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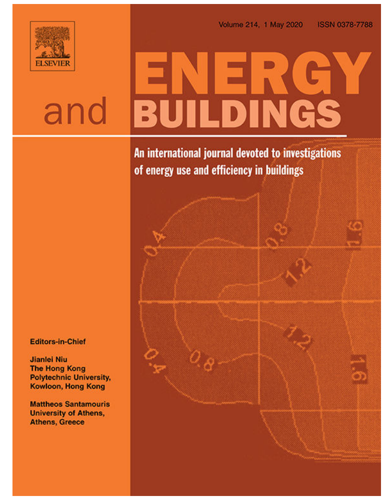

Invited Review Article

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Active prefabricated façade with building-integrated photovoltaic (APF-BIPV) technologies for high energy efficient building renovation: a systematic review of recent research advancements

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Active prefabricated façade with building-integrated photovoltaic (APF-BIPV) technologies for high energy efficient building renovation: a systematic review of recent research advancements

Abstract

Active Prefabricated Façade with building-integrated photovoltaic (APF-BIPV) technologies used in the prefabricated building envelope component offer a promising approach to energy-efficient building renovation, combining renewable energy generation with modular construction advantages. This study systematically reviews APF-BIPV technologies, assessing their technological development, performance optimization, economic feasibility, and policy implications. Based on PRISMA methodology, the review includes not only peer-reviewed publications from Scopus and Web of Science but also analyzes research outputs from European-funded projects, highlighting the significant technological advancements that have transformed prefabricated façade components from basic cladding systems into highly integrated, multifunctional building elements, integrating PV technology for renewable energy production. This systematic review study shows that the combination of PV integrated in modular prefabricated construction holds significant future relevance, offering a dual benefit: reducing the energy consumption while promoting energy self-sufficiency in buildings. Over the past decade, the number of research publications on Active Prefabricated Façades (APF) has increased by approximately 3.5 times across the Scopus and Web of Science databases, demonstrating the significant potential of this technology. At the same time, APF-related projects in Europe have been strongly supported and promoted through funding schemes and policy initiatives. The integration of PV systems in modular prefabricated construction represents a strategic win-win collaboration between research and industry projects, where academic innovation meets practical application. This research aims to establish a reference framework for innovation in the field of active prefabricated envelope systems, offering a comprehensive overview of current technologies, integration strategies, and emerging trends.

Keywords:

Active prefabricated façade, BIPV, Prefabricated panels, Off-site construction, Bibliometric analysis, Building modular technology, Building renovation, Building energy efficiency.

Nomenclature

APF	Active Prefabricated Façade
PPF	Passive Prefabricated Façade
PV	Photovoltaics
BIPV	Building Integrated Photovoltaics
APF-BIPV	Active Prefabricated Façade with Building Integrated Photovoltaic
BIPV/T	Building Integrated Photovoltaic/Thermal
BIPV-dPCM	Double-PCM BIPV
T-BIPV	Transparent BIPV
ST-BIPV	Semi-Transparent BIPV
EPBD	Energy Performance of Buildings Directive
NZEB	Nearly zero energy buildings
SCH	Solar Honeycomb
PCM	Phase change material
a-Si	Amorphous Silicon
c-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
OSC	Off-site construction
BIM	Building Information Modelling

AAF	Advanced Active Façade
ASF	Active solar façade
LCA	Life Cycle assessment
LCCA	Life Cycle Cost assessment
TLCC	Total Life Cycle Costs
SSR	Self-Sufficiency Rate
GWP	Global Warming Potential
EPBT	Energy Payback Time
GHG	Greenhouse Gas
UST	Unglazed Solar Thermal
PVT	Photovoltaic-Thermal solar
IEQ	Indoor Environmental Quality

1 Introduction

The building industry is responsible for nearly 39% of global carbon dioxide emissions, including both operational energy use and emissions generated during construction and material production [1,2]. Given the rapid pace of urban growthand the related ingrease of global energy demands, the building sector is progressively opting for sustainable solutions, especially in renovation, to improve energy efficiency and reduce environmental impact. The European building stock is of particular significance in the context of decarbonisation strategies, given its substantial age and poor efficiency [3]. Approximately 75% of buildings within the European Union do not comply with minimum energy performance standards [4], revealing a significant gap between the existing stock and the energy efficiency benchmarks required for climate targets. Furthermore, approximately 40% of the building stock was constructed before 1970 [5], indicating a significant proportion of low energy-efficient buildings. Achieving carbon neutrality in the building sector necessitates considerable efforts to reduce building energy consumption and promote technological innovation [6]. In this context, building facades are of critical importance, as they account for up to 70% of a building's thermal load [7]. Consequently, innovative façade systems have assumed increasing importance in the development of sustainable built environments, particularly in the context of building renovation. Among these, prefabricated façade panels have gained significant attention in recent years for their applicability in façade retrofitting projects, offering faster project delivery, improved quality, cost efficiency, reduced on-site disruption, enhanced safety and increased flexibility and scalability, making it a compelling alternative to traditional construction methods. Moreower the use of prefabricated façade, belonging to the off-site construction method, contribute to the reduction of the embodied carbon, minimize disruption to building occupants during building retrofitting, and significantly enhance overall building energy performance [8]. When integrated with active energy technologies such as building-integrated photovoltaics (BIPV), prefabricated façade panels transition from traditional passive structural elements to active prefabricated wall technology. Such a type of façade has been denoted within this research as APF (Active Prefabricated Façade), being able to reduce dependence on external energy sources and improve "actively" the energy efficiency through the onsite electrical generation from PV [9]. APFs are characterized by their integration of energy harvesting, energy-saving, or smart control technologies into prefabricated building façade panels to enhance the overall performance of the building. Conventional passive prefabricated panels primarily provide insulation and finishing functions; APFs, in contrast, actively participate in a building's energy balance, producing energy from renewables. These systems facilitate on-site electricity generation, thereby enhancing the thermal regulation of the building envelope, leading to a reduction in heating and cooling demands [10]. The prevailing focus of contemporary research endeavors is on the integration of active energy technologies into prefabricated façade systems. In particular, prefabricated panels incorporating renewable energy systems, such as BIPV modules, solar thermal collectors [11], mechanical ventilation with heat recovery, and smart energy management systems [12] have emerged as promising technological pathways to address these challenges. In addition to these approaches, some studies have explored the combination of prefabricated components with smart monitoring technologies and advanced materials to further optimize overall building performance. Regulatory developments have also played a significant role in driving innovation. For instance, the European Commission mandates that all new public and commercial buildings must integrate photovoltaic systems by 2026, with residential buildings to follow by 2029 [13]. This regulatory framework indicates BIPV-integrated prefabricated façades as a compliant and forward-thinking solution. The Energy Performance of Buildings Directive (EPBD) further reinforces these requirements by mandating that all new buildings must comply with zero-carbon emission standards, and explicitly defines renewable energy technologies, including active façade panels, as central components in future building design and functionality [14]. Accordingly, the objective of this study is to systematically analyze recent developments in Active Prefabricated Façade (APF) technologies, with a particular emphasis on the integration of photovoltaic (PV) systems into prefabricated building envelope components, referred to in this study as APF-BIPV (Active Prefabricated Façade with Building-Integrated Photovoltaics).This study utilizes a comprehensive review of relevant literature published over the past decade in the most relevant database such as Scopus and Web of Science databases, and incorporates findings from selected EU-funded projects, to i) summarize emerging trends in integration technologies, ii) application contexts, iii) innovation domains, and iv) performance evaluation methods. The primary contribution of this research lies in its role as a critical link between predominantly theoretical and simulation-based studies and practical applications. This study integrates a systematic literature review with empirical data derived from real case studies funded under European Union (EU) research projects, providing a comprehensive evaluation of the development trajectory and key challenges associated with APF-BIPV.Furthermore, it underscores the current absence of comprehensive research addressing the integration of BIPV with prefabricated façade systems, despite the technological advancement of PV technologies. A critical review of academic and project-based studies was conducted to provide an evidence-based overview of the current state of research on PV-integrated prefabricated panels. Although previous reviews have addressed various aspects related to the prefabricated wall technologies with a high interest in the thermal insulation aspects, this study aims at mapping the research advancement regarding the coupling of prefabricated wall panel technologies with active systems such as PV. Within this context, the availlbale literature on active prefabricated façades, especially those regarding BIPV, demonstrates notable progress in incorporating solar technologies into building envelopes, while also highlighting several persistent challenges. Review articles serve as an effective means of synthesizing and evaluating existing studies. Therefore, a comprehensive analysis of prior review papers in this domain is essential to clearly define the scope and research focus of this study. Existing review studies on APF-BIPV can generally be categorized into two main types: the first type adopts a technology-oriented perspective, focusing on aspects such as BIPV materials, PV cell types, and system performance; the second type emphasizes design strategies, architectural integration, and construction-related issues associated with BIPV implementation. Zhang et al. review the energy performance and life-cycle assessment of BIPV systems, which focus on it's the integration in buildings [15]. Similarly, the review by Romani et al. also approaches the topic from the perspective of material composition, focusing specifically on two types of building-integrated photovoltaics: transparent and semi-transparent BIPV (T- and ST-BIPV). The study analyzes and summarizes these systems in terms of cell efficiency, cost, service life, and potential applications, enabling designers to directly compare the advantages and limitations of different BIPV systems [16]. Yu et al. presents a review on façade-based building integrated photovoltaic-thermal (BIPV/T) development and focuses on the designs of integrated solar systems with building façades and its influence on electricity generation, thermal performance of PV cells, and energy consumption of buildings for space heating and cooling, which is useful for researchers and engineers to select appropriate BIPV/T designs for renewable energy application in buildings [17]. Lopez et al. focus on integrating BIPV technologies in architectural heritage, emphasizing conservation, energy benefits, analyzing case studies rather than reviewing existing literature in the specified field[18]. D'Ambrosio et al. review systematising criteria for assessing the integrability of BIPVs in architecture and developing BIPV products and case study catalogues for design methods [19]. Based on the analysis of existing review articles, it is evident that many studies have focused either on BIPV technologies or on the application of BIPV in specific building types. However, few reviews have addressed the integration of BIPV into prefabricated building façade panels, and none have analyzed the research advancements reported in EU-funded projects. Since BIPV systems function as inherently prefabricated cladding components, their use in off-site façade panel construction can significantly improve the integration and efficiency of building renovation processes.Therefore, this review aims to provide a systematic analysis of APF-BIPV through a combination of bibliometric and application-based approaches, offering acomprehensive synthesis of their development potential, application prospects, and existing limitations.

