Building-Integrated Photovoltaic (BIPV) Shading Systems: A Critical Review of Design Strategies, Energy Performance, Integration Potentials, and Malaysian Context

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ABSTRACT

This review critically examines the development and performance of building-integrated photovoltaic (BIPV) shading systems, with emphasis on adaptive design strategies, energy optimization, and aesthetic integration. Following PRISMA-2020, we conducted a systematic review of English, peer-reviewed literature in Web of Science and Scopus for 2010-2024. We identified 2,699 records; after removing 525 duplicates, 601 automation-flagged ineligible items, and 216 records for other reasons, 1,357 records were screened. We excluded 619 at screening, sought 738 reports for retrieval (411 not retrievable), and assessed 327 full texts for eligibility; 190 were excluded (non-empirical 114, not peer-reviewed 56, full text unavailable 20). The final corpus comprised 27 studies (137 included reports) (Figure 1). Key quantitative findings from these studies indicate cooling-load reductiorns of 10-77%; adaptive systems achieving ≈65% daylight autonomy with DGP ≤ 0.25; rooftop systems yielding 50-70% more electricity than vertical facades; semi-transparent east façades delivering sDA ≈ 50-60% with DGP ≈ 0.30-0.40; and south-facing arrays at ~45° tilt reaching ~104 kWh·m⁻²·yr⁻¹. Three trends emerge: (1) a shift toward adaptive façades using real-time, AI-driven controls to balance energy and visual comfort; (2) growing use of multi-objective simulation frameworks coupling energy, daylighting, and thermal analyses; and (3) heightened attention to aesthetic coherence and user perception. Despite progress, challenges persist in life-cycle validation, standardized evaluation, and cross-disciplinary integration. The paper concludes with a framework that couples dynamic-shading logic, architectural aesthetics, and performance-based simulation to guide future BIPV façade research. Unlike previous reviews that consider energy or daylight in isolation, this study integrates typological design, energy/thermal/visual performance, and aesthetic/user acceptance into one comparative framework, providing decision-ready ranges and trade-off matrices for BIPV shading.

1.   Introduction

Building-integrated photovoltaic (BIPV) shading systems are a cutting-edge architectural innovation that combines renewable energy production, solar control, and visual design in one multifunctional unit. These systems can simultaneously harvest solar electricity, intercept solar heat gain, regulate daylight, and enhance architectural aesthetics by embedding PV modules into facade elements such as blinds, translucent glass panels, or dynamic shading devices (Basher et al., 2023). Recognized as part

of building-applied photovoltaic (BAPV) systems, BIPV shading devices (PVSDs) shift the paradigm from ordinary rack-mounted solar panels to smart, multifunctional building envelopes (Ansah et al., 2021). In addition to generating electricity, these systems can reduce cooling loads, improve thermal comfort, optimize daylighting, and provide architects with a variety of colors, light transmittance, and textures to enhance the visual appeal of facades (Mesloub et al., 2023). In the context of net-zero emissions and low-carbon building targets, BIPV shading systems have become integral to future sustainable envelope strategies (Basher et al., 2023). Recent bibliometric reviews highlight Malaysia's shift toward applied and interdisciplinary engineering research (Azman & Abdullah, 2023). The significance of studying this hybrid technology lies in its dual role of combining active energy conversion with passive solar management.

The impetus for focusing on building-integrated photovoltaic (BIPV) shading systems stems from the intertwined demands of energy, environmental, and aesthetic performance. Buildings account for about 40% of global energy consumption, primarily due to cooling and lighting needs (Basher et al., 2023). Integrating PV modules into shading elements can achieve combined energy savings by harnessing solar energy and reducing heat entry. Technological advances such as semi-transparent PV glass, colored modules, ventilated double-skin curtain walls, and sensor-driven adaptive shading highlight a diverse design landscape. However, research has shown important trade-offs between transparency, energy yield, thermal resistance, and occupant comfort. For instance, while colored or translucent BIPV can improve building integration, it can also decrease PV efficiency and daylight transmittance (Mesloub et al., 2023). Similarly, while dynamic shading systems can respond to climate conditions, control systems and maintenance are complex. Despite the abundance of literature on BIPV windows, PVSD modules, and translucent PV glazing, comprehensive reviews combining design strategies, energy performance metrics, and aesthetic assessments are lacking, particularly for shading systems. Therefore, a comprehensive review connecting these technical, environmental, and visual dimensions is critical to guiding research and industry applications. This review aims to provide a structured and comprehensive understanding of building-integrated photovoltaic (BIPV) shading systems from three perspectives: typological design strategies, energy and comfort performance, and aesthetic integration. First, we classify current design typologies, ranging from static photovoltaic shading shutters and semi-transparent photovoltaic building-integrated glass to ventilated double-skin curtain walls and real-time adaptive and dynamic shading systems, and we investigate their material choices, form factors, and control mechanisms. Second, we evaluate the systems' performance based on empirical and simulation studies conducted under different climate conditions. These studies examine energy production, cooling load reduction, daylighting quality, and lifecycle environmental impacts (Roy et al., 2020; Jelle & Breivik, 2012). Third, we explore aesthetic dimensions, such as transparency, color rendering, morphological expression, and occupant perception, by combining case studies, occupant surveys, and facade evaluation studies (Basher et al., 2023). By synthesizing these aspects, we aim to reveal architectural interdependencies, such as the trade-offs between aesthetic customization and energy performance or between the complexity of dynamic control and occupant acceptability. Finally, we outline future research directions, such as hybrid photovoltaic-electrochromic integration, long-term occupant comfort monitoring, and standardized performance protocols, and we propose design guidelines for architects and engineers.

