Literature Review on Unitized Installation Technology for Building-Integrated Photovoltaic (BIPV) Curtain Walls

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Abstract

Building-Integrated Photovoltaic (BIPV) curtain wall systems constituted a transformative technology in the advancement of sustainable architectural design, serving the dual function of renewable energy generation and building envelope enclosure. This review article presented a systematic examination of 20 peer-reviewed studies published within the past five years, with a specific focus on the unitized installation technology of BIPV curtain walls. The scope of analysis encompassed several critical domains, namely performance evaluation across diverse climatic conditions, structural safety and seismic resilience, thermal and energy performance optimization, lifecycle economic assessment, long-term durability and reliability, and integration with intelligent building management systems. The review delineated notable advancements in the field, including climate-adaptive design methodologies, multi-objective optimization algorithms, and novel mounting solutions. Concurrently, the analysis revealed persistent research gaps, such as the absence of unified international design standards, elevated initial capital and maintenance expenditures, a deficiency in long-term empirical performance data under real-world operating conditions, and the inherent technical complexity associated with the integration of BIPV systems into smart building management systems (BMS). This synthesis was intended to furnish researchers and industry practitioners with a comprehensive understanding of the current state of knowledge, while delineating prospective research trajectories aimed at enhancing the efficiency, reliability, and broader adoption of unitized BIPV curtain wall systems.

Keywords: BIPV Curtain Wall; Unitized Installation; Performance Evaluation; Structural Safety; Smart Integration; Literature Review

Introduction

Rationale

The escalating global commitment to achieving carbon neutrality had necessitated the systematic integration of renewable energy technologies within the built environment (Balaras et al., 2021; Huang & Wen, 2021). In this context, Building-Integrated Photovoltaics (BIPV) have gained considerable scholarly and industrial attention as a viable strategy for converting building envelopes into active energy-generating surfaces (Kim & Kim, 2022). Among the various BIPV configurations, unitized curtain wall systems presented notable advantages, encompassing off-site factory prefabrication, enhanced installation efficiency, rigorous quality assurance, and improved architectural integration (Cai et al., 2022; Hasan et al., 2023). Nevertheless, the broader dissemination and adoption of unitized BIPV systems remained constrained by several persistent challenges, including performance variability attributable to diverse climatic conditions (Akbari et al., 2024), structural integrity concerns under extreme loading scenarios (Chen et al., 2025; Li & Wang, 2023), substantial capital and operational expenditures (Feng et al., 2024), and the inherent complexity of system integration with existing building infrastructure (Guo et al., 2025). Consequently, a rigorous and comprehensive understanding of the prevailing research landscape was indispensable for addressing these impediments and realizing the full technological and economic potential of unitized BIPV curtain wall systems.

Review Question

This review endeavored to address the following central research question: What were the principal technological advancements, prevailing challenges, and unresolved research gaps pertaining to the unitized installation technology of BIPV curtain walls, as evidenced by peer-reviewed academic literature published within the most recent five-year period?

Objective(s) of the Article

This study was guided by three principal objectives: (1) to conduct a systematic synthesis and critical analysis of contemporary research findings concerning the performance characteristics, structural safety, economic feasibility, and smart system integration of unitized BIPV curtain walls; (2) to delineate the predominant technical and economic barriers that impeded the widespread adoption of unitized BIPV systems; and (3) to identify salient research gaps within the existing body of literature and propose viable directions for future scholarly inquiry aimed at advancing the field.

Materials and Methods

Literature Review Approach

This study employed a systematic literature review methodology to ensure a rigorous and reproducible synthesis of the existing body of knowledge. The literature search was performed across established academic databases, including Scopus, Web of Science, and ScienceDirect, utilizing a predefined combination of search terms. The keywords employed comprised "BIPV," "unitized curtain wall," "installation technology," "performance evaluation," "structural safety," "smart integration," and "lifecycle cost." Boolean operators were applied to refine the search queries and maximize the retrieval of relevant scholarly publications.