1.1 Aims and objectives

To facilitate the application of APF-BIPV for building renovation, it is essential to provide comprehensive information on current research trends, key focus areas, performance characteristics, technological applications, and implementation challenges. Therefore, this review aims to fill the existing gap in the literature by conducting an updated and in-depth analysis of studies and projects related to APF-BIPVof the last 10 years. The objective is to establish a shared information base that supports future research by systematically collecting, analyzing, summarizing, and evaluating the major achievements to date, while also identifying existing challenges and limitations in the field. To achieve the main objectives of this study and address the research questions, the paper is structured into five main parts. The first part introduces the topic and outlines the aims and objectives of the study. Section 2 describes the research methods and techniques used for the analysis. It presents the research methodology and outlines the data collection methods employed in the analysis, including the review strategy, inclusion and exclusion criteria, and decision-making procedures. Section 3 presents a bibliometric analysis of the existing literature, focusing on authorship trends, geographical distribution, and publication dynamics, followed by a discussion of the key findings. This section investigates both theoretical studies from the inclusion step and practical insights from selected EU-funded research projects. The analysis includes background context, key innovative technologies, applied optimization techniques, and optimization objectives. By integrating findings from both academic research and practical implementations, this part provides strategic technical guidance not only for researchers and policymakers but also for BIPV producers and construction stakeholders. Section 4 explores the integration of Building-Integrated Photovoltaics (BIPV) into Active Prefabricated Façades (APF), particularly in the context of building retrofitting. This section includes: i) an overview of APF-BIPV technologies and applications; ii) an analysis of EU-funded research projects in this domain; iii) life Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) considerations; iv) integration technologies and strategies; v) barriers and challenges associated with BIPV adoption. Section 5 concludes the paper by summarizing key findings and highlighting areas for future research. This structured approach ensures a comprehensive analysis of BIPV applications in building façade panels for building renovation, highlighting current research hotspots, effective strategies, tools, and techniques, and offering valuable insights for future research and practical implementation.

2 Methods and techniques

This section outlines the structured methodology adopted to investigate and explore current scholarly researches on active prefabricated wall panel technology, including BIPV. In order to address the limitations of purely academic research, which often lacks insights into the actual construction and assembly processes of real-world projects, this study incorporates a systematic review of funded projects (Figure 1).

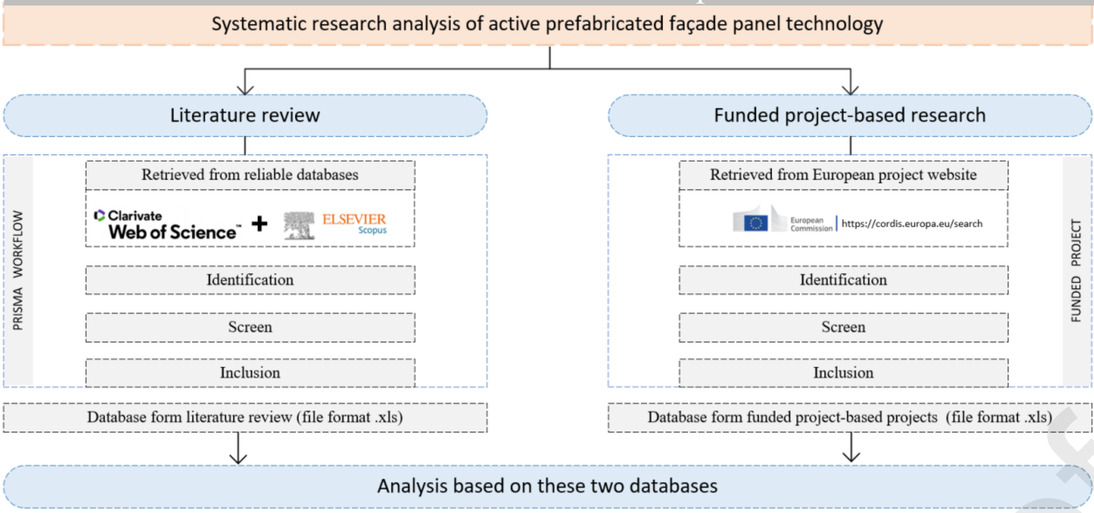


Figure 1: Methodological scheme of the systematic research (Source: Author self-painted)

The initial review involves a mapping process, which is divided into two sub-steps: i) literature review and ii) analysis of funded projects. Information gathered in each sub-phase is systematically reviewed, and the results are mutually refined and supplemented to ensure a comprehensive understanding of the research domain. Subsequently, a knowledge management phase is conducted. The literature review provides insights into research interests, trends, geographical distribution, and researcher collaboration networks. The analysis of funded projects identifies best practices, offering a foundation for practical integration of APF-BIPV in building. To define the current trends, characteristics, and potential applications of BIPV integrated in off-site construction wall technologies for building renovation, a systematic literature review has been performed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) approach. PRISMA method [20] combines a systematic review with a meta-analysis. The former is used to obtain a holistic picture of a particular topic, while the latter is used to summarize empirical studies and provide interesting results that allow a quantitative analysis. At the outset of the investigation for the literature review sub-step, a set of search terms was developed and deployed to gather data from the well-established literature repositories, namely, Scopus and Web of Science (WoS). The search terms employed in this study consisted of related keywords combined with Boolean operators (Boolean operators are logical connectors such as AND, OR, and NOT used to combine or exclude keywords in database searches, helping to refine and control the search results). The defined set of keywords, as identified in Figure 2, was identified starting from the decomposition of the problem into four main pillars: the construction method, the investigated technologies, the scope of the technology, and the type of application.

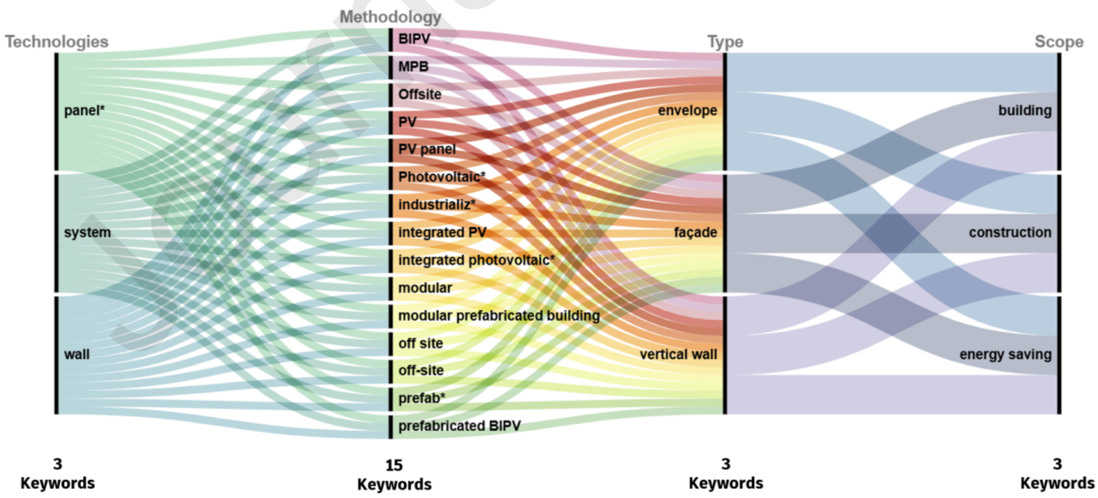


Figure 2: The keywords defined for the search query (Source: Author self-painted)

As shown in Figure 3, the PRISMA flowchart illustrates the systematic selection process of the reviewed studies, ensuring the transparency and rigor of the literature review. During the identification phase, a total of 5,589 records were retrieved from academic databases, including 3,719 from Scopus and 1,870 from Web of Science. After the removal of 1,009 duplicate records, the remaining 4,480 records proceeded to the screening phase, where 4,179 were excluded based on relevance, research focus, or quality criteria (

Table 1). Subsequently, 301 reports were sought for retrieval, but 11 could not be accessed, leaving 254 studies for eligibility assessment. At this stage, further exclusions were applied based on relevance and content quality, resulting in a final selection of 103 publications for inclusion step. Additionally, 45 EU-funded projects were identified from organizational sources. Following further assessment, a total of 18 highly relevant funded projects were included in the eligibility assessment. After this rigorous screening process, a total of 103 studies were included in the final review, supplemented by 18 additional funded projects, ensuring the comprehensiveness and high quality of the research dataset. In the final inclusion phase, only the papers that would provide a clear description of the investigated APF-BIPV technology were included.

