

Review

A Systematic Review of the Scalability of Building-Integrated Photovoltaics from a Multidisciplinary Perspective

Baitong Li ¹, Dian Zhou ¹, Mengyuan Zhou ², Duo Xu ¹, Qian Zhang ¹, Yingtao Qi ¹ , Zongzhou Zhu ³ and Yujun Yang ^{1,*} 

¹ School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an 710049, China; qi.yingtao@xjtu.edu.cn (Y.Q.)

² Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu 808-0135, Japan

³ School of Mechanics and Transportation Engineering, Northwestern Polytechnical University, No. 1 Dongxiang Road, Xi'an 710072, China

* Correspondence: yujun_yang@xjtu.edu.cn; Tel.: +86-185-9192-6850

Abstract

Over the past two decades, Building-Integrated Photovoltaics (BIPV) has become a core technology in the green building sector, driven by global carbon-neutrality goals and the growing demand for sustainable design. This review adopts a scalability-oriented perspective and systematically examines 82 peer-reviewed articles published between 2001 and 2025. The results indicate that existing research is dominated by studies on electrical and thermal performance, with East Asia and Europe—particularly China, Japan, and Germany—emerging as the most active regions. This dominance matters for scalability because real projects must satisfy comfort, compliance, buildability, and operation/maintenance constraints alongside energy yield; limited evidence in these dimensions increases delivery risk when transferring solutions across regions and building types. Accordingly, we interpret the observed distribution as an evidence-maturity pattern: performance gains are increasingly well characterized, whereas deployment-relevant uncertainties (e.g., boundary-condition sensitivity and validation depth) remain less consistently reported. Multidimensional integration of thermal, optical, and electrical functions is gaining momentum; however, user-centered performance dimensions remain underexplored. Simulation-based approaches still prevail, whereas large-scale empirical studies are limited. The review also reveals extensive interdisciplinary collaboration but also identifies a notable lack of architectural perspectives. Using Biblioshiny, this study maps co-authorship networks and research structures. Based on the evidence, we propose future research directions to enhance the practical scalability of BIPV, including strengthening interdisciplinary integration, expanding empirical validation, and developing product-level design strategies.



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1. Introduction

The issue of global carbon emissions has been escalating in severity. The construction industry, as a major contributor to carbon emissions, accounts for 39% of global emissions, as reported in references [1,2]. In the context of China, this proportion reaches 45% according to China Building Energy Consumption and Carbon Emission Research Report [3]. Specifically, approximately 20% of emissions stem from the operational phase of buildings,

underscoring the crucial role of the construction industry in carbon emission reduction efforts [4].

Against this backdrop, photovoltaic façades represent a high-value green technology with substantial research and application potential. In China, more than 60 billion square meters of building façades are considered suitable for solar-energy utilization, and an additional 2 billion square meters are added annually [3]. Photovoltaic façades can enhance energy efficiency, reduce carbon emissions, improve thermal comfort, and elevate indoor environmental quality, making them a key pathway toward sustainable and green buildings.

Despite the recognized potential of BIPV for energy conservation and renewable-energy utilization, its adoption in real-world projects remains limited, and a comprehensive promotion mechanism has yet to be established. Several factors contribute to this gap. First, although BIPV is widely framed as an integral component of the building envelope, it often remains peripheral in practice. Limited integration with building structure, spatial organization, and formal aesthetics makes it difficult to secure sufficient attention in the early design phase [5]. Second, BIPV design involves multiple performance dimensions—including thermal, electrical, and daylighting performance—yet existing studies largely emphasize single aspects or specific scenarios, with limited interdisciplinary collaboration and a lack of systematic integration methodologies [6]. In addition, an incomplete standards system, perceived cost barriers, and insufficient policy support [7] further constrain broader deployment in building practice.

From a building-design perspective, scalability is often determined in early-stage design, when project teams set overall building form, envelope-integration strategies, and performance priorities. Yet the evidence needed for these decisions is dispersed across disciplinary silos and typically reported as isolated performance results (e.g., thermal, electrical, or daylighting), rather than synthesized into design-relevant guidance that can be implemented within routine project workflows. This design–evidence disconnect helps explain why BIPV remains underutilized despite its recognized technical potential.

Despite extensive research and many promising performance claims, it remains insufficiently explained why engineering evidence on PV façades has not consistently translated into scalable and repeatable adoption in real buildings. Resolving this question requires connecting performance outcomes with validation depth and with the practical constraints that shape early design and project delivery.

This review aims to explain how PV-façade evidence becomes deployment-ready knowledge for scalable building adoption. We synthesize the literature as an evidence system spanning (i) coupled performance dimensions (heat–electricity–light–comfort and emerging indoor-environment functions), (ii) methodological pathways (simulation/modelling versus empirical validation/monitoring), and (iii) building-design integration contexts. Specifically, we map the distribution and temporal evolution of research focus areas, synthesize dominant methods and typical evidence across key performance dimensions, and examine how validation and integration contexts shape the strength and transferability of reported findings. On this basis, we identify actionable evidence gaps and deployment levers that can support repeatable, code-compliant, and financeable implementation.

Accordingly, the scientific purpose of this review is to explain how and why PV-façade evidence does—or does not—convert into deployment-ready knowledge for scalable building adoption. A central problem is that existing studies often generate performance claims within isolated disciplinary workflows and non-comparable validation settings, leaving gaps between reported gains and what building delivery actually requires (repeatable design rules, code-compliant detailing, reliability evidence, and operation-ready perfor-

mance). This review therefore targets the evidence-to-deployment translation bottleneck by identifying where the chain breaks across methods, metrics, and integration contexts, and by clarifying which missing evidence most constrains scalability. To this end, the review synthesizes the literature as an evidence system across coupled performance dimensions (heat–electricity–light–comfort and emerging indoor–environment functions), methodological pathways (simulation versus empirical validation/monitoring), and building–design integration contexts. Specifically, it (i) maps the distribution and temporal evolution of research focus areas, (ii) synthesizes dominant methods and typical evidence across key performance dimensions (thermal, electrical, optical, comfort-related, and air-purification-related outcomes), and (iii) examines how evidence is distributed across validation pathways and architecture–engineering integration contexts. Based on these syntheses, the review distills deployment-relevant implications and actionable levers for scalability, including integrative evaluation frameworks, empirical validation priorities, and product-level integration/standardization considerations.

To make the synthesis usable in practice, the review is organized around decision points in building design—especially early-stage envelope integration—so that multidisciplinary evidence can be translated into actionable guidance for scalable implementation. This paper undertakes a review of existing research findings regarding photovoltaic façades and their implications for the comprehensive performance of buildings. The objective of this review is to conduct a thorough and systematic analysis of research literature on BIPV from the perspectives of heat, electricity, light, comfort, and air purification. By leveraging the principles of multi-disciplinary integration and system performance synergy, this analysis aims to identify commonalities, disparities, and key influencing factors across different construction strategies and climatic conditions. Overall, the findings are intended to support early-stage building–design and project–delivery decisions, and to inform researchers as well as industry, policy, and standards stakeholders working to scale “buildings + photovoltaics” toward carbon-neutral targets.

By enhancing their understanding of the design value and scalability of BIPV systems, this paper endeavors to promote the effective integration of BIPV in building practices, expedite the integrated development of “buildings + photovoltaics”, and thereby contribute to the timely achievement of urban carbon neutrality goals.

2. Methodology

2.1. Search Strategy and PRISMA Framework

This systematic review was conducted in strict accordance with the PRISMA guidelines [8], with reference to both the checklist and the flow diagram. This study adopted the PRISMA flow diagram (As shown in Figure 1) to clearly present the entire process from literature identification, screening, and assessment to final inclusion, which helps enhance the credibility and reproducibility of the review. A comprehensive literature search was carried out using the Web of Science and Scopus databases. The included evidence was synthesized through a structured narrative approach.

To enhance the applicability and domain focus of the study results, the subject areas and application scope were clearly defined before literature screening. Only original research led by scholars from architecture and engineering backgrounds, and focusing on building component performance or integrated system design, was included. Studies from materials science, pure sciences (such as physics and chemistry), or environmental disciplines that did not involve the building scale were excluded.

While this scoping choice strengthens relevance to building-scale performance and deployment, it may underrepresent device- and material-level innovations; therefore, the

evidence base synthesized here reflects an architecture/engineering-oriented lens that should be considered when interpreting scalability implications.

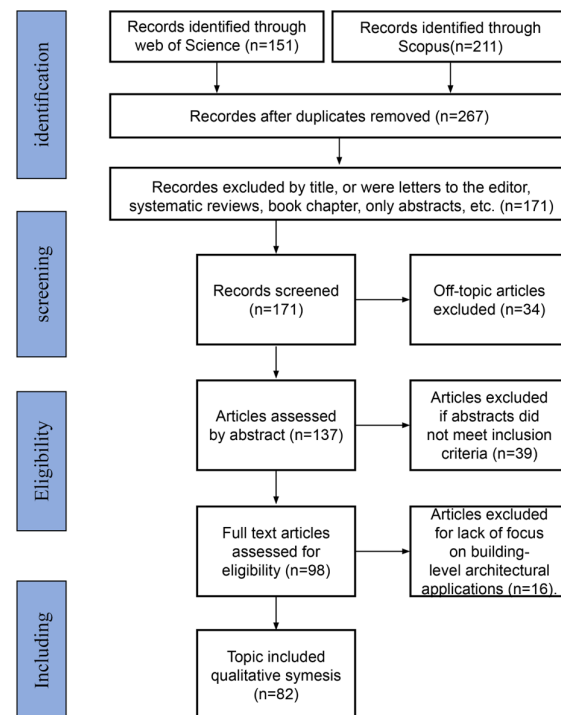


Figure 1. Flowchart of Article Selection.

2.2. Keyword Framework and Classification

The keyword selection strategy was guided by the core logic of “multi-disciplinary–multi-dimensional–building scalability-oriented” research, aiming to establish a robust and targeted search framework that captures the coupling between BIPV façades and various dimensions of building performance. The keywords were classified into three thematic categories, as summarized in Table 1.

Table 1. Keyword Categories.

Category	Keywords
Photovoltaic Façades Related Terms	Photovoltaic Façades, Solar Façades, PV Façades, BIPV, Building-Integrated Photovoltaics, PV Wall, Photovoltaic Windows, Trombe Wall, Photovoltaic Building Integration, Solar Powered Façades
Building Performance Related Terms	Building Performance, Building Energy Consumption, Building Thermal Efficiency, Indoor Comfort, Energy Efficiency, Building Energy Performance, Energy Demand Reduction, Thermal Performance, Building Thermal Regulation
Building Design and Environmental Optimization	Daylighting, Natural Ventilation, Indoor Air Quality, Green Buildings, Thermal Environment, Building Thermal Comfort

The first category includes terms related to photovoltaic façades, covering commonly used descriptors across the literature (e.g., Photovoltaic Façades, BIPV, Trombe Wall). This ensures broad coverage of heterogeneous terminology used across different disciplines, geographic regions, and research periods, thereby reducing the risk of omitting relevant studies.

The second category comprises terms focused on building performance, particularly core variables (e.g., Building Energy Consumption, Thermal Efficiency, Building

Performance, Building Thermal Regulation). These terms capture the evaluative dimensions through which BIPV façades affect building energy flows, especially thermal and electrical dynamics.

The third category covers terms associated with architectural design and environmental optimization. At the macro spatial level, this includes passive performance determinants (e.g., Natural Ventilation, Daylighting, Air Quality, Building Thermal Comfort), reflecting the integrative role of BIPV systems in regulating indoor environments, improving health and comfort, and supporting green building goals.

This tripartite classification enables the study to examine not only the technical performance of photovoltaic components as energy systems, but also their systemic value in building integration, spatial experience, and environmental modulation. The keyword framework therefore supports comprehensive coverage of multiple performance dimensions—including thermal, electrical, visual, comfort, perceptual, and environmental aspects—thus facilitating a structured, multidimensional, and cross-disciplinary analysis of the impact pathways of photovoltaic façade systems. This framework underpins both literature selection and subsequent in-depth analysis.

2.3. Screening Process and Eligibility Criteria

This study established explicit inclusion and exclusion criteria to ensure consistent data sources and alignment with the research focus. The inclusion criteria were (1) peer-reviewed original research published in English; (2) involvement of BIPV applications at the building component or system level; (3) reporting of building-related performance data, such as thermal performance, electrical performance, environmental regulation, or comfort; and (4) direct relevance of the study object to building design or engineering integration. The exclusion criteria were (1) full text not accessible; (2) a primary focus on macro-level policies or urban-scale carbon emissions without addressing the building scale; and (3) materials science or nano-optoelectronic studies that lack practical relevance to building performance.

Accordingly, advances reported primarily at the materials/device level may not be fully captured, which may bias the review toward building-application evidence.

This study followed a systematic review screening process and conducted a comprehensive literature search using the Web of Science and Scopus databases. As shown in Figure 1, a total of 362 records were initially retrieved (151 from Web of Science and 211 from Scopus). After duplicate removal, 267 records remained for the initial screening stage.

In the initial screening stage, we excluded records based on title and document type, removing 96 items that fell outside the scope of this study. These included editorials, book chapters, conference abstracts, systematic review articles, and records for which full texts could not be obtained.

Next, the remaining 171 records were screened for title and topic relevance, and 34 records with weak relevance were excluded. These mainly comprised studies focused solely on building energy policy, urban-scale carbon emissions, or topics not involving research at the building component level.

A total of 137 records entered the abstract evaluation stage. At this stage, 39 records were further excluded because they did not meet the inclusion criteria—for example, they did not involve BIPV systems or their impacts on building performance, or their research subjects were not actually related to photovoltaic components.

Ultimately, 98 articles entered the full-text evaluation stage. During full-text review, 16 articles with an overly strong emphasis on materials science or nano-optoelectronic performance were excluded. Although these articles used keywords such as “BIPV,” their research focus deviated substantially from building performance assessment.

In total, 82 articles were included in the qualitative synthesis. These articles report evidence on the thermal performance, electrical performance, light environment control, thermal comfort, indoor air quality, and design integration of photovoltaic façade systems in buildings, providing the empirical foundation for this study.

2.4. Data Extraction

After defining the research scope of the included literature, this study conducted structured data extraction for each paper. A unified coding framework was developed to capture publication year, study region, climate type, BIPV system configuration, research method (five standardized categories), and evaluation dimensions (thermal performance, electrical performance, optical performance, indoor thermal comfort, visual comfort, and air purification). In addition, economic and policy content closely related to these performance dimensions was summarized and organized, together with the academic background of the first author. For studies addressing multiple performance dimensions, the attribute characteristics of each dimension were recorded separately. To ensure classification consistency and reliability, two researchers independently performed dual coding for a subset of the sample.

2.5. Thematic Synthesis Approach

Each topic was synthesized based on the previously coded performance dimensions and research methods, integrating the literature's quantitative distribution, research strategies, application system types, and temporal characteristics to identify patterns and trends. Through this comprehensive process, six main research themes were identified: thermal performance, electrical performance, optical performance, indoor thermal comfort, visual comfort, and air purification capacity. This thematic categorization not only reflects the primary focal areas in current BIPV research but also provides the structural framework for the literature review in Section 3, enabling the results of this study to be presented in a more systematic and well-organized manner.

The structure of this article is as follows: Section 1 introduces the background, Section 2 details the research methods, Section 3 reviews existing literature, Section 4 analyzes the impacts and research gaps, and Section 5 provides a summary.

3. Results

3.1. Overall Analysis

This study conducted a systematic review of 82 articles related to BIPV to identify and summarize the current research hotspots and development trends. Starting from the practical needs of architectural design and usage functions, and considering the impact paths of BIPV components on building performance, we identified six key performance dimensions that architects and researchers commonly focus on during the design and evaluation processes: thermal performance, electrical performance, optical performance, visual comfort, indoor thermal comfort, and air purification capacity. These six directions not only cover the main impacts of BIPV components on the building environment and users but also represent the current research hotspots.

After clarifying these six directions, this study classified and statistically analyzed the 82 articles, and further refined the research scale and development history of each direction. As shown in Figure 2, the research attention to each direction varies significantly. Among them, the research scales of electrical performance (91.5%, 75/82) and thermal performance (86.6%, 71/82) are the largest, indicating that in the past and current stages, the research on BIPV still centers on improving energy efficiency. The research on optical performance is also relatively significant (58.5%, 48/82), reflecting that while focusing

on the energy efficiency of buildings, the transparency, optical performance, and other characteristics of photovoltaic materials that are closely related to the visual environment have gradually attracted attention. In contrast, the research proportions of visual comfort (23.2%, 19/82), indoor thermal comfort (9.8%, 8/82), and air purification capacity (7.3%, 6/82), which are directly related to user comfort and health, are relatively low. This indicates that the research on non-energy consumption performance directions is still in the early exploration stage, and architects and researchers' awareness and attention to human factors and environmental improvement performance need to be further enhanced.