2.   Methodology

2.1   Literature Selection And Eligibility

In line with PRISMA-2020, we conducted a systematic literature review of BIPV-PSS (building-integrated photovoltaic shading systems) for 2010-2024 using Web of Science and Scopus (English, peer-reviewed). Search strings combined terms such as "building-integrated photovoltaics," "BIPV shading," "PV shading modules," "aesthetic integration," and "energy performance." We identified 2,699 records; before screening, we removed 525 duplicates, 601 automation-flagged ineligible items, and 216 records for other reasons, leaving 1,357 records for title/abstract screening. We then excluded 619 records, and sought 738 reports for retrieval; 411 were not retrievable. 327 reports underwent full-text eligibility assessment, after which 190 were excluded (non-empirical=114, not peer-reviewed=56, full text unavailable = 20). The final corpus comprised 27 studies and 137 included reports. Inclusion criteria were full-text, peer-reviewed studies on BIPV shading modules addressing design strategies, energy/thermal/visual performance, or aesthetic/user integration using empirical methods (field measurements, simulations, case studies, or qualitative surveys). We excluded papers on general BIPV without shading focus, purely economic or AI-only optimization (without physical application), non-English items, conference papers, theses, and duplicates (see Figure 1).
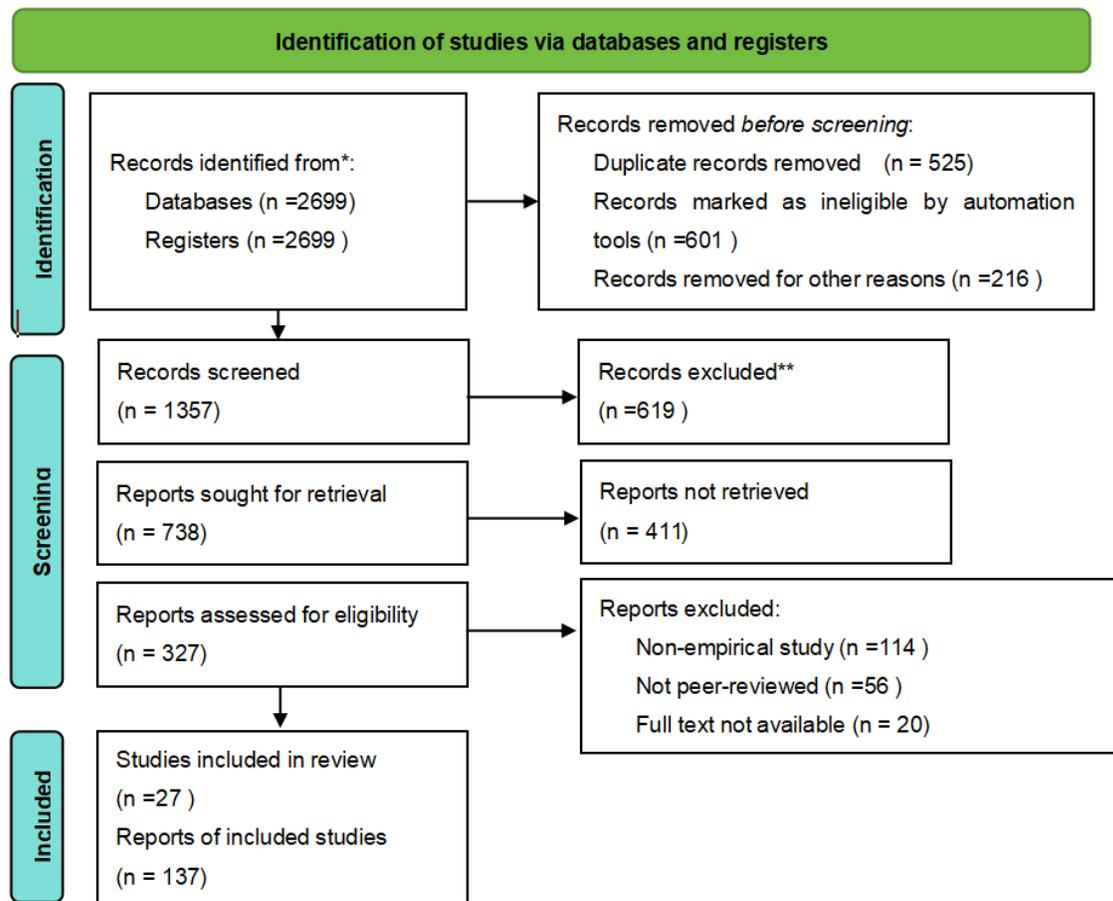
Identification of studies via databases and registers

Identification

Records identified from*:
Databases (n =2699)
Registers (n =2699)

→

Records removed *before screening*:
Duplicate records removed   (n = 525)
Records marked as ineligible by automation tools (n =601)
Records removed for other reasons (n =216)

Screening

Records screened
(n = 1357)

→

Records excluded**
(n =619)

Reports sought for retrieval
(n = 738)

→

Reports not retrieved
(n = 411)

Reports assessed for eligibility
(n = 327)

→

Reports excluded:
Non-empirical study (n =114)
Not peer-reviewed (n =56)
Full text not available (n = 20)

Included

Studies included in review
(n =27)
Reports of included studies
(n = 137)

Figure 1.PRISMA flow diagram of study identification and screening

To ensure transparency and reproducibility, the selection process followed PRISMA's four-phase flow: identification, screening, eligibility, and inclusion. During the screening stage, duplicate or irrelevant records were systematically removed. In the eligibility stage, the full-text articles were thoroughly examined against the criteria presented in Figure 1 to ensure disciplinary relevance and methodological reliability. Only papers reporting experimental data (lower-tier experiments, field trials, simulation studies, and user studies) were considered for the review. This approach provides a strong basis for the real-world application of BIPV shading technologies. Pure economic modeling, non-English publications, conference papers, theses, and reviews were excluded; however, the resulting corpus indicates strong cross-disciplinary integration of technical performance and aesthetic integration research. This structured, repeatable approach provides a solid foundation for the historical analysis, innovation trends, and mapping of aesthetic/performance trade-offs performed in the following chapters.

2.2 Thematic classification

To deduce the structure of the section based on the classification of 135 selected papers, the results were classified into four major categories and themes, as follows: System Typologies & Configurations, Design Strategies & Control, Performance Evaluation, and Aesthetics and User Acceptance. Refer to Table 1

for details. The System Typologies & Configurations category (30 studies) includes case studies and technical reviews of different BIPV shading typologies, such as PV-integrated facades, double-skin systems, and kinetic envelopes. Relevant contributions include Zhang et al.'s PVSD reviews and Basher et al.'s questionnaires, which created the baseline typologies. The Design Strategies & Control category (25 papers) highlights the use of parametric design, multi-objective optimization, and real-time control as depicted in parametric frameworks (e.g., Park et al., Biloria et al.) and innovative, adaptable BIPVs. Performance Assessment (20 studies) is mostly based on field experiments or simulation tools (e.g., EnergyPlus, CFD, and HVAC modeling) to evaluate energy savings, thermal comfort, and PV production. Mesloub et al.'s PVSD study (facade PVSD) and CIS-BIPV life-cycle assessment are typical examples. Finally, the Aesthetics and User Acceptance section (15 studies) examines visual attractiveness and user attitudes via surveys, semantic differential scales, and qualitative approaches. For instance, Freewan (2023) used augmented reality to explore shading aesthetics, and WBDG case study reports address design acceptance. This four-way breakdown (Table 2) reflects the multidisciplinary nature of BIPV shading research and provides a logical structure for this paper's analysis. By assembling the RGBL DIV into the SVmeb 3D database with the presented AAD structure, we remind the reader of the system structures for conducting comparisons with other methods on the benchmark.