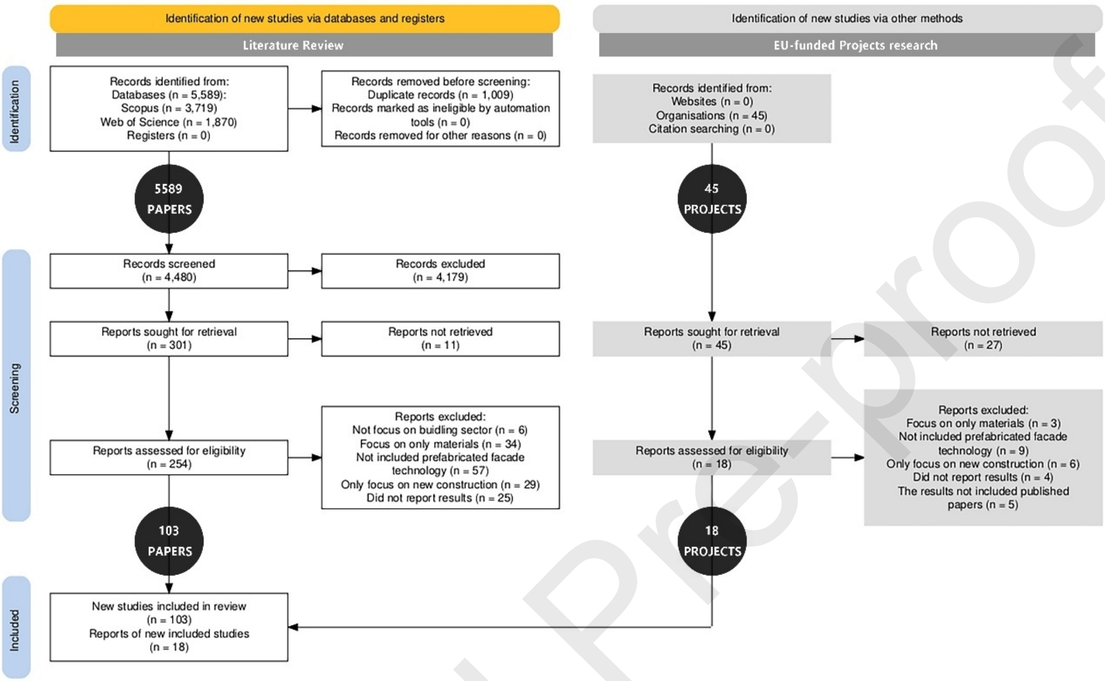


Figure 3: PRISMA flowchart. Visual representation of the study selection process in the conducted systematic review according to the PRISMA guidelines (Source: Author self-painted)

Table 1: List of inclusion and exclusion criteria of research (Source: Author self-painted)

	Inclusion Criteria	Exclusion Criteria
Research topic	Studies related to the application of prefabricated façade panel technology and their impact on building energy efficiency; Studies related to active façade technology	Studies unrelated to façade sector; Studies focus solely on passive technologies (e.g., passive façade system, thermal insulation coatings) without addressing active technologies.
Type of study	Includes experimental studies, case studies, review articles, simulation studies, and technical evaluations.	Conceptual discussions only, non-peer-reviewed articles, news reports, blogs, or market reports.
Time frame	Studies published within the last 10 years (2014–2024) to ensure relevance and technological advancements.	Studies published more than 10 years ago (before 2014).

Study population	Studies focusing on prefabricated façade panels integrating BIPV systems, especially for building renovation.	Studies addressing photovoltaic systems unrelated to the façade system sector (e.g., PV shading system, roof solar system).
Data source	Retrieved from reliable databases (Scopus, Web of Science). Retrieved from European Commission official website [21]	Studies retrieved from non-peer-reviewed sources, non-scientific websites, or databases that do not ensure academic reliability.
Language	Only studies published in English or available with an English translation.	Studies published in non-English languages without available translations.
Accessibility	Full-text articles are available through open access or institutional subscriptions.	Abstract-only studies with no access to the full-text version.

To focus the investigation on funded projects, the European database that collects results of EU research and innovation was used as the main data repository [21]. The database included all the EU-funded projects, including those related to the built environment and specifically related to the renovation methodologies based on the application of prefabricated façade panel technology. Similarly to what has been done for the scientific literature, projects were listed into an electronic dataset and classified through the following characteristics: i) general project description (starting and closing year, brief description, general project topic, project coordinator and its country, links to the project), ii) panel technology type (layer-based modular system/frame-based modular system/combination of two), iii) main use of the technology (renovation/new construction), iv) prefabrication level (which ones of the layers composing the described product are offsite produced), v) integrated active systems (BIPV, electrical, hydraulics, renewables, mechanical ventilation, climatization).

3 Bibliometric analysis and results

This section presents a comprehensive synthesis of the research findings concerning APF-BIPV, combining insights from both academic literature and funded research projects. Through an integrated approach, the following sections explore the development trends in scholarly research, the application of APF technologies in real-world projects, and the current methods used to evaluate their performance. By examining these dimensions, this section aims at providing a multidimensional understanding of the state of the art in APF-BIPV systems, revealing both the progress achieved and the challenges that remain in advancing their implementation within the construction industry. To ensure a comprehensive and systematic bibliometric analysis, a multi-step workflow was adopted, as illustrated in Figure 4. First, relevant publications were retrieved from two major academic databases: Scopus, with a total of 3,719 articles, and Web of Science (WoS), yielding 1,870 articles. After data extraction, the datasets were merged to eliminate duplicates, resulting in 4,480 articles for further analysis. Subsequently, two sets of analysis tools were employed. CiteSpace, in conjunction with Gephi software, was used to perform network-based analyses such as co-citation and collaboration mapping, which offer insights into the intellectual and social structure of the research field. In parallel, R Studio with the Bibliometrix package and its web-based interface Biblioshiny, were utilized to conduct descriptive statistical analysis and visualize publication trends, keyword evolution, and thematic development over time. This combined methodology ensures a robust and multifaceted understanding of the knowledge domain related to Active Prefabricated Façades and associated technologies.

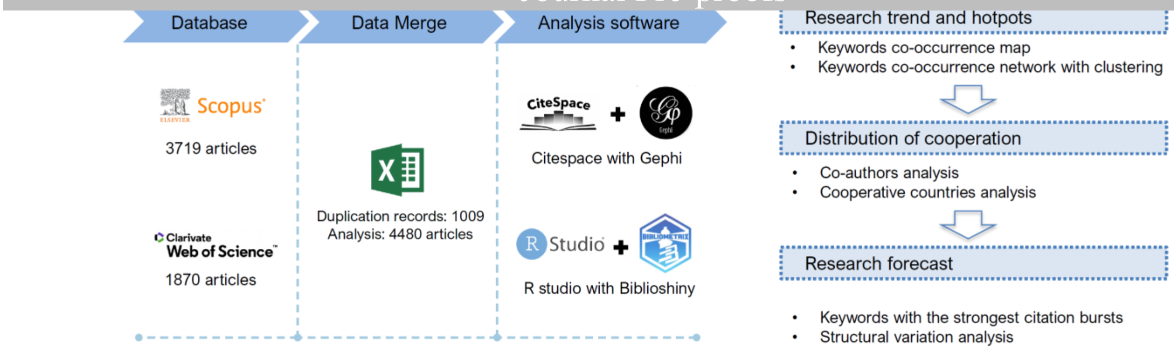


Figure 4. Methods of literature analysis (Source: Author self-painted)

As shown in Figure 5, a keyword-based search in the WOS Core Collection and Scopus (2014–2024) reveals a clear and continuous growth in publications related to BIPV and off-site construction technologies, both Scopus and Web of Science (WOS) databases exhibit an increasing number of publications, with Scopus showing a more pronounced upward trend. The total number of publications in Scopus have grown from 168 in 2014 to over 3,500 in 2024, while WOS have grown from 80 to approximately 2,000 over the same period. The annual publication count in Scopus also experienced substantial acceleration after 2020, reaching 598 publications in 2024, whereas WOS maintained a more stable but slower growth, culminating in 261 publications in 2024. The most notable growth phases occurred between 2016 and 2021, with a particularly sharp rise in publications after 2019, reflecting an increased academic interest and expanding research focus on this domain. The divergence in growth rates between the two databases suggests that Scopus may encompass a broader spectrum of emerging research and conference proceedings. Given this trajectory, it is anticipated that research output in this field will continue to rise, although WOS may experience a gradual deceleration compared to Scopus. This trend highlights the increasing importance of BIPV incorporated into off-site construction technologies within the academic community, driven by advancements in technology, policy incentives, and industry adoption.

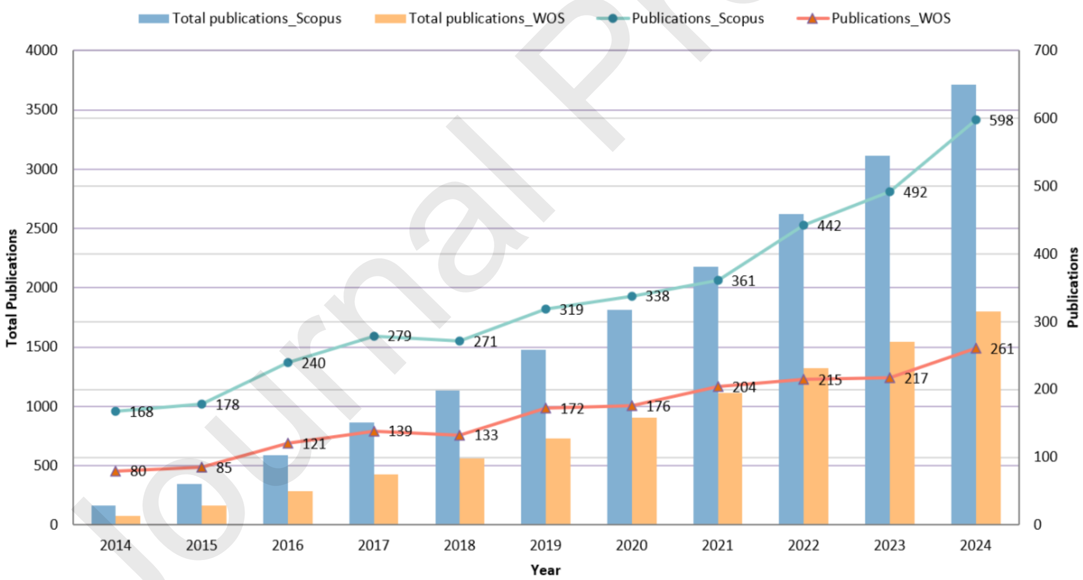


Figure 5: Trends in Publications on Prefabricated Façade Panels in Scopus and WOS (Source: Author self-painted)

In the following section, a bibliometric analysis is conducted to provide a comprehensive overview of existing studies on APF-BIPV, examining the evolution and research trends in this field. The studies published over the past decade related to APF have been systematically summarized and classified. Using co-occurrence analysis of keywords and themes, the node size in the resulting network reflects the frequency of each research focus, while the connecting line colors indicate the publication year as per the color scheme on the graph. Citation tree rings illustrate the timeline of influence, where thicker rings represent higher citation frequency within specific time intervals. Centrality values highlight the significance of each node in shaping the structure of knowledge within the APF research landscape [22].