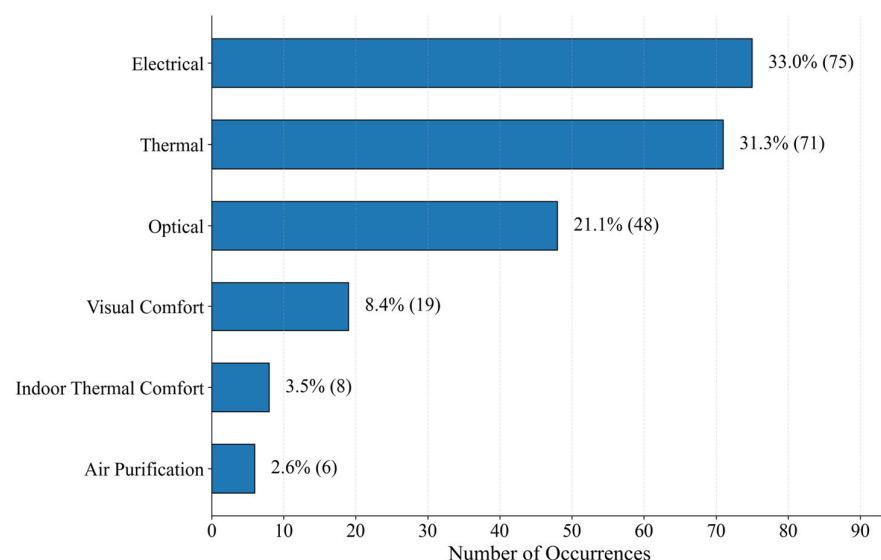


Figure 2. Distribution of Research Focus Areas in Photovoltaic-Related Studies.

A further analysis of the overall publication trends from 2001 to 2024, as shown in Figure 3, indicates a significant increase in BIPV-related research, especially after 2015. The annual number of publications reached its highest point in 2024, accounting for 24.4% of the total reviewed studies (20 out of 82). Among the various technical directions, electrical performance, thermal performance, and optical performance exhibit relatively long development histories and have continuously attracted scholarly attention under the global backdrop of energy transition and increasingly stringent building energy efficiency standards.

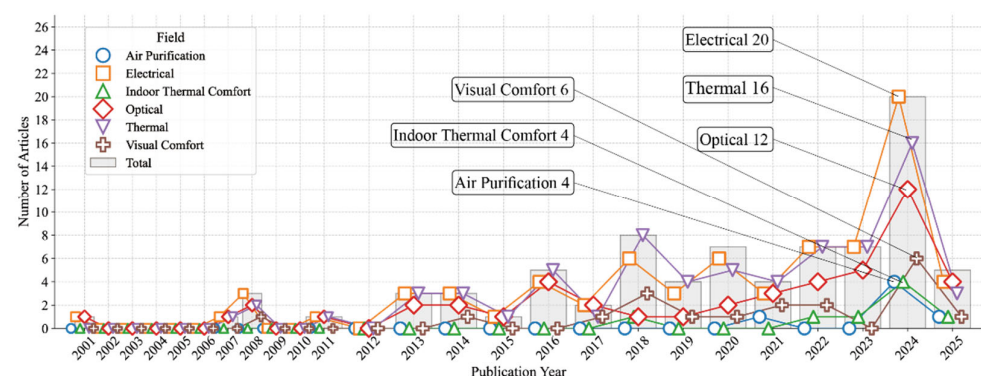


Figure 3. Trends of Research Focus Areas Over Time in PV-Related Studies.

According to Table 2, these three traditional directions all first appeared in the early 2000s (2001 for electrical and optical, 2007 for thermal) and simultaneously reached their publication peaks in 2024, with their 2024 outputs accounting for 24.0% (18/75), 22.5% (16/71), and 25.0% (12/48) of their respective total publication volumes. In contrast,

three user-oriented performance topics—visual comfort, indoor thermal comfort, and air purification capacity—emerged more recently (first appearing in 2008, 2018, and 2021, respectively), yet demonstrated particularly rapid growth. Their respective publication peaks also occurred in 2024, with strikingly high proportions: 36.8% (7/19), 62.5% (5/8), and 50.0% (3/6). These trends suggest that the research focus in the BIPV field is undergoing a notable transition—from conventional energy efficiency improvement to a more holistic, multi-dimensional integration of user comfort and environmental quality. This evolution reflects the increasing emphasis on human-centric and climate-responsive design practices in the built environment.

Table 2. First Appearance and Peak Year of Research Fields.

Field	Total Count	First Appeared	Peak Year
Air Purification	6	2021	2024
Indoor Thermal Comfort	8	2018	2024
Visual Comfort	19	2008	2024
Optical	48	2001	2024
Thermal	71	2007	2024
Electrical	75	2001	2024

Figure 4 presents a co-occurrence heat map of research directions, revealing the coupling degree among various fields. Among them, the “thermal-electrical-optical” combination is highly integrated, indicating that BIPV research is typically a composite system study; the coupling between “optical” and “visual comfort”, and between “thermal” and “thermal comfort” is also very obvious, demonstrating that human factors have been embedded in system design; while “air purification” is weak, it still has connections with mainstream technical directions and has expansion potential.

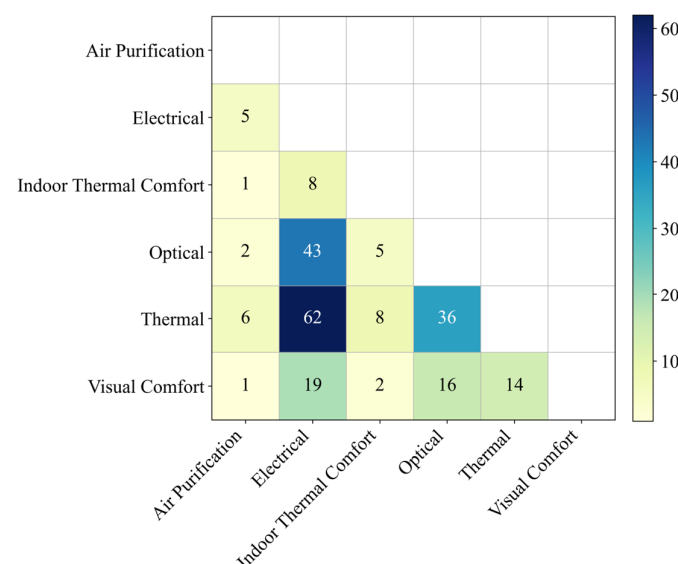


Figure 4. Co-occurrence of Research Focus Areas in PV-Related Studies.

A statistical analysis of the study regions represented in the 82 selected research papers reveals a distinct geographical concentration of BIPV research efforts, primarily in East Asia, Europe, and selected areas of North America (Figure 5). Notably, China, Japan, and South Korea constitute the most active regions, exhibiting the highest density of publications. These countries correspond to the darkest areas on the global research intensity heatmap, highlighting their leading positions in both theoretical and applied aspects of BIPV development. In Europe, nations such as Germany, Italy, France, and

the United Kingdom show widespread research activity, while localized hotspots are also observed along the U.S. West Coast and in parts of the Middle East (e.g., Iran [9]).

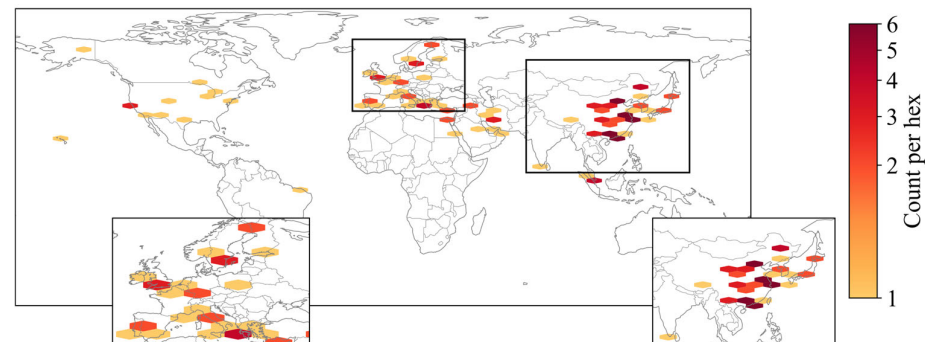


Figure 5. Global Distribution of Research Areas.

It is important to note that only studies which explicitly identified a geographic focus or research site were included in the regional statistical analysis. Papers that solely focused on theoretical modeling or lacked a specified building context were excluded. In cases where a single study involved multiple geographic sites, each location was counted independently to accurately reflect the scope of spatial coverage. As a result, the total number of recorded research locations exceeds the number of reviewed publications.

Collectively, current BIPV research demonstrates a distinct “East Asia–Europe” dual-core spatial distribution pattern. From a scalability perspective, this uneven spatial coverage matters because PV-façade deployment depends on local delivery conditions, including code and approval practices, product certification pathways, procurement routines, and the availability of experienced integrators—factors that shape whether reported performance can be replicated and financed at scale. Within developing-region contexts represented in our sample, China appears most frequently, whereas evidence from many other developing regions remains sporadic and case-based (e.g., building-scale BIPV assessments reported for Egypt [10], Iran [9], Brazil [11], and Turkey [12]). This imbalance suggests that scalability guidance derived mainly from mature markets should be transferred cautiously, and that more in situ monitoring and project documentation are needed for underrepresented contexts. This geographic clustering reflects the combined influences of regional energy policies, climate conditions, and building energy performance standards. It also underscores the growing global interest in building-integrated photovoltaics and the gradual diversification of research efforts across different climatic and socio-economic contexts.

To further elucidate the environmental context of BIPV research, a climatic classification of study sites was conducted based on the Köppen–Geiger system and compared with an applied climate classification scheme. The analysis only included sites with clearly defined geographic information, and for studies involving multiple regions, climate types were recorded individually. Only those climate categories that appeared more than once in the dataset were included in the final summary.

As illustrated in Figure 6, research efforts are notably concentrated within specific climate zones. The most frequently represented Köppen category is Cfa (humid subtropical climate: fully humid, hot summer), accounting for 28.8% of cases ($n = 40$). This climate type is prevalent in southern China, parts of Japan, and the southeastern United States—regions that have shown significant interest in the energy and thermal performance of BIPV systems.

Following this, Csa (Mediterranean climate: dry and hot summer, mild and humid winter) and Cwa (humid subtropical with dry winter and hot summer) represent 12.9% ($n = 18$) and 10.1% ($n = 14$) of the cases, respectively. These are primarily located in

Mediterranean coastal areas and central China (e.g., the middle Yangtze River basin). Other climate zones of note include Dwa (humid continental with dry winters and hot summers), BSk (cold semi-arid), and Cfb (temperate oceanic), suggesting a growing diversification in research locations.

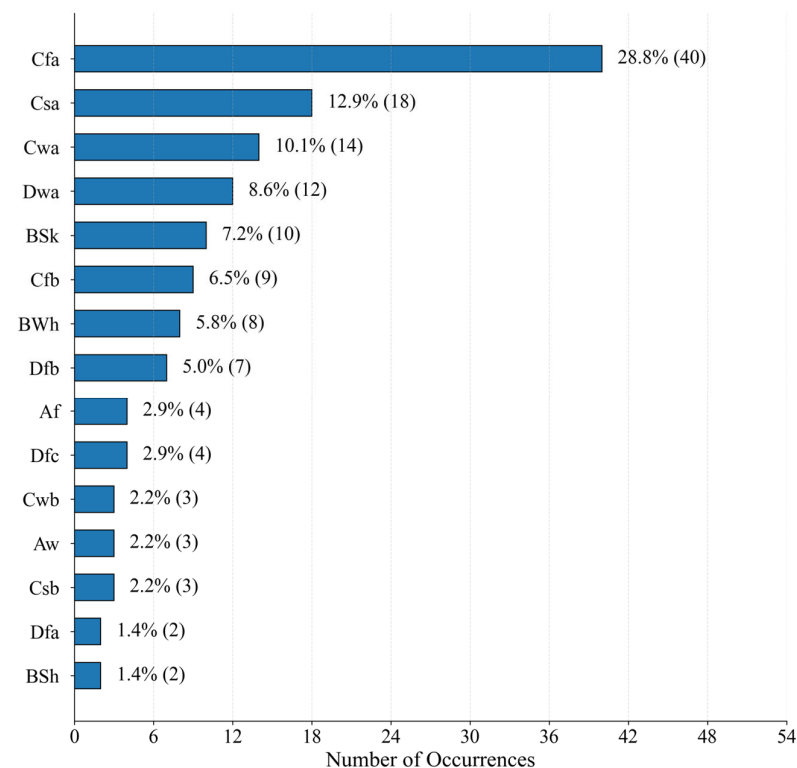


Figure 6. Köppen Climate Zone Representation in Research Areas.

Under the applied climate classification system (Figure 7), the most common category is “Humid Subtropical with Dry Winter”, accounting for 27.2% ($n = 37$), which broadly corresponds to the Cfa and Cwa classifications in the Köppen system. The next most frequent types are “Mediterranean” (15.4%, $n = 21$) and “Monsoon-Influenced Humid Continental” (7.4%, $n = 10$). Additionally, less frequent categories such as “Hot Desert”, “Temperate Oceanic”, and “Tropical Rainforest” were also identified, indicating that BIPV research is gradually extending into diverse and climatically challenging environments.

To uncover the underlying knowledge structure of current BIPV research, we conducted a statistical analysis of the disciplinary backgrounds of the first authors in the reviewed literature. Specifically, the classification was based on the institutional affiliations, departmental affiliations, and declared research fields of the first authors as indicated in the publications. Each author was accordingly assigned to one or more academic disciplines based on their professional focus.

In total, over 40 distinct disciplinary categories were identified. As illustrated in Figure 8, the top ten most frequently occurring fields are presented. Among them, Energy Engineering and Architecture & Urban Planning were the most prevalent, accounting for 11.2% and 10.0% of the total sample, respectively. Other prominent disciplines included Civil Engineering (9.6%), Built Environment (8.9%), and Environmental Engineering (7.4%). These findings underscore the central role of interdisciplinary collaboration—particularly among architecture, energy, and environmental disciplines—in advancing BIPV research.

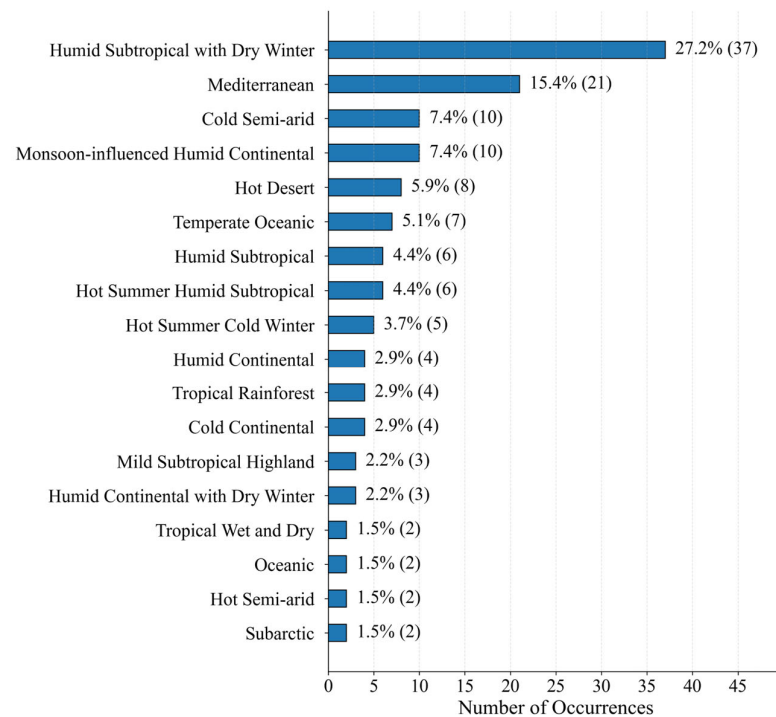


Figure 7. Climate Type Representation in Research Areas.

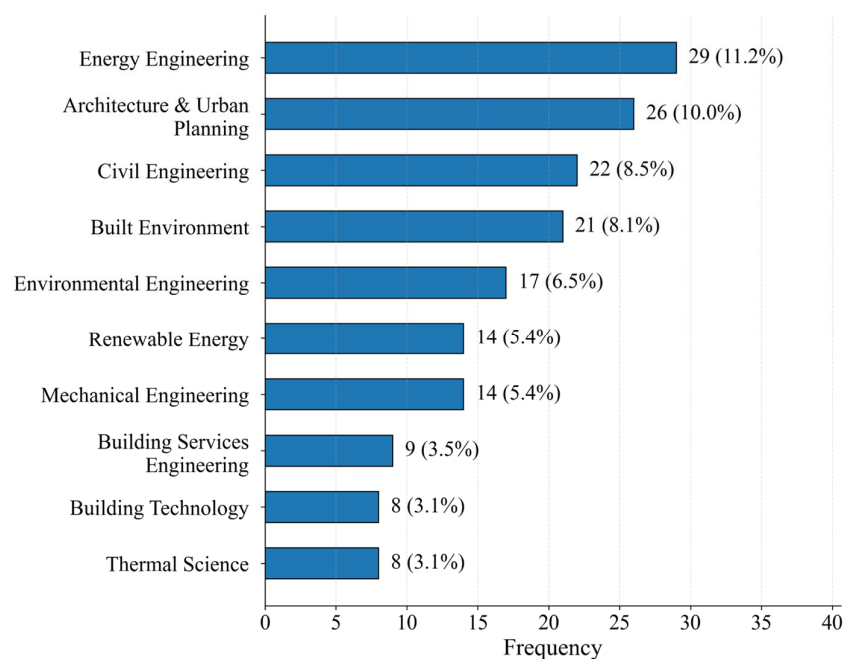


Figure 8. Top 10 Research Fields of First Authors.