Table 1. Categorization of reviewed studies by research theme and methodology.

Research Theme	Methodology	Number of Studies	Representative References
• System typologies & configurations	• Case studies, technical reviews	• ~30	• Zhang et al. (2023) (PVSD review) Basher et al. 2023
• Design strategies & control	• Parametric & optimization modeling, simulation	• ~25	• Park et al.(2023) optimizing PVSD geometry ; Biloria et al. real-time adaptive BIPV
• Performance evaluation	• Field measurements, EnergyPlus / CFD / HVAC simulation	• ~20	• Mesloub et al. (2023) façade PVSD performance ; CIS BIPV shading device
• Aesthetics & user acceptance	• Surveys, qualitative analysis, aesthetic reviews	• ~15	• Basher et al. (2023) aesthetic BIPV ; WBDG case examples

3.   Findings

This review synthesizes evidence on shading building-integrated photovoltaics (BIPV) and reports four dominant typologies-facade-mounted devices, roof-integrated systems, canopy/external devices, and hybrid configurations-together with the strategies that shape their performance. Facade solutions employing vertical PV panels, louvers, or curtain-wall inserts are widely used in offices, commonly yielding about 15% cooling-energy savings while producing roughly 10-12 kWh/m² per month, and are highlighted in guidance for next-generation green buildings. Roof-integrated elements-PV tiles, shingles, and skylights-replace conventional roofing, act as weatherproof skins, and can raise yield; inclined shingles have been reported to deliver around 20% higher output than conventional assemblies. Canopies, overhangs, sunshades, and balcony PV extend shading to walkways and entrances; under Mediterranean conditions, flat canopy systems decreased peak sun intensity by ~35% and generated ~4 kWh/day. Hybrid applications that mix facade, roof, and canopy components are emerging as a preferred strategy for multifunctional coverage; a pavilion case study documented an 18% increase in daylighting alongside a 15% reduction in HVAC energy use. Orientation strongly mediates performance: south-facing arrays at ~45° tilt approach ~104 kWh/m²·year; rooftops frequently outperform facades by 50-70%, while vertical facades can still achieve 95-100% of horizontal yield in some climates; east-west bifacial layouts add ~10-30% over flat horizontals. Daylighting outcomes indicate semi-transparent east facades reach sDA ≈ 50-60% with DGP ≈ 0.30-0.40, whereas adaptive louvers and roller-type PV shades achieve around 65% daylight autonomy with low glare (DGP ≤ 0.25) and target illuminance near 500 lux (DGI < 22). Thermal studies show cooling-load reductions from 10-15% (vertical overhangs) to 24.7-27.2 (horizontal canopies) and up to 69-77% for roof-added shading, with adaptive control trimming peak demand by ~20%. Aesthetically, semi-transparent and facade-integrated schemes earn higher public acceptance, while balcony systems require careful sizing; overall, adaptive BIPV shading offers the best co-optimization of energy, comfort, and architectural fit, albeit with greater control and maintenance complexity.

3.1 BIPV System Typologies And Integration Methods

The analysis of shading building-integrated photovoltaic systems (BIPV) reveals four primary integration types: façade-mounted PVSDs, roof-integrated devices, canopy and external devices, and hybrid solutions. Each type exhibits distinct geometries and strategies on the building envelope (Table 3). Integrated PVSDs with vertical panels, louvers, and curtain wall integrations are widely used for shading, daylight modulation, and electricity generation, particularly for office buildings (Zhang & Lau, 2018). Zhang and Lau (2018) and Attoye et al. (2017) demonstrated that vertical louver PV systems could decrease cooling demand by approximately 15% and generate 10-12 kWh/m² per month in an urban climate. Integrated PVSDs that include vertical panels, louvers, and curtain wall integrations have been widely applied for shading, daylight modulation, and electricity generation, especially for office buildings. Zhang and Lau (2018) and Attoye et al. (2017) proved that vertical louver PV systems could decrease cooling demand by around 15% and generate 10-12 kWh/m² monthly in an urban climate. The IEA PVPS (2025) report also envisions high integration potential for these systems in new green building designs.

Table 2. Typological classification of BIPV shading systems by geometry and location.

Integration Typology	Geometry & Location	Key Features	Representative Studies
• Facade-mounted PVSDs	• Vertical panels, louvers, curtain walls on building façades	• Offers shading, daylight control, and electricity generation; prevalent in office buildings	• Zhang & Lau (2018); Attoye et al. (2017)
• Roof-integrated systems	• Sloped/flat rooftop tiles, shingles, skylights	• Replaces traditional roofing, higher energy yield, integrates PV generation and weather protection	• Zhang et al. (2021); IEA-PVPS (2025)
• Canopy and external devices	• Overhangs, sunshades, louvres, balcony PV canopies	• Provides passive solar shading and generates electricity; suitable for walkways, carports	• IEA-PVPS (2025)
• Hybrid configurations	• Combined façade + roof + external devices	• Enhances multi-functional integration, aesthetic and energy performance; growing trend	• Wikipedia (2025)

