Renewable Energy and Power Quality Journal

https://repqj.com/index.php/repqj/index
RE&PQJ, Vol. 23, No. 1, 2025

Integrating Building-Integrated Photovoltaics (BIPV) into Sustainable Architecture: A Review of Architectural-Scale Applications and Emerging Performance Strategies

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Abstract. Driven by the global energy crisis and carbon neutrality goals, Building-Integrated Photovoltaic (BIPV) systems are increasingly recognized as a key solution in sustainable architecture. This study presents a comprehensive review of BIPV integration approaches and emerging performance strategies at the building scale. Combining qualitative analysis with bibliometric methods, the research is based on publication data from the Web of Science Core Collection, using relevant topics in photovoltaic technology and green building, and covering the years 2001 to 2025. The paper traces the evolution of BIPV technologies, identifies research hotspots, and reveals shifts in structural and performance paradigms. Technically, BIPV systems have evolved from simple energy-generating add-ons to multifunctional building envelope components that integrate structural, protective, visual, and environmental regulation functions, with applications in roofs, façades, shading systems, and more. Performance assessment has become increasingly multi-dimensional, encompassing energy conversion efficiency, thermal management, environmental impact, aesthetic integration, and economic viability. Bibliometric analysis reveals a transition from structural integration to multi-objective performance optimization, with smart modeling, AI-assisted design, and urban energy network integration emerging as future directions. Despite this progress, BIPV implementation still faces systemic barriers such as structural complexity, high costs, regulatory fragmentation, and limited interdisciplinary collaboration. In response, this paper proposes a framework addressing intelligent modeling, policy incentives, standard development, and design education to advance the deep integration and widespread adoption of BIPV in green buildings. The findings aim to provide theoretical insights and practical guidance for BIPV deployment, policymaking, and future research.

Key words. Building-Integrated Photovoltaics, Green Building, Performance Optimization, Bibliometric Analysis, System Integration Barriers, Multi-Objective Design

1. Introduction

Rapid urbanization and mounting climate stress have made buildings central to environmental solutions. The construction sector now plays a key role in addressing global ecological challenges. The 2024 United Nations Environment Programme (UNEP) report states that construction consumes 32% of the world's energy and produces 34% of CO_2 emissions [1]. According to the International Energy Agency's World Energy Outlook 2024, achieving global net-zero targets will require tripling renewable energy capacity and doubling energy efficiency by 2030, with solar PV—including BIPV—projected to deliver the largest share of new capacity additions. In 2023 alone, solar PV contributed a record 347 GW to global renewables growth, highlighting the central role of building-integrated photovoltaics in the transition to a low-carbon built environment [2].

Integrating renewable energy into architecture is now a core strategy for green development. Building-integrated photovoltaics (BIPV) place solar modules directly into façades, roofs, and shading systems. This approach uses space efficiently and responds to environmental needs. BIPV also helps manage building temperature, boosts energy performance, and adds visual appeal. BIPV outperforms building-applied photovoltaics (BAPV) in both integration and flexibility. These systems support carbon reduction goals and improve architectural form. Field data from Singapore, Egypt, and Switzerland show that BIPV can cut grid reliance, improve indoor comfort, and increase property value [3-7].This transformation has been driven by advances such as the development of thin-film photovoltaic technologies, transparent and semi-transparent BIPV modules, and smart multifunctional components, all of which enable PV systems to serve not only as energy generators but also as structural, thermal, and aesthetic elements within the building envelope.

New technologies are driving faster adoption. Thin-film PV, cadmium telluride (CdTe), and semi-transparent modules bring new possibilities. Digital tools like Building Information Modeling (BIM) and artificial neural networks (ANN) allow more precise integration at early design stages [8,9]. Multi-objective optimization lets designers consider daylighting, comfort, costs, and aesthetics at once [10]. Decision-making now places more weight on lifecycle costs, structural soundness, and coherent appearance [11,12].

Recent bibliometric studies have shown that the rapid growth of machine learning and deep learning applications is fundamentally transforming design, optimization, and implementation in the built environment. The integration of artificial intelligence and data-driven strategies has accelerated innovation and performance improvement in intelligent manufacturing, and this influence is increasingly evident in the building sector as well [13].

Despite ongoing technological progress, the widespread adoption of BIPV continues to face obstacles including the lack of standardized technical frameworks, economic uncertainties, insufficient policy mechanisms, and limited public awareness [14,15]. Especially in dense urban areas or retrofit projects, balancing aesthetics with technical performance remains a major challenge for architects and engineers. Against this backdrop, a systematic review of integration models and performance optimization strategies at the architectural scale holds both academic significance and practical relevance. This study examines BIPV systems in the setting of sustainable architecture. The focus lies on scalable integration methods and design strategies that prioritize performance. Using both qualitative analysis and bibliometric techniques from the Web of Science Core Collection, the research maps out major trends, keyword clusters, and future directions. It evaluates technology pathways, architectural adaptability, and environmental benefits. The findings offer a theoretical base for multi-objective BIPV design and support sustainable architectural practice.

2. Theoretical Foundations and Technological Background

A. The Role and Significance of BIPV in Sustainable Architecture

The climate crisis and rapid urbanization are placing the built environment at the forefront of renewable energy integration and environmental adaptation. Buildings now serve as key sites for adopting clean energy solutions. Incorporating renewables across the full building lifecycle has shifted from a design option to a fundamental standard for green building evaluation. Building-integrated photovoltaics (BIPV) stands out as a core technology, merging energy production with architectural design. This trend is reshaping the role of the building envelope. No longer limited to insulation or shading, it now generates electricity, regulates temperatures, and shapes the city's visual identity.

BIPV's value lies in its dual function: it acts as a structural element and an energy producer. Photovoltaic modules take the place of traditional roofs, façades, and shades. This integration avoids additional land use, making BIPV ideal for dense cities with limited space. Čeněk and Hlaváček have shown that effective BIPV deployment in complex urban settings requires architectural strategies that blend photovoltaics with urban and cultural layers [16]. Such integration preserves the visual continuity of cityscapes and enhances public engagement with sustainability. In technical and economic terms, BIPV offers clear benefits. Abuhussain's multi-climate analysis of 50 buildings found that façade and semi-transparent PVs can cut annual energy use by up to 37.8%. The average payback period is around 6.2 years [8]. These results confirm that BIPV supports green building values while providing measurable energy and financial returns. For renovation projects, BIPV's adaptability and flexibility offer a strong route for urban renewal [17]. BIPV demonstrates strong visual adaptability and contextual compatibility, supporting both historic preservation and technological progress.

The application scope of BIPV is gradually shifting from a "green technology" to a "multifunctional component" within architecture. Zhang et al. proposed an envelope system integrating thin-film photovoltaics with hydroponic agriculture, enabling buildings to generate electricity while contributing to urban food production and biodiversity [18]. Youssef et al. employed a shape grammar-based generative method to design a commercial façade in Egypt, achieving coordinated optimization of daylight access and photovoltaic performance [13]. In such practices, BIPV functions as a core parameter in form generation, serving both as a design constraint and a key variable within the generative logic of architectural design. BIPV plays a growing role in urban climate regulation. Tian et al. conducted modeling studies demonstrating that ventilated photovoltaic façades reduce surface temperatures in urban canyons, suppress daytime heat flux, decrease the intensity of the urban heat island effect [19]. The results position BIPV as a functional element within building energy systems and as a component in urban thermal control infrastructure. BIPV should no longer be regarded merely as an add-on clean energy system, but rather as a system-integrated architectural component that connects energy generation, formal expression, microclimate regulation, and urban memory. Its cross-domain performance compels designers to reconsider the boundaries of building technology—treating space, environment, and energy as interdependent design variables rather than isolated functional fragments.

B. Overview of Application Types at the Architectural Scale

At the architectural scale, the integration forms of BIPV systems are primarily influenced by their installation location, structural characteristics, and compatibility with building functions. From rooftops and facades to shading elements and double-skin façades, various systems exhibit a high degree of diversity in spatial utilization, thermal regulation, and design expression. Table 1 provides a typological overview of these categories. The following sections elaborate on the construction logic and performance characteristics of each system based on current research.