Furthermore, we analyzed the number of distinct research domains associated with each author, as shown in Figure 9. The data indicate that 33.3% of authors were affiliated with two disciplines, 28.4% with three, and 21.0% focused on a single discipline. Notably, 17.3% of authors had cross-disciplinary affiliations spanning four or more fields. This distribution reveals a strong trend toward multidisciplinary integration among BIPV researchers, which provides a solid theoretical and technical foundation for addressing challenges related to functional integration, energy efficiency optimization, and environmental adaptability in building-integrated photovoltaic systems.

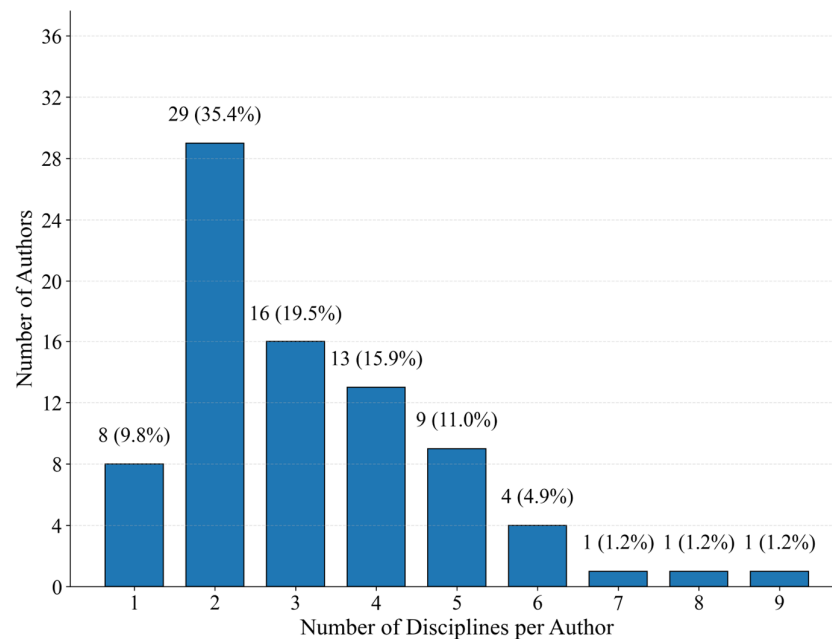


Figure 9. Number of Disciplines per First Author.

3.2. The Impact of Photovoltaic Façades on Building Thermal Performance

In recent years, the rapid application of photovoltaic (PV) façade systems in the architectural domain has drawn increasing attention to their thermal performance optimization. Research has evolved from component-level thermal dissipation testing to more comprehensive investigations involving aerodynamic coupling, thermal energy storage synergy, thermal comfort response, and dynamic building-scale energy consumption assessments. A multidimensional research framework has emerged, spanning structural design, passive strategies, and integrated hybrid systems. Overall, the trend has shifted from passive structural optimization toward active thermal control techniques, with methodologies expanding from field measurements and numerical simulations to building energy analysis and system-level co-simulation.

To make the thermal Results synthesis-oriented, we first consolidate several cross-study findings that recur across the thermal-tagged papers in our database. The evidence points to four transferable messages:

- (1) Thermal outcomes fall into bounded, repeatable ranges once the operating regime is aligned. Across ventilated cavities and PCM buffering, PV/module temperature moderation most often lies in the single-digit to low-double-digit °C band: modest airflow/operation changes typically yield ~1–2 °C, while effective ventilation or latent buffering repeatedly reports ~6–11 °C reductions. PCM solutions also provide time-domain benefits (peak delays of ~114–125 min) with modest electrical gains (typically ~0–5%, best-case ~4.8%) [13,14]. Under intensified (ducted/forced-flow) cooling, performance becomes more sensitive to airflow and geometry, including reported ~19% power increases and an engineering channel-depth ratio (e.g., $b/L \approx 0.11$) proposed to reduce overheating and improve predictability [15].
- (2) Evidence is usually built through a “measurement → physics correlation/sensitivity → annual simulation” chain. Measurements anchor temperature rise, airflow, and heat-flux behavior; physics-based modeling generalizes results via geometry sensitivity (air gap, openings, channels) and boundary-condition handling. Several studies update/derive convection correlations (e.g., Nusselt-type formulations) to keep wind/no-wind cases comparable and note saturation effects (e.g., limited additional cooling beyond ~1 m/s in some regimes) [16,17]. Annual simulation (often

multi-orientation or multi-climate) then translates façade behavior into building demand and seasonal balance, with multi-objective optimization emerging when daylight–thermal trade-offs become explicit [18–21].

- (3) Climate and mode selection change the mechanism and even the sign of outcomes. Subtropical numerical work reports season-matched PCM selection (higher melting temperature for summer insulation; lower for winter heat storage) and non-linear heat–electric coupling, with efficiency gains up to ~8.05% under certain settings [18]. Seasonal experiments on PCM-integrated ventilated PV windows report positive indoor temperature differences in heating mode (e.g., ~7.04 °C) versus negative differences in cooling mode (approximately −4.26 °C to −1.26 °C), motivating transitional-season mode switching [22]. In tropical contexts, thermal results are often framed through compliance-relevant envelope metrics (e.g., in situ U-value testing and Low-E pairing) as deployment enablers [23]. In cooling-dominated Hong Kong, results emphasize reduced solar heat gains and tilt-dependent trade-offs (overall benefit around ~20° vs. generation-maximizing around ~30°, with cooling-load saving potential up to ~69.16 kWh/m²·yr) [19,20].
- (4) Scalability is limited by boundary sensitivity and buildability, not only peak temperature drops. Several studies identify wind/external convection (hext) as performance-dominant, implying that transfer requires boundary-consistent reporting and, ideally, calibrated assumptions rather than defaults [24]. Practical constraints recur (cost, waterproofing/fire safety, structural integration), while certification-facing envelope metrics act as adoption gates in tropical façade work [13,23]. Control-oriented studies (e.g., ANN-based adaptive operation in plateau climates) further suggest that scalable performance depends on robust operating logic and fast prediction as well as component design [25].

These synthesis points frame the following strategy-based results as supporting evidence for climate-conditioned operating envelopes and deployment-relevant constraints, rather than a sequence of mini-reviews.

At the level of passive structural strategies, natural ventilation configurations have been most widely studied. Agathokleous and Kalogirou conducted a three-month field experiment on a BIPV/T vertical façade system in the Mediterranean climate, evaluating energy conversion efficiency and exergy performance. The results showed thermal efficiency fluctuating between 0% and 10%, increasing with runtime and inlet-outlet temperature difference. Outlet air temperatures were consistently higher than inlet temperatures, suggesting heat recovery potential for building heating. The total (electrical + thermal) efficiency reached 26.5–33.5%, while exergy efficiency remained at 13–16%, indicating room for thermal quality improvement [26]. Their subsequent research revealed that natural convection speeds ranged from 0.26 to 0.34 m/s, with module surface temperatures reduced by 6–9 °C and corresponding efficiency gains of approximately 2.1% [16]. COMSOL simulations (using COMSOL Multiphysics 4.3b) further identified an optimal air gap thickness of 0.1 m, maintaining PV surface temperatures below 35 °C [17].

Additional studies proposed various enhancements to natural ventilation designs. Yun et al. developed a PV façade with adjustable inlet/outlet openings, achieving optimal annual performance on south-facing façades and demonstrating heating potential in cold seasons [27]. Zhang & Yang recommended DSF cavity thicknesses of 0.2–0.6 m to balance thermal resistance and airflow stability [28]. Tonui & Tripanagnostopoulos showed that finned channels increased outlet air temperature by 9 °C and reduced PV surface temperature by over 10 °C [29]. Yang et al. emphasized that indoor airflow patterns also influenced PV temperatures, with displacement ventilation reducing surface temperature by 1–2 °C and indoor heat gain by approximately 11.7% [30]. Xu et al. observed a

6.5–11 °C temperature reduction and 75% decrease in heat flux with CdTe PV windows on marine passenger vessels [31]. Wong et al. demonstrated that STPV skylights in Japanese residential roofs delayed daytime heat peaks and maintained a temperature differential of 8–9 °C under high solar irradiation [32]. Fan's atrium-based simulations indicated that integrating STPV with natural ventilation skylights could maintain indoor temperatures within 24–27 °C [33]. Qiao et al. developed a multi-objective optimization model for office buildings, showing that a 40% PV coverage ratio offered an optimal balance between thermal load and daylighting, with ventilation cavity thickness and orientation combinations strongly affecting cooling loads [34]. Wheeler et al., using EnergyPlus across eight climate zones, found that dynamic PV glazing could reduce annual heating demand by 8000 GJ and CO₂ emissions by 350,000 kg [35].

Thermal buffering materials such as phase change materials (PCMs) have demonstrated excellent temperature control under diverse climates. Karthick et al., using Glauber salt in tropical India, observed an 8 °C surface temperature drop and a 10% efficiency gain, with east-facing façades showing the most improvement [14]. Ziasistani & Fazelpour compared PV-DSF systems with and without PCM across six cities including Tehran, finding PCM reduced winter heating loads by 10.4% and cooling loads by 39.3 MWh [9]. Zheng et al. proposed a liquid-cooled PCM structure (MPCMS) with 9.75 h of sustained thermal regulation and a 4.8% efficiency increase [13]. Pan et al. reported an 18.3% increase in annual thermal recovery efficiency with a STPV + PCM system [36]. Wang et al. achieved 479.4 kWh/m² annual thermal savings using a spectrally selective CdTe PV-DSF configuration [37], while Zhang et al. integrated a photocatalytic air purification module, boosting winter indoor temperatures by 62.5% and reducing annual cooling loads by 34.86% [38]. Koyunbaba et al. combined semitransparent PV modules with Trombe walls, recording winter indoor temperature increases of 6 °C in cold climates, demonstrating the passive heating potential of BIPV components [12]. Saadon et al., through energy and exergy analysis, concluded that STPV systems incorporating natural ventilation and low-conductivity materials can improve exergy efficiency by 5–12% in hot climates [39].

In terms of structural innovation, Huang & Hewitt developed a bionic aluminum shell with dual PCM layers, achieving an 11.2 °C temperature drop and a 210 min heat release delay, suitable for high-temperature façades [40]. Chen et al. created a multifunctional PV window integrating thermal exchange and air purification, with peak thermal efficiency of 49.5% under 600 W/m² irradiation and 45° louver angle, optimal within a temperature range around 290 K [41]. A subsequent design removed the PV module, introducing a solar-driven photocatalytic double ventilated window (PC-DVW), whose thermal efficiency increased with both irradiance and temperature, with best performance at 288 K inlet temperature [42]. Luo et al. incorporated PV-blind systems into DSF structures, validating their effectiveness in enhancing thermal resistance while providing shading and daylight control [43].

For active thermal control, Luo et al. proposed a thermoelectric cooling system capable of generating a −25 W/m² reverse heat flux in summer, significantly improving thermal autonomy [44]. Gonçalves et al., using the Modelica platform, identified the external convective heat transfer coefficient (*h_{ext}*) as a key factor in thermal performance and used sensitivity analysis to support structural optimization of BIPV façades [24,45]. Wang et al. developed a multifunctional PV/T window system with 13–16% energy savings and adaptive cooling/heating via water/air switching modes [46]. C. Wang et al. further proposed a window-wall coordinated control strategy using artificial neural networks (ANN) to enhance thermal adaptability and control precision in plateau climates [47].

At the system integration and climate adaptability level, research has shifted toward cascade system strategies and regional adaptation analyses. Marchwinski & Kurtz-Orecka

demonstrated that combining PV with heat pumps significantly reduces primary energy consumption in cold regions [48]. Mitsopoulos et al. found that integrating PCM and cooling fins improved heat pump efficiency [49]. Nada & El-Nagar observed a 16 °C surface temperature drop with nano-PCM back panels [50]. Shabunko et al. conducted U-value testing for five BIPV configurations, providing tropical curtain wall references [23]. Peng et al., through modeling of PV-DSF systems, found that maintaining the ventilation cavity thickness between 400 and 600 mm effectively mitigates heat accumulation and improves thermal dissipation [51,52].

Finally, at the whole-building scale, Zhang et al., Li & Lam, and Kapsis & Athienitis confirmed via simulation and experiments that PV systems can effectively reduce cooling loads [19,53,54]. Jun et al., Oliveira Pano & Gonçalves, Wang et al. and Skandalos & Karamanis explored various PV façade configurations in terms of orientation, structural integration, radiant membrane hybridization, and Mediterranean climate adaptability, offering feasible design pathways for climate-responsive BIPV applications [55–58].

In summary, current research on PV façade thermal performance has evolved into a comprehensive network involving natural ventilation, PCM integration, bionic design, active cooling technologies, and system-level modeling. Future studies are expected to focus on modular component standardization, dynamic thermal load control mechanisms, and climate-specific regional design indicators to support optimal BIPV performance under complex thermal environments.

3.3. The Impact of Photovoltaic Façades on Building Electrical Performance

As photovoltaic (PV) systems in buildings transition from add-on applications to fully integrated components, their electrical performance has become a critical metric for evaluating energy efficiency and economic viability. Current research has extensively investigated PV module types, structural configurations, thermal coupling mechanisms, and environmental adaptability through both experimental studies and modeling approaches. These efforts have progressively extended toward annual dynamic power generation analysis, building energy coupling simulations, and structural optimization strategies, revealing an integrated trend across system modeling, component-level optimization, and building-scale integration.

To make the electrical Results synthesis-oriented, we first consolidate recurring patterns observed across the electricity-tagged studies in our database. Across these works, electrical performance is reported not only as annual yield or PCE, but as a coupled outcome shaped by envelope/daylight interactions, operating mode, and boundary conditions.

- (1) Reported generation outcomes cluster into explainable bands once scale is aligned. PV-DSF electricity yield in cooler climates is frequently reported in the tens of $\text{kWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ range (e.g., $\sim 65 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) [52], while mode-defined experiments on ventilated PV windows report explicit daily production (e.g., $\sim 0.383 \text{ kWh}$) and peak power ($\sim 61.16 \text{ W}$) under heating-mode operation [E6]. For PV shading, geometry controls the net outcome: in Hong Kong, best overall benefit is reported around $\sim 20^\circ$ tilt (vs $\sim 30^\circ$ for maximum generation), with cooling-load saving potential up to $\sim 69.16 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ [20]; an optimization framework reports primary-energy reduction up to $\sim 48.7\%$ and annual generation exceeding building energy use by $\sim 1034.4 \text{ kWh}$ [59]. A dynamic PV light-shelf further reports an $\sim 12\%$ annual generation increase over a fixed configuration [60].
- (2) Methods converge on coupling rather than single-tool proof: measurement/simulation chains are commonly extended to electro-thermal/daylight co-evaluation, with annual simulation translating device-level output into net building impacts [19,20,59,61].

- (3) Climate and operating context change the dominant mechanism: hot-humid glazed buildings (e.g., Singapore) emphasize net benefit under cooling/daylight trade-offs [E1], while cooling-dominated Hong Kong highlights solar-heat-gain reduction as a key driver of net electricity value [19,20]; Mediterranean PV-DSF results similarly depend on seasonal/operational framing [22,52].
- (4) Scalability is constrained by boundary sensitivity and adoption metrics: hext/wind assumptions are performance-dominant in naturally ventilated BIPV [24], high operating temperatures (up to $\sim 64^{\circ}\text{C}$) raise degradation concerns [54], and roof studies show payback divergence (e.g., 6.08 vs. 7.6 years) even under comparable annual generation [62]; self-sufficiency targets also introduce cost-threshold constraints [63]. These synthesized points provide the frame for reading the following strategy-based results as supporting evidence rather than standalone mini-reviews.

Annual power output and efficiency remain core evaluation indicators for PV systems. Wheeler et al. employed EnergyPlus to simulate the annual performance of three PV window types—wavelength-selective, non-selective, and dynamic—in eight U.S. climate zones, finding that when the photovoltaic conversion efficiency (PCE) reached 12.5%, up to 40% of the total building energy consumption could be offset [35]. Xu et al. recorded a maximum daily output of 0.83 kWh and peak efficiency of 16.2% for PV windows under dynamic ventilation conditions, marking a 12% improvement over static setups [31]. Jun et al. simulated that STPV windows with a VLT of 25% achieved the optimal trade-off between power output and daylight-driven energy savings in subtropical cities [55]. Fan reported an annual electricity yield of 82 kWh/m² from courtyard STPV systems under high-irradiance conditions [33], while Yun et al. observed 89.4 kWh/m² per year from south-facing ventilated PV façades [27]. Wong et al. recorded a stable annual STPV roof system efficiency of 14.3%, with output maintained above 99% of its rated capacity. Ziasistani and Fazelpour simulated PV-DSFs in six Iranian cities, with south-facing configurations generating up to 97.9 MWh annually, while performance dropped significantly on the north-facing façades [9]. Cheng et al. documented 46.7 kWh/m² annual output from STPV façades in cold climates, maintaining a stable 3–4% efficiency under low irradiance conditions [64].