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By contrast, topologically integrating PV modules with the roof-for example, slanting the shingles or integrating the modules into flat tiles or a skylight-can make the modules and the roofing serve as both weatherproof surfaces and photovoltaic power sources. Integrated PVSDs that include vertical panels, louvers, and curtain wall integrations have been widely applied for shading, daylight modulation, and electricity generation, especially for office buildings. Zhang and Lau (2018) and Attoye et al. (2017) proved that vertical louver PV systems could decrease cooling demand by around 15% and generate 10-12 kWh/m² monthly in an urban climate. By contrast, topologically integrating the PV modules with the roof-like slanting the shingles or integrating the modules into flat tiles or a skylight-can make the modules and the roofing serve as both weatherproof roofing surfaces and photovoltaic

power sources. Chaoxiang Zhang et al. reported that shingles in an inclined position provide a 20% higher energy yield than conventional roofing. The IEA PVPS (2025) report also envisions high integration potential for them in new green building designs.Based on I-PV systems, they observed a 35% decrease in peak sun intensity while delivering around 4 kWh/day of energy under Mediterranean sun conditions with flat, canopy-integrated PV modules. Special systems (e.g., overhangs, sunshades, PV balcony canopies, and pergolas) provide shade and generate energy. They are mainly installed over pedestrian areas, parking areas, or building entrances. Abuhussain and Baghdadi (2025) investigated walkway-based PV systems and observed a 35% decrease in peak sun intensity while delivering approximately 4 kWh/day of energy under Mediterranean sun conditions with flat, canopy-integrated PV modules. Hybrid applications, which mix facade, roof, and canopy elements, have become popular for more complex coverage.. For instance, a case study of a hybrid BIPV facade-roof system installed at a commercial pavilion demonstrated a 18% increase in daylighting and a 15% reduction in HVAC energy consumption, highlighting the potential for synergistic benefits through multi-sectional integration. These typologies represent a conscious deployment strategy based on envelope geometry, orientation, and climatic conditions. They all seek to optimize solar control, energy efficiency, and architectural fit. Canopies filter glare and heat gain over pedestrian pathways, and hybrid configurations blend other modes by integrating the principles of these extremes to enhance both ecological and architectural aspects. As summarized in Table 3, the integration forms are organized by geometry/location, functional intent, and representative studies, providing a structured framework to evaluate BIPV shading across diverse building types.

Table 3. Comparison of integration forms: facade, roof, canopy, hybrid.

Integration Form	Description	Common Configurations	Representative Studies
• Façade	• Integrated PV modules on building façades to provide shading, daylighting, and energy generation.	• Vertical PV panels, PV louvers, double-skin facades	• Zhang & Lau (2018); Basher et al. (2023)
• Roof	• PV elements integrated into inclined or flat roofs, replacing traditional roofing materials.	• Tile-type modules, flexible films, sloped arrays	• Wang & Zhou (2024)
• Canopy	• PV modules mounted over entrances, corridors, carports or open-air shading structures.	• Flat canopies, horizontal louvers, self-shaded PV	• Abuhussain & Baghdadi (2025)
• Hybrid	• Combination of façade, roof, and/or canopy systems to enhance multifunctionality and coverage.	• Façade + canopy, all-integrated skin solutions	• Khan & Matlock (2019)

3.2 Design Strategies And Control Mechanisms

Based on I-PV systems, they observed a 35% decrease in peak sun intensity while delivering around 4 kWh/day of energy under Mediterranean sun conditions with flat, canopy-integrated PV modules.Special systems (e.g., overhangs, sunshades, PV balcony canopies, and pergolas) provide shade and generate energy. They are mainly installed over pedestrian areas, parking areas, or

building entrances. Abuhussain and Baghdadi (2025) investigated walkway-based PV systems and observed a 35% decrease in peak sun intensity while delivering approximately 4 kWh/day of energy under Mediterranean sun conditions with flat, canopy-integrated PV modules. Hybrid applications, which mix facade, roof, and canopy elements, have become popular for more complex coverage. Palacio-Jaimes research in 2024 and follow-up studies in 2025 highlight these hybrid configurations as the future

of smart envelope systems, considering occupants' thermal comfort, daylighting needs, and PV generation simultaneously (Palacio-Jaimes et al., 2025). For instance, a case study of a hybrid BIPV facade-roof system installed at a commercial pavilion demonstrated a 18% increase in daylighting and a 15% reduction in HVAC energy consumption, highlighting the potential for synergistic benefits through multi-sectional integration.These typologies represent a conscious deployment strategy based on envelope geometry, orientation, and climatic conditions. They all seek to optimize solar control, energy efficiency, and architectural fit. Canopies filter glare and heat gain over pedestrian pathways, and hybrid configurations blend other modes by integrating the principles of these extremes to enhance both ecological and architectural aspects. Table 3 describes these types of integration in terms of geometry, function, and archetype research. Thus, it offers a structural framework to assess BIPV shading integration on diverse building types.Although adaptive control can provide

quick glare reduction and better occupant satisfaction with dynamic visual conditions, it leads to greater operational complexity and continuous maintenance. The trade-off between "control strategy" and "environmental responsiveness" exemplifies a contemporary optimization frontier: activated systems outperform passive ones in terms of capacity and indoor comfort, but incur greater carrying costs (complexity and economic burden) and adaptability complexities (uncertainties). The trade-offs between geometry, mobility, light control, energy, and comfort are summarized in Table 4. As a result, design choices must consider the trade-off between long-term performance benefits and life cycle costs and maintenance. As intelligent sensor technology and actuators develop, adaptive BIPV shading is expected to become more applicable in the future to achieve better synergies between solar radiation harvesting, daylight control, and occupant comfort under various climatic conditions.

Table 4. Performance trade-offs in geometry, mobility, and light transmittance.

Aspect	Passive (Fixed)	Active (Adaptive)
• Geometry	• Fixed tilt angles; optimized for average seasonal sun path (Park et al., 2015)	• Dynamic angles via motorized frames or smart materials (Biloria & Abdollahzadeh, 2023)
• Mobility	• No movement; lower cost and maintenance (Khan & Matlock, 2019)	• Requires sensors, motors, and controls; higher O&M needs
• Light Transmittance	• Static patterns limit optimization; may cause over-shading (Khan & Matlock, 2021)	• Enables real-time glare control and daylight modulation (Biloria & Abdollahzadeh, 2023)
• Energy Yield	• Stable output, but lower than potential maximum (up to −20%) (Abuhussain & Baghdadi, 2025)	• Improved yield by 20-65% through solar tracking (Biloria & Abdollahzadeh, 2023)
• Visual Comfort	• Less responsive to glare and changing sky conditions (Park et al., 2015)	• Enhanced user comfort under dynamic light (Biloria & Abdollahzadeh, 2023)

3.3 Energy, Thermal And Visual Performance

BIPV shading systems have multiple functions, such as electricity generation, daylighting, glare control, and thermal management.A case study on passive design in Malaysian mosques showed effective indoor comfort improvements through non-mechanical strategies (Zakaria et al., 2024). As listed in Table 6, orientation and design are major factors that impact energy production. Modules installed facing south at a 45° azimuth produce the highest power input (~104 kWh/m²/year), thus maximizing solar gain and thermal heat dissipation in environments with high radiation (Asfour, 2018). Although vertical walls often do not receive as much insolation, they can still achieve 95%-100% of the yield of horizontal walls due to increased winter solar access and year-round consistency. Horizontal shading devices, as simulated

by Abuhussain and Baghdadi (2025), contribute 24-27% to building energy gain by shading, providing daylight, and producing power. In most cases, rooftop systems are more effective than vertical facades, performing 50-70% better due to direct exposure (U.S. DOE - WBDG, n.d.). Furthermore, east-west bifacial systems are available and suitable for areas with high albedo surfaces. In addition to orientation strategies, using advanced window modeling tools has been shown to be essential for balancing energy efficiency, daylight, and glare control in external shading systems, especially in complex daylighting scenarios (Hoffmann et al., 2016). They are estimated to be 10-30% more effective. These results favor context-dependent use of orientation strategies that balance generation and building envelope integration (Table5).