Article Selection Criteria

The article selection process had been governed by four principal criteria. First, with respect to relevance, selected articles were required to address the unitized installation technology of BIPV curtain walls or closely associated domains, including system design, performance characterization, and structural analysis. Second, concerning timeliness, the review was restricted to peer-reviewed articles published between January 2021 and December 2025, thereby ensuring that the synthesis reflected the most contemporary state of scholarly knowledge. Third, in terms of impact, preferential consideration was accorded to articles disseminated in high-impact journals within the disciplines of renewable energy, building engineering, and sustainable construction. Fourth, regarding language, only articles published in the English language were eligible for inclusion. Through the application of these criteria, a final corpus of 20 articles was identified and subjected to in-depth analysis, collectively encompassing the full spectrum of research pertaining to unitized BIPV curtain wall systems.

Results

The systematic analysis of the selected literature revealed a multifaceted and evolving research landscape, which could be thematically categorized into four principal domains.

1. Performance Evaluation and Optimization

The body of research within this domain underscored the imperative for climate-adaptive design strategies in unitized BIPV systems. Akbari et al. (2024) provided empirical evidence of substantial performance variability across distinct climatic zones, thereby reinforcing the necessity for location-specific optimization protocols. Ali & Ibrahim (2023) applied the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to formulate a multi-objective optimization framework that reconciles thermal comfort with energy generation, yielding a model capable of balancing occupant well-being against photovoltaic output. Kim and Kim (2022) conducted a complementary investigation into the thermal and electrical performance optimization of BIPV unitized configurations, advancing strategies for the enhancement of aggregate energy yield. Majumdar & Saini (2022) undertook a parametric analysis targeting the simultaneous improvement of daylighting penetration and energy capture, thereby furnishing practitioners with quantitative insights for integrated design objectives. Qi et al. (2023) performed a comparative evaluation of ventilated and non-ventilated system configurations, concluding that the incorporation of ventilation cavities substantially augmented both thermal regulation and electrical generation efficiency under specific operational conditions. Furthermore, Huang and Wen (2021) assessed the performance characteristics of unitized BIPV façades subjected to varying environmental loading scenarios, establishing critical baseline data for subsequent performance benchmarking endeavors. It should be noted that the performance evaluation of BIPV modules reviewed in these studies should be benchmarked against established international standards, specifically IEC 61215 (Terrestrial Photovoltaic Modules – Design Qualification and Type Approval), which defines the testing procedures for assessing module durability and reliability under simulated environmental stresses, and IEC 61853 (Photovoltaic Module Performance Testing and Energy Rating), which provides standardized methodologies for measuring module efficiency and energy yield under diverse operating conditions. The adoption of these standards as a consistent evaluation framework would facilitate more rigorous and comparable assessments of BIPV module performance across the studies reviewed herein.

2. Structural Safety and Installation Technology

The assurance of structural integrity constituted a fundamental prerequisite for the deployment of unitized BIPV curtain wall systems. Chen et al. (2025) conducted an investigation into the seismic performance of unitized PV curtain wall assemblies, determining that while prevailing design configurations demonstrate adequate resistance, connection interfaces necessitated reinforcement, and the development of standardized seismic design guidelines remained an unresolved need. Notably, a review of major international structural codes revealed that current provisions do not explicitly address the seismic design of unitized BIPV curtain wall assemblies. Specifically, ASCE 7-22 (Minimum Design Loads and Associated Criteria for Buildings and Other Structures) provides general requirements for nonstructural components but lacks BIPV-specific clauses; EN 1998 (Eurocode 8: Design of Structures for Earthquake Resistance) addresses curtain wall anchorage without differentiating photovoltaic-integrated panels; and JIS A 1414 (Performance Evaluation of Curtain Walls) focuses on conventional curtain wall testing without accommodating the additional mass and electrical connectivity requirements of BIPV modules. This absence of dedicated provisions across multiple regulatory frameworks confirms that the identified gap reflects both a genuine lack of technical provisions and an unresolved need for international harmonization. Li & Wang (2023) examined wind load resilience, corroborating satisfactory structural performance across most geographical regions while concurrently identifying the absence of prescriptive design standards for extreme aeolian events, such as typhoon-induced loading. Cai et al. (2022) and Müller & Haas (2024) explored modular and prefabricated construction approaches, demonstrating that such methodologies enhanced installation adaptability and substantially reduce on-site construction duration, notwithstanding the attendant increase in initial capital expenditure. Hasan et al. (2023) provided a comprehensive review of innovative mounting technologies that improve both installation efficiency and on-site safety, thereby addressing a key practical implementation challenge. Das and Raj (2023) contributed a computational design and simulation study of BIPV unitized façades for high-rise building applications, elucidating specific challenges associated with maintenance accessibility at elevated heights. Additionally, Jiang and Liu (2024) proposed a design-for-maintainability framework for unitized BIPV curtain walls, emphasizing the critical importance of lifecycle serviceability considerations within the broader installation planning process.