PV efficiency is highly sensitive to thermal management. Agathokleous and Kalo-girou demonstrated through natural ventilation experiments that system efficiency typically ranged between 24 and 28.5%, while component temperatures exceeding 57°C caused notable losses. Introducing a 0.1 m air gap effectively mitigated this decline [26]. Kaiser et al. showed that forced ventilation could reduce module temperatures by 19°C —raising efficiency by 11% and power output by 19% as wind speed increased from 0.5 m/s to 6 m/s [15]. Gonçalves et al. developed a highly accurate electro-thermal coupling model with monthly prediction errors below 2% and daily errors under 3% [45]. Zheng et al. used microencapsulated PCM to cool the PV back surface, lowering temperatures by 8.8°C and increasing efficiency by 4.8%, with a peak PCE of 15.5% [23]. Wang et al. integrated cooling membranes into CSTPV systems, achieving an annual output of 114.8 kWh/m²—17% higher than traditional double-glazed windows [57]. Skandalos & Karamanis reported efficiency gains of $\sim 3\%$ from 6 to 9°C temperature reductions [58]. In tropical regions, Karthick et al. used Glauber salt-based PCM to reduce average temperatures by 8°C and improve efficiency by 10% [21]. Nada and El-Nagar applied nano-PCM materials to lower PV module temperatures by 16°C , boosting efficiency and enhancing indoor thermal comfort [50].

PV-integrated construction has become a central research direction. Pan et al. developed a coupled photothermal-electric model demonstrating that STPV modules under thermal stability conditions could achieve a 12.4% increase in daily efficiency [36]. Zhang et al. en-

hanced a double-skin ventilated system using catalytic coatings and pre-heating channels, achieving a total output of 414.9 kWh—nearly four times higher than conventional designs [38]. Li et al. reported an annual yield of 133.2 kWh from bifacial BIPV systems in Shenzhen, with rear-side modules contributing 28% and overall efficiency improved by 19.7% [65]. Subsequent parameter optimizations elevated generation to between 927.5 and 8697.9 kWh, reduced cooling loads by 12.6%, and yielded payback periods of under four years [66]. Kwag et al. showed that when rooftop PV failed to meet 60% of the building's ESSR, integrating BIPV into south-facing façades could boost self-sufficiency to 76.9% [63]. Numerous empirical and simulation studies have validated the stable generation capacity of STPV in urban buildings, including those by Zhang et al., Li & Lam, Oliveira Panao & Gonçalves, Kapsis & Athienitis, and Vartiainen [19,53,54,56,67].

Dynamic PV elements have emerged as promising solutions to enhance electricity generation. Chen et al. studied multifunctional PV louvers, noting that under low-angle, high-irradiance conditions, efficiencies reached 16–18.5%, with the highest exergy efficiency observed at an 85° tilt angle [41]. Su et al. proposed seasonally adjustable PV louvers for Harbin, reducing annual energy consumption by 13.1% and improving generation stability [68]. Wang et al. developed a dynamic PV canopy yielding 108.57 kWh annually—12% more than its fixed counterpart [60]. Sun et al. introduced a foldable BIPV shading structure that balanced power generation, daylighting, and shading across multiple climate zones [69]. Huang and Hewitt applied a bionic dual-PCM design that reduced temperatures by 11.2 °C and delayed heat release by 210 min—supporting dynamic systems in high-temperature regions [40].

Thermal-electrical coupling has shown consistent performance benefits. Yang et al. found that displacement ventilation increased PV module efficiency by approximately 0.4% [30]. Luo et al. developed two thermoelectric cooling models and a PV-blind thermal-optical-electric coupling model, achieving reverse heat flow of -25 W/m^2 and improved output stability through optimized louver angles [43,44]. Saadon et al. evaluated STPV performance from an exergoeconomic perspective, finding that north- and west-facing configurations extended the economic payback period by approximately 1.8 years [39]. Qiao et al. used genetic algorithms to optimize STPV setups and identified that 40% PV coverage with a 200 mm air gap produced optimal electricity output [34]. Wang et al.'s spectrum-selective PV-DSF structure demonstrated 18.2% higher annual output than conventional PV in simulations [37]. Shabunko et al. provided empirical U-value measurements for various configurations, offering a physical foundation for envelope design [23]. Tonui & Tripanagnostopoulos highlighted that finned heat sinks increased PV outlet air temperature by 9 °C and reduced module temperature by 10 °C [29].

Material selection, irradiance levels, and operational context also significantly influence electrical performance. Ng et al. proposed the Net Electricity Benefit (NEB) indicator to quantify overall PV effectiveness, which reached $20.84 \text{ kWh/m}^2/\text{year}$ in tropical climates [61]. Olivieri et al. found that medium-transparency (30%) a-Si modules achieved a generation efficiency of 3.2% [70]. Peng et al. simulated PV-DSF systems in cold climates and estimated annual output at 65 kWh/m^2 [52]. Zhang et al. verified the low-irradiance responsiveness of CdTe-DSV systems through empirical and simulation data, with peak south-facing efficiency reaching 8% [71]. Yang et al. demonstrated that perovskite modules exhibit superior thermal stability compared to a-Si and DSSC in cold climates [21]. Zheng et al. used PCM-coupled models to show that thermal regulation strategies could improve PV efficiency by 8.05%, revealing the potential of integrated photothermal-electric designs [18].

In summary, the electrical performance of PV façades is shaped by a complex interplay of material types, structural design, thermal management strategies, and environmental

responsiveness. Existing studies have quantified annual generation potential across different configurations and identified key mechanisms—such as thermal coupling, structural integration, and dynamic regulation—for performance enhancement. Future research should prioritize (1) stability testing of PV materials under high-temperature and sub-zero conditions; (2) multi-objective thermo-optical-electrical optimization at the component scale; and (3) development of predictive generation models tailored to building typologies and orientations.

3.4. The Impact of Photovoltaic Façades on Building Optical Performance

With the increasing application of BIPV systems in façade design, their performance in daylighting has emerged as a significant research focus within the field of architectural environmental design. Current studies on the optical performance of PV-integrated façades primarily explore how optimization of component geometry, structural typologies, and control strategies can improve indoor daylight availability, illuminance uniformity, and light-energy conversion efficiency, while achieving functional synergies with shading and power generation. The employed methodologies are diverse, spanning parametric simulations, multi-objective optimization, algorithm-based control, and empirical validation.

It has been shown that the optical properties of PV components directly affect their contribution to natural lighting, their ability to ensure visual comfort, and their coupling with artificial lighting energy consumption. Daylighting performance is constrained by multiple factors, including visible light transmittance (VLT), the morphology of shading devices, component control logic, and building orientation, all of which determine system adaptability across varying climatic contexts.

To make the optical Results synthesis-oriented, we consolidate recurring regularities across the optics-tagged papers in our database. When studies are aligned to comparable indicators (UDI/DA/DF-based availability, uniformity, glare-related constraints, and net-energy coupling), daylighting outcomes fall into bounded and interpretable ranges. Dynamic PV shading typically delivers modest but repeatable annual UDI gains ($\sim 1.39\text{--}3.1\%$) under practical operating constraints [72], while geometry-first optimization combined with adaptive control can shift daylight performance much more sharply (reported UDI up to $\sim 71.6\%$) alongside large energy impacts (reported primary-energy reduction up to $\sim 48.7\%$) [59]. Form-factor modulation shows similarly structured effects: a curved PV window reports sUDI gains of $\sim 3.94\text{--}5.94\%$ with only small glare-side changes (sGA reduced by $\sim 1\text{--}2.6\%$) and, in high-latitude contexts, a generation increase of $\sim 7.38\%$ [73]; bifacial PV sunshades extend effective daylight duration ($+39.44\%$) while reducing cooling demand (-12.61%) [66]. Across building types, several studies also report “safe” design windows that preserve daylight thresholds while avoiding glare, such as atrium STPV skylights recommending ARPM bands of $\sim 30\text{--}70\%$ depending on solar availability [33], and cold-region double-glazed STPV optimization indicating a balanced configuration around south-facing, PV coverage $\sim 30\%$, WWR $\sim 30\%$ for stable daylight–energy outcomes [74].

Methodologically, the optical evidence increasingly converges on Radiance-class daylight simulation coupled with annual energy evaluation, supported by optimization and surrogate/control models; an ANN–EnergyPlus approach trained on Radiance outputs reports $\sim 91.7\%$ time reduction and reveals systematic underestimation in common EnergyPlus daylight engines (split-flux/DElight by $\sim 5.3\%/9.7\%$) [75]. Climate dependence is therefore first-order: cooling-dominated/high-solar contexts favor tilt/coverage/shading logic to stabilize distribution while limiting cooling penalties, whereas low-sun/high-latitude contexts rely more on maintaining sufficiency via form-factor and rear-zone enhancement (e.g., light-shelves) [33,60,73,74]. As a result, scalable implications hinge on transferable design

envelopes (coverage/tilt/curvature + glare constraints) and reusable evaluation/control pipelines, rather than isolated “best-case” illuminance snapshots.

Regarding control mechanisms, research has shifted from static shading systems to dynamically adjustable components. Jayakumari et al., using the RMIT Design Hub in Australia as a case study, compared the daylighting performance of fixed disk curtain walls and dual-axis rotatable a-Si PV modules across different climates. The latter increased the proportion of space within the green illuminance zone by over 20% and enhanced annual illuminance uniformity [76]. Liu et al. integrated an Adaptive Control Model with a DTC model, incorporating seven input variables such as solar altitude and public holiday schedules. Under Guangzhou’s hot-humid climate, this approach enabled real-time dynamic control of PV components, increasing the Useful Daylight Illuminance (UDI) by 71.6%, reducing cooling loads by nearly 50%, and meeting annual lighting and cooling energy demands with onsite generation [59].

In the domain of component parameter optimization and multi-objective strategies, Li et al. employed Rhino–Grasshopper and NSGA-II algorithms to simultaneously optimize PV component length, aspect ratio, and layout density based on UDI500–2000, building energy consumption (EC), and payback period (PB) as objective functions. The optimal solution achieved 42.2% UDI, 12.6% energy reduction, and a 3.87-year payback period [66]. Qiao et al. further indicated that a PV coverage rate of 40% combined with an air cavity thickness of 200 mm can yield optimal performance in lighting, electricity output, and thermal load management [34].

In terms of structural systems and climate adaptability, Kyrrou et al. conducted simulations on seven commercial TPV components in four European cities, recommending the use of TPV in daylight-sensitive zones and opaque PV modules in thermal load zones to achieve functional zoning of façades [77]. Leite Didoné and Wagner demonstrated in tropical cities that south-facing TPV components with low VLT (10–20%) could reduce cooling loads by 30% while maintaining minimum daylighting thresholds of 300 lux [11].

Numerous studies have investigated daylighting performance through both simulation and empirical measurements. Vartiainen reported favorable daylight factor (DF) values for STPV systems on south and southwest-facing façades [67]; Wong et al. recorded indoor summer illuminance of 300–800 lux under an STPV roof in Japanese residences [32]. Fan found that STPV configurations with 30–40% VLT yielded optimal lighting performance in mid-latitude cities [33]; Pan et al. developed a multiparameter modeling framework showing that VLT values between 25 and 35% balance power output and illuminance stability [36]. Jun et al.’s field measurements indicated that high-transmittance PV components enhance daylight but are prone to high-contrast glare, suggesting zoned component configurations [55]. Wheeler et al., using EnergyPlus, simulated dynamic spectral PV glazing and found that it could reduce annual lighting energy consumption by 37% [35]. Kapsis and Athieniti showed that STPV south-facing façades can achieve a daylight autonomy (DA) of 50%, though high PV coverage requires supplemental artificial lighting [54].

In terms of structural and material modulation strategies, Li and Lam, along with Zhang et al., compared the year-round daylighting performance of STPV and Low-E glazing. While STPV systems yielded 18% lower illuminance than conventional glazing, they exhibited superior shading compatibility and solar distribution uniformity [19,53]. Skandalos & Karamanis measured the transmittance of Si-based PV components, finding favorable performance in the 550–800 nm range for balanced brightness [58]. Oliveira Pano and Gonçalves noted that STPV can slow the movement of light spots, thereby stabilizing indoor illuminance [56]. Zhang et al. found that a 30° PV shading panel maintained midday illuminance within the 300–500 lux range, mitigating glare risks [20]. Yun et al.

simulated north-facing PV façades and demonstrated their ability to deliver soft diffuse light in low-sunlight regions, suitable for galleries and reading rooms [27].

In the field of spectral selectivity and dimming systems, Wang et al. proposed a CdTe STPV system that enables spectral separation and maintains transmittance at around 38%, facilitating concurrent daylighting and electricity generation [37]. Subsequent research incorporated low-emissivity coatings to enhance VLT to 32%, while achieving high color rendering and aesthetic integration [57]. W. Wang et al. demonstrated that an adjustable PV canopy improved rear zone illuminance uniformity from 21% to 28% [60]. Su et al. designed a flip-louver PV system that provides summer shading and winter daylighting, exemplifying the coupling of component behavior and daylight control logic [68]. Sun et al. developed a linear relationship model between component morphology parameters and average daylight factor (ADF), offering a performance-informed pathway for early-stage design [69].

Qiu et al. trained an artificial neural network (ANN) model using RADIANCE simulation data to predict annual UDI fluctuations, improving the efficiency of daylight analysis during the design phase [75].

In summary, as BIPV systems continue to evolve to optimize power generation and shading, their influence on indoor daylighting has become a critical aspect of structural design and performance assessment. The adaptability of PV components to lighting environments is determined by a combination of VLT range, construction configuration, climatic conditions, and functional usage. Future research should further explore (1) the dynamic response capacity of dimmable PV components; (2) spectral-selective materials and their light-energy distribution strategies; and (3) façade zoning systems and structural co-design approaches aligned with functional partitioning.

3.5. The Impact of Photovoltaic Façades on Indoor Thermal Comfort

In recent years, BIPV systems have been increasingly applied in high-performance building design due to their dual role in renewable energy supply and building envelope functionality. Researchers have progressively extended their attention beyond energy recovery to the indoor environmental regulation potential of BIPV systems, particularly their impact on thermal comfort. Studies have shown that BIPV systems exhibit notable advantages in both winter heating and summer cooling through mechanisms such as solar shading, radiation blocking, and thermal buffering [22,78,79].

Empirical and simulation-based research has confirmed that composite window/wall systems integrating photovoltaic glazing and phase change materials (PCM) can effectively delay heat loss in winter, achieving indoor temperature increases up to 7.04 °C [22], along with improvements in predicted mean vote (PMV) values and thermal comfort ratio (TCR). In summer, these systems primarily utilize ventilated cavities and PCM heat absorption to realize cooling effects within a range of 1–4 °C [78,80]. Some studies have introduced composite thermal comfort indices, such as the Comprehensive Evaluation Index (CEI) or TCR, to evaluate the integrated regulatory capacity of PV façades on indoor thermal environments from multiple dimensions [22,81].

Across the thermal-comfort-tagged studies in our database, the comfort impact of PV façades is most consistently reported as a season- and mode-dependent indoor temperature moderation, with repeatable magnitudes once the operating regime is aligned. In heating-dominant operation, coupled PV–air–PCM assemblies can deliver multi-degree indoor benefits, including reported indoor temperature differentials reaching ~7.04 °C in winter-mode operation under specific configurations [22]. In cooling operation, the comfort effect is typically smaller but still measurable, most often in the ~1–4 °C class, while some seasonal datasets report a wider negative indoor temperature difference band (e.g.,

~ -4.26 °C to -1.26 °C) under ventilation/heat-absorption modes [22]. At the system scale, comfort outcomes frequently appear as load-shaping rather than only temperature change: in subtropical demand-response settings, PV-induced shading can strengthen PCM cycling and reduce cooling demand from ~ 73.5 to 67.9 kWh/m² (about 7.6%) while shifting peaks [79].

Methodologically, the dominant evidence pathway is a combination of seasonal field testing with explicit operation modes (heating/cooling/transition strategies), followed by co-simulation or calibrated annual assessment (e.g., TRNSYS/EnergyPlus-class workflows) and, increasingly, data-driven surrogates (ANN) to generalize performance across climates and design variables [22,79,81]. Climate dependence is therefore not a contextual note: results repeatedly indicate that PCM melting/transition targets and ventilation strategies must be tuned to local solar availability and seasonal priorities, otherwise the same façade can shift from beneficial buffering to added cooling burden in warm climates [62,79]. Finally, scalability hinges on (i) reporting boundary-consistent assumptions (solar/wind exposure, operational mode definitions), (ii) buildability of composite layers (integration with HVAC/controls, moisture/fire/waterproofing constraints), and (iii) whether studies provide transferable comfort-relevant envelopes rather than isolated “best-case” points [10,82].