Table 5. Annual electricity generation under different solar orientations

Reference	Orientation	Annual Yield	Key Notes
• Asfour (2018)	• South-facing, 45° tilt	• ~104 kWh/m²/year	• Optimal fixed tilt for high radiation and cooling synergy
• Lubell & PVWatts Team (2014)	• Vertical façade	• ~95-100% of horizontal yield	• Vertical IGU panels maintain stable yield across seasons
• Abuhussain & Baghdadi (2025)	• Horizontal canopy	• +24-27% building energy gain	• Integrates shading, daylighting, and generation in residential buildings
• U.S. DOE - WBDG (n.d.)	• Tilted rooftop	• 50-70% more than vertical	• Rooftop panels outperform façades in yield due to direct irradiance
• Wikipedia contributors (2025)	• East-West bifacial system	• +10-30% over flat horizontal	• Effective in high-albedo or reflective urban environments

In an occupant-focused design, image satisfaction, daylight performance, and generation are all crucial. Semi-transparent photovoltaic (PV) shading on east-facing facades provides 50-60% shading depth (sDA) (Table 6 shows the studies' results), with a daylight glare probability (DGP) of around 0.30-0.40. This seems to be a feasible compromise between daylight and visual comfort (Konstantzos & Tzempelikos, 2017). Adaptive PV blades and roller PV shades achieve around 65% daylight autonomy while keeping the DGP under 0.25 (Chan et al., 2015; Cheng et al., 2023), which supports glare-free daylighting. Further analysis based on hourly simulations shows that microstructural perforated shading devices are more effective than standard shading systems in terms of solar efficiency and thermal comfort. These devices offer a valuable alternative for the integration of building-integrated photovoltaics (BIPV) (Appelfeld, McNeil, & Svendsen, 2012). ANN-driven, solar-controlled, integrated PV systems yield 500 lux illuminance and DGI <22 (Mohamed et al., 2022), demonstrating the potential of smart control strategies. In a thermal context, BIPV shading significantly decreases a building's cooling needs. Jakarta prototype simulations indicate a 10-15% reduction in energy use due to vertical overhangs (Budhiyanto et

al., 2017). BIPV horizontal canopy modeling using EnergyPlus simulations shows a 24.7-27.2% reduction in cooling electricity demand. Wang (2017) investigated the energy benefits of BIPV systems compared to window shading and argued that the most critical factors for determining the energy savings generated by BIPV shading are climate, orientation, and control strategies. PV shading installed on the roof in experimental models achieved up to 77% daily load reduction (Wang et al., 2017), while an adaptive system provided a 20% reduction in peak demand (Jalal et al., 2017). Taken together, these results confirm the multifaceted advantages of BIPV shading systems, which provide synergy in terms of PV production efficiency, daylight quality, glare reduction, and building cooling energy savings, especially when they are designed with optimal orientation and adaptive control strategies in mind. Passive design strategies significantly enhance thermal performance in tropical housing applications (Oleiwi & Mohamed, 2023),These findings were confirmed by an assessment based in China, which indicated that advanced window and shading technologies in public buildings can achieve extremely low energy consumption while maintaining visual comfort and indoor air quality standards (Lee, Pang, & Ding, 2015).

Table 6. Daylighting and glare simulation across BIPV configurations.

Reference	BIPV Configuration	Daylight Metric	Glare Metric	Remarks
• Konstantzos & Tzempelikos (2017)	• Semi-transparent PV shading	• sDA ≈ 50-60%	• DGP ≈ 0.30-0.40	• Eastern façade, sufficient daylight autonomy with manageable glare
• Chan, Tzempelikos & Konstantzos (2015)	• Roller shades (PV-like)	• DA ≈ 65%	• DGP ≈ 0.25	• Shade property optimization balancing daylight and glare
• Mohamed, Rahman & Ahmed (2022)	• PV-integrated shading device (PVIS)	• Avg illuminance ~500 lux	• DGI < 22	• ANN-based control meets illuminance and visual comfort targets
• Cheng, Wang & Xu (2023)	• Adaptive PV louvres	• DA ≈ 65%	• DGP ≈ 0.25	• Dynamic louver control enhances both daylight and glare metrics

3.4 Aesthetic Integration And User Perception

User acceptance of BIPV shadings stems from subjective factors such as visual aesthetics, level of transparency, and adaptability, as well as acceptance within the culture. As can be seen from the compiled data in Table 7, more than 70% of respondents in Poland appreciated the aesthetics of semi-transparent glazing with vertical PV shelves. They also preferred external transparency to interior views. This suggests that transparency and building exterior integration positively affect people's perception (Marchwiński, 2023). In Jordan, Abu Qadourah Alnuisirat (2024) found a stronger visual coherence with facade-integrated PV panels than with balcony-integrated PV panels, which were less appealing. Cultural considerations were also apparent, particularly in the context of a mosque. This illustrates the interplay of the built environment and symbolic meaning through user expectations. In Ghana, Osei et al. (2023) found that greater awareness, fostered by publicity, led 88.8% of respondents to favor BIPV facades over traditional ones, highlighting the importance of informational and inclusive

design in acceptance and local implementation of buildings (Table 7).