Roof-integrated BIPV systems are widely applied in low-rise or standalone buildings, offering advantages such as high solar exposure and minimal shading interference. Studies have shown that incorporating a ventilated air gap behind the modules can effectively reduce operating temperatures and improve energy efficiency. This configuration is especially well-suited for rooftop designs in tropical and temperate residential contexts [20] (see Table 1, Item 1).

Façade-integrated BIPV systems are widely deployed in high-rise and public buildings, serving dual purposes of energy generation and architectural expression. Empirical studies have shown that south-facing ventilated façade systems exhibit higher energy output per unit area under Middle Eastern climate conditions, while also offering favorable thermal inertia and significant energy-saving potential [21] (see Table 1, Item 2).

Shading-integrated BIPV systems incorporate elements such as louvers, overhangs, or balcony panels to simultaneously provide shading, visual control, and energy collection. Research indicates that optimizing the tilt angle and spacing of shading components can significantly reduce cooling loads while enhancing photovoltaic performance. This configuration is particularly well-suited for sun-intensive tropical urban areas [22] (see Table 1, Item 3).

Table 1. Architectural typologies of bipv systems and their performance attributes.

Integration Type	Installation Site	Technical Features	Performance Advantages	Applicable Conditions or Regions	Reference Source
Roof-Integrated BIPV	Sloped or flat rooftops	Mostly c-Si or CIGS modules; suitable for large flat installations	High energy efficiency, easy installation, good natural ventilation and cooling	Widely applicable in tropical and temperate regions	[20]
Façade-Integrated BIPV	Building exterior walls, curtain walls	Can adopt ventilated façade structures; typically uses c-Si or CdTe modules	Saves land, enhances architectural aesthetics, provides partial shading and insulation	Suitable for mid- to high-rise office buildings, especially east-, west-, or south-facing façades	[23]
Shading-Integrated BIPV	Window eaves, overhangs, balconies	Installed on shading components like operable louvers or horizontal shading panels; may use STPV modules	Combines power generation with shading, reduces cooling load, improves light quality	High-sunlight regions; suitable for integration with shading designs	[24]
Double-Skin BIPV	Between inner and outer curtain wall layers	Combines natural ventilation and thermal buffering to enhance module cooling and heat recovery	High thermal efficiency, good sound insulation, effective for winter heating and summer cooling	Regions with large seasonal temperature variations or buildings with high energy efficiency demands	[25]
Window-Integrated PV (Window/STPV)	Window glass areas	Semi-transparent photovoltaic glass; balances transparency and energy generation	Reduces solar heat gain, mitigates glare, lowers cooling load, provides natural daylight	Commercial building façades or atriums; can be integrated with daylighting strategies	[26]
Balcony Movable BIPV	Balcony railings or overhangs	Combines with movable components; adjustable orientation and shading angles	Generates electricity while improving privacy and shading; ideal for high-rise residential units	High-rise housing with limited space but sufficient daylight exposure	[27]

Double-skin BIPV systems enhance thermal regulation by creating a ventilated thermal buffer zone between two layers of the building façade. Simulation studies have shown that BIPV double-skin façades (BIPV-DSF) can effectively control heat transfer pathways, offering significant advantages in improving both acoustic performance and thermal comfort within the building [28] (see Table 1, Item 4).

Window-integrated photovoltaic systems (Window/STPV) emphasize the integrated coordination of daylight transmission, visual comfort, and shading performance. These systems utilize semi-transparent photovoltaic modules as substitutes for conventional glazing. Field measurements have shown that they can achieve energy savings exceeding 37%, while also providing the combined benefits of glare reduction and decreased solar heat gain [29] ((see Table 1, Item 5).The balcony movable BIPV system provides a dynamic solution for power generation and shading control in high-rise residential buildings. This adjustable balcony photovoltaic system also enhances privacy and comfort for residents. (see Table 1, Item 6).

The construction of BIPV systems is evolving from the simple substitution of single-function building materials toward the development of multilayered, multifunctional components. Experts recommend incorporating BIM-assisted modeling in the early stages of architectural design to enable multidimensional optimization of structural dimensions, module layout, and solar-thermal parameters. This collaborative design approach enhances system compatibility, streamlines construction processes, and reduces energy consumption and maintenance costs during the operation phase [30].

As digitalization and the integration of open, interoperable communication frameworks become increasingly vital in building technologies, recent bibliometric analyses in mobile network research emphasize that open architectures—such as Open RAN—play a crucial role in enabling modularity, adaptability, and real-time optimization across complex systems. The emergence of flexible, vendor-neutral infrastructures fosters more dynamic, intelligent, and sustainable solutions for both networked environments and next-generation building systems [31]. The diverse application types of BIPV systems at the architectural scale highlight their advantages in climate adaptability and technological flexibility. More importantly, they signal a shift from being mere energy-generating components to becoming integrated architectural elements. Future development will place greater emphasis on holistic system design, multi-objective performance coordination, and expanded adaptation to urban application scenarios.

C. Performance Evaluation Dimensions of BIPV Systems

The performance assessment of Building-Integrated Photovoltaic (BIPV) systems involves multiple dimensions, including electrical output, thermal management efficiency, environmental benefits, aesthetic integration, and economic feasibility. Given that BIPV systems serve dual functions—both energy conversion and structural integration—their evaluation requires a multidisciplinary perspective, drawing from architecture, energy engineering, and environmental science.

Electrical conversion efficiency (η) remains one of the core indicators for assessing BIPV system performance. Both the construction type and ventilation conditions have a significant impact on this efficiency. In a comparative study conducted in Italy, D'Orazio et al. examined three roof integration methods and found that systems incorporating a 20 cm air gap significantly reduced module temperatures and increased annual power generation by approximately 4% [32].BIPV/T (Building-Integrated Photovoltaic/Thermal) systems enhance power generation efficiency while simultaneously enabling effective thermal energy recovery. Their overall energy utilization efficiency can exceed 70% [33].

Unlike traditional rack-mounted photovoltaic systems, BIPV systems—being embedded within the building envelope—are more susceptible to thermal accumulation. In an analysis of multiple European case studies, Sauzedde et al. found that the equivalent thermal resistance values typically ranged between 0.0297 and 0.0397 K·m²/W. Without optimized airflow pathways, this thermal buildup can lead to a significant decline in system efficiency [34].Related studies have also indicated that the presence of a rear-ventilation layer, the configuration of air-cooling channels, and the thermal conductivity of materials all directly influence the thermal response and stability of BIPV systems [35].

BIPV systems offer significant environmental advantages over their life cycle. Through life cycle assessment (LCA), Zhang et al. found that CdTe and thin-film photovoltaic technologies perform best in terms of CO_2 emission reduction, with an energy payback time (EPBT) as low as 1.5 years [36].Lamnatou's research further highlights that the manufacturing of PV modules and the use of metal support structures are key contributors to the system's total life-cycle greenhouse gas emissions (GWP) and toxicity load. Implementing recycling strategies can significantly reduce these environmental impacts [37].

With the increasing application of BIPV systems in dense urban centers and heritage architecture, the visual dimension of integration has become a critical component in evaluating overall system performance. To address this, Chandrasekar proposed an aesthetic evaluation framework that synthesizes findings from multiple prior studies. His analysis revealed that façade-integrated BIPV systems generally achieved visual compatibility scores exceeding 0.5 on a 0–1 scale, underscoring their high degree of architectural congruence in diverse built environments [38].

From an economic standpoint, the assessment of BIPV typically involves evaluating initial capital expenditure, life-cycle cost (LCC), and the anticipated payback period. In a study focused on high-insolation regions, Liu et al. demonstrated that strategic system configuration—especially in terms of module orientation and selection—could reduce the average payback time to fewer than eight years. The study found particularly favorable economic outcomes in applications involving south-facing façades and inclined roof structures [39]. A robust evaluation of BIPV performance requires a multidimensional framework that spans not only energy generation and thermal regulation, but also environmental footprint and architectural synergy. To strengthen the reliability of such assessments, future models should integrate simulation-based techniques, in-situ performance data, and comprehensive life cycle assessments. These enhancements will provide more structured and evidence-based decision-making tools for the optimized design, deployment, and policy alignment of BIPV technologies.

In line with these trends, recent research emphasizes that the integration of advanced sensing and communication technologies—collectively referred to as integrated sensing and communication (ISAC)—will further expand the possibilities for multidimensional BIPV performance assessment, enabling real-time monitoring, adaptive system control, and data-driven optimization across both individual buildings and larger urban networks [40].

