance while enhancing constructability, planning, and scheduling.

In Jelle,[87] the future of BIPV is envisaged through the lens of new materials and technologies. Here, a strategy employing several material layers and cells with diverse spectral absorbances is suggested to maximize solar radiation harvesting across a broad wavelength range, epitomized by the sandwich or stack solar cells and the PV triple amorphous cell. Costwise, organic modules are considered viable, whereas, for efficiency, quantum cells and nanodevices are deemed more suitable. Polymer PV cells are projected to find their footing in commercial applications, particularly in BIPV systems. DSSCs may initially offer a limited efficiency range; however, titanium dioxide (TiO_2) PV cells are anticipated to burgeon market share and significantly impact BIPV's future.[142] Another notable exploration is the integration of CIGS and CdTe for their flexibility and lightweight attributes, proving to be feasible for building integration without imposing additional weight, thus cutting installation costs.

7 | CONCLUSION

This exploration into the myriad facets of BIPVs presents a fertile ground for advancing the quest for sustainable energy solutions within architectural realms. Through a meticulous review of the literature and analytical discourses encompassing various aspects from the conceptual frameworks to technological advancements, a remarkable trajectory of BIPV, particularly semitransparent BIPV, emerges as a pivotal player in redefining renewable energy landscapes. The paper delineated several determining factors, such as WWR, transmittance, solar irradiation, ambient temperature, and tilt angle, which significantly impact the performance and efficiency of BIPV systems. The evolving tapestry of PV cell technology has continually striven toward enhancing efficiencies, showcasing a promising pathway for the holistic integration of BIPV systems into contemporary and future architectural designs.

Through a myriad of experimental and simulation studies reviewed, diverse perspectives and results were unearthed, employing varying parameters including electrical and thermal aspects. A juxtaposition of these methodologies exhibited a minimal numerical error, accentuating the reliability and robustness of findings and recommendations derived therein. This, in essence, underscores the vital role of continuous research and development endeavors aimed at minimizing gaps between theoretical projections and practical implementations.

The discussion on challenges and future opportunities provides a nuanced understanding of the existing barriers, predominantly centered around technical, economic, informational, and policy domains. It further unveils a plethora of solutions and forward-looking strategies aimed at mitigating these challenges. The notable emphasis on cost factors, governmental policies, educational frameworks, and technical advancements heralds an integrated approach toward fostering an enabling environment for BIPV adoption and optimization.

Moreover, the anticipation of emerging innovations, such as the use of AI, smart technologies, and novel material sciences in advancing BIPV technology echoes a resonant optimism. This optimism is further bolstered by global initiatives and commitments toward scaling up the adoption of PV systems, as exemplified by India's ambitious targets.

In summation, semitransparent BIPV stands out as a remarkable proposition, harmoniously merging architectural aesthetics with renewable energy generation. While challenges abound, the horizon is replete with innovative solutions and robust research avenues, propelling BIPV technology closer to becoming an integral component of the building facade, fostering a symbiotic relationship between built environments and sustainable energy generation. This discourse has indeed reaffirmed the critical role of BIPV systems in steering global communities toward a cleaner, greener, and sustainable energy future.

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