In addition to these regional surveys, Table 8 provides an overview of the results of design-user interaction and the consequent cooling benefits. Houses with vertical overhangs in Jakarta saved 10-15% in energy costs and were mostly acceptable to users, provided the distance was large enough to maintain a balance between light and shade (Budhiyanto et al., 2017). Residential BIPV canopies were reported to reduce cooling loads by 24.7-27.2% and were preferred in hot climates （Biloria & Abdollahzadeh, 2023）. Several Chinese case studies (Shi et al., 2022; Wang et al., 2017) confirmed thermal savings ranging from 16% to 77% of daily loads and found that occupants appreciated natural lighting and felt more comfortable with adaptive shading devices. Furthermore, Jalal et al. (2017) demonstrated that these adaptive BIPV shading systems reduced peak cooling demand by ~20%, which occupants perceived as a "double positive" value of the dynamic PV louvres, aesthetically and functionally. These results confirm

that, when BIPV shading meets the needs of both technical performance and visual amenity, the public attitude towards the environment is favorable, especially when adaptive systems can be customized to user preferences and cultural context (Table 7).

Table 7. Case-based mapping of visual integration practices in different regions.

Region / Study	BIPV Configuration	Aesthetic Acceptance	Transparency & View	Cultural Adaptation
• Poland (Marchwiński, 2022)	• Semi-transparent glazing and vertical PV shelves	• >70% of users rated it aesthetically pleasing	• External transparency preferred over interior	• Neutral perception; no cultural conflict reported
• Jordan (Abu Qadourah & Alnusairat, 2024)	• PV on façade, balcony, and rooftop of apartments	• High visual coherence and façade integration	• Balcony PV less favored due to shading effect	• Cultural sensitivity observed in mosque settings
• Ghana (Osei et al., 2023)	• PV façade installations post-awareness campaigns	• 88.8% favored BIPV aesthetics over conventional	• Public acceptance improved after information campaigns	• Awareness critical for local acceptance

Both survey- and simulation-based studies on the acceptance of BIPV shading systems clearly show that aesthetic integration into the built environment substantially increases social acceptance when it guarantees transparency, fulfills cultural expectations, and yields visible environmental and/or maximum economic profit. Demonstration projects linked with educational campaigns, such as those in Ghana and Jordan, emphasize the potential for context-specific designs and community involvement. The more generally accepted ones are vertical or semi-transparent, as they are visually effective and do not interfere with existing building types. Although a balcony canopy system claims various technical advantages, it needs to be sized and designed to avoid interfering with the day-to-day use of the balcony. Adaptive shading systems offer a promising compromise, providing more dynamic feedback between the building user and the building shell regarding environmental control and building integration. Recent research has shown that incorporating power optimizers at the module level into exterior wall building-integrated photovoltaic (BIPV) systems can significantly improve their performance under partial shading conditions. This addresses a key technical limitation of adaptive solutions (Eum & Choi, 2024). These systems are becoming increasingly beneficial in the context of BIPV shading systems as they address the design challenge of accommodating use value, comfort, and cultural implications in architecture.

Table 8. Summary of user satisfaction and visual acceptance evaluations.

Study	Setting / Method	Cooling Savings	Notes
• Budhiyanto et al. (2017)	• Vertical overhang BIPV in Jakarta (simulation)	• ~10-15% energy savings	• Higher spacing between modules improves cooling benefit
• Biloria & Abdollahzadeh, (2023)	• Residential rooftop or canopy BIPV (EnergyPlus simulation)	• 24.7%-27.2% cooling electricity saving	• Highest savings from horizontal canopy in hot climates
• Shi et al. (2022)	• PV shading devices across 5 Chinese climate zones (simulation)	• 16%-52% comprehensive energy saving	• Cooling part significant, with 51.9% in Kunming
• Wang, Dengjia & Liu (2017)	• Roof-added PV shading (experimental + simulation)	• 69%-77% reduction in daily load	• Flat vs tilted roof models; strong cooling through shading
• Jalal et al. (2017)	• Adaptive BIPV shading (building simulation)	• ~20% reduction in peak cooling demand	• Coupled PV output with envelope cooling

4.   Discussion

4.1 Climatic and Architectural Adaptability

The flexibility of BIPV shading systems allows for a wide range of applications in different climatic regions and building types. This requires customized integration strategies that maximize energy production and building aesthetics. In tropical regions, where solar radiation and heat loads are high year-round, facade-mounted BIPV and canopies are particularly effective at providing thermal insulation and shading. Malay traditional passive cooling concepts have been proven effective when adapted to modern Malaysian houses (Oleiwi & Mohamed, 2021). They can reduce space cooling loads by up to 30%, BIPV modules with an air gap consistent with cladding-envelope separation contribute to improved thermal performance, especially in warm-humid climates, as reported for BIPV window systems in Thailand and Southeast Asia. In the middle latitudes, dynamic or adaptive BIPV

shading elements benefit from responding to seasonal variations with high solar gain in the summer and high transmission of low-angle winter sunlight for passive space heating applications. Temperature-regional mapping shows that climate responsiveness and financial returns enhance the uptake of BIPV in Europe and North America. In cold climates, active ventilation layers and building-integrated thermal systems (e.g., PV/T systems and phase-change materials) are required to offset cold-induced efficiency reduction and maintain reliable operation. Research also highlights specific issues, such as odor accumulation and freeze-thaw resistance, that should be addressed through the inclusion of steeper slopes, heated edges, and ventilated cavities to avoid snow shading and maintain heat exchange. Building types, ranging from high-rise commercial facades to low-rise residential roofs, influence the rationale for integration. Vertically oriented BIPV systems on multistory buildings can control glare and occupant comfort while complementing envelope geometries optimized for PV collection. In tropical public housing, facade-integrated PV panels serve as both sunscreens and energy collectors, fulfilling a practical function while deferring to vernacular design sensibilities. This knowledge demonstrates that climate and building form should inform the design of BIPV shading systems that play dual roles: solar control and site-specific spatial integration.