(1) Application of Composite Systems in Seasonal Thermal Comfort Regulation

A majority of studies have employed composite configurations—combining PV modules, PCM, and air layers—to enhance thermal buffering capabilities and optimize indoor thermal environments across seasons. For example, He developed a PV/PCM ventilated wall system using PCM with a melting point of 298 K, which led to an earlier heating activation in winter, a heating intensity increase of 1.59 K, and a minor reduction in peak summer temperatures. The study also introduced the CEI to integrate assessments of thermal comfort and air purification performance [81]. Through seasonal field testing, Ke validated the performance of a multi-layer CdTe PV ventilated window (PCMVMW) system, reporting a maximum indoor temperature increase of 7.04 °C and a 107% rise in TCR during the heating season, along with a peak cooling of 4.26 °C during the cooling season [22]. Zhou established a BIPV + PCM wall + smart HVAC collaborative control model on the TRNSYS platform, indicating that BIPV modules could trigger the heat storage-release cycle of PCM through shading effects, thereby reducing daily temperature fluctuations [79].

(2) Dynamic Shading Control for Thermal Comfort Modulation

Dynamic photovoltaic shading systems (PVSD) have been widely studied for improving summer thermal comfort. Oh employed a genetic algorithm to optimize four PV shading geometries, finding that large-panel synchronous control outperformed independently adjusted small panels, with a daytime indoor temperature reduction of 1.5 °C [80]. Martinopoulos combining EnergyPlus simulations and field measurements, investigated a building with adjustable PV shading in the Mediterranean climate and found that the PMV values ranged between 0.4 and 0.8. This system also reduced cooling loads by approximately 70% compared to conventional fixed shading [82].

(3) Influence of PV Construction Typologies on Indoor Temperature and Comfort

Construction typologies (e.g., BAPV vs. BIPV) have been shown to significantly affect indoor thermal responses and cooling demand. In a tropical climate study, Wei reported that BIPV roof systems exhibited lower thermal resistance, leading to daytime indoor temperature increases and a 13% rise in cooling load compared to BAPV configurations [62]. Tang’s field measurements demonstrated that PV-PCM windows in summer effectively reduced peak indoor temperatures by up to 10.94 °C and delayed temperature rise, enhancing thermal inertia [78]. Abdelsamie developed a thermal-electrical-optical performance

model for multifunctional fluid-window PV systems (MFW), which achieved a U-value as low as $2.1 \text{ W/m}^2\cdot\text{K}$ and provided bidirectional thermal regulation benefits—insulation in summer and heating in winter [10].

3.6. The Impact of Photovoltaic Façades on Visual Comfort

As photovoltaic (PV) components become increasingly integrated into building façades, their potential to disturb indoor visual environments—despite contributing to natural lighting—has drawn growing attention. Researchers have assessed visual comfort across dimensions such as illuminance uniformity, glare control, color rendering, and light quality distribution, evaluating the performance of PV components under different configurations, materials, and lighting conditions. A performance assessment system has gradually taken shape based on indicators such as Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), spatial Glare Autonomy (sGA), and Daylight Glare Probability (DGP), and has been extended by incorporating spectral response and human perception to broaden the conceptual scope of visual comfort.

Across the visual-comfort-tagged studies, evidence is increasingly framed as annualized comfort envelopes rather than point-in-time illuminance checks. When indicators are harmonized (DA/UDI/sDA for availability; sGA/DGP/DGI for glare), several bounded “typical ranges” recur: cold-region façade work repeatedly identifies a mid-range transmittance window as a pragmatic comfort–energy compromise, with reported optimal transmittance around ~50–60%, while pushing above ~60% tends to increase glare risk even if daylight availability rises [64]. For atrium/skylight contexts, recommended PV/transmittance envelopes remain city-sensitive but bounded; across multiple Chinese cities, ARPM ~30–70% is repeatedly suggested to avoid either dim interiors or high summer glare [33].

Methodologically, the dominant pathway converges on Radiance-class daylight simulation coupled to annual energy evaluation, often embedded in optimization-based selection. Office-building optimization studies show that “best” comfort is not achieved by maximizing VT alone; balanced solutions report sDA ~78.99% and sGA ~60.89%, with an ~15.63% increase in annual mean illuminance after retrofit, implying that comfort is achieved through joint control of sufficiency and glare [83]. Geometry modulation adds another transferable pattern: curved PV windows can improve annual daylight sufficiency (sUDI + ~3.94–5.94%) with only small glare-side changes (sGA – ~1% to –2.6%) and may even increase generation in high-latitude contexts, implying a bounded “optimal curvature” region rather than monotonic improvement [73].

Climate dependence shapes which mechanism dominates: cooling-dominated, high-solar contexts favor designs that stabilize distribution and reduce cooling penalties (coverage/tilt and shading logic), whereas low-sun/high-latitude contexts prioritize maintaining sufficiency and rear-zone performance. Scalability therefore hinges on whether studies report transferable design envelopes (transmittance/coverage/WWR/geometry) explicitly linked to annual glare constraints and implementable glazing packages, rather than isolated “good illuminance” snapshots.

In terms of daylight availability and illuminance balance, multiple studies have shown that semitransparent PV glazing systems have the potential to enhance natural light transmission, especially when the visible light transmittance (T_{vis}) is within the range of 0.3–0.5, where daylight distribution tends to be more balanced [73,83–85]. Simulation analysis by Fan demonstrated that STPV components with a visible light transmittance (VLT) of 30–40% can effectively balance the UDI range and glare event frequency, making them suitable for high-transparency skylight and roof applications [33]. Field measurements by Cheng et al. indicated that STPV façades in cold regions can maintain DA above 60% while keeping peak

illuminance below 1000 lx, thus avoiding discomfort caused by strong direct sunlight [64]. Jun et al. conducted quantitative analysis of the illuminance distribution of PV glazing with varying transmittance in office scenarios and found that medium-transmittance components yielded the best uniformity [55]. Simulation by Li and Lam showed that STPV systems installed on south- and southeast-facing façades outperform conventional glazing in reducing sunlight interference [53].

Glare control is a key component in the evaluation of PV façades. DGP (Daylight Glare Probability) and sGA (spatial Glare Autonomy) have become the primary indicators. Studies have shown that increasing PV coverage or integrating it into shading structures can effectively control glare [25,86,87]. Zhao & Gou introduced the annual sGA metric, expanding simulation from specific points to the entire building scale, offering a global approach to glare management [83]. Jiang et al. and Oh et al. emphasized the adaptive potential of dynamic shading systems in responding to seasonal sunlight variations, effectively enhancing glare adaptability [49,72].

In terms of light quality and color rendering, Wang et al. measured CSTPV systems and found that the transmitted light had a CRI above 80 and a VLT around 30%, achieving both shading and high-quality visual perception [57]. The CdTe PV glazing system proposed by C. Wang et al. showed even greater advantages, with a CRI as high as 95 and a correlated color temperature around 5000 K, meeting the visual needs of both work and living spaces [47]. Field measurements by Oliveira Pano and Gonçalves demonstrated that STPV systems can reduce the speed of light patch movement, improving spatial daylight stability [56]. The PV-blind system proposed by Luo et al. achieves dual optimization of daylight and view through blade angle adjustment. At a tilt angle of 25–30°, it maintains illuminance at 300 lx and illuminance uniformity above 0.5, making it suitable for visually sensitive zones [43].

Additionally, Peng et al. and Yao et al. examined the effects of different patterned layouts and glazing coverage on the balance between lighting and visual performance, noting that appropriately designed patterns can enhance the quality of light and shadow and improve brightness distribution. Curved PV windows and vacuum-insulated double-skin PV components have also been shown to possess light-guiding capabilities, directing light into the deeper parts of the interior space and reducing the demand for artificial lighting [74,88].

In summary, while PV façade components contribute to enhanced natural lighting, they also introduce more stringent requirements for visual comfort. By adjusting component transmittance, controlling solar intensity, optimizing spectral response, and refining structural configuration, PV systems can effectively reduce glare frequency, improve illuminance uniformity, and enhance color rendering performance. Future studies should further integrate parameters related to visual psychology, dynamic user response, and scene-specific functional adaptation strategies to realize indoor light environments that are “visible, viewable, and visually comfortable.”

3.7. The Impact of Photovoltaic Façades on Air Purification Capacity

As BIPV systems evolve toward multifunctional integration, increasing attention has been directed to their potential in improving indoor and outdoor air quality. This emerging application primarily leverages mechanisms such as photocatalytic reactions and thermally driven airflow to facilitate pollutant decomposition and particulate matter removal. Current research has focused on CdTe-based semitransparent PV components, dual-layer ventilated façades, and the construction of multi-physical coupling pathways involving light, heat, and air, with an emphasis on the synergy between air treatment performance and energy operations.

Across the air-purification-tagged studies, purification performance is consistently constrained by irradiance–temperature–airflow regimes, and optimal operation is typically a trade-off between reaction kinetics (UV activation/residence time) and ventilation-driven delivery. Reported performance spans both annualized and rate-based indicators: a spectrum-splitting double-skin concept reports treated air delivery on the order of $\sim 7014 \text{ m}^3/\text{m}^2$ alongside electricity generation ($\sim 46.3 \text{ kWh}/\text{m}^2$) and substantial annual thermal saving ($\sim 479 \text{ kWh}/\text{m}^2$) [37], while catalytic PV/T window studies report CADR $\sim 3.43 \text{ m}^3/\text{h}$, with purification effectiveness sensitive to solar radiation and temperature [38].

Methodologically, the dominant pathway combines controlled experiments (pollutant decay, UV/solar measurement, airflow and temperature instrumentation) with multi-physics modeling that couples radiation–convection and reaction kinetics (e.g., Langmuir–Hinshelwood-type formulations). This coupling helps explain a recurrent result: increasing airflow can improve electrical/thermal performance yet weaken purification by reducing residence time, so most studies identify geometry/operation “optima” rather than monotonic improvement [38,41,42]. Consistent with this, louver angle is reported to shift the dominant objective, with $\sim 85^\circ$ favorable for purification (CADR) while $\sim 30\text{--}45^\circ$ may maximize total energy efficiency, and an indoor-environment optimum around $\sim 290 \text{ K}$ is reported for overall performance in at least one multifunctional configuration [41].

Climate dependence is therefore decisive: performance and net-building implications vary by season and solar availability. A comprehensive seasonal assessment reports that integrated shading/solar-gain changes can increase net energy consumption in winter and summer by $\sim 6.59\%$ and $\sim 6.26\%$, despite gains in integrated energy and purification functions [38]. Scalability hinges on transfer-ready operating envelopes (flow/angle/UV transmittance and maintenance assumptions), catalyst durability/fouling, and standardized IAQ reporting (CADR/treated volume per area) that can be compared across sites.

One representative approach involves a CdTe double-skin photovoltaic façade system proposed by Wang et al., which utilizes a spectral separation and photocatalytic synergy mechanism. In this system, the near-infrared portion of solar radiation is harnessed for electricity generation and preheating ventilation air, while the ultraviolet and visible light spectra are reserved to activate an embedded photocatalytic membrane, enabling simultaneous power generation and air purification. Experimental results indicated that under clear-sky conditions, the system achieved a PM_{2.5} removal rate of up to 84.5%. The catalytic efficiency was found to be highly correlated with incident irradiance, and the spectrally selective glazing design contributed to maintaining favorable reaction temperatures and operational continuity [37].

Building on this foundation, Zhang et al. integrated a thermal catalysis module to develop a composite PV/T dual-ventilated façade system that realizes the tri-functional integration of air purification, heating, and power generation. Experimental measurements showed that the system achieved a purification volume of $0.134 \text{ m}^3/\text{h}/\text{m}^2$ under ventilation mode. The purification efficiency was influenced by air velocity, distribution of catalytic coatings, and wall surface temperatures. The system also exhibited a passive heating benefit in winter, with an average temperature increase of 4.5°C , demonstrating the feasibility of a PV façade path driven primarily by air quality management [71].

Expanding this multifunctional concept, Chen et al. proposed a naturally ventilated solar window system integrating photovoltaic thermal conversion and air purification. The system employs rotatable PV louvers to absorb solar radiation and drive air circulation through natural ventilation. A TiO₂ photocatalytic coating is applied on the inner surface of the outer glazing, which is activated by ultraviolet light to degrade formaldehyde pollutants. This “PV–photocatalysis–thermal energy” coupling system demonstrated its effectiveness under a 85° louver angle, yielding optimal clean air delivery rate (CADR) and

formaldehyde removal efficiency. Annual clean air production reached 28,500 m³, reflecting a significant contribution to indoor air quality improvement. A multifactorial analysis of airflow rate, UV transmittance, and reaction time further elucidated the dynamic behavior of the purification process [41].

In summary, air purification is emerging as a novel functional dimension in photovoltaic façade systems. Through technologies such as photocatalysis, thermal decomposition, and ventilation-induced flow pathways, initial integration has been achieved. Current studies focus on the co-design of PV components and catalytic materials, the adaptive dynamics of double-skin ventilated structures, and the multidimensional coupling of heat, electricity, and air. Future research may further expand the range of target pollutants, enhance the long-term stability of reaction systems, and explore the integration potential of air quality management strategies at the building scale.

3.8. Policy Support for the Scalability of Building-Integrated Photovoltaics

The large-scale deployment of BIPV systems relies heavily on systematic policy support. Countries promote and safeguard BIPV through multi-level measures such as legislation, standard formulation, financial incentives, and technology promotion.

In Asia, particularly in China, under the guidance of the “dual carbon” strategic targets, BIPV technologies have been gradually incorporated into regulatory indicator systems such as the Green Building Evaluation Standard and the Building Energy Consumption Quota Standard [47,62]. The integration level of power-generating components and the coverage rate of renewable energy directly determine a building’s energy performance rating and the level of financial subsidies [38]. Semi-transparent photovoltaic windows [74,83], façade systems with integrated ventilation ducts [37,71], and phase change material (PCM) passive thermal regulation technologies [50,78] have been gradually incorporated into regional building energy efficiency standards and technical regulations for near-zero energy pilot projects. In addition, for special regions such as cold plateaus and offshore platforms, policies have been introduced to encourage the adoption of building self-generation systems to ensure energy independence and sustainability [25,31]. South Korea, through the Green Building Certification System (G-SEED) and the “Climate Adaptive Buildings” initiative, focuses on supporting adjustable BIPV technologies such as thermochromic and dynamic shading systems [74]. Singapore highlights the application advantages of BIPV systems in solar control and heat gain management in its BCA Green Mark scheme [61].

In Europe, the policy foundation for BIPV promotion primarily revolves around the EU’s near-zero energy building (nZEB) roadmap and the Energy Performance of Buildings Directive (EPBD), emphasizing the integration of technical standardization with market mechanisms. Southern European countries place particular emphasis on the high compatibility of shading-type BIPV systems with green building certification systems such as LEED and BREEAM [77,86]. The Swiss Minergie standard and Portugal’s Solar XXI project have, respectively, promoted the widespread application of semi-transparent PV curtain walls and BIPV systems combined with natural ventilation [56,70]. Greece and other Mediterranean coastal countries support the use of BIPV in shading and passive cooling through financial rebates and feed-in tariff policies [26,29]. Central and Eastern European countries such as Poland encourage demonstration BIPV projects in small- and medium-sized public buildings through the EU Green Fund and renewable energy purchase policies, thereby enhancing public acceptance [48].

In North America, policies focus more on certification systems and lifecycle performance management. Canada’s net zero energy building (ZEB) program and tax incentive policies promote the adoption of STPV systems in commercial buildings [54]. In the United States, the LEED system and ASHRAE standards have facilitated the application of STPV

systems in façade components [33,64]. In addition, California's Title 24 legislation explicitly requires new high-performance buildings to adopt active power-generating components, promoting the wide application of technologies such as photovoltaic glass windows [35]. Australia's BASIX system similarly emphasizes increasing the proportion of building energy self-sufficiency, supporting the adoption of photovoltaic glass windows and double-skin façades [21].

In South America, although countries such as Brazil have yet to establish a comprehensive policy support system, abundant solar resources and localized incentive policies have preliminarily promoted BIPV market development [11].

Overall, BIPV policies in different regions exhibit diversified, localized, and integrated characteristics. A policy ecosystem combining regulatory standards, incentive mechanisms, and evaluation systems effectively enhances the market acceptance and large-scale deployment potential of BIPV technologies. In the future, more precise policies and multi-system coordination will further enhance the institutional resilience and technological expansion capacity of BIPV.

3.9. Economic Feasibility for the Scalability of Building-Integrated Photovoltaics

Economic feasibility is a core evaluation dimension for achieving the large-scale deployment of BIPV systems. Variations in climate, building function, and energy structure across regions lead to significant geographical differences in investment payback periods and operational returns.