3.1 Bibliometric analysis with a focus on authorship and country of publications

To analyze research hotspots and forecast trends, this study employed a i) keyword co-occurrence map, ii) keyword clustering, and iii) keywords with citation burst based on the keyword co-occurrence network generated in CiteSpace. The keyword co-occurrence map was constructed by statistically analyzing the frequency with which keywords appeared together in different research between 2014-2024, providing a foundational structure that reflects the semantic associations within the research field. This allows for an overview of the core terms that have emerged over the past decade concerning APF, building retrofitting, off-site construction, and building energy efficiency. Building on this network, keyword clustering groups together frequently co-occurring terms into thematic clusters, enabling the identification and categorization of major research topics and knowledge domains within the field. It offers a clear structural understanding of the intellectual organization and development of the research landscape. In parallel, keywords with citation burst monitors the temporal dynamics of keyword usage, identifying terms that exhibit a sharp increase in frequency over a specific time interval. Together, these three approaches, grounded in the co-occurrence network, offer a multi-dimensional interpretation of the field, capturing its relational structure, thematic organization, and temporal progression. They provide a comprehensive lens for understanding the development patterns and future directions of research in this domain. Figures 6, 7 and 8 were generated using the CiteSpace software, employing the Pathfinder algorithm for pathfinding and applying both "pruning sliced networks" and "pruning the merged network" options to enhance the clarity and interpretability of the graphs. Before presenting the analytical results, it is necessary to explain the key parameter settings. The g-index ($k = n$) was adopted as the node selection criterion, meaning that in each time slice, only the top n most influential nodes, based on citation performance, were retained. The Look-Back Years Factor (LRF) and Look Back Years (LBY) were used to control the retrospective depth of the analysis. The L/N Ratio, defined as the ratio between the maximum path length (L) and the number of nodes (N), was employed to adjust the depth of the pathfinding process. A higher L/N value allows for more extensive path exploration, resulting in a denser and more complex network structure [23]. In the output parameters of the network, N represents the number of nodes and E represents the number of edges in the constructed network. Betweenness centrality is defined for each node within the network and serves as an indicator of the node's structural importance. In Figure 6, nodes with high betweenness centrality are highlighted with purple rings,the thicker the ring, the higher the node's centrality. In the keyword co-occurrence map, such nodes function as bridges between different research topics or domains, indicating their role in connecting multiple thematic areas. A centrality score of ≥ 0.1 is typically interpreted as high, signifying that the node plays a key intermediary role, whereas a score of 0 indicates minimal structural bridging capacity [23,24]. In the clustering analysis results, Modularity (Q) and Silhouette (S) values are used to evaluate the quality and clarity of the clustering structure. Generally, a Q value greater than 0.3 indicates a significant modular structure, while a Silhouette score above 0.7 suggests that the clustering results are convincing and well-defined [25]. In the co-occurrence map (Figure 6), each node represents a keyword from research articles, and the size of each node is indicative of the frequency of the corresponding keyword. In detail the label on the left side of the Figure 6 shows the color of nodes that reflects the year of appearance. The results of this analysis identify "energy efficiency" as the most frequently occurring keyword (748 occurrences, centrality = 1.11) as reported in Table 1 and Figure 6. Other high-frequency keywords, including "walls (structural partitions)," "solar power generation," and "energy utilization," underscore a pronounced research emphasis on renewable energy integration within building systems. The prominence of solar-related terms, particularly "photovoltaic system" (436 occurrences) and "photovoltaic cells" (400 occurrences), signifies the expanding role of photovoltaic technology as a cornerstone of energy-efficient building practices. Concurrently, the prevalence of terms such as "architectural design" and "building envelopes" indicates a growing interdisciplinary convergence between architecture and energy technologies. Emerging research interests, notably "modular construction," "prefabrication," and "thermal insulation," reveal a marked shift towards off-site construction methods and enhanced thermal performance, reflecting a broader commitment to sustainability in construction practices. Keywords exhibiting high centrality, such as "photovoltaic system" (centrality = 1.24) and "energy efficiency" (centrality = 1.11), play critical roles in connecting distinct yet related research disciplines（Table 2). These two keywords demonstrate a significant influence in linking various topics withinthe research network. A review of the publications containing these keywords reveals that energy efficiency is frequently presented as a primary research objective, which aligns with the focus of this review. This indicates that over the past decade, researchers have paid considerable attention to building energy performance in the context of APF-BIPV studies. Valinejadshoubi et al. aim to enhance building energy efficiency by proposing and evaluating a dynamic photovoltaic façade system integrated with lighting control, demonstrating its effectiveness in reducing energy consumption, optimizing daylight performance, and improving indoor visual comfort through parametric simulation [26]. The study conducted by Rapone et al. focuses on improving the energy performance of prefabricated temporary buildings by assessing advanced envelope solutions that balance thermal comfort, minimize overheating, and maintain transportability to achieve building energy efficiency [27]. Bot et al. employ an experimental approach in a controlled test room to assess the thermal performance of a BIPV/T system under real boundary conditions, to evaluate its energy efficiency and occupant comfort within the context of the Mediterranean climate in Portugal [28]. While PV system is commonly featured as a core technology in the literature, with extensive research focusing on their development. Such studies often concentrate on innovative aspects of PV systems, particularly the integration of novel materials into their design. . A categorization of the subject is generally possible into two main types. The first type focuses on the technological innovation of the PV system itself, such as the integration of novel materials into PV system design such as Phase Change Material (PCM). Yang et al. proposed a double-PCM BIPV composite envelope (BIPV-dPCM) that integrates double-layer PCM with

PV systems, demonstratingthat the energy efficiency and insulation performance of the façade canbe enhanced through thermal modeling and parametric analysis [29]. Čurpek et al. experimentally investigated the relationship between the physical properties of PCM and the operating temperature of PV systems, revealing that PCM significantly reduces PV panel temperatures under high solar radiation, thereby enhancing electricity generation performance [30]. Clua Longas et al. integrated a photovoltaic system with façade panels and designed a full-scale Advanced Active Façade (AAF) demonstrator to showcase the architectural integration potential of BIPV systems [31]. Jayathissa et al. investigated a dynamic photovoltaic shading system that integrates PV modules as building shading elements, optimizing their orientation to simultaneously enhance electricity generation and building energy performance, achieving up to 80% net energy savings [32]. The primary focus of the present review is on the aforementioned integration of photovoltaic systems in APF-BIPV.

Table 2. The top 15 keywords that co-occur in the literature (Source: Author self-painted)

Rank	**Frequency**	**Centrality**	**Publication Year**	**Keywords**
1	748	1.11	2014	Energy efficiency
2	682	0.06	2014	Walls (structural partitions)
3	508	0.26	2014	Solar power generation
4	478	0.67	2014	Energy utilization
5	436	1.24	2014	Photovoltaic system
6	400	0.61	2014	Life cycle
7	394	0.31	2014	Solar energy
8	369	0.11	2014	Architectural design
9	358	0.16	2014	Buildings
10	343	0.66	2014	Building integrated photovoltaics
11	306	0.00	2016	Energy conservation
12	258	0.00	2014	Thermal insulation
13	249	0.66	2014	Building envelopes
14	233	0.11	2015	Prefabrication
15	218	0.06	2014	Modular construction

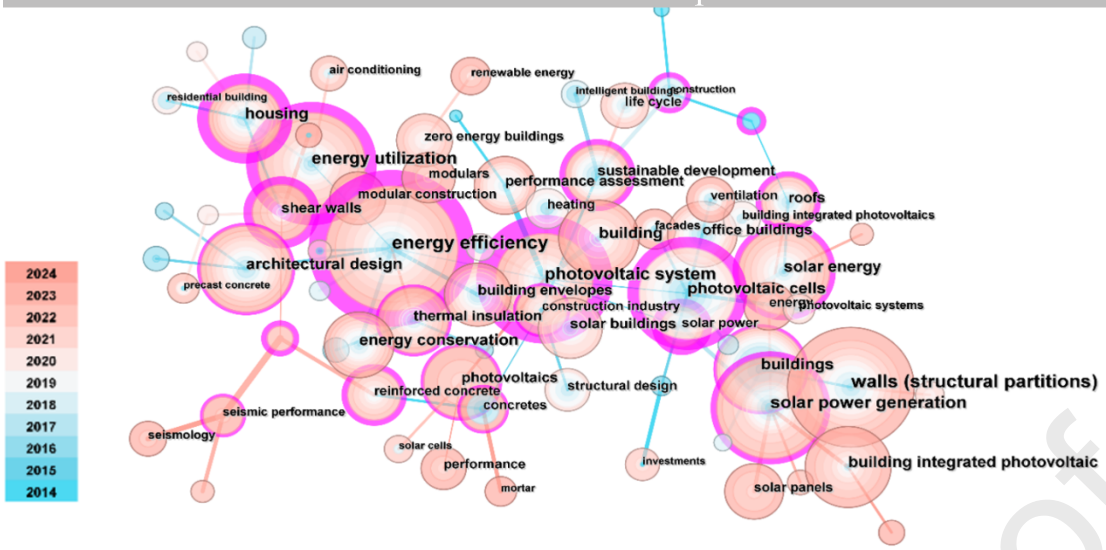


Figure 6: Keyword co-occurrence map drawing in Citespace. Selection criteria: Top 30 per slice, LRF=2.5, L/N=10, LBY=5, e=1.0; Network: N=73, E=82 (Density=0.0312) Pruning: Pathfinder. (Source: Author self-painted).