3. Evolutionary Trends and Thematic Focus in BIPV Research

A. Data Sources and Analytical Parameters

To systematically trace the evolution of research themes related to Building-Integrated Photovoltaic (BIPV) systems within the context of green architecture, this study conducts a bibliometric analysis based on data from the Web of Science Core Collection. The data retrieval was conducted in March 2025. The search strategy focused on the intersection of two semantic fields—"photovoltaic technology" and "green building design"—using the following query: TS = (("photovoltaic" OR "building integrated photovoltaic" OR "BIPV") AND ("green building" OR "environmental design" OR "sustainable architecture" OR "building envelope")). The initial search yielded a total of 608 records.To enhance the academic rigor and thematic relevance of the dataset, a two-stage screening process was employed. In the first stage, filters were applied based on document type, index source, language, and time range. Only peer-reviewed journal articles and reviews published between 2000 and 2025 in English were retained. Moreover, only records indexed in SCI-E, SSCI, A&HCI, ESCI, and CPCI-S were included, while conference proceedings, book chapters, communications, and editorial materials were excluded. After this stage, the dataset was reduced to 474 records.In the second stage, a manual review of titles and abstracts was conducted to eliminate records not directly related to the research topic. Ultimately, 465 highly relevant English-language publications were retained as the core dataset for subsequent bibliometric analysis and thematic identification.

To ensure scientific rigor and reproducibility, the following key parameters were specified for the bibliometric analysis: The dataset spans the years 2001–2025, with annual time-slicing applied to capture the year-by-year evolution of research trends and thematic structures. Keyword co-occurrence networks and thematic clustering were performed using the Louvain modularity optimization algorithm, with a minimum cluster size set to 5 to ensure the stability and interpretability of major themes. All co-occurrence analyses utilized fractional counting and normalization by the annual number of publications to address publication volume disparities across years. Network structure analysis included calculation of modularity, average degree, and betweenness centrality to evaluate the clustering and connectivity within the keyword networks.

The value of combining systematic literature review with robust bibliometric analysis has been widely recognized in reliability and engineering research. Recent studies have shown that employing reproducible bibliometric workflows—such as the use of fractional counting, time-slicing, network modularity assessment, and co-occurrence clustering—not only enhances analytical transparency, but also enables deeper mapping of knowledge structures and the identification of thematic trends across large datasets [41].
Thematic evolution was visualized and tracked using Sankey diagrams and thematic river plots to map the differentiation and transformation paths of major research topics. All analytical parameters and procedures strictly followed the default and recommended settings of the bibliometrix R package and its GUI, Biblioshiny, thus ensuring full reproducibility and methodological consistency.

The second stage involved a manual relevance review based on titles and abstracts. This step aimed to exclude works not directly related to BIPV within architectural contexts. The excluded documents fell into three main categories: studies focused on off-grid microgrids or rural electrification systems; research concerning photovoltaic agriculture or greenhouse-based energy applications; and general photovoltaic technology studies lacking any reference to building integration or envelope-specific design. After this refinement, a total of 465 publications were identified as the final dataset for bibliometric analysis.

Spanning the years 2001 to 2025, the dataset captures a 25-year period of academic inquiry, reflecting the progression of BIPV research from early explorations in component replacement and energy efficiency enhancement to more recent focuses on system-level integration, multifunctional performance optimization, and the development of evaluation frameworks. The bibliometric analysis was conducted using the bibliometrix package in R and its graphical interface Biblioshiny, which enabled the generation of visualizations including annual publication trends, keyword co-occurrence networks, and thematic evolution maps.

B. Research Growth Trends and Publication Activity

To trace the developmental trajectory of BIPV research, this study analyzes the annual number of publications (N) and the mean number of citations per article (MeanTCperArt) from 2001 to 2025 based on data from the Web of Science Core Collection (Figure 1). The data reveal a three-stage evolution: an initial exploratory phase, a period of stable growth, and a phase of diversified expansion. Research activity and academic impact show clear phase-specific characteristics.

During the initial phase (2001–2010), annual publications remained in the single digits, generally below ten articles per year. However, the average citation frequency was relatively high, with notable peaks in 2006 (103.00) and 2011 (243.00), suggesting that some early foundational studies exerted substantial academic influence. Research during this period primarily focused on component substitution and basic integration strategies, laying a theoretical foundation for subsequent developments.From 2011 to 2017, the field entered a stable growth phase, with the number of publications steadily rising above 20 per year and peaking at 29 in 2016. Average citation frequencies remained strong—83.25 in 2012 and 84.17 in 2016—indicating broad attention from the academic and professional communities. This phase marked a shift from experimental validation to technological integration and performance optimization.

Since 2018, the field of BIPV research has witnessed a significant increase in publication volume. Between 2021 and 2024, the number of annual publications consistently exceeded 50, reaching a peak of 61 articles in 2022. This notable growth reflects the expanding application of digital modeling tools, AI-driven optimization techniques, and climate-responsive design methodologies. Despite this momentum, the rise in publication numbers was accompanied by a substantial decline in academic impact. The average number of citations per article dropped sharply—from 28.91 in 2018 to only 0.71 by 2025. This pattern points to an emerging imbalance between quantity and quality, raising concerns that many recent contributions have yet to gain scholarly traction. The underlying causes may include the fast pace of technological innovation, as well as persistent challenges in real-world deployment and validation.

In a broader sense, BIPV research demonstrates increasing dynamism, with scholarly attention progressively shifting toward the integration of multi-objective performance criteria and the exploration of diversified application contexts. Nevertheless, the uneven distribution of high-impact studies suggests that the field would benefit from more rigorous system modeling, enhanced cross-disciplinary and cross-scale collaboration, and a deeper emphasis on design-led inquiry. These directions are essential to steering the field toward a new phase characterized by higher research quality and stronger practical relevance.

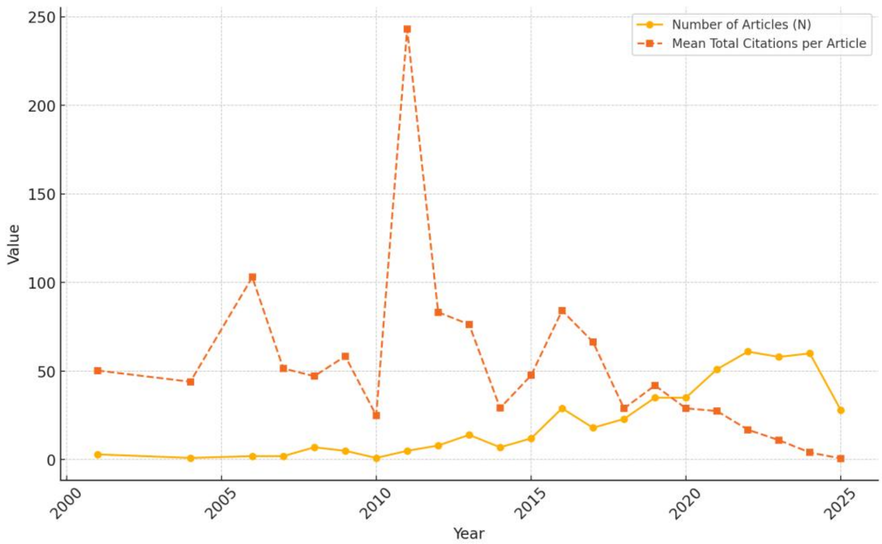

Figure 1. Annual Number of Publications and Average Citations per Article in BIPV Research (2001-2025).

In the field of Building-Integrated Photovoltaics (BIPV), citation frequency is commonly regarded as a key indicator of a publication’s academic influence and foundational contribution to the discipline. Figure 2 presents the ten most highly cited core publications in this research area worldwide. The study by Sadineni et al. (2011) stands out for its comprehensive assessment of the energy-saving potential of building envelopes. The authors proposed a series of structural strategies—including passive walls, green roofs, and high-performance windows—providing an early conceptual framework and material foundation for integrating BIPV systems into architectural structures [42]. Jelle et al. (2012) provided a systematic classification of BIPV product types. The review highlighted material innovation, structural durability, and visual integration as priorities for future progress. This work established a long-term research path for BIPV technology. It remains an important reference for standardizing products and guiding application trends in the field [43].