In China and East Asia, the economic benefits of BIPV are primarily reflected in energy efficiency improvements and operational cost reductions. For example, a CdTe photovoltaic double-skin ventilated façade with heat recovery functionality in northern office buildings can achieve annual energy savings exceeding 20%, with heat recovery contributing over 50% of the total, resulting in a payback period of 8–9 years [71]. Spectral-splitting designs further enhance long-term operational benefits by improving photovoltaic efficiency and reducing cooling loads [37]. In tropical and subtropical regions, the shading and cooling effects of BIPV systems deliver substantial energy-saving returns, such as the STPV system in Singapore that significantly reduces air-conditioning electricity consumption [61], and intelligent façade systems in Korea with lifecycle payback periods of 6.8–9.3 years [80].

European research places greater emphasis on life-cycle cost (LCC) and net present value (NPV) models, underscoring long-term operational economics. In Switzerland, STPV systems have achieved positive returns over a 25-year period through energy savings and subsidies [70]. In the Mediterranean region, hybrid PV/T systems demonstrate rapid payback potential in areas with diverse energy loads, supported by EU energy efficiency funds and credit mechanisms [26]. Portugal's Solar XXI project, combining natural ventilation with BIPV, shows remarkable energy-saving performance [56].

In North America, studies focus on the economics of BIPV in commercial and educational buildings, highlighting the economic spillover effects of LEED certification, tax incentives, and green financing mechanisms. For instance, STPV systems in Canada reduce cooling loads and delay HVAC activation [54], while STPV skylight systems in U.S. educational buildings demonstrate strong economic performance [33].

In high-solar-radiation, high-energy-demand regions, shading-type BIPV systems also exhibit economic advantages, such as Mediterranean designs where annual PV generation meets 40% of lighting demand, with payback periods of 6–7 years [86]. Geometric optimization further improves output efficiency and return on investment [59].

Although multifunctional hybrid systems entail higher initial costs, they offer comprehensive energy-saving benefits. CdTe multilayer ventilated windows integrating heat recovery with photovoltaic generation have a payback period of around 7.2 years, which

can be reduced to 5.8 years with government subsidies [22]. AI-optimized operations can also enhance the economic performance of advanced intelligent BIPV systems [81].

In Central and Eastern Europe, project scale management and fiscal policies improve economic feasibility; for example, a kindergarten project in Poland achieved an 8-year payback period through green fund support [48]. In developing countries lacking strong incentive mechanisms, such as Brazil, semi-transparent PV window systems leveraging natural daylight savings can still achieve payback within approximately 10 years [11].

Current economic evaluations are evolving from a single payback period focus toward multidimensional life-cycle analyses, incorporating energy return on investment (EROI), maintenance costs, willingness to pay, and the added value of green building certification [12,77]. Overall, the economic viability of BIPV systems depends on factors such as building function, solar radiation resources, system configuration, and policy environment. Achieving multi-objective optimization requires an integrated approach combining design, energy efficiency simulation, and financial analysis, thereby establishing the critical economic foundation for large-scale deployment.

4. Discussion

Building on the evidence mapping in Section 3, this Discussion advances an interpretive argument: the persistent adoption gap of PV façades is driven less by the absence of promising performance results than by a translation failure between disciplinary evidence and building delivery requirements. In the literature, performance findings are often produced within disciplinary silos and reported as context-specific optimizations, whereas scalable adoption requires those findings to be converted into repeatable project routines—namely, decision rules and deliverable packages that align building design, envelope detailing, electrical integration, compliance documentation, procurement, and operation. Accordingly, this review moves beyond single-objective summaries and synthesizes PV-façade research as an evidence system: (i) mapping disciplinary participation and collaboration patterns to identify where building-design input is weak, (ii) reading evidence pathways and validation depth (simulation versus measurement/monitoring) to interpret reliability and transferability, and (iii) translating coupled performance claims into deployment-facing implications for early-stage design, procurement, and standardization. This framing motivates the three adoption frictions discussed in Section 4.1 and the integration agenda distilled in Sections 4.1 and 4.2.

4.1. Key Challenges in the Adoption of BIPV Technology

In the current research and application of BIPV technology, although certain technological advancements have been made, numerous challenges still persist. To thoroughly investigate the bottlenecks in the promotion and implementation of BIPV technology, this paper will analyze three key deficiencies. First, the lack of an architectural perspective, where the involvement of the architecture field has been relatively limited, resulting in insufficient integration of BIPV systems with building design and form. Second, the disparity in methodologies and challenges in practical applications, primarily manifested in the over-reliance on simulation models while lacking sufficient empirical data verification, which creates a significant gap between theoretical results and real-world applications. Lastly, the conflicts in economic calculations and the difficulty of industry coordination, where BIPV projects face complex conflicts in economic evaluations, including electricity price calculations, carbon sequestration estimates, and the coordination of industry interests, which pose barriers to the commercialization and widespread adoption of these projects.

The following sections will provide a detailed analysis of these issues, beginning with the absence of an architectural perspective and its impact on the integration of BIPV

technology, followed by a discussion on the gap between current research methodologies and practical implementation, and finally addressing the challenges and potential solutions in economic evaluation and industry collaboration.

4.1.1. Absence of Architectural Perspectives

As illustrated in Figure 10, researchers in the BIPV field are predominantly concentrated in technical disciplines such as energy engineering, building physics, and building services (e.g., Ji J. and Peng J.), while participation from architecture and urban planning remains relatively limited. This pattern highlights the technology-driven nature of current BIPV research. In particular, researchers in energy-related fields exhibit strong interconnections, forming dense academic communities that lead the optimization of BIPV system performance. In contrast, architectural scholars appear more dispersed within the co-authorship network and show weaker ties with technical disciplines, suggesting a comparatively marginal role of architecture in the current BIPV research landscape.

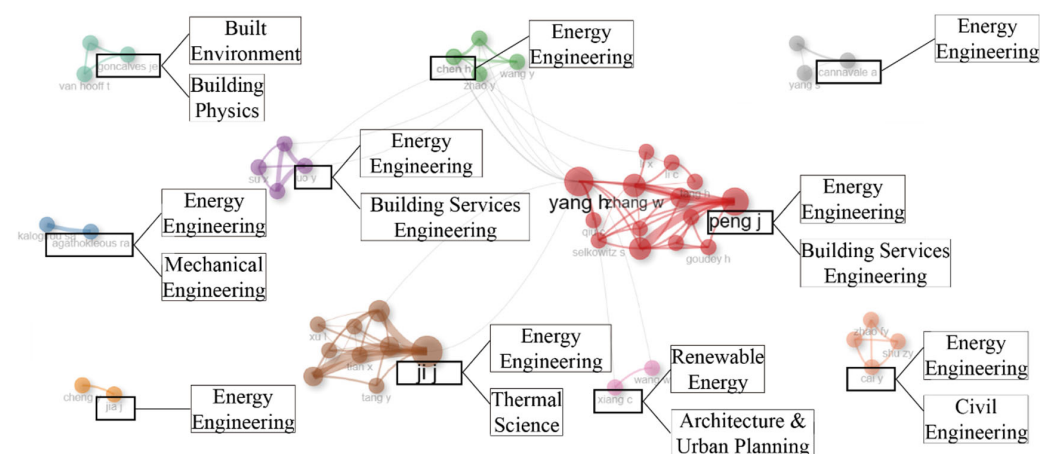


Figure 10. Disciplinary Distribution and Co-authorship Network.

The limited involvement of architectural expertise—especially in aspects such as building aesthetics, spatial programming, and construction simplification—has contributed to the insufficient integration of PV systems into architectural design. Although BIPV is by definition an “integrated” technology, the absence of architectural perspectives presents significant challenges for the deep integration of PV systems with building form, function, and performance, ultimately affecting the applicability of BIPV in actual construction projects.

Further analysis of the disciplinary network reveals that scholars from energy engineering, building physics, and building services maintain strong collaborative ties, reinforcing their dominant role in BIPV research. In comparison, connections among architectural researchers remain sparse, exacerbating the difficulty of embedding BIPV considerations within architectural design workflows. The diagram also suggests some degree of overlap between energy engineering and building services, indicating potential interdisciplinary collaboration in technical domains; however, cross-disciplinary engagement between architecture and other fields remains weak, further limiting the integration of BIPV technologies into design practice.

Research in energy engineering primarily focuses on optimizing the performance of PV systems, particularly in relation to thermal effects, energy efficiency, and integration with building electrical infrastructure. While these efforts contribute to improving overall system efficiency, they often overlook practical architectural requirements such as electrical layout planning, inverter integration, and spatial deployment of PV modules. Building physics research, meanwhile, emphasizes the thermal interactions between PV systems

and building environments, aiming to enhance thermal performance. Nonetheless, the functional implications for thermal comfort, temperature regulation, and natural lighting are frequently underexplored. Contributions from thermal sciences and renewable energy research have also advanced the technological development of BIPV, yet these efforts have not adequately facilitated the incorporation of architectural perspectives. As a result, the lack of coordination between architectural design and photovoltaic systems continues to limit the full-scale implementation and practical adoption of BIPV technologies.

4.1.2. Methodological Differences and Challenges in Real-World Applications

This statistical analysis is based on the standardized breakdown and classification of the “research method” field from the 82 BIPV-related publications included in the study. If a paper involves multiple research approaches (e.g., both simulation and experimental measurement), each approach is counted in its corresponding category to avoid underestimating the proportional distribution of methods due to mutually exclusive classification.

Simulation-based methods have taken a leading role in the study of BIPV. However, this methodological emphasis may introduce noticeable gaps between predicted performance and real-world outcomes. As shown in Figure 11, an analysis of 82 representative BIPV studies reveals that 80.5% employ simulation or modeling techniques, while only 36.6% include empirical validation or in situ monitoring. This classification was based on standardized parsing of each study’s methodological description, allowing for multiple method types to be recorded per paper.

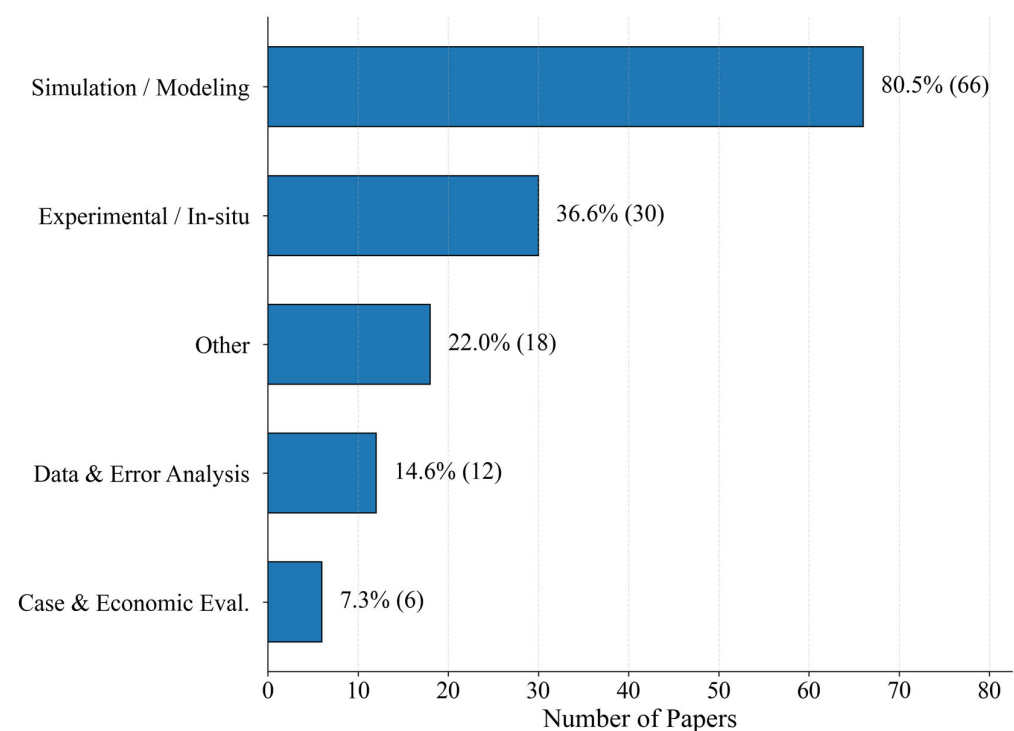


Figure 11. Distribution of Research Methods.

This methodological imbalance could be one of the underlying factors contributing to the challenges in scaling up BIPV technologies. While simulations offer a valuable framework for design exploration and theoretical optimization, their assumptions are often based on idealized environmental and operational conditions. As a result, the simulated outcomes may not fully capture the performance of BIPV systems when deployed in complex and dynamic building contexts—particularly where a high degree of architectural integration is involved.

One area of consideration is that simulations may not comprehensively reflect real-world variability, such as fluctuating climatic conditions or the diversity of building operational patterns. Moreover, physical installation details and occupant behaviors, which can significantly affect system performance, are often simplified or generalized in modeling processes. These differences between assumed and actual conditions can influence the reliability and generalizability of simulation outcomes over extended periods or in different seasonal contexts.

In addition, many simulation models are constructed based on ideal design configurations, which may not align with practical constraints related to architectural layouts, surrounding environmental features, or local microclimates. These unmodeled factors can influence energy performance in ways that are not easily captured through simulation alone.

Another aspect that tends to be simplified in current simulation-based studies is the long-term performance of BIPV systems. In practical applications, issues such as material degradation, surface soiling, and system aging may affect energy efficiency over time. These factors are rarely incorporated into predictive models, despite their relevance to the sustained operation and maintenance of BIPV technologies.

Therefore, while simulation remains a fundamental tool in BIPV research, its application would benefit from closer integration with empirical data and long-term field observations. Strengthening this connection can improve the representativeness and accuracy of performance assessments—particularly when considering real-world influences such as environmental variability, aging effects, and user interaction—thereby supporting more robust evaluations of BIPV systems in practical settings.

For the experimental studies, we analyzed 30 investigations containing measured data. By examining different monitoring durations (short-term vs. long-term) and measurement approaches (system-level monitoring vs. component-level testing), we explored how these factors influence the stability, applicability, and depth of the research conclusions.

Among the studies included in the analysis, 21 were system-level experimental investigations, of which 15 employed short-term monitoring (see Table 3). These studies typically focused on measurements conducted over 1–3 days under typical clear-sky conditions, such as those by Wang et al. [47], Xu et al. [31], Kaiser et al. [15], and Tang et al. [78]. Such research primarily reveals the instantaneous response characteristics of BIPV systems under representative operating conditions, including thermal lag effects and the enhancement of electrical efficiency through air-cooling. However, these studies often lack data for assessing annual-scale thermal comfort, total energy savings, and payback period. For example, the study by Tang et al. [78] demonstrated that the PV-PCM window could achieve an instantaneous cooling effect of approximately 2.4–2.6 °C under typical clear-day conditions and delay the occurrence of the indoor temperature peak by about 1–1.5 h; however, whether this performance can be maintained across seasons still requires verification through annual simulations.

In contrast, four system-level experimental studies exhibited long-term monitoring characteristics, 1 of which is a multi-season observation [22] and another three involving monthly or quarterly on-site measurements of actual buildings [16,32,56]. These studies clearly revealed the seasonal trends in BIPV system performance. For example, the long-term monitoring conducted by Ke et al. [22] showed that the CdTe multilayer PV ventilated window system achieved summer power generation efficiency and air purification efficiency that were 1.9 times and 2.4 times higher than those in winter, respectively, indicating the substantial impact of seasonal variations on system performance. Long-term studies not only provide support for annual energy consumption calculations, CO₂ reduction assess-

ments, and optimized operational strategies but also offer higher extrapolation reliability and greater value for policy recommendations.

Table 3. Measurement Approaches of BIPV Studies.

Reference	Measurement Type	Monitoring Duration	Research Object	Actual Measurement Period
Wang et al. [37]	System-level	Short-term + Annual simulation	STPV + PCM ventilated window	3 days measurement, annual simulation
Ke et al. [22]	System-level	Long-term	CdTe multilayer PV ventilated window	3 seasons measurement, annual simulation
Jun et al. [55]	System-level	Short-term + Annual simulation	Solar chimney + PCM system	Short-term: thermal response validation; annual simulation: energy saving and CO ₂ reduction prediction
Koyunbaba et al. [12]	System-level	Short-term (within long-term background)	BIPV-Trombe system	4-month long-term operation, 4-day short-term analysis
Peng et al. [87]	System-level	Short-term	PV-IGU window	Typical clear day (several hours)
Wang et al. [47]	System-level	Short-term	STPV double-skin ventilated window	Several days typical clear-day measurement
Zhang et al. [71]	System-level	Short-term + Annual simulation	Thermo-catalytic + STPV double-skin façade	Short-term: thermal and power verification; annual simulation: regional adaptability analysis
Cheng et al. [64]	System-level	Short-term + Annual simulation	STPV	3 days measurement, annual simulation
Xu et al. [31]	System-level	Short-term	STPV window	Typical clear-day, several days measurement
Shabunko et al. [23]	System-level	Short-term	BIPV glass	72 h + multi-day validation
Tang et al. [78]	System-level	Short-term	PV-PCM window	Several days measurement (hot summer/warm winter zone)
Kaiser et al. [15]	System-level	Short-term	Air-cooled BIPV module	Several weeks measurement, hourly sampling
Tonui & Tripanagnos-topoulos [29]	System-level	Short-term	Naturally ventilated PVT collector	Several weeks measurement, hourly sampling
Wang et al. [25]	System-level	Short-term	BIPVT hybrid façade (STPV + thermal recovery)	Several typical winter days measurement

Table 3. Cont.