The keyword co-occurrence network with clustering offers an insightful depiction of the primary research themes and their interrelationships within this field from 2014 to 2024 (Figure 7). The application of the pathfinder pruning technique effectively streamlined the visualization by eliminating redundant linkages, thereby enhancing the interpretability and clarity of keyword relationships. Additionally, the high weighted mean silhouette score ($S = 0.9679 > 0.7$) and modularity ($Q = 0.8804 > 0.3$) demonstrate the reliability of the clustering and the presence of strong internal consistency among the groups. The clustering results indicate a total of 17 clusters, with smaller cluster numbers corresponding to a greater number of keyword nodes contained within each cluster [33]. The cluster #0 "photovoltaics" predominantly focuses on technologies and systems related to photovoltaic energy conversion. The core components of this cluster include “building-integrated photovoltaics (BIPV)”, “photovoltaic (PV) cells”, “solar power generation”, “energy renovation”, “thermal performance”, and “economic analysis”. These keywords reflect an underlying research interest in the energy generation and energy-saving capabilities of PV systems, as well as their economic viability. Performance evaluations related to PV systems encompass two primary domains: the performance of PV cells themselves and their impact on overall building performance. Zheng et al. conducted a thermal analysis of air-cooled channels with different dimensions in naturally ventilated PV wall panels, investigating the influence of vertically installed heat dissipation fins on cooling efficiency and airflow, and optimizing the corresponding design parameters [34]. Furthermore, Brandl et al. analyzed the power generation capacity and the building thermal performance. They investigated the thermal performance and airflow characteristics of the Solar Honeycomb (SHC) façade with various PV cell configurations to determine the setup that offers the optimal balance between thermal regulation and electrical output [35]. Despite the comprehensive research conducted on PV technologies and integration methods, and the relative maturity of these technologies, the practical implementation of BIPV in façade systems remains constrained. From an economic perspective, Evola and Margani investigated the feasibility of retrofitting multi-storey residential buildings with BIPV-integrated façades in temperate climates, emphasizing payback periods and the critical role of fiscal incentives in enhancing investment appeal [36]. Their work underscores salient economic impediments that could hinder the broader implementation of BIPV solutions in practical construction settings. Cluster #10“energy saving“ comprises key terms like “energy efficiency”, “energy utilization”, “zero energy building”, “energy optimization”, “indoor environmental comfort”, and “active building”. This cluster emphasizes the optimization of building energy consumption and system performance, while also taking occupant comfort into account. Studies within this cluster typically highlight the role of technological integration in achieving energy-saving goals, demonstrating a clear performance-driven orientation. Net-zero energy building (NZEB) refers to a building with net-zero energy consumption, which meets its energy demand and consumption by generating on-site energy from renewables [37]. The deep energy retrofit of the NZEB-based school building achieved a 68% to 82% reduction in net energy consumption for space heating [38]. However, this approach also resulted in a marked decline in indoor environmental quality during the non-heating season [39]. This overheating issue can be effectively mitigated by incorporating additional active strategies, such as ventilation façades and dynamic shading devices. Active buildings integrate renewable energy systems with intelligent control technologies to dynamically manage energy flows, thereby enhancing both energy efficiency and occupant comfort [40]. Cluster #11 “façade” focuses on strategies and technological integration at the building envelope level. Its primary keywords include “ventilation”, “solar heating”, “thermal insulation”, “modular construction”, and “structural design”, which highlights the critical role of façade performance in achieving high-performance buildings, with particular emphasis on the integration of active technologies with façade systems and the importance of constructional innovation.

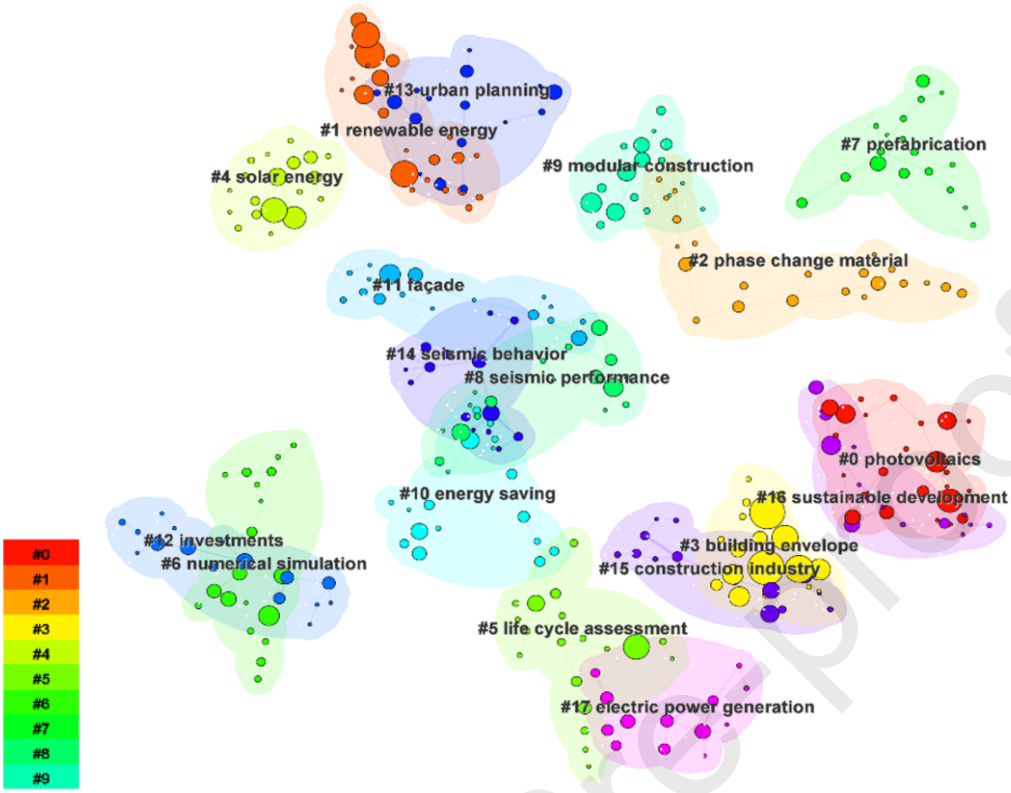


Figure 7: keyword co-occurrence network with clustering.Selection criteria: g-index (k=10), LRF=2.5, L/N=10, LBY=5, e=1.0; Network: N=345, E=379 (Density=0.0064) Pruning: Pathfinder; Modularity Q=0.8804; Weighted Mean Silhouette S=0.9679; Harmonic Mean(Q,S)=0.922. (Source: Author self-painted)

Keyword burst detection analysis can be used to explore the staged evolution of research in recent years and to forecast emerging frontiers. It enables the identification of the developmental trajectory of research hotspots and the prediction of future academic trends. The results reveal the evolution of research trends in this field from 2014 to 2024 (Figure 8). The burst year refers to the year when the citation burst for the keyword was first detected. Early research (2014–2018) was dominated by topics such as "buildings," "photovoltaic cells," and "concrete," indicating a focus on structural design and the integration of photovoltaics into buildings. During this period, significant attention was given to solar power technologies, intelligent buildings, and building envelopes, reflecting an early push toward energy-efficient and smart building solutions. Between 2018 and 2021, research interest shifted towards zero-energy buildings, thermal performance, and building-integrated photovoltaics (BIPV), emphasizing sustainable construction practices and energy-efficient building design. The emergence of solar buildings and the construction industry in citation bursts suggests growing academic interest in integrating renewable energy solutions with large-scale building developments. More recently, from 2022 to 2024, the most intense citation bursts have been observed in "photovoltaics," "solar panels," and "modular construction", indicating a strong focus on scalable solar energy solutions and prefabrication techniques. Overall, this analysis reflects a clear transition in research priorities from fundamental building and photovoltaic technologies in the early years to energy efficiency and solar integration in the mid-period, and now toward modular, high-performance, and sustainable construction solutions. These trends indicate a growing commitment to building energy efficiency, solar energy adoption, and sustainable development in the built environment.