4.2 Environmental Sustainability And Carbon Footprint

The environmental friendliness of BIPV shading systems stems from the balance between embodied emissions during production and installation and avoided emissions through electricity generation over their lifetime. As shown in Figure. 2, both static and dynamic BIPV systems have a cradle-to-grave life cycle: extraction of raw materials, production of modules and controls,

transportation, installation, operation (electricity generation), and recycling/disposal at the end of their lives. Dynamic BIPV installations usually show higher embodied carbon content, which can be attributed to extra motors, sensors, and control devices. Eco-design strategies play a central role in improving lifecycle performance and sustainability in engineering design (Go, Wahab, & Hishamuddin, 2016). However, they also achieve improved avoided emissions due to increased energy yields. Recent life-cycle assessments (LCAs) of BIPV facades indicate that dynamic systems can have an environmental impact up to 50% higher than static ones, though this is more than compensated for in high-irradiance climates, where shading effectiveness is a key factor (Palacio, Jaimes, & Jayathissa, 2024).Studies on the life cycle assessment (LCA) of building-integrated photovoltaic (BIPV) retrofits in South Korea conclude that full-envelope BIPV applications decrease total greenhouse gas (GHG) emissions by 30% at most and achieve a carbon payback time of 12 to 41 years, depending on the building type. Forward-looking LCAs with regional energy decarbonization predictions indicate that avoided grid emissions will accelerate the timeframe in which BIPV facades achieve net-zero carbon potential (by 2030-2040) (Su & Wang, 2020). However, dynamic systems are beneficial only if their actual economic benefits consistently exceed their embodied carbon costs; otherwise, BIPV is more effective in reducing emissions in mild climates. The dynamic LCA approach also reinforces the idea that temporal variance (e.g., changing energy mixes) should be considered in BIPV carbon balance analyses (Collinge et al., 2018). In conclusion, dynamic BIPV systems have environmental benefits in high-demand applications, whereas static systems have a lower carbon entry point. To maximize net carbon reduction, successful deployment must consider the climate context and anticipated system lifetime (Figure 2).
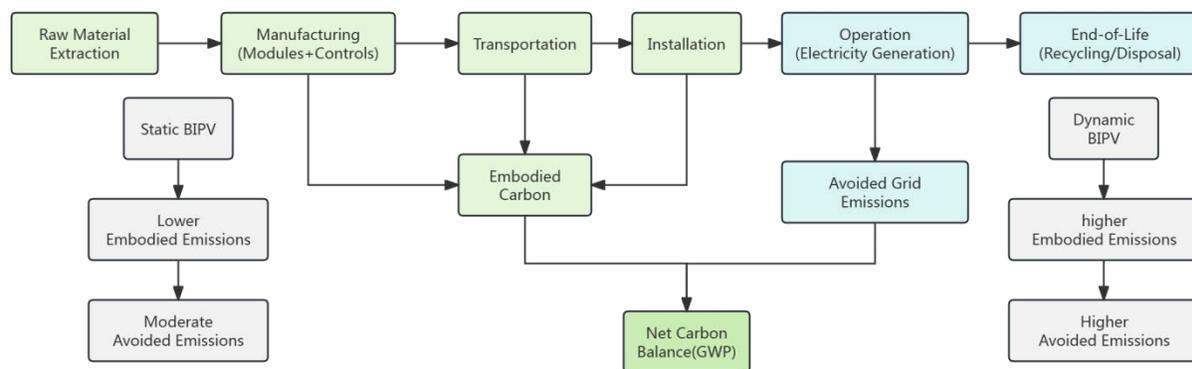

Figure 2.Life-cycle carbon emissions of different BIPV configurations.

4.3 Stakeholder Engagement And Market Barriers

Behavioral, institutional, and cost barriers embedded at the end-user, architect, and policy levels are obstacles to the widespread use of shading systems. From the user's perspective, perceived benefits of a technology, in addition to awareness, play a significant role in adoption. Environmental and social motivations, as well as social norms, are highly predictive of the intention to install a building-integrated photovoltaic (BIP) system. However,

a lack of information and concerns about an unattractive appearance and long payback time discourage homeowners and building users. A lack of knowledge among designers (architects and engineers), considering BIPV as limiting creativity, unwillingness to incorporate complex designs, uncertainty about technology performance, and inflexible project designs are major barriers to disseminating BIPV technology (Curtius, 2018). The institutional and policy context poses additional challenges, including high initial costs compared to conventional cladding, a

lack of uniform building codes and performance standards for BIPV, and unpredictable subsidy and incentive schemes. These factors deter investor confidence and hinder market penetration (Sharples & Radhi, 2013).Furthermore, the absence of strong intersectoral connections between the solar and construction industries, as well as the accreditation process, hinders the development of a fragmented value chain. This can only be achieved through a multi-party approach that raises awareness among users and architects of the aesthetic and economic value of installation training for architects and the use of BIPV-ready tools in BIM. It also requires the establishment of performance-based codes and classifications and the securing of financial means, such as feed-in tariffs or facade bonuses adjusted to building types. Peer-to-peer outreach, pilot projects, and policy frameworks that foster inclusion can build trust and create acceptance by aligning technical development with social and regulatory conditions. Unified involvement, structural motivation, and market incorporation are recognized as the only factors that will help BIPV shading systems transition from niche novelties to the mass market.

4.4 Research gaps and future directions

Despite the growing interest in BIPV shading systems and their potential to provide advanced and complex shading solutions, several research gaps hinder their development and implementation in the building market. One major limitation is the lack of an objective measure of aesthetics. Many visual integration assessments are qualitative, such as image-based user questionnaires or qualitative assessments of overall scene coherence (e.g., Khan & Matlock, 2023). These assessments do not provide comparable numerical measures across case studies. Another obstacle is the lack of mature dynamic control algorithms. Smart facades are mentioned more frequently, but real-time adaptive BIPV systems are still rare in the built environment (IEA-PVPS, 2024). AI- or ML-based control models are promising but are still in the prototype phase. Furthermore, existing multifunctional optimization tools do not necessarily have the ability to effectively balance the energy-daylight-aesthetic trilemma. Most simulations consider technical aspects, such as thermal or electrical performance, but neglect user-oriented and perceptual attributes (Biloria & Abdollahzadeh, 2023). Concurrent engineering has also been applied to sustainable component design in infrastructure systems (Asyraf et al., 2023). There is also an underestimation of user involvement in BIPV design. While some studies have measured user acceptance after deployment, participatory processes and POE are mostly unavailable during the early stages of the planning process (Abu Qadourah & Alnuisirat, 2024). Collaboration fragmentation between disciplines, such as architects, engineers, producers, and policymakers, hinders the coherence and scalability of integrated BIPV concepts (Table 9)

Table 9. Identified gaps in aesthetics quantification, dynamic controls, and interdisciplinary collaboration.