Reference	Measurement Type	Monitoring Duration	Research Object	Actual Measurement Period
Wong et al. [32]	System-level	Long-term	STPV system	Several months measurement, daily/hourly sampling
Oliveira Panao & Gonçalves [56]	System-level	Long-term	Solar XXI building	3 years data, daily sampling
Agathokleous & Kalogirou [16]	System-level	Long-term	Naturally ventilated BIPV system	2 months continuous measurement (10 s interval)
Wang et al. [60]	System-level	Short-term + Annual simulation	Dynamic PV light-guiding panel	Several hours measurement, time-interval sampling
Peng et al. [88]	System-level	Short-term + Annual simulation	c-Si semi-transparent PV window	Typical clear-day (08:00–18:00)
Wang et al. [57]	System-level	Short-term + Annual simulation	Semi-transparent PV window + passive radiative cooling film	Several days typical clear-day measurement, annual simulation
Chen et al. [42]	System-level	Short-term	Photocatalytic double-skin ventilated window	1–2 days measurement
Pan et al. [36]	Component-level	Short-term + Annual simulation	PV insulating glass unit	Several hours measurement, annual simulation
Zhang et al. [19]	Component-level	Static parameters + Annual simulation	STPV module	Electrical efficiency and transmittance test for EnergyPlus simulation
Cannavale et al. [84]	Component-level	Static parameters + Annual simulation	Perovskite STPV module	Optical and electrical performance test for EnergyPlus simulation
Martinopoulos et al. [82]	Component-level	Static parameters + Annual simulation	BAPV and BIPV modules	Performance test for annual energy consumption simulation
Qiu et al. [75]	Component-level	Static parameters + Annual simulation	VPVW module	Electrical performance test, ANN + EnergyPlus simulation
Peng et al. [51]	Component-level	Short-term + Annual simulation	PV + PCM combination	Short-term measurement, annual simulation analysis
Karthick et al. [14]	Component-level	Short-term	BIPV + PCM module	Laboratory simulation, short-term sampling
Skandalos & Karamanis [58]	Component-level	Long-term	STPV module	30-day measurement, thermal and electrical performance analysis
Olivieri et al. [70]	Component-level	Static parameters + Annual simulation	STPV module	Transmittance and electrical efficiency test, annual simulation for energy performance

In addition, this study found that short-term studies, if not combined with annual simulations or cross-season comparisons, may overestimate system benefits or overlook potential disadvantages under different seasonal conditions. For instance, Peng et al. [87] found that the PV-IGU glazing system exhibited a favorable cooling effect in typical summer measurements, but they did not assess its thermal insulation performance in low-irradiance winter conditions, leaving the conclusions on winter performance without data support. By contrast, Jun et al. [55] verified the thermal catalytic mechanism through short-term experiments and employed EnergyPlus to conduct annual simulations, concluding that the system could achieve an annual energy saving of 18.42% and a CO₂ reduction of 17.43 kg/m²—significantly enhancing the comprehensiveness and applicability of the study's conclusions.

From the perspective of measurement methods, six of the included studies were component-level experimental studies combined with annual simulations. These studies typically tested only parameters of PV modules, such as transmittance, electrical efficiency, or thermal resistance (e.g., Zhang et al. [19]; Cannavale et al. [84]; Peng et al. [51]), for use as model inputs. While these studies are useful for comparing the impact of different material parameters on annual energy consumption, their lack of testing in real buildings or system prototypes results in significant gaps in thermal comfort evaluation, airflow coupling, and dynamic energy efficiency response—making it difficult to reveal actual system performance under complex boundary conditions.

In summary, experimental studies indicate that

1. Short-term studies are more suitable for revealing the performance mechanisms and component behavior of BIPV systems.
2. Long-term monitoring can provide more realistic performance data under actual environmental conditions, capturing the influence of climate and human factors on BIPV. The conclusions are closer to real-world performance but contain uncontrollable variables, making them unsuitable for evaluating the ideal operating state of a BIPV system.
3. System-level monitoring is more capable than component-level testing in capturing the multi-dimensional coupling between building, system, and environment, making it a key pathway for translating BIPV research outcomes into practical application assessments.

This study further supports the adoption of a combined approach of cross-season system-level monitoring and annual simulation to enhance the credibility and practical applicability of BIPV research.

4.1.3. Economic Conflicts in Cost Calculation and Industry Coordination Issues

A core issue faced by the promotion of BIPV technology is the conflicts in economic calculations, particularly the contradictions between carbon sequestration calculations, carbon trading, and electricity price calculations. First, BIPV projects have a long payback period, and traditional returns primarily depend on electricity prices, i.e., recovering costs through self-generated electricity and electricity sales. However, the potential of the carbon sequestration market has not been fully reflected in the cost calculations of BIPV projects, and the benefits of carbon trading have not been widely implemented globally, failing to provide sufficient economic incentives for BIPV projects. This creates a conflict with the return model based on electricity prices, which heavily relies on price stability, resulting in an excessively long payback period. Additionally, the differences between carbon sequestration calculation methods and electricity price calculation methods pose challenges for investors and policymakers in evaluating the economic viability of BIPV projects, further complicating the promotion of BIPV technology.

Furthermore, the implementation of BIPV projects faces coordination difficulties within the industry. In both the building and energy sectors, the leading forces are not unified, and there is a lack of effective collaboration mechanisms. The building sector is primarily led by contractors and designers, while the energy sector is dominated by power companies. The differing goals and responsibilities of the two sectors lead to coordination challenges in project execution. This is especially true when it comes to emerging environmental functions such as carbon sequestration and carbon trading, where the interests and responsibilities of the building and energy sectors are difficult to align, further increasing the complexity of promoting BIPV technology.

Therefore, to advance the commercialization of BIPV technology, it is essential to resolve the conflicts between electricity prices, carbon sequestration calculations, and carbon trading incentives, and to facilitate coordination and cooperation between the building and energy sectors. This can be achieved through policy support and market incentive mechanisms to promote the application and widespread adoption of the technology.

4.1.4. From Evidence to Repeatable Deployment: A Cross-Professional Integration Agenda

Across the evidence patterns summarized in Section 3 and the adoption frictions discussed in Section 4.1, a consistent theme emerges: BIPV uptake is constrained less by any single performance metric than by the ability to translate multidisciplinary requirements into repeatable design-and-delivery routines. In practice, scalability depends on whether building-design intent, envelope detailing, electrical integration, compliance documentation, and cost/benefit accounting can be aligned early enough to avoid late-stage redesign, uncertainty in permitting, and fragmented responsibilities during delivery. A key reason this translation repeatedly fails is limited knowledge exchange across professional communities: technical optimizations, product/material evidence (e.g., durability, fire performance, aging/soiling), and delivery/market requirements (e.g., bankability, warranty, risk allocation, O&M responsibilities) are often developed and reported separately. As a result, improvements on the “supply side” of performance do not automatically convert into deployable, financeable solutions, and can even lead to underutilized generation value when building-side operation and demand are not considered together with design and product decisions.

Accordingly, an integration agenda for scalable BIPV can be articulated through several complementary levers that connect research evidence to deployable practice.

To make this translation logic explicit, Figure 12 synthesizes the multi-lens evidence mapped in Section 3 with the adoption frictions discussed in Section 4.1. It shows why deployability depends on aligning performance evidence, validation maturity, and delivery constraints early in the design-and-delivery workflow.

Conceptual framework linking multi-lens evidence to repeatable BIPV deployment.

First, front-loading integration into design workflows reduces downstream coordination costs. This requires making BIPV an “envelope-and-energy” decision at concept and schematic stages, with explicit role interfaces between architects, façade engineers, and electrical/energy specialists. Practical instruments include standardized detail libraries (mounting, drainage, fire and maintenance access), BIM-ready component objects, and checklists that couple façade aesthetics with wiring routes, inverter placement, and maintenance logic.

Second, strengthening the evidence-to-guidance pipeline is essential for deployment-oriented decisions. Simulation remains indispensable for exploring design space, but its outputs become actionable when constrained by monitored data and reported in a form that can be compared across projects. A scalable evidence backbone therefore prioritizes (i) longer-term or multi-season monitoring, (ii) harmonized reporting of boundary

conditions and operational settings, and (iii) explicit documentation of constructability and operation/maintenance variables (installation tolerances, aging/soiling, controls, and user-driven operation), so that conclusions can inform design briefs and procurement specifications rather than remain as isolated performance claims.

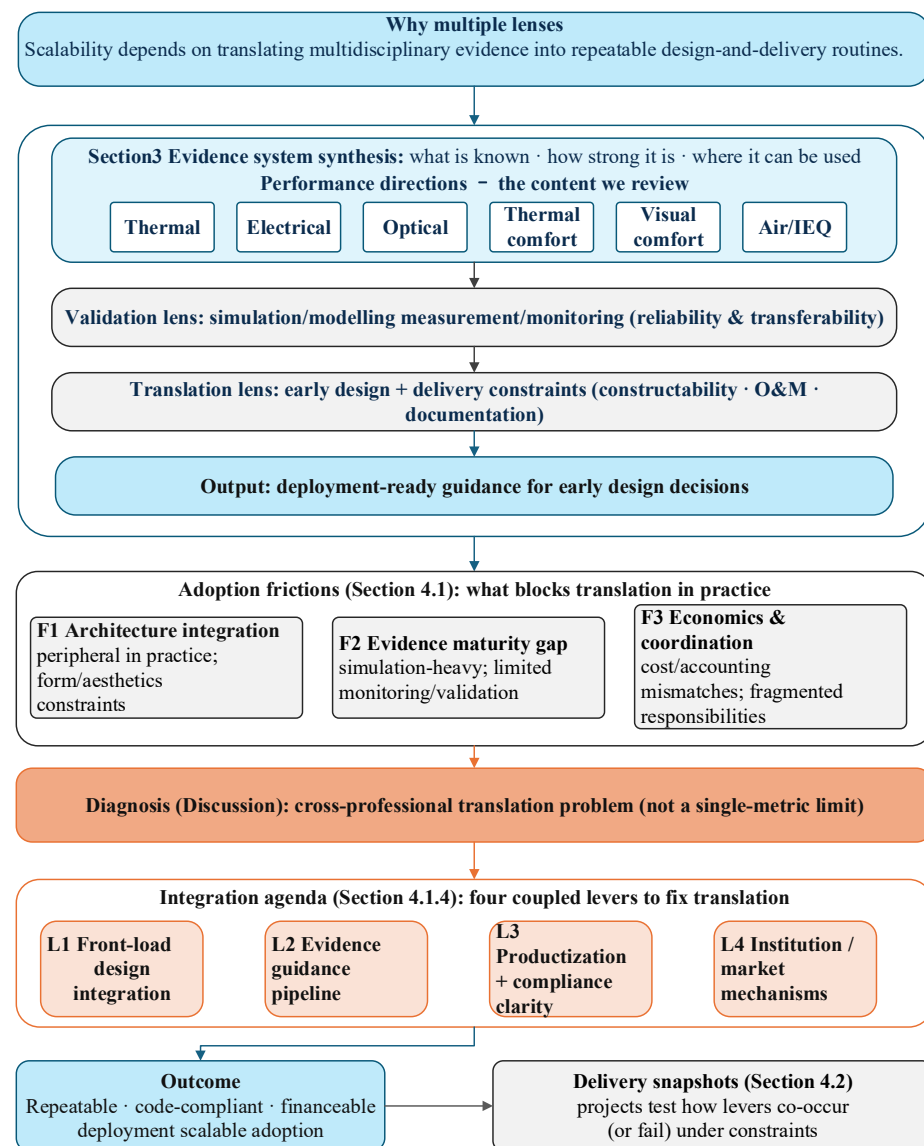


Figure 12. Conceptual framework linking multi-lens evidence to repeatable BIPV deployment.

Third, productization and compliance clarity can convert bespoke façade solutions into replicable delivery models. Standards that treat BIPV modules and systems as building products—linking building-related requirements with electrotechnical requirements—help reduce uncertainty at the architecture–façade–PV interface. For instance, IEC 63092 specifies requirements for BIPV modules and systems when PV is used as a building product, supporting clearer compliance pathways and documentation practices [89]. Complementarily, EN 50583 addresses photovoltaic modules and systems used as construction products within buildings, further reinforcing the “building product” framing that is critical for permitting and liability allocation [90].

Fourth, institutional and market mechanisms determine whether integration becomes routine rather than exceptional. Regulatory and procurement signals can shift BIPV upstream in workflows by embedding solar-readiness and compliance expectations into

permitting and delivery. The EU’s Energy Performance of Buildings framework includes “solar-ready/solar-optimized” orientations for new buildings, effectively requiring buildings to be designed to optimize solar energy generation potential. In California, building energy standards operationalized PV deployment through code-based compliance pathways for new low-rise residential buildings, turning adoption into a predictable permitting requirement rather than a discretionary add-on [91]. In China, expanding government-procurement pilots that encourage green building materials illustrates how procurement can connect certified product lists, documentation, and delivery accountability—an institutional template that can support standardization for integrated envelope technologies [92].

Taken together, these observations support a clear position: the adoption bottleneck is increasingly a translation problem rather than a single technical limit. When results are produced in fragmented professional channels, high-efficiency solutions can still fail to become “usable” building deliverables—because key interfaces (product reliability, responsibility and risk allocation, and operation/maintenance readiness) are not aligned early in building design and delivery. Strengthening cross-professional linkages—e.g., connecting materials and product evidence with design detailing, procurement/contracting routines, and building-level operation and monitoring—helps convert performance potential into realizable value, reducing mismatch and avoidable waste in real deployment.

These levers are not substitutes; they operate as a coupled system. Design-workflow integration without product/compliance clarity remains bespoke; compliance without evidence can misalign incentives; and strong evidence without delivery mechanisms may not reach practice. Section 4.2 therefore examines real-world projects as delivery “snapshots” to observe how these levers co-occur (or fail to co-occur) under practical constraints and to extract deployment-oriented lessons.

4.2. Field Experience and Lessons from International BIPV Applications

To ground the preceding discussion in practical delivery conditions, Section 4.2 reviews representative real-world projects as deployment “snapshots” to examine how scalability levers manifest in practice. Specifically, this study systematically reviews nine real-world projects documented in the IEA-PVPS Task 15 report Successful Building Integration of Photovoltaics: A Collection of International Projects [93]. These cases span different countries and climate zones, covering various building types such as office buildings, educational facilities, and residential dwellings. Compared with simulation and experimental studies under idealized conditions, they offer greater practical value in revealing scalability pathways and bottleneck factors under real deployment conditions.

The basic information, performance focus dimensions, and integration characteristics of the relevant projects are systematically compiled in Table 4 to provide a clearer presentation of their differences in functional focus and system configuration.

Table 4. Summary of representative real-world BIPV projects.

Location	Context	Project	Performance	Integration	Highlights
North America (Canada)	Developed region	Performing Arts Centre	Electrical: 75 MWh/yr Thermal: High-performance envelope + heating Optical: PV on all façades, uniform texture Indoor comfort: Floor air supply	Multi-façade	Educational demo; emission reduction; PV as structure
N. Europe (Norway)	Developed region	Brynseng Primary School	Electrical: 105 MWh/yr façade PV Thermal: 90% heating from GSHP + borehole	South curtain wall	Educational; near-zero energy; subsidy support

Table 4. Cont.