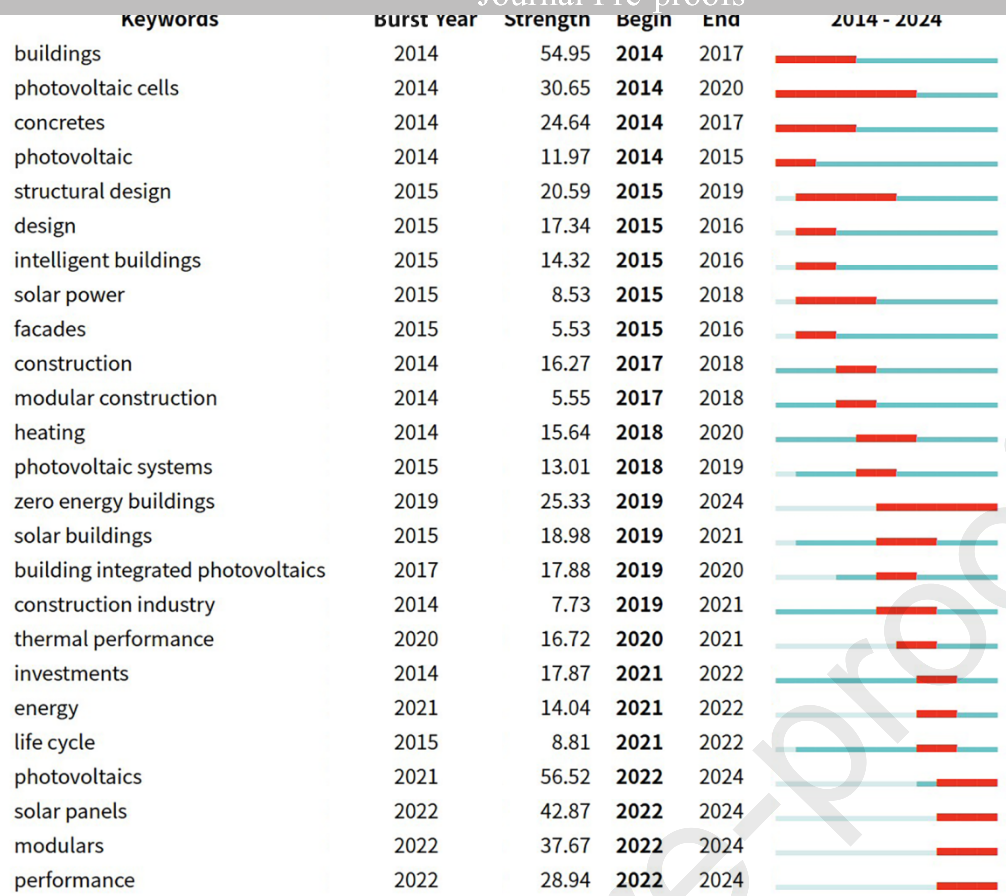


Figure 8: Top 25 keywords with the strongest citation burst (Source: Author self-painted)

3.2 Bibliometric analysis with a focus on authorship and country of publications

The co-authorship network analysis (Figure 9) identifies the most influential researchers in the field of BIPV façade research in last 10 years. Among the most productive authors, Jie Ji stands out as the leading contributor (Table 3), with 34 publications and the highest centrality (0.07), making them a key researchers in collaborative research. Other notable contributors include Mohamed Al-Hussein (13 publications, Canada), Targo Kalaames (12 publications, Estonia), and Heim, Dariusz (12 publications, Poland), indicating a diverse geographical representation. Chinese researchers such as Zhongbing Liu, Ling Zhang, Wei Ke, and Xi Chen, also play a dominant role in this field, highlighting China's strong presence in façade-related research. The color-coding of nodes represents the time evolution of authors' contributions, with red nodes indicating recent bursts in research activity (2020–2024), signifying an increasing consolidation of research efforts in recent years, particularly in topics related to prefabrication, modular construction, and energy-efficient façade technologies. The modularity score (Q = 0.8044) reflects overlapping collaborations rather than strictly isolated research groups. However, the network remains relatively dispersed, with many small, unconnected clusters, indicating that international collaborations are still underdeveloped. The study did not apply pruning techniques, meaning that all detected co-authorship relationships were retained, contributing to the visualization of both strong and weak ties within the network. The burst detection analysis further highlights that several authors, such as Ji, Jie, and Zhang, Chengyan, have experienced significant surges in influence over the last five years, aligning with the growing research focus on prefabrication and façade panel innovations. Their works spans a broad spectrum, from materials and performance analysis to structural integration demonstrating high centrality (0.07) and frequent interdisciplinary collaboration.The findings suggest that, while the field includes key contributors and emerging leaders, fostering broader and more integrated collaborations will be essential to advance sustainable façade technologies in the coming years.. Ji's research focuses on the integration of multifunctional photovoltaic systems into building envelopes, emphasizing material innovation, system performance evaluation, and climate adaptability to support energy-efficient building applications [41–45]. Al-Hussein's research has proffered a number of contributions to the industrialization of the building construction process through the development of modular and off-site construction (OSC) technologies using Building Information Modelling (BIM) [46]. Kalaames conducts research on energy-efficient renovation of residential buildings, exploring topics such as ventilation systems, prefabricated insulation solutions, building envelope performance, and the impact of occupancy patterns and data-driven approaches on energy outcomes [47,48]. Liu investigates building energy technologies with a strong emphasis on thermoelectric cooling, photovoltaic-thermal integration, active envelope systems, and battery optimization, aiming to enhance thermal performance and support the transition toward zero energy buildings [49–52]. Zhang's research is characterized by a strong data-driven and simulation-oriented approach, with a particular emphasis on multi-scale modeling and multi-objective optimization [53–55].

Table 3: Most productive authors in the façade field during 2014-2024 (Source: Author self-painted)

Rank	Authors	Institutions	Publications	Centrality
1	Ji, Jie	China	34	0.07
2	AI-hussein, Mohamed	Canada	13	0.00
3	Kalamees, Targo	Estonia	12	0.01
4	Liu, Zhongbing	China	12	0.03
5	Zhang, Ling	China	12	0.04
6	Heim, Dariusz	Poland	12	0.02
7	Ke, Wei	China	12	0.00
8	Chen, Xi	China	12	0.01
9	Chen, Zhihua	China	11	0.00
10	Yang, Hongxing	China	11	0.00

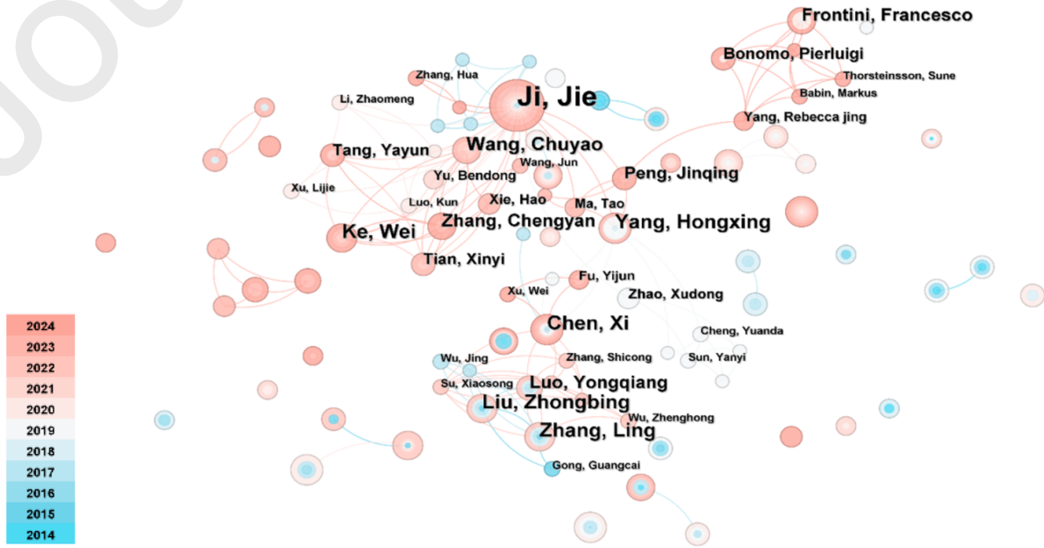


Figure 9. Knowledge map of co-authors of papers published from 2014 to 2024. Selection criteria: g-index (k=25), LRF=2.5, L/N=10, LBY=5, e=1.0; Network: N=535, E=562 (Density=0.0039). (Source: Author self-painted)

The country collaboration network analysis, conducted using CiteSpace (Figure 10), provides insights into international research cooperation in the field of façade research from 2014 to 2024. The network consists of 113 nodes (representing countries) and 108 edges (collaborative links between countries), with a density of 0.0171, indicating a relatively moderate level of international collaboration. The largest connected component includes 98 countries, accounting for 86% of the total network, showing that most of the research activities are connected in a global research framework. In terms of productivity, as shown in Table 4 China leads with 828 publications and the highest centrality (0.22), reinforcing its dominant position in façade-related research. Italy (411 articles, 0.13 centrality), the USA (350 articles, 0.12 centrality), and the UK (211 articles, 0.14 centrality) are also key contributors, indicating strong research activities in Europe and North America. Other major contributors include Canada, Germany, Australia, Spain, India, and Switzerland, all of which demonstrate moderate research output and global collaborations. The thicker connecting lines between China, Italy, and the USA indicate frequent academic collaboration among these leading countries. The presence of smaller nodes like Slovenia, Cyprus, and Romania suggests emerging research contributions, though their influence remains limited compared to major contributors. Overall, the analysis reveals that international collaborations in façade research are increasing, with China, Italy, Germany, the UK, Canada, and the USA playing pivotal roles in shaping global research trends. However, some countries remain relatively isolated, highlighting the potential for enhanced global partnerships to further advance knowledge exchange and innovation in sustainable façade technologies.