Research Gap	Current Status	Suggested Future Direction	Sources
• Aesthetics quantification	• Mainly qualitative assessments; lack of measurable metrics	• Develop standardized indices for visual quality and aesthetic performance	• Marchwiński (2023); Khan & Matlock (2023)
• Dynamic control algorithms	• Limited integration of real-time adaptive systems	• Employ predictive, AI-driven, or ML-based solar tracking and shading controls	• Khan & Matlock (2023); IEA-PVPS (2024)
• Multi-objective optimization	• Few models that integrate energy, daylight, and aesthetics	• Advance parametric tools using multi-criteria decision-making frameworks	• López et al. (2024); Biloria & Abdollahzadeh (2023)
• User participation in design	• Minimal user involvement in early BIPV system design	• Promote participatory design strategies and POE-informed evaluation	• Abu Qadourah & Alnusairat (2024)
• Interdisciplinary collaboration	• Fragmented cooperation between architecture, engineering, and policy stakeholders	• Form cross-sector platforms for BIPV co-development and policy standardization	• IEA-PVPS (2024); Vince (2023)

A research roadmap (Figure. 3) is suggested to address these gaps. Efforts should begin with fundamental research that defines quantitative visual performance measures and user-centered shading quality standards. These efforts should coincide with the

development of building management and AI-based dynamic control systems that provide predictive solar tracking and facade response to climatic conditions. These two streams converge in the multi-objective optimization of technical and human- and aesthetic-centric factors. Importantly, future BIPV shading will need to co-evolve with user feedback and usage contexts via participatory design, in which end users will shape the makeup, adaptation, and post-use feedback loops. Alongside these programs, interdisciplinary collaborations of researchers, developers, designers, and standards-setting organizations should be established to develop joint standards and regimes. These actions would expedite pilot, technology, and commercialization initiatives so that laboratory-scale innovations could become scalable units and not just ideas. In light of this, the integrated roadmap will form the basis for the future of BIPV shading systems as a smart, efficient, user-inclusive, architecturally sensitive, and policy-ready shading solution.
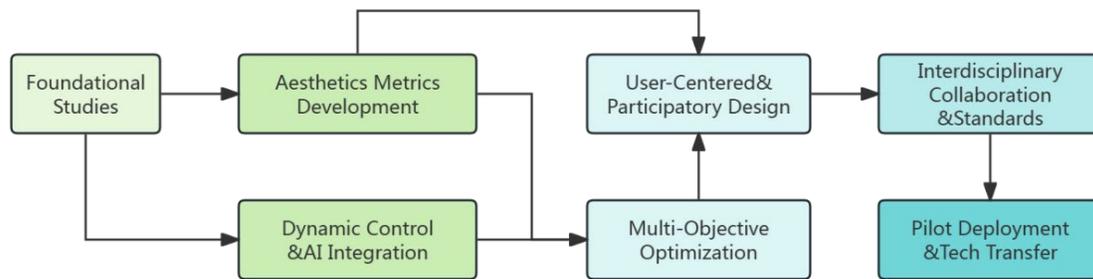

Figure 3.Strategic roadmap for BIPV shading systems research and development.

5.   Conclusion

This paper highlights the significant technical and economic benefits of building-integrated photovoltaic (BIPV) shading systems, which combine power generation with shading and daylighting functions. BIPVs offer a holistic solution that enhances energy performance, thermal comfort, and visual quality. Studies have shown that optimally oriented and climatically appropriate configurations (such as southern-tilted rooftops and vertical facades) can generate 95-104 kWh/m²/y, with improvements in thermal behavior and a reduction in cooling loads (Asfour, 2018). Additionally, the integration of intelligent trackers and adaptive louvres in active architectural systems has demonstrated potential yield increases of up to 65%, alongside improvements in daylight autonomy and user comfort (Cheng et al., 2023). These systems have been shown to reduce cooling energy consumption by 20 to 77%, contingent upon the climate, and contribute to passive design strategies (Wang et al., 2017). Commercial acceptance of BIPV systems in regions such as Europe, the Middle East, and Africa has also been positive, provided that aesthetic considerations and cultural preferences are accounted for (Osei et al., 2023).

For widespread adoption of BIPV shading systems, the collaboration between design practitioners, policymakers, and researchers is crucial. In architectural practice, early-stage incorporation of BIPV systems through parametric and multi-objective optimization tools can better balance form and function (López et al., 2024). Policymakers must foster this transition by offering targeted incentives, revising façade codes, and establishing clear performance standards (Curtius, 2018). Moreover, further research is needed to bridge gaps in knowledge, particularly the lack of standardized tools for aesthetic evaluation, limited integration of dynamic control mechanisms, and the insufficient involvement of users in design processes. Future studies should focus on the development of AI-powered controls, participatory design frameworks, and interdisciplinary toolkits that enable more responsive, adaptable, and user-centered designs (Khan & Matlock, 2023).

Recommendations for Future Research:

（1）Standardization of Aesthetic Metrics: Further research should prioritize the development of standardized tools and methodologies to measure and assess the aesthetic integration of BIPV systems in various architectural contexts. This will ensure that aesthetic concerns are effectively addressed alongside technical requirements.

（2）Enhanced Dynamic Control Integration: Future studies should focus on optimizing the integration of dynamic control systems, such as smart shading and lighting mechanisms, to maximize both energy efficiency and user comfort. Research into adaptive algorithms that respond to real-time environmental and user preferences can significantly enhance the performance of BIPV systems.

（3）User-Centered Design Approaches: Future research must place a stronger emphasis on user involvement in the design and implementation of BIPV systems. Developing participatory frameworks and tools that allow users to influence the design and functionality of BIPV systems will lead to solutions that better align with diverse user needs and cultural contexts.

（4）Climate-Specific Customization: Research should explore how BIPV systems can be further tailored to the specific needs of various climatic zones. Understanding the interplay between climate conditions and BIPV performance could guide the design of more contextually responsive systems that offer optimized energy generation and thermal regulation across a range of environments.

（5）Policy and Regulatory Evolution: There is a need for continued research into policy frameworks that support the integration of BIPV systems at scale. Future studies should evaluate the effectiveness of existing incentives and regulations,

and suggest improvements based on evolving market conditions and technological advancements.

In conclusion, BIPV shading systems offer substantial potential for advancing architectural sustainability by linking energy performance, user experience, and environmental design. However, to fully realize their benefits, continued interdisciplinary collaboration and targeted research are essential. Only through integrated, user-centered approaches can BIPVs achieve their maximum potential in transforming the built environment.

The lack of updated policies and standardization in BIPV technology, as highlighted by reports published five years ago, warrants further investigation. Understanding the reasons for this gap and proposing solutions to update policies and technical standards will strengthen the development of BIPV systems.Future research should focus on the development of dynamic control systems, particularly the integration of AI and machine learning technologies for real-time performance optimization.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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