3. Economic and Environmental Impact

The economic feasibility of BIPV systems represented a decisive determinant of market adoption and scalability. Feng et al. (2024) conducted a lifecycle cost analysis (LCCA) of unitized BIPV curtain walls, reporting favorable long-term financial returns; however, the extended payback periods identified continued to constitute a substantial impediment to investment. Specifically, the LCCA data reported by Feng et al. (2024) indicated an initial capital cost premium of approximately 35–45% compared with conventional curtain wall systems, an estimated payback period of 12–15 years under standard grid electricity pricing assumptions, an internal rate of return (IRR) of 6.8–8.2%, and a net present value (NPV) of USD 120–180 per m² over a 25-year project lifespan. Annual operation and maintenance costs were estimated at 1.2–1.8% of the initial investment. These quantitative indicators, while demonstrating long-term economic viability, underscored the sensitivity of financial returns to energy pricing policies, government incentive structures, and regional solar irradiance levels. Zhang et al. (2024) directed their investigation toward system performance under coastal environmental conditions, a context in which durability challenges and maintenance expenditures were exacerbated by salt-induced corrosion mechanisms. González and Bernardo (2022) examined the durability and long-term operational performance of PV modules integrated within unitized curtain wall assemblies, contributing empirical evidence on degradation trajectories and module reliability across extended service periods. With regard to environmental considerations, although BIPV systems inherently confer environmental benefits through the reduction of fossil fuel dependency, the research of Balaras et al. (2021) demonstrated their appreciable positive contribution to the mitigation of building cooling and heating loads, while simultaneously noting that the indirect implications for indoor air quality remained insufficiently investigated and warranted further scholarly attention.

4. Intelligent Technology Integration

The convergence of BIPV technology with intelligent building management systems constituted a rapidly expanding area of scholarly inquiry. Guo et al. (2025) and Lu et al. (2025) investigated strategies for the integration of unitized BIPV modules with advanced building automation platforms and sensor networks, facilitating real-time performance monitoring and the implementation of predictive maintenance protocols. Notwithstanding these advancements, such integration introduced considerable technical complexity and necessitated specialized interdisciplinary expertise, thereby creating a notable barrier for architectural and engineering professionals who lack proficiency across both domains. Song & Cao (2025) proposed an integrated structural and energy modeling framework, representing a significant progression toward a more holistic and unified design methodology for intelligent BIPV façade systems.

Discussion: Analysis Table and Information for Research

Table 1 presented a consolidated summary of the principal findings and identified research gaps derived from the reviewed body of literature, systematically organized according to the four thematic domains established in the preceding section.

Table 1 Summary of Key Findings and Research Gaps in Unitized BIPV Curtain Wall Studies

Theme	Key Findings from Literature	Identified Research Gaps
Performance Evaluation	System performance exhibited substantial variability across climatic zones (Akbari et al., 2024). Multi-objective optimization methodologies demonstrably enhanced thermal comfort and energy output (Ali & Ibrahim, 2023). Ventilated configurations yielded measurable improvements in thermal and electrical performance (Qi et al., 2023).	Insufficient availability of long-term empirical performance data under extreme climatic conditions. Inadequate consideration of indirect environmental impacts, including indoor air quality. Absence of standardized performance evaluation metrics.
Structural Safety	Seismic performance was deemed adequate; however, connection interfaces required reinforcement (Chen et al., 2025). Wind load resilience was satisfactory across most geographical regions (Li & Wang, 2023). Modular and prefabricated design approaches enhanced installation efficiency (Cai et al., 2022; Müller & Haas, 2024).	Absence of internationally accepted seismic design guidelines specific to BIPV systems. Elevated initial capital costs of modular components constitute a significant adoption barrier. Limited scholarly investigation into maintenance accessibility for high-rise applications (Das & Raj, 2023).
Economic Impact	LCCA demonstrated favorable long-term returns, albeit with extended payback periods (Feng et al., 2024). Coastal environmental conditions exacerbated durability concerns and elevated associated maintenance costs (Zhang et al., 2024).	Considerable uncertainty persists in the forecasting of future energy pricing and policy incentive structures. Absence of standardized protocols governing LCCA methodologies for BIPV projects.
Smart Integration	Integration with BMS facilitated intelligent energy management and real-time system monitoring (Guo et al., 2025; Lu et al., 2025). Integrated structural-energy modeling frameworks emerged as a nascent research direction (Song & Cao, 2025).	Elevated technical complexity and prohibitive costs associated with sensor network deployment impeded widespread adoption. Requirement for specialized interdisciplinary expertise constituted a significant barrier for industry practitioners. Absence of interoperability standards governing the interface between BIPV systems and BMS platforms.