Table 4. List of contributing countries and number of records contributed (Source: Author self-painted)

Rank	Country	Number of articles	Centrality
1	China	828	0.22
2	Italy	411	0.13
3	USA	350	0.12
4	UK	211	0.14
5	Canada	192	0.04
6	Germany	180	0.17
7	Australia	171	0.05
8	Spain	164	0.13
9	India	132	0.07
10	Switzerland	108	0.06

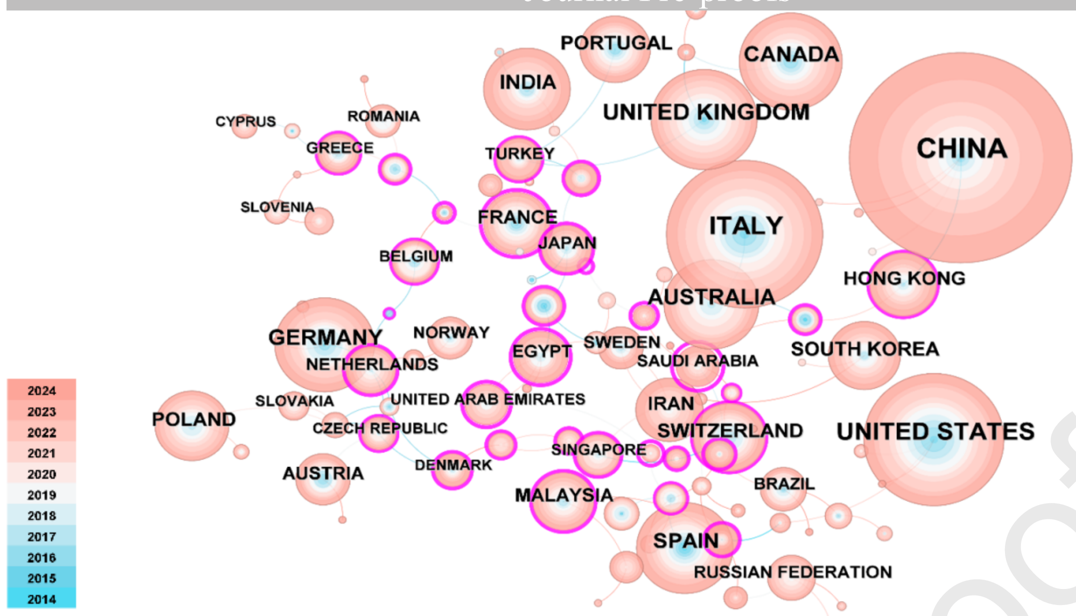


Figure 10: Knowledge map of cooperative countries in the research during 2014-2024.Selection criteria: g-index (k=10), LRF=2.5, L/N=10, LBY=5, e=1.0; Network: N=113, E=108 (Density=0.0171); Pruning: Pathfinder. (Source: Author self-painted)

3.3 Discussion of bibliometric analysis results

The thematic evolution and variability analysis provides an insight into the research dynamics and clustering patterns in the field of façade technology and energy-efficient buildings from 2014 to 2024 (Figure 11). Key clusters identified in the analysis include “#10 modular construction,” “#9 building-integrated solar thermal system,” “#6 architectural characteristics,” and “#2 case study.” These clusters indicate a strong focus on energy efficiency, building performance, and renewable energy integration into façade design. The presence of “#19 thermal evaluation” and “#8 thermo-economic analysis” suggests an increasing interest in economic feasibility assessments of façade technologies, while “#7 building energy saving” and “#11 building envelope” emphasize efforts to improve thermal performance. Unlike previous analyses, this study did not apply pruning techniques, meaning that all detected thematic relationships were retained, which provides a comprehensive view of research variability and thematic interconnections. The harmonic mean of modularity and silhouette scores (Q, S = 0.8143) further supports that the network is both structurally sound and thematically cohesive. In summary, this thematic evolution analysis highlights the progression of research trends in façade technology, from early-stage experimental studies on laboratory-based performance testing to the integration of renewable energy solutions in modular construction in recent years. The emergence of clusters related to sustainability, thermal efficiency, and economic assessments suggests that future research will likely focus on optimizing cost-effective, high-performance building envelope systems. This analysis provides valuable insights into how research in the field has evolved and where it is heading, emphasizing the importance of interdisciplinary approaches and sustainable innovation. This structural variation analysis map illustrates the degree of collaboration and the relationships between different research domains. The red connections represent the top 10 most closely linked collaborative clusters. Through the collaboration analysis in this map, it can be observed that PV systems exhibit significant interdisciplinary integration with architecture, building energy, and performance simulation. Additionally, strong relationships are evident between photovoltaic systems and building façades, as well as renewable energy generation. However, the connection between photovoltaic systems and modular construction appears to be relatively limited, which may become the direction of future development. In light of this, the present study aims to investigate the underlying factors contributing to the limited integration of these two relatively well-established research domains.

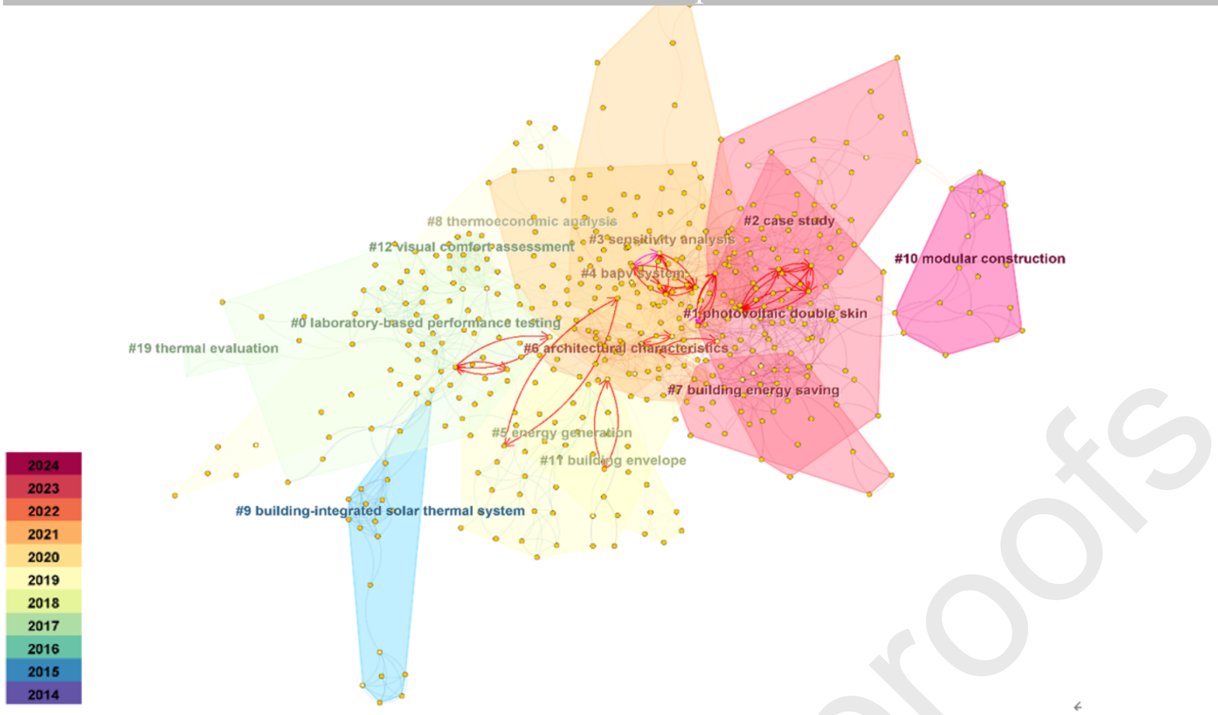


Figure 11. Structural Variation Analysis (SVA) Map.Selection criteria: g-index (k=25), LRF=2.5, L/N=10, LBY=5, e=1.0; Network: N=630, E=1731 (Density=0.0087); Modularity Q=0.7524; Weighted Mean Slihouette S=0.8873; Harmonic Mean(Q,S)=0.8143. (Source: Author self-painted)

The three-field plot reporte in Figure 12 provides a comprehensive visualization of the relationship between authors, research topics, and contributing countries in the field of PV and prefabricated wall panel technologies. The rectangular node height corresponds to the frequency of occurrences for each entity (authors, keywords, and countries), while the line width between nodes represents the strength of association, indicating how frequently these elements are connected in the scientific literature. The results show that China, Italy are among the most prominent contributing countries, demonstrating strong research activity and collaboration in renewable energy applications in prefabricated façade panel technology. Other significant contributors include Egypt, India, Spain, Iran, and the UK, reflecting a global interest in photovoltaic-integrated façades and building modular technology.

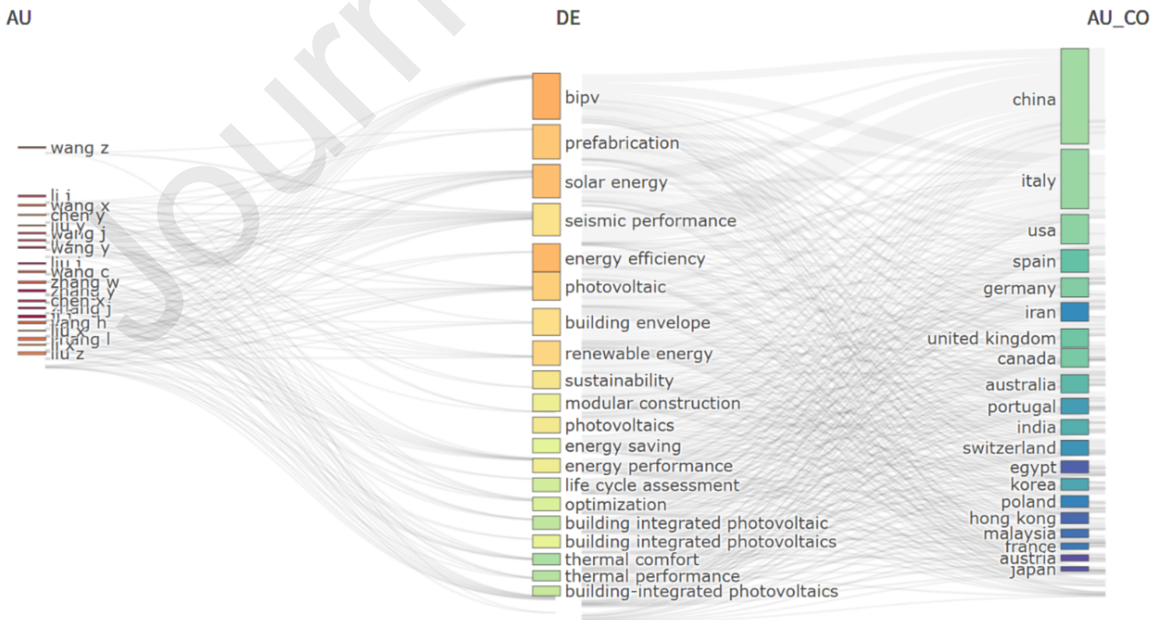


Figure 12. Represents three field plot analyses of cited author (AU), descriptors (DE), author country (AU_CO) in the strategic entrepreneurship field (Source: Author self-painted)

The bibliometric analysis reveals several key insights. Keyword co-occurrence analysis uncovers interdisciplinary connections, such as the link between modular construction and solar energy technology, highlighting opportunities for collaboration and new research directions aligned with sustainability goals. The geographical analysis indicates that research from China and Italy has received the highest number of citations (828 and 411, respectively), emphasizing their influence in the scientific community. Furthermore, clustering analysis enhances the understanding of international collaboration patterns, helping researchers identify potential global partnerships. Overall, this study provides a valuable overview of global research trends, pinpointing major contributors, emerging themes, and collaboration opportunities. By analyzing these interconnections, scholars can identify key research partners and explore new research frontiers in prefabricated façades and photovoltaic-integrated construction technologies.