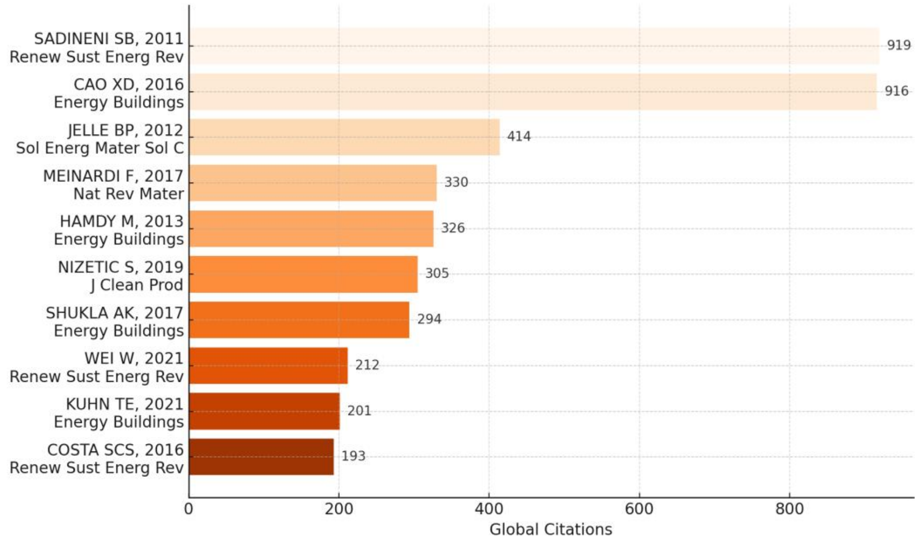

Figure 2. Top 10 Most Globally Cited Articles in BIPV Research (2001-2025).

Cao et al. (2016) analyzed global trends in building energy use from a macro energy systems perspective. They identified three core pathways to nearly zero-energy buildings (ZEB): passive design, high-efficiency systems, and renewable energy integration. Their framework places Building-Integrated Photovoltaics (BIPV) at the center of the shift to sustainable, energy-neutral architecture [44]. Highly cited work in this area now forms a knowledge base covering theory, construction methods, and system integration. These studies have shaped research approaches and technical directions in BIPV. They also provide key conceptual and practical guidance for ongoing progress in the field.

C. High-Frequency Keywords and Shifts in Research Focus

Figure 3 shows the median year for common keywords in BIPV publications. The data reveal a layered evolution of research themes. The field moved first from a focus on "structure" to "performance," and later from "system" and "simulation" to "environment." Between 2014 and 2018, keywords like "photovoltaic systems," "building envelope," and "life-cycle assessment" appeared most often. Early research concentrated on component integration, structural design, and assessing sustainability across a building's lifespan. After 2020, new themes became prominent. "Simulation," "comfort," and "performance" began to appear more frequently, indicating growing interest in thermal optimization and modeling how PV systems interact with building operations. Since 2022, keywords such as "prediction," "energy performance," and "cells" have emerged. This shift points to a new phase, with research focusing on artificial intelligence, detailed simulation, and high-efficiency PV technology development.

Figure 4 displays a word cloud of high-frequency keywords in BIPV research. The largest cluster—centered on "performance," "design," "system," "energy," and "simulation"—reflects the main research focus on optimizing building-integrated systems through design and simulation methods. Surrounding terms like "optimization," "thermal performance," and "energy performance" further emphasize the priority of efficiency and sustainability. More specialized keywords, such as "double-skin facade," "phase-change materials," and "life-cycle assessment," appear on the periphery, indicating that while innovative materials and component-level studies exist, most research is concentrated on integrated, system-level approaches. The visible clusters thus illustrate that the field is dominated by performance-driven strategies, with emerging interest in material innovation and specific building applications.

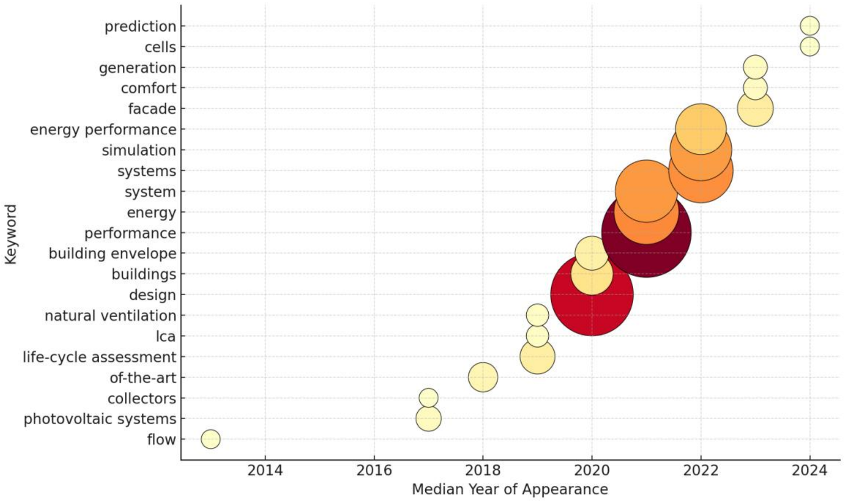

Figure 3. Keyword Evolution Trend in BIPV Research.

Figure 4. Distribution of High-Frequency Keywords in BIPV Research Literature.

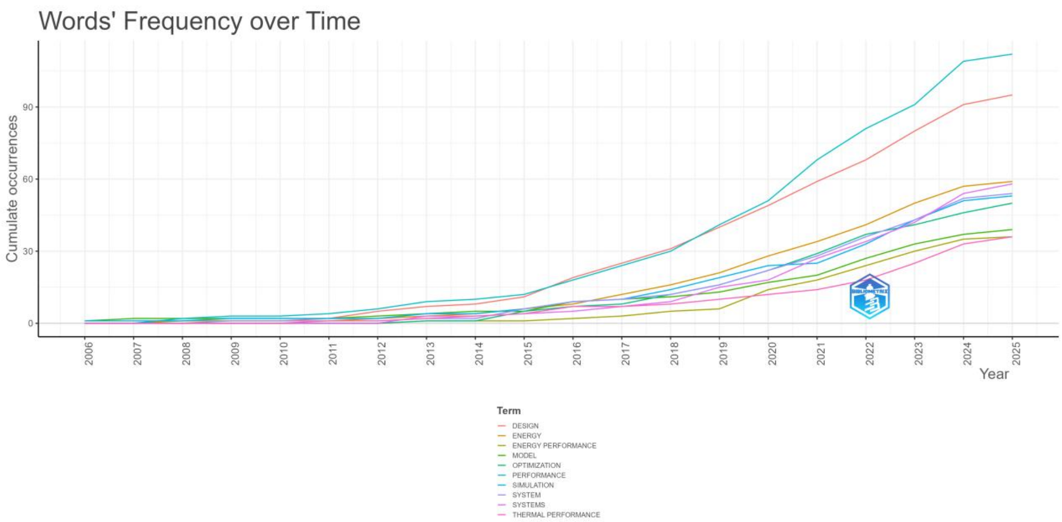

Figure 5. Temporal Evolution of High-Frequency Keywords in BIPV Research.

Figure 5 illustrates the cumulative frequency trends of major BIPV keywords from 2005 to 2025. "Performance," "design," and "energy" have shown a steady and consistent rise, maintaining their dominance in the field. Notably, "optimization" and "simulation" display a sharp increase starting around 2020, indicating a research shift toward computational modeling and multi-objective optimization in BIPV. Since 2022, "thermal performance" and "energy performance" have accelerated more rapidly than other terms, highlighting a recent surge in interest in thermal optimization and energy efficiency. These patterns reveal the evolving priorities in BIPV research, from broad performance metrics to more specialized and data-driven strategies.

Keyword changes in the BIPV field show a clear timeline and topic clusters. The focus has shifted from technical, component-level issues to integrated system optimization. Research now values coordination across thermal, structural, aesthetic, and environmental aspects, rather than just single-performance targets. This move from "structural substitution" to "high-performance integration" marks a turning point. The field is now moving toward intelligent simulation, integrated design, and climate-responsive strategies for future BIPV development.