Conclusions

This systematic literature review, encompassing 20 peer-reviewed studies published within the preceding five-year period, furnished a comprehensive synthesis of the prevailing state of scholarly knowledge pertaining to unitized BIPV curtain wall installation technology. The consolidated findings substantiated notable advancements across three principal research domains: performance optimization methodologies (Akbari et al., 2024; Ali & Ibrahim, 2023; Kim & Kim, 2022; Majumdar & Saini, 2022; Qi et al., 2023), structural integrity analysis (Chen et al., 2025; Li & Wang, 2023), and intelligent system integration (Guo et al., 2025; Lu et al., 2025; Song & Cao, 2025). Notwithstanding these advancements, four overarching challenges of critical significance persisted and collectively delineated the most pressing areas warranting sustained research attention and technological development.

First, the absence of internationally recognized and harmonized standards governing the design, installation, and performance evaluation of unitized BIPV systems engendered inconsistencies in industry practices and impedes cross-border collaboration and knowledge dissemination (Chen et al., 2025; Li & Wang, 2023). Second, the aggregate burden of initial capital investment and lifecycle maintenance expenditures remained prohibitively elevated for a considerable proportion of construction projects, thereby substantially constraining market penetration, particularly within cost-sensitive regions and developing economies (Cai et al., 2022; Feng et al., 2024; Müller & Haas, 2024). Third, a pronounced deficiency existed in the availability of empirical, longitudinal performance data concerning module durability, degradation trajectories, and overall system reliability under real-world, heterogeneous environmental stresses (González & Bernardo, 2022; Huang & Wen, 2021; Zhang et al., 2024). Fourth, the technical integration of BIPV systems with intelligent building management platforms presented formidable challenges that necessitated specialized interdisciplinary competencies, constituting a significant impediment to the broader architectural adoption and mainstreaming of this technology (Guo et al., 2025; Lu et al., 2025; Song & Cao, 2025).

Future Work

The successful large-scale deployment of unitized BIPV curtain wall systems was contingent upon the systematic resolution of the identified research gaps through sustained and coordinated collaborative endeavors encompassing academia, industry stakeholders, and governmental policy-makers. In light of the findings synthesized in this review, future research initiatives should have accorded priority to the following strategic directions: (1) the formulation and promulgation of internationally harmonized design, installation, and performance evaluation standards to ensure cross-jurisdictional consistency and facilitate global knowledge transfer (Chen et al., 2025; Li & Wang, 2023); (2) the advancement of costeffective, high-durability materials and innovative mounting solutions capable of reducing both capital expenditure and long-term maintenance burden (Cai et al., 2022; Hasan et al., 2023; Müller & Haas, 2024); (3) the establishment of comprehensive longitudinal monitoring programs for the systematic collection and analysis of real-world performance data pertaining to module degradation, system reliability, and environmental resilience (González & Bernardo, 2022; Huang & Wen, 2021; Zhang et al., 2024); and (4) the development of streamlined integration frameworks and interoperability protocols to reduce the technical complexity inherent in coupling BIPV systems with intelligent building management platforms (Guo et al., 2025; Lu et al., 2025). Through the progressive resolution of these challenges, unitized BIPV technology was positioned to fulfill its considerable promise as a foundational element of sustainable, energy-positive building design in the broader context of global climate change mitigation.

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