Location	Context	Project	Performance	Integration	Highlights
W. Europe (Austria)	Developed region	Aktiv Energy Tower	Electrical: 630 m ² PV (roof + façade) Thermal: Geothermal + PV synergy Optical: 63% transparency Visual comfort: Transparent façade Indoor comfort: Ventilated PV curtain wall	Curtain walls (SE–W)	Brand showcase; transparent façade
C. Europe (Switzerland)	Developed region	MFH Hofwiesenstraße	Electrical: 750 m ² façade + 500 m ² CIGS balcony Thermal: Rear ventilation + low-conductivity connectors	Multi-façade + balcony	Colored modules; energy-positive demo
S. Europe (Italy)	Developed region	Single-family House (Lasa)	Electrical: Balcony + rooftop PV (>850 kWh/yr) Thermal: Electric water heating + control Optical: 37–38% semi-transparent stripes	Balcony + rooftop	Semi-transparent BIPV; shading
E. Asia (China)	Developing region	Singyes Solar Office	Electrical: 150,000 kWh/yr (4 PV systems) Thermal: PVT hot water (60,000 L/yr) Optical: Ceramic-like PV + transparent glass Indoor comfort: Ventilated wall + climate control Visual comfort: Lighting, airflow, shading	Curtain wall + canopy + louver + rooftop	Microgrid; multi-system synergy
E. Asia (Japan)	Developed region	NTT Aoba Dori Building	Electrical: 37 kWp façade + rooftop PV Thermal: Dry dehumidifying AC + ventilated wall	South façade wall	Post-disaster memorial; AC-heat integration
W. Europe (Netherlands)	Developed region	Social Housing Apartment	Electrical: 250 kWp façade + balcony + rooftop Thermal: Unit heat pumps + BIPV integration	Multi-façade + balcony	Policy-driven; rent-energy link
N. Europe (Sweden)	Developed region	Väla Gård Office	Electrical: 70 kWp rooftop PV Thermal: GSHP + insulation Indoor comfort: Occupant load consideration	S-facing pitched roof	Net-zero; occupant behavior focus

From an integration perspective, the projects demonstrate considerable diversity in form, including curtain walls, pitched roofs, balcony railings, canopies, louvers, and multi-façade systems, highlighting the deep embedding of BIPV within building structures and façade aesthetics. In terms of energy system configuration, most combine PV with geothermal heat pumps, electric water heating, PVT systems, or microgrid scheduling, implementing electricity–heat coupling strategies to enhance system efficiency. Regarding performance dimensions, all projects prioritize electrical performance; thermal performance is universally addressed, reflecting its fundamental role in energy efficiency. Optical performance receives explicit design consideration in four cases—typically through transmittance control or shading strategies—while indoor thermal comfort is incorporated into four projects, mainly via ventilated façades and dedicated air supply systems. Visual comfort is explicitly addressed in two cases, and air purification is absent in all. These patterns suggest that while BIPV practice has advanced beyond mere power generation, a comprehensive, user-oriented design framework remains underdeveloped, and multidimensional integration is key to improving scalability. Across the reviewed projects,

multidimensional integration tends to co-evolve with the maturity of the local delivery ecosystem. Where financing channels, certification pathways, and integrated procurement routines are relatively established, design teams can more readily translate coupled heat–electricity–daylight–comfort objectives into replicable solutions. Where these enabling conditions are weaker, scalability is more strongly conditioned by deliverability—such as bankability, the availability of code-compliant products, and contracting arrangements that support early cross-disciplinary coordination.

The IEA-PVPS Task 15 [93] collection documents 25 BIPV projects across 11 countries, yet the publicly reported “successful-project” evidence is still concentrated in mature BIPV markets. In the nine cases synthesized here, only one project is situated in a developing-region context (China), indicating that many best-practice insights have been generated under comparatively mature standards, established procurement routines, and more accessible financing conditions. Therefore, the synthesis below distills cross-cutting scalability levers while emphasizing that implementation pathways may differ when these enabling conditions are less established. Analysis of these nine cases yields several cross-cutting lessons and challenges relevant to scalable BIPV deployment. First, component standardization and integrated system design consistently emerge as critical strategies for cost reduction, streamlined installation, and project replicability. In applications where PV modules replace building envelope elements, standardized solutions directly influence construction efficiency. For example, Japan’s Sendai Communications Hub standardized PV module dimensions and arrangements during façade design to meet both energy and aesthetic goals, while the Netherlands’ Best residential project optimized thin-film module sizes to match folded façade geometries, reducing non-standard components and associated costs. In developing regions, this lever may also depend on clear certification and code-compliance pathways; modular details that can be inspected and replicated by local contractors can scale more readily than bespoke façade solutions.

Second, thermo-electrical co-optimization and intelligent control mechanisms are essential for achieving high energy performance and meeting nearly zero-energy building (nZEB) targets. The “GREEN YES” project in Zhuhai, China, integrated double-skin ventilated façades with semi-transparent PV to balance summer cooling and winter insulation, simultaneously enhancing energy performance and maintaining indoor comfort. Sweden’s Väla Gård office building incorporated life-cycle energy accounting from the outset, pairing high-efficiency heat pumps with strict load management to deliver strong performance without subsidies, demonstrating feasibility in cold climates. In developing regions where cooling demand, grid constraints, and operational variability may be more pronounced, co-optimization that delivers robust comfort and peak-load relief can be particularly important for adoption.

Third, non-technical barriers—notably financing and organizational structures—remain significant constraints. Inadequate incentive schemes can extend payback periods, while conventional procurement practices limit early-stage collaboration among architects, electrical engineers, and energy specialists, reducing integration potential. These frictions can be amplified in developing regions, where the cost of capital can be higher and incentive schemes may be less stable, making payback risk a central adoption barrier. Likewise, limited experience with integrated procurement (e.g., design–build or performance contracting) can hinder early alignment of architectural intent with electrical and energy-system design. The Väla Gård project, excluded from national subsidies, relied on corporate green certification to justify investment. The Best project in the Netherlands faced misaligned benefit distribution between investors and tenants; its THUIS sub-project addressed this by introducing an Energy Performance Fee to reflect energy savings in rental pricing, improving both tenant acceptance and investor returns.

Fourth, several projects illustrate the symbolic and socio-cultural value of BIPV. In post-earthquake reconstruction, the Sendai Communications Hub adopted a BIPV façade to convey an image of “green recovery,” enhancing public engagement and acceptance. Similarly, the Singyes Solar office in Zhuhai leveraged its energy-generating façade as part of corporate branding, transforming the system into a visible statement of sustainability. Such visibility and co-benefits may be influential in developing regions where stakeholder trust and perceived risk strongly affect uptake.

Finally, demonstration projects play a pivotal role in the early-stage BIPV market. The Best project and Japan’s NTT Aoba Dori building, both high-integration pilots, validated technical feasibility under complex conditions and informed the evolution of standards, design workflows, and market mechanisms. Such exemplars strengthen industry confidence and lay the groundwork for institutionalized deployment. For developing regions in particular, pilots paired with standard-setting, capacity building, and replicable tender templates can help convert one-off showcases into scalable delivery models.

Overall, these real-world cases provide robust, cross-regional evidence on the practical dynamics of BIPV scalability. Their lessons—spanning technical standardization, system co-optimization, financing models, and societal engagement—are transferable in principle but remain context-dependent, especially for developing regions where financing terms, compliance capacity, and procurement/project-delivery practices can differ substantially. These case-based insights also represent a critical complement to experimental and simulation-based research. They highlight that scaling BIPV requires not only technical advances but also integrated strategies addressing governance, market mechanisms, and public perception.

4.3. Architectural Aesthetics and Spatial Integration Potential of BIPV Systems

Against the backdrop of the intersection between architectural theory and sustainable design, BIPV has gradually evolved from a purely energy-generating component into a design medium with spatial expressiveness and formal participation. Numerous studies have shown that the introduction of semi-transparent PV modules and curved configurations not only maintains façade transparency and formal integrity but also expands the expressive dimensions of lightness and visual continuity in architectural materials [73,77,94]. Certain dynamic shading and deformable components break through the boundaries of traditional static façades, introducing spatial concepts such as “transformability,” “responsiveness,” and “skin movement,” thereby enriching perceptual diversity and enhancing façade interactivity [69,76].

In addition, transparent or semi-transparent BIPV window systems have been proven to be highly compatible with façade systems in modern architecture that emphasize simplicity and geometric order, transforming energy components from add-on equipment into integral elements of the overall architectural form strategy [10,85]. This integration approach responds to the architectural principle of “form–function unity” and expands façade design narratives involving light and shadow, solids and voids, and inside–outside permeability. Furthermore, numerous empirical studies emphasize that the arrangement strategies of PV components significantly affect glare control, daylight uniformity, thermal environment regulation, and preservation of landscape views—factors that, in turn, influence users’ spatial perception and subjective comfort evaluations [34,83]. This indicates that the architectural value of BIPV is not limited to optimizing performance parameters, but lies in its role as a mediating component that integrates energy production and spatial organization logic, inspiring new paradigms in architectural design.

4.4. Limitations

This review primarily adopts an engineering-oriented perspective on BIPV, with an emphasis on feasibility and scalability across energy, architecture, and environmental systems. Given this technical focus, the review does not extensively engage with scholarship from psychology, economics, aesthetics, or other non-engineering disciplines. Consequently, several non-technical factors that are critical to BIPV adoption—such as user behavior, societal acceptance, and cultural compatibility—are not examined in depth, which narrows the overall scope.

This emphasis also reflects a methodological preference for architecture- and engineering-based studies that typically address simulation, performance evaluation, and system design. As a result, research centered on user experience, perception, or behavioral feedback may not be fully captured under the current search strategy.

In addition, this study draws exclusively on English-language publications indexed in the Web of Science and Scopus databases. Although these databases provide broad coverage of mainstream academic output, excluding non-English literature—particularly from non-Anglophone countries—may underrepresent region-specific insights and localized technological applications. While the selected sources offer a comprehensive overview of global BIPV research, the potential omission of diverse or locally grounded perspectives remains a limitation.

More specifically, the language and database constraints may have led to the omission of region-specific empirical studies with practical relevance, especially those reporting experience and feedback from real-world implementation contexts. Such omissions may limit the depth of analysis regarding the scalability and feasibility of large-scale BIPV deployment across regions, as local climate conditions, policy frameworks, and market maturity can substantially shape outcomes. Furthermore, the review does not adequately address several practical design and deployment challenges—such as modular integration, standardization, and product-level optimization—that are essential for scalability. This highlights an insufficient coverage of implementation-oriented issues in BIPV system design, integration, and product optimization.

Finally, because this study focuses on peer-reviewed research within architecture and engineering and primarily evaluates scalability through technical logic and methodological frameworks, it does not systematically incorporate grey literature or project-based documentation. Although this approach supports analytical consistency, it also reduces coverage of real-world project practices and region-specific scalability evidence. Future research should therefore broaden data sources and literature types by integrating interdisciplinary perspectives and implementation experience, so as to more comprehensively capture BIPV scalability challenges across different regions and application contexts.

5. Conclusions

This systematic review comprehensively examines research progress and scalability assessment of BIPV within the engineering domain, with particular attention to energy efficiency, thermal performance, visual comfort, and pathways for integration with architectural structures. Through a rigorous retrieval and screening process, 363 publications published between 2001 and 2025 were initially identified. After multi-stage filtering, 82 highly relevant studies were ultimately included, spanning energy engineering, thermal science, building environment, and architectural design. All selected publications were sourced from the Web of Science and Scopus databases, ensuring the systematicity and representativeness of the review sample. This provides a robust basis for identifying research hotspots, development trends, and pathways for interdisciplinary integration.

The findings indicate that existing BIPV research remains predominantly technology-oriented, with a notable lack of architectural perspectives. This disciplinary imbalance limits the depth of PV system integration in real-world building design practice. In addition, current research methods rely heavily on simulation-based approaches. Although simulations provide operational flexibility and broad applicability, they often struggle to capture the dynamic complexities of actual built environments.

To support future development and broader adoption of BIPV, the following directions are proposed.

Across Sections 3 and 4.1, a recurring pattern emerges: BIPV evidence is often generated within discipline-specific channels, while real deployment depends on early alignment across façade detailing, electrical integration, compliance documentation, and lifecycle responsibilities. This translation gap helps explain why promising performance gains do not consistently convert into repeatable, code-compliant, and financeable delivery routines, motivating the cross-professional integration logic summarized in Section 4.1.4.

For researchers, strengthening interdisciplinary collaboration remains essential, but the integration agenda in Section 4.1.4 suggests a more specific priority: producing evidence that is portable across professional boundaries and can be translated into repeatable design-and-delivery routines. Fields such as architecture, aesthetics, psychology, and the social sciences are crucial for improving user acceptance and spatial compatibility, because BIPV systems are not only technological artifacts, but also integral elements of architectural expression and spatial experience. At the same time, research designs should more explicitly couple performance claims with delivery-relevant constraints (e.g., envelope detailing, wiring routes, inverter placement, access for inspection/cleaning, and maintenance logic), so that “optimized” results do not remain detached from buildability and operation. In parallel, further advances in model construction and simulation methodologies are needed; however, predictive accuracy depends strongly on boundary conditions and input parameters. Future studies should therefore prioritize rigorous model calibration and validation against empirical data, and report assumptions in harmonized, comparable formats (boundary conditions, operational settings, and control strategies), enabling cross-project synthesis and procurement-ready guidance rather than isolated case-specific claims. In addition, the evidence base should better integrate product/material reliability (durability, fire performance, aging/soiling) with delivery/market requirements (warranty logic, risk allocation, and O&M responsibilities), because these “non-performance” interfaces often determine whether solutions become financeable and code-compliant in real deployment.

For architectural design practitioners, expanding the scale and improving the quality of empirical studies is critical to narrowing the gap between research and practice, but Section 4.1.4 indicates that the timing and form of evidence are equally important: scalability improves when integration is front-loaded into concept and schematic design rather than addressed late through redesign. Large-scale, full-scale prototype testing and product pilot trials are essential for translating research into deployable solutions; yet many existing measurement campaigns still rely on small samples and short observation periods, limiting assessment under complex climatic conditions, long-term operation, and user interactions. Establishing longitudinal monitoring platforms across diverse climate zones and building types would generate more representative datasets, supporting evidence-based design decisions and the development of relevant standards and policies. To reduce downstream coordination costs, design practice can also benefit from “translation instruments” that connect architectural intent to delivery routines—such as standardized detail libraries (mounting, drainage, fire and maintenance access), BIM-ready component objects, and checklists that explicitly couple façade aesthetics with electrical integration (wiring routes, inverter placement) and maintenance/commissioning requirements. These instruments

operationalize evidence early, reduce interface uncertainty, and help prevent underutilized generation value caused by mismatches between building operation/demand and design/product decisions.

For senior practitioners, a shift in practice is needed—from optimizing isolated technical components to delivering fully integrated BIPV products and repeatable delivery models. This requires ensuring structural compatibility and seamless integration with electrical systems, while also addressing construction logistics and on-site feasibility. Section 4.1.4 further suggests that repeatability depends on clarifying role interfaces and lifecycle responsibilities: without explicit allocation of responsibility and risk (e.g., warranty boundaries, liability at the architecture-façade-PV interface, and O&M ownership), bespoke coordination costs remain high and bankability remains uncertain even when technical performance is strong. Future development should therefore prioritize modular, standardized, and user-friendly solutions that are easy to deploy, maintain, and scale in real architectural projects, supported by packaging of documentation that is usable for permitting and procurement (installation tolerances, commissioning protocols, inspection/maintenance access logic, and degradation/soiling assumptions). In this sense, “productization” is not only about hardware modularity, but also about delivering a replicable bundle of detailing, documentation, and operational readiness that reduces late-stage redesign and fragmented responsibilities during delivery.

For policymakers, future industry standards and planning strategies should adopt a holistic perspective that incorporates multiple performance dimensions: thermal performance, electrical performance, optical performance, indoor thermal comfort, visual comfort, and air purification. Rather than optimizing a single parameter, evaluation frameworks should seek a global optimum that balances energy efficiency, user experience, and environmental benefits. Importantly, Section 4.1.4 indicates that policy can accelerate routinization by strengthening compliance clarity and reducing permitting uncertainty through a “building product” framing—i.e., standards and documentation pathways that link building-related requirements with electrotechnical requirements and clarify liability allocation. Standards such as IEC 63092 (requirements for BIPV modules/systems used as building products) and EN 50583 (PV modules/systems as construction products in buildings) exemplify this direction and can support more predictable compliance documentation and approval pathways [89,90]. Beyond standards, institutional and market mechanisms determine whether integration becomes routine rather than exceptional: embedding solar-readiness expectations into permitting and delivery processes can shift BIPV upstream, and code-based compliance pathways can turn adoption into a predictable requirement rather than a discretionary add-on [91]. Procurement mechanisms that connect certified product lists with documentation and delivery accountability can further reduce fragmentation and support standardization of integrated envelope technologies [92]. Establishing such comprehensive assessment and governance systems would enable more equitable and effective policy incentives, improve compatibility across diverse building contexts, and support large-scale, sustainable deployment of BIPV.

Taken together, these implications converge on a single synthesis: scalability hinges on the translation of multidisciplinary evidence into repeatable workflows, product/compliance clarity, and delivery governance.

Importantly, this review adopts a clear position: the primary barrier to scalable BIPV deployment is not a lack of promising technical results, but a persistent mismatch between how evidence is generated across professional domains and what real building delivery requires. When architectural design, engineering validation, product/material development, and investment-operation decision-making remain weakly connected, “optimized” solutions often fail to translate into repeatable, code-compliant, and financeable building de-

liverables, and their performance gains may not be fully realized in practice. Future research and implementation should therefore strengthen cross-professional linkages—especially between materials/product reliability evidence and delivery governance (procurement pathways, responsibilities, and risk allocation), as well as operation/maintenance readiness (commissioning, monitoring, and performance-based feedback)—so that technical advances can be converted into usable, non-wasteful real-world adoption.

In conclusion, future progress in BIPV depends not only on continued technical enhancement, but also on deeper interdisciplinary cooperation. Such integration is essential for translating technological potential into practical architectural applications, enabling scalable deployment and seamless assimilation into the built environment.

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