D. *Evolutionary Pathways of Structural Types and Performance Dimensions in BIPV Research*

Figure 6 maps BIPV research themes by centrality and density. In the lower-right quadrant, core topics like "performance," "design," and "energy" cluster together, showing these are both central and mature in the field. The upper-right quadrant features themes such as "BIPV system" and "photovoltaic thermal-systems," highlighting ongoing innovation and the growing importance of system-level integration. Specialized but less central topics like "electrochromic windows" and "green facades" appear in the upper-left, while emerging or less developed areas—such as "impermeant" and "health"—are in the lower-left. The distribution illustrates that research is expanding from core performance and design issues toward new interdisciplinary and system-focused directions.

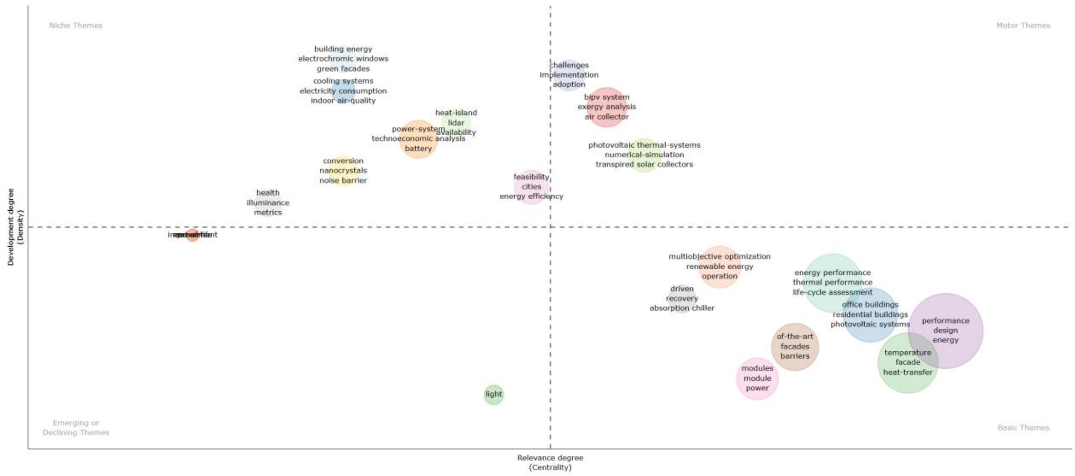

Figure 6. Thematic Structure Map of BIPV Research Keywords (Two-Dimensional Distribution of Centrality vs. Density).

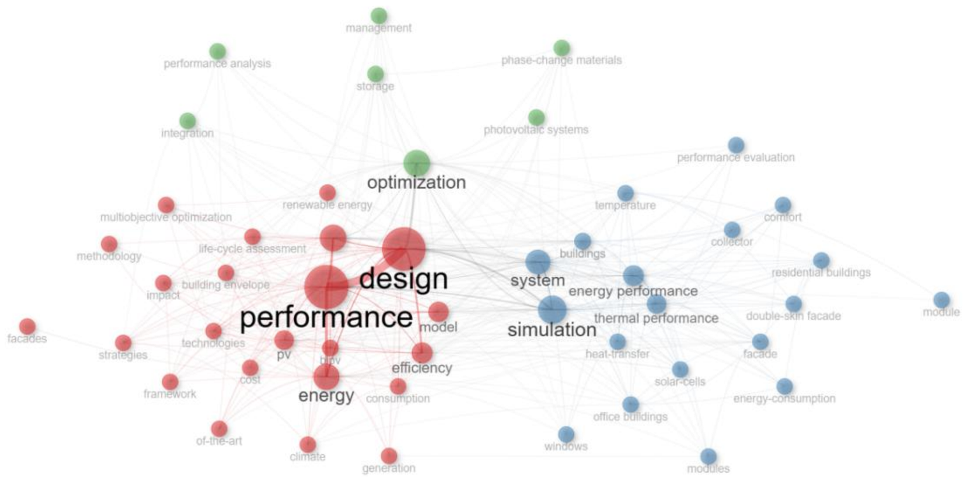

Figure 7. Co-occurrence Clustering Network of High-Frequency Keywords in BIPV Research.

Figure 7 presents a keyword co-occurrence network divided into three major clusters—red, blue, and green—each representing distinct research directions in BIPV. The central red cluster, dominated by "performance," "design," and "energy," forms the foundation of the field. This cluster extends outward to include high-frequency keywords such as "optimization," "life-cycle assessment," "building envelope," and "technologies," reflecting research that links BIPV system performance with design strategies, energy sustainability, and optimization methods. The close connectivity within this group illustrates an integrated approach that moves from design and construction to system evaluation, emphasizing multi-objective optimization and theoretical depth.

To the right, the blue cluster features terms like "simulation," "system," "thermal performance," "comfort," and "residential buildings." This group highlights the growing use of simulation tools for analyzing building operations, thermal management, and occupant comfort. The cluster's structure suggests a shift in BIPV research focus from simple energy efficiency to a broader concern for adaptive building operation, indoor comfort, and space-user interactions. System-level modeling and thermal performance now play a more prominent role in the field.

The green cluster, while smaller and more dispersed, contains keywords such as "storage," "management," "integration," "photovoltaic systems," and "phase-change materials." This group captures emerging and interdisciplinary research trends, focusing on advanced energy storage strategies, integrated management systems, and the application of innovative materials for improved system performance. Although less central, the green cluster points to future directions where BIPV is closely linked with broader energy management and material science innovations. Together, these clusters reveal the evolving structure of BIPV research: a solid core of performance and design, expanding into simulation-driven, occupant-centered studies, and reaching toward advanced integration and new technologies.

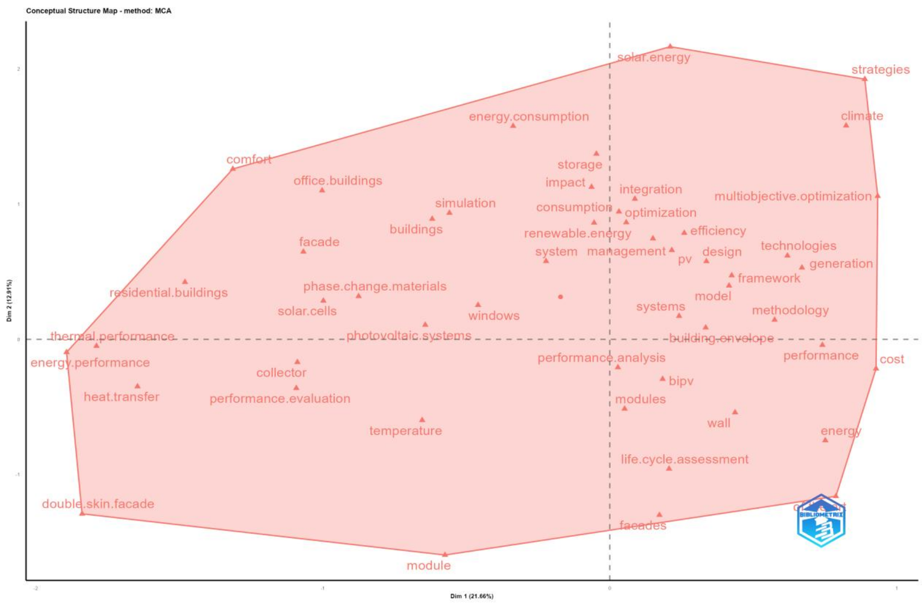

Figure 8. Conceptual Structure Map of Building-Integrated Photovoltaics (BIPV) Research (Based on MCA Method).

Figure 8 illustrates the conceptual landscape of BIPV research through Multiple Correspondence Analysis, plotting key terms along two major axes: from structural integration to performance evaluation horizontally, and from environmental responsiveness to strategy optimization vertically. This spatial arrangement reveals how the discipline's priorities have gradually evolved over time.

In the lower-left area, keywords such as "thermal performance," "energy performance," and "heat transfer" cluster together, pointing to the initial phase of BIPV studies that centered on physical properties and technical integration. These topics reflect a stage when researchers were primarily focused on component efficiency and solving engineering challenges at the interface of photovoltaic technology and building envelopes.

As research advanced, the thematic focus moved toward the center of the map, where terms like "simulation," "building envelope," and "photovoltaic systems" are found. This region marks the emergence of holistic approaches, connecting detailed performance analysis with broader design strategies. The emphasis here is on the integration of simulation and modeling as essential tools for optimizing system behavior, and on enhancing buildings' capacity to adapt to environmental variables.

In the upper-right quadrant, terms including "optimization," "integration," and "management" stand out. Their distribution reflects a newer direction in BIPV research, emphasizing system-level coordination, planning, and the pursuit of multi-objective solutions. Scholars in this area increasingly explore how BIPV can be integrated into building operations and energy management, balancing energy generation, operational flexibility, and user comfort within a single design framework.

Overall, this conceptual map highlights a shift in the field: from isolated studies of energy performance and thermal properties, toward more integrated and adaptive strategies that address the complexity of real-world buildings. Today, BIPV research not only considers technology and efficiency, but also seeks to optimize for environmental context, usability, and long-term sustainability across a range of building types.

4. System Integration Challenges and Limiting Factors

A. Technical Bottlenecks: Structural Coupling Complexity, Thermal Management Issues, and Insufficient Weather Resistance

Large-scale deployment of Building-Integrated Photovoltaic (BIPV) systems still faces major technical barriers. One key challenge is the complex structural coupling involved. This complexity makes it difficult to standardize and smoothly integrate BIPV components into building envelopes, unlike with regular construction materials. BIPV parts must take on multiple functions at once. They need to support structural loads, protect against the environment, and generate energy on-site. Integrating these elements into façades, roofs, or shading systems means meeting strict requirements for strength, fire safety, and waterproofing. Each step in design and installation must address issues like cable routing between modules, configuring electrical interfaces, and handling thermal expansion. These technical demands make BIPV system implementation much more complicated than traditional approaches [45].

Thermal management emerges as a particularly critical technical constraint contributing to the operational efficiency loss of BIPV systems. In typical façade- or rooftop-mounted scenarios, BIPV modules suffer from inferior heat dissipation compared to free-standing photovoltaic arrays, rendering them more vulnerable to the development of thermal "hot spots." These localized areas of elevated temperature can significantly degrade energy output and may even cause irreversible physical damage to the modules. Empirical studies have shown that BIPV components often operate at temperatures 15–20 °C higher than their stand-alone counterparts, resulting in efficiency losses ranging from 5% to 25% [46]. Although several active and passive cooling strategies—such as ventilated cavities and thermal exchange modules—have been proposed, their adoption in real-world engineering applications remains limited due to structural complexity and increased maintenance demands [47].

Weather resistance is also a key factor limiting the long-term performance stability of BIPV components. In regions with high humidity, elevated temperatures, and intense UV radiation, BIPV systems face increased risks of encapsulation failure, electrical degradation, and mechanical aging. Current standards are often developed separately by the photovoltaic and construction industries, leading to a regulatory gap. As a multifunctional composite component, BIPV is frequently marginalized and lacks dedicated testing protocols—such as wind pressure cycling, thermal shock, or water vapor permeability—which places it at a disadvantage during bidding and approval processes [48].

B. Economic and Market Constraints: Unstable Returns on Investment and Lack of Financial Instruments

Building-Integrated Photovoltaic (BIPV) systems face significant economic feasibility challenges in real-world implementation. One of the most prevalent barriers is the high initial capital investment. Compared to conventional building materials or traditional rack-mounted PV systems, BIPV products tend to incur substantially higher unit area costs, installation expenses, and custom development fees. According to relevant studies, the average upfront cost of BIPV systems is typically 40% to 60% higher than that of standard construction materials, and the payback period tends to be relatively long [49].

Economic constraints are not limited to high absolute costs but are also closely tied to the uncertainty of return on investment (ROI). In regions lacking clear electricity subsidies, mandatory quota systems, or feed-in tariff guarantees, the revenue models for BIPV-generated electricity are highly volatile. This instability significantly dampens the enthusiasm of developers and building owners to invest in such systems [45]. Even in regions with incentive mechanisms in place, factors such as policy volatility, gradually decreasing subsidies, and cumbersome approval procedures further undermine the economic appeal of BIPV systems.

In addition, the absence of tailored financial instruments represents another major barrier to BIPV adoption. Most commercial banks and green funds lack dedicated assessment models for BIPV projects, and the design of financing products remains underdeveloped. This makes it difficult to accurately evaluate the asset value derived from BIPV's dual function as both a power generator and a building component. The issue is particularly acute for small- and medium-sized real estate projects, where developers often struggle to secure supportive loans or adequate risk coverage [50].

From a market standpoint, Building-Integrated Photovoltaics (BIPV) remains in the early phase of its technological diffusion, and large-scale commercial demand has yet to fully materialize. A significant barrier lies in the limited awareness among architects, developers, and building owners, many of whom lack a comprehensive understanding of BIPV's performance benefits and applicable use cases. This knowledge gap results in high market education costs and contributes to hesitation in adoption. Compounding this issue is the underdeveloped nature of the current supply chain, which remains fragmented between technology providers and design service firms. The lack of integrated delivery platforms and cohesive product ecosystems further impedes the seamless adoption of BIPV solutions across the building industry [48].

C. Absence of Standards and Regulations: Lack of Unified Testing Systems and Integration Assessment

The promotion and widespread adoption of Building-Integrated Photovoltaic (BIPV) technology are constrained not only by technical and economic challenges but also by substantial gaps in the regulatory environment and the absence of standardized frameworks. As a hybrid solution that functions simultaneously as a building envelope component and an energy-generating system, BIPV occupies a long-standing regulatory gray zone—straddling the boundaries between architectural building codes and electrical engineering standards. This ambiguity contributes to policy delays, unclear permitting procedures, and institutional inertia, all of which represent major obstacles to streamlined project implementation. In many countries, BIPV has yet to be formally integrated into national or regional building codes. Critical performance attributes—such as structural load-bearing capacity, fire safety, water resistance, thermal performance, and long-term durability—still lack universally accepted testing protocols and evaluation benchmarks. While electrical certification standards for photovoltaic modules, such as IEC 61215 and IEC 61730, are widely adopted, regulatory systems addressing the building-specific characteristics of BIPV remain incomplete. For instance, although the EN 50583 standard series provides partial guidance, it does not yet offer a comprehensive framework for integrating BIPV into construction practices. Consequently, BIPV systems often encounter considerable challenges during building code compliance reviews and quality assurance inspections, further impeding their market penetration and deployment potential [46]. The uncertainty of approval processes further exacerbates institutional risk. Currently, BIPV systems typically require permits from multiple authorities—including housing and urban development, energy, fire safety, and electrical departments—without a unified coordination mechanism. This fragmented approach leads to low administrative efficiency, increasing both the time cost and unpredictability for developers. The fragmentation of policy frameworks results in significant regional disparities in the acceptance and implementation of BIPV projects, severely hindering large-scale replication and cross-regional deployment [45].

Instability in incentive policies has hurt market confidence. The profitability of BIPV projects relies on steady, predictable support. In many regions, policy measures change often, creating uncertainty. For example, Singapore’s Green Mark system uses credits to encourage green buildings, but BIPV is not part of any mandatory incentive program. This limits its market reach and slows mainstream adoption [51]. Policy categories rarely capture the full range of BIPV’s functions. For taxation, subsidies, and carbon asset calculations, BIPV is usually classified as standard photovoltaic equipment. This narrow view misses its value in material use, building integration, and visual design. As a result, financial incentives rarely match BIPV’s actual benefits. The gap between real value and policy recognition causes inefficiency, reduces private investment, and lowers developer interest [48].

D. Challenges in Design Collaboration

Building-Integrated Photovoltaic (BIPV) systems act as “power-generating building components” at the intersection of architecture, electrical engineering, and energy planning. This multidisciplinary nature adds complexity. Successful implementation depends on strong collaboration across sectors, especially early in the design process. In reality, lack of integrated professional systems and poor coordination often result in BIPV being overlooked during the crucial first stages of architectural planning. This results in insufficient component integration, weak performance synergy, and ultimately compromises both energy efficiency and architectural coherence. Architects, who typically shape key decisions related to spatial configuration, building orientation, and structural systems in the conceptual design stage, often possess limited knowledge of BIPV technologies—particularly regarding their functional parameters, material limitations, and integration methods. This gap largely stems from the lack of renewable energy content and specialized BIPV training in traditional architectural education. Consequently, photovoltaic modules are frequently perceived as peripheral additions rather than core, load-bearing, or envelope-integrated elements. Such a limited perspective severely constrains early-stage coordination in crucial aspects of BIPV performance, including façade planning, solar access optimization, and structural detailing.

In addition to professional and educational gaps, the lack of standardized software tools for BIPV design further constrains its applicability in practice. Most mainstream architectural design platforms—such as BIM, SketchUp, and Revit—offer only generalized modeling capabilities and do not include dedicated functionalities for BIPV-specific performance evaluation. Essential analyses, such as solar irradiation mapping, thermal flow modeling, and photovoltaic power generation forecasting, must therefore be conducted using separate, often incompatible tools. This fragmented workflow significantly increases the complexity of interdisciplinary collaboration and reduces overall project efficiency, presenting a substantial barrier to the widespread adoption of BIPV in integrated building design [51].

In cross-disciplinary collaboration, differing perceptions of BIPV’s value among stakeholders further exacerbate system fragmentation. Architects tend to focus on façade aesthetics and visual coherence, electrical engineers prioritize wiring logistics and power output, while project managers are mainly concerned with cost control and return on investment. Without effective communication frameworks or interdisciplinary coordination mechanisms, these misaligned objectives often lead to the BIPV system being sidelined or downgraded in the later stages of project development—ultimately reducing it to a marginal or purely decorative photovoltaic feature.

A major cognitive barrier remains among the public and building owners. BIPV systems are seen as complex and costly, often viewed as high-risk with limited returns. This impression grows worse because few high-profile demonstration projects exist and public education on BIPV is lacking. As a result, market acceptance stays low. Developers and design teams are reluctant to use BIPV early in project planning. This creates a cycle: low awareness leads to fewer decisions to implement, which in turn limits broader adoption [48]. Two main non-technical obstacles stand out: misconceptions about BIPV and weak interdisciplinary collaboration in design. Addressing these problems requires a broad approach. Four areas need focus—education and training, better design tools, improved cross-disciplinary communication, and more visible demonstration projects. These steps can build shared understanding, encourage early engagement, and support wider, integrated use of BIPV in sustainable construction.

5. Future Research Directions and Integrated Development Prospects

A. Intelligent Modeling and AI-Assisted Design

As Building-Integrated Photovoltaic (BIPV) technology moves toward more intelligent and adaptive solutions, older methods based on experience and scattered simulations no longer meet practical needs. Performance coordination is complex, and optimization cycles are frequent. Intelligent modeling and AI-driven design are gaining traction. Artificial intelligence now automates design, improves decision accuracy, and boosts multi-parameter optimization. The key lies in creating models that link architectural details, PV components, and environmental data in a single system. With this approach, factors like layout, orientation, area, shading, and wiring can be predicted and adjusted quickly. Artificial Neural Networks (ANN) map design choices to energy outcomes. Algorithms like NSGA-II balance goals for energy use, cost, and comfort, making traditional simulation less demanding. In one Melbourne housing project, this method cut design time by over 60% without sacrificing energy performance [52].

The deep integration of BIM and energy simulation platforms, such as PVSITES and EnergyPlus, enables the completion of BIPV component layout, shading analysis, and economic evaluation within a unified, visualized workflow. In a Swedish residential cluster project encompassing 18 layout scenarios, the BIM–PVSITES toolchain improved both the accuracy of solar utilization and lifecycle cost assessment [53]. Parametric modeling is widely used to optimize internal wiring and shading configurations within BIPV systems. Three-dimensional parametric geometric modeling, combined with high-resolution solar analysis and single-diode electrical modeling, is driven by genetic algorithms to evolve photovoltaic module wiring schemes. Under complex shading conditions, this approach reduces energy losses by 8% and enhances electrical compatibility between PV units [54].

The widespread adoption of design platforms such as Rhino–Grasshopper–Ladybug has further expanded architects' capabilities in modeling sunlight, thermal environments, and real-time performance analyses. The BiPVS project employs a multi-objective optimization process that balances metrics such as solar comfort, cooling load, and payback period, while interactive visual feedback offers stronger support for integrated architectural decision-making [55]. These platforms, with their strong scalability and user-friendliness, are particularly suitable for the repeated conceptual design iterations required in the early stages of BIPV projects. To address high-dimensional parameters, system nonlinearity, and multi-objective conflicts, a range of hybrid optimization methods have been employed. Large datasets generated through Monte Carlo simulations are used to construct surrogate models via random forest regression algorithms, after which the NSGA-II algorithm identifies Pareto-optimal solutions. In the case of office buildings, this approach has achieved a 40% reduction in carbon emissions, a 13.5% decrease in lifecycle costs, and a 2.4% increase in photovoltaic output [56]. Intelligent modeling and AI-driven design methodologies are profoundly reshaping the innovation logic of BIPV systems. Enhanced capabilities in performance prediction and real-time optimization are opening new pathways for the multi-objective coupling of building form, energy performance, economic viability, and aesthetics. As digital toolchains and computational power continue to advance, the entire process of BIPV—from spatial layout to adaptive energy control—will increasingly rely on integrated and intelligent design systems.

Beyond simulation and optimization, AI technologies are also being leveraged for predictive maintenance in BIPV applications. By analyzing real-time operational data and historical trends, machine learning algorithms can forecast equipment failures, schedule timely maintenance, and thus improve system reliability and reduce downtime. Furthermore, AI-enabled adaptive control systems dynamically adjust energy output, shading, and storage strategies in response to environmental fluctuations and building usage patterns, optimizing performance on a continual basis. In addition, AI-driven market forecasting tools are emerging to predict trends in BIPV component prices, policy impacts, and deployment potential, helping stakeholders make more informed decisions throughout the project lifecycle. These expanded applications highlight the broader value of AI in supporting not just the design phase, but also the operation, management, and long-term planning of BIPV systems.

In addition to simulation and optimization, AI is increasingly applied for predictive maintenance in BIPV systems. By analyzing real-time operational data, AI models can predict potential faults and help schedule timely repairs, which reduces system downtime and maintenance costs [57]. AI-based adaptive control systems further enable BIPV to automatically adjust energy flows and system settings for optimal performance and reliability [58].

B. *Synergistic Integration of BIPV with Urban Energy Networks*

As urban energy systems evolve toward decarbonization, decentralization, and digitalization, Building-Integrated Photovoltaics (BIPV) are no longer passive energy solutions confined to individual buildings. Instead, they are increasingly positioned as critical nodes within city-scale energy networks. Under the growing demand for resilient urban power systems and integrated management of “generation–grid–load–storage,” the role, deployment strategies, and interaction mechanisms of BIPV are undergoing a fundamental transformation.

BIPV systems inherently function as distributed energy resources, featuring high installation density and proximity to load centers. These attributes make BIPV ideally suited for the creation of “microgrid-based local energy systems” within urban building clusters, enabling on-site load balancing, reduced transmission losses, and mitigation of peak demand. Such a “building–community–distribution grid” synergy, structured around BIPV, is poised to become a foundational layer in next-generation urban energy infrastructures. Large-scale urban simulation studies have shown that when BIPV systems are intelligently coupled with medium/low-voltage distribution networks, overall building energy consumption can be reduced by up to 37.8%, demonstrating strong adaptability and supply stability across various climatic regions[7].

From the perspective of urban planning and façade utilization, BIPV deployment can significantly enhance the energy output capacity of building envelopes while integrating into the visual logic of urban landscape systems. Sun et al., through a comprehensive visual–energy–shading assessment of building skins along commercial corridors in Singapore, developed a 3D urban feasibility map for BIPV deployment. The results indicated that without compromising the visual coherence of the cityscape, approximately 62% of rooftops and 37% of south-facing façades could achieve efficient photovoltaic conversion, demonstrating considerable potential for widespread application in high-density urban areas [59].

The integrated promotion of BIPV also signals a shift in urban energy governance logic. BIPV is not merely a physical electricity-generating component—it serves as a tangible carrier for emerging energy governance models, such as community-level Virtual Power Plants (VPPs), city-scale energy autonomy frameworks, and energy digital twin networks. In pilot projects across several cities in North America and Europe, BIPV systems have been incorporated into "visible–controllable–tradable" distributed energy platforms. These platforms enable surplus electricity sharing between buildings and time-of-use pricing adjustments, significantly enhancing the flexibility and responsiveness of regional energy dispatch systems [60].

In urban energy networks, Building-Integrated Photovoltaic (BIPV) systems are not merely confined to serving as “energy-saving components” at the building level—their collaborative value extends to a much broader scope. In the future, the development of BIPV should focus on strengthening its integration with energy storage systems, electric vehicles, and smart grid platforms. At the same time, BIPV should be incorporated into the core infrastructure of urban renewal, spatial planning, and digital energy governance. This transformation will propel BIPV beyond the optimization of individual building performance, toward the coordinated evolution of urban energy systems, thereby fully unlocking its overall potential.

C. *Multi-Objective Performance Co-Optimization Pathways*

Building-integrated photovoltaic (BIPV) systems combine multiple functions: power generation, building envelope performance, environmental adaptation. Design optimization is complex. Goals often conflict. Key indicators include energy output, thermal comfort, return on investment, life-cycle carbon emissions. These metrics interact, raising the difficulty of integrated design. Multi-objective optimization (MOO) now stands at the research forefront. Tools include NSGA-II genetic algorithms, machine learning surrogate models, multi-performance simulation platforms. Suitable for early-stage BIPV design.

Khaki et al. applied a genetic algorithm with two objectives, studying BIPV/T systems under the climate of Kermanshah, Iran. The study set air quality and thermal efficiency as goals, tuning airflow and geometry. Annual average efficiency increased by 5.6%. Results highlight the need to consider both thermal and energy aspects in initial design stages [61]. Qiao et al. explored BIPV window system adaptation in five Chinese cities. Variables included building orientation, window size, visible transmittance, photovoltaic type. An NSGA-II model aimed to reduce both annual net electricity cost and initial investment. Payback periods ranged from 7 to 14 years, with electricity expenses dropping by up to 6.83%. Visual comfort, energy use, and economics can align in design [62]. Li et al. integrated BIPV/T with ground source heat pumps (GSHP), building a three-objective optimization: total energy use, life-cycle carbon emissions, overall cost. TRNSYS + jEPlus simulations showed energy use down by 50.05%, carbon emissions down 25.86%, economic gains up 61.66%.

Multi-source integration supports low-carbon building strategies [63]. Evidence shows BIPV optimization should not remain single-objective. Effective approaches require balance: energy, environment, economics. Future optimization tools may focus on transparent models, visual decision-making, human–machine collaboration. Architects may gain real-time, data-driven support in design choices.

D. Institutional Evolution and Policy Recommendations

Advancing Building-Integrated Photovoltaic (BIPV) systems from "cutting-edge technology" to "mainstream practice" relies not only on breakthroughs in component technology and the evolution of design tools but also—critically—on the maturity of institutional frameworks and the optimization of the policy environment. Addressing institutional and policy barriers such as fragmented incentives, lagging standards, and unclear regulatory pathways requires coordinated action across multiple levels.

At the policy level, a comprehensive, lifecycle-oriented support framework should be established. As direct subsidies gradually decrease, incentives should shift from one-off support to ongoing mechanisms, including green credit access, carbon reduction buyback schemes, and energy efficiency rewards. Encouraging developers to integrate BIPV at the early design stage and linking renewable energy ratios to green building certification will reinforce a positive cycle of incentives, performance, and accountability. Maintaining policy stability through annual roadmaps or updated guidelines is also crucial for boosting market confidence and supporting long-term planning.

In terms of regulation, it is essential to accelerate the standardization and certification framework for BIPV products. Mandatory technical standards—covering structural safety, thermal performance, electrical stability, and visible light transmittance—should be tailored to BIPV components. Clear classification and application boundaries within building codes will help resolve current ambiguities in project approval. Improving regulatory procedures should focus on establishing unified approval and filing systems, enabling shared processes among construction, power supply, and fire safety authorities. A dedicated service window for BIPV projects, along with digital regulatory platforms for full lifecycle tracking, can significantly enhance both transparency and efficiency in project administration.

Financial mechanisms must also evolve to support the scaling-up of BIPV. Establishing a dedicated BIPV Development Fund can provide stable support for long-term demonstration projects and reduce financial risks for investors. Further incentives—such as green loans, pay-for-performance models, and public–private partnerships—will help drive innovation and adoption throughout the industry. Education and capacity-building play a fundamental role in the mainstreaming of BIPV. Universities, design firms, and construction companies should strengthen BIPV-related training and continuing education, raising sector-wide awareness and technical competence. Enhanced professional training can support the industry's transition from niche demonstration projects to a widely adopted and sustainable practice. Coordinated actions at the policy, regulatory, financial, and educational levels are essential for removing institutional barriers and accelerating the large-scale implementation of BIPV. These efforts will help move the industry toward mainstream status and advance the broader objective of zero-carbon urban development.

Despite these efforts, several persistent barriers continue to impede the widespread adoption of BIPV. High initial investment costs remain a primary concern, particularly for small- and medium-sized projects lacking access to specialized financing. To address this, governments and financial institutions should develop risk-sharing mechanisms, such as guarantee funds or concessional loans, specifically tailored for BIPV deployments. The lack of unified standards and certification schemes creates uncertainty for both manufacturers and developers, often resulting in delays and increased approval costs. Accelerating the development of national and international BIPV standards—covering not only product performance but also integration methods and maintenance protocols—will provide a more predictable market environment. In addition, the limited knowledge and experience among architects, engineers, and contractors restricts the quality and effectiveness of BIPV integration in actual building projects. This challenge can be mitigated through targeted professional education, the incorporation of BIPV modules into architectural curricula, and the promotion of interdisciplinary collaboration across design and engineering fields. Finally, public awareness campaigns and high-profile demonstration projects can help to showcase the practical benefits of BIPV, shifting perceptions from experimental technology to reliable mainstream solution. Taken together, these targeted strategies form a comprehensive roadmap for overcoming current obstacles and enabling BIPV to fulfill its potential as a cornerstone of sustainable urban development.

6. Conclusion

This review demonstrates that Building-Integrated Photovoltaic (BIPV) systems have become a crucial component in advancing sustainable architecture, enabling buildings to achieve both improved energy performance and aesthetic integration. Through a combination of theoretical analysis and bibliometric methods, this study reveals that BIPV has evolved from a supplementary energy technology into a fully integrated architectural element capable of delivering structural, energy, and environmental benefits. Over the past two decades, the focus of BIPV research has shifted from simple structural integration to multi-objective performance optimization, with increasing attention given to intelligent modeling, AI-assisted design, and urban energy system integration. The diverse application of BIPV in roofs, façades, and shading devices illustrates its high flexibility and adaptability to different building types and climatic conditions. Despite these advances, BIPV adoption in practice remains challenged by technical complexity, high upfront costs, fragmented regulatory systems, and limited cross-disciplinary cooperation. Looking ahead, the deep integration of AI-driven design, collaborative workflows, and smart energy networks will be critical for overcoming these barriers. Unified standards, stable policy support, and enhanced interdisciplinary collaboration are essential to unlock BIPV's full potential. Ultimately, BIPV should be recognized not only as a renewable energy technology, but as a strategic link between architectural innovation, energy transformation, and sustainable urban development. The findings of this review offer valuable insights and practical guidance for future research, policy formulation, and the large-scale application of BIPV in green buildings.

For future research, more specific efforts are recommended to address current knowledge gaps and advance the practical application of BIPV. In particular, further studies could focus on the long-term performance and durability of emerging BIPV technologies such as transparent or bifacial modules under diverse climatic conditions. Additionally, in-depth investigations into integrated energy management systems—combining BIPV with energy storage and smart control at the building or district scale—would offer valuable insights into maximizing energy self-sufficiency and operational resilience. Attention should also be given to user-centric design approaches, evaluating how aesthetic integration and occupant perception influence acceptance and market uptake of BIPV systems. Finally, comparative research on the implementation of standardized regulatory frameworks and financial mechanisms across different regions could help to identify best practices and accelerate mainstream adoption. These targeted directions will help ensure that future advances in BIPV research are closely aligned with real-world challenges and opportunities.

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