4 BIPV-integrated in APF for building retrofitting

4.1 Overview of APF-BIPV technology

4.1.1 Overview of application and evaluation methods for active prefabricated façades

In the analysis of APF panels, this research primarily focuses on BIPV technology and its integration methods.The collected literature is categorized and summarized into the literature-based database, as shown as Table 5 using the classification framework shown in Figure 13. This framework includes four main aspects: context of application, construction methods, performance objectives, and effect evaluation techniques. It provides a structured approach to reviewing existing literature related to APF systems.

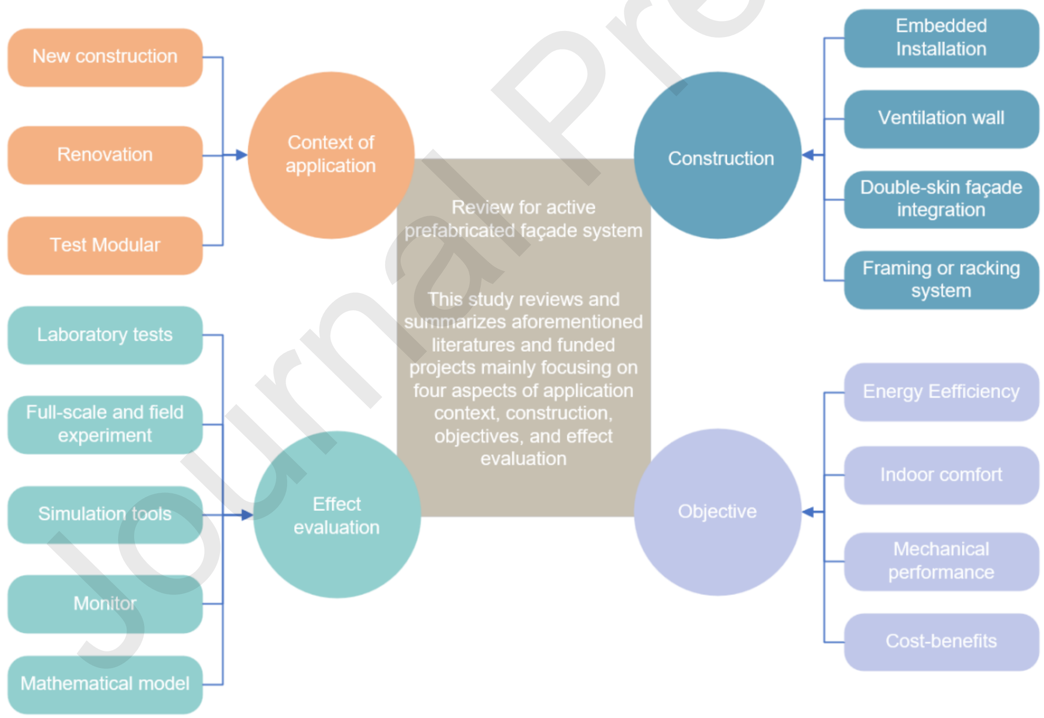
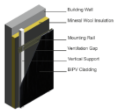
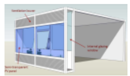
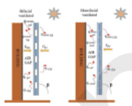
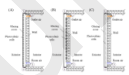


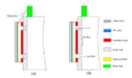
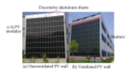
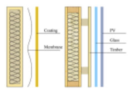
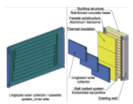
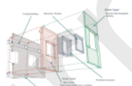
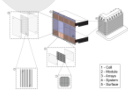
Figure 13. The classification rules of the database. (Source: Author self-painted)

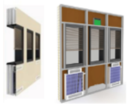
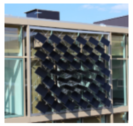
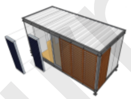
Consequently, the classification of these technologies is structured around the types of composite systems formed by combining BIPV panels with existing façades (Table 5). This section synthesizes findings from 20 relevant studies on prefabricated façade panels integrated with photovoltaic technology. Among these, 6 studies focused on double-skin façades, 11 explored frame-based modular system, and 3 investigated adhesive or sealant connection methods. Notably, 55% of the studies adopted a framing or racking construction approach, with over 60% of the retrofit cases utilizing framed solutions. In this method, APF-BIPV panels are prefabricated off-site and subsequently installed onto prefabricated structural frames on-site, allowing for efficient integration with the existing façade. The higher degree of prefabrication and simplified on-site assembly inherent in this approach contributes to its growing popularity. Babin et al. integrated photovoltaic systems into façade components to enhance building energy efficiency and improve the thermal insulation performance of façades [56–59]. Du et al. developed a conceptual framework encompassing façade modularity, modular façade retrofitting, and the integration of renewable energy technologies using the Grounded Theory methodology [60]. They introduced the concept of "modular façade retrofit" with integrated renewable systems. In their study, Alvarez-Alava et al. focused on the layered composition of modular and prefabricated façade elements, integrating active technologies within modular frameworks [61]. This research specifically investigates BIPV-integrated APF systems. Alhammadi et al. compared BIPV ventilated façades oriented in three different directions, detailing how the ventilated panels were integrated onto existing wall systems, thereby enhancing indoor thermal comfort and reducing overall building energy consumption [62]. Another study by Giovanardi et al. employed a modular PV wall with a multi-layer panel system and evaluated its performance through a test module [63]. Additionally, Vassiliades et al. investigated photovoltaic panels adhered directly to lightweight panels [64], however, this method demands high-performance adhesives and is limited to lightweight facing materials, thus offering lower thermal insulation efficiency compared to multi-layer racking systems. In terms of application contexts, this research classifies studies into three categories: renovation, new construction, and laboratory test modules. Among the reviewed studies, eight applied APF to renovation contexts, two targeted new construction projects, and twelve remained at the laboratory testing stage. Notably, approximately 60% of the studies have not advanced beyond laboratory-scale testing to actual building implementation, which is a critical area of interest. The current study seeks to analyze the reasons behind the limited practical application of composite APF-BIPV system in real-world projects. Regarding evaluation methods, the studies are categorized into full-scale or field experiments, simulation-based analyses, and monitoring approaches. Eleven studies utilized full-scale or field experimentation, ten employed simulation methods, and ten involved practical monitoring of panel performance. Research employing full-scale experimentation frequently combined monitoring to evaluate long-term panel performance; indeed, ten studies adopted both methods simultaneously. Additionally, one study combined simulation with monitoring to bridge the gap between simulated results and real-world performance. The majority of recent studies integrate multiple evaluation methods, thereby enhancing data reliability and facilitating cross-validation of results. In terms of performance evaluation, 13 studies utilized test modules for experimental validation under on-site pilot buildings conditions. While early investigations on BIPV often relied solely on software-based simulations, the increasing global demand for energy reduction, fueled by governmental policies and funding initiatives, has shifted recent research trends toward full-scale and on-site experiments to obtain more accurate assessments. Several studies also adopted hybrid approaches combining simulations with experimental data, particularly in cases involving multi-objective optimization or adaptive BIPV façades, to calibrate simulation outputs and predict future performance regarding energy efficiency and indoor comfort improvements. Notably, 90% of the studies employing full-scale or on-site testing also incorporated post-construction monitoring, enabling dynamic visualization of long-term energy generation, improvements in indoor comfort, and PV thermal behavior. This is especially relevant since the thermal characteristics of PV modules, such as performance degradation due to overheating under prolonged solar exposure,are often overlooked in simulation-based studies. However, only two studies conducted a thermal analysis specifically on the PV modules. Regarding research objectives, the majority of studies focused on energy performance, driven by the intrinsic electricity-generating capacity of BIPV systems. When integrated into prefabricated panels, these systems not only produce on-site energy but also enhance the thermal insulation of façades, resulting in improved indoor comfort and reduced heating and cooling energy demands for occupants. In high-rise buildings, transparent BIPV panels are commonly employed in curtain wall systems for energy generation, and when integrated with appropriate shading systems, could enhance both visual comfort and indoor thermal comfort [65,66]. Additionally, two studies investigated cost-effectiveness, although this was primarily assessed from the perspective of energy yield and operational savings, with relatively limited attention to the initial cost and economic feasibility of the APF-BIPV systems themselves.

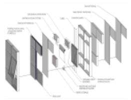
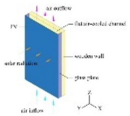
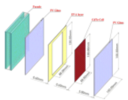
Table 5. List of contributing countries and number of records contributed (Source: Author self-painted)

Type	Ref.	Research context		Design concept scheme	Prototype	Application context		Evaluation method				Active technology	Research Objectives
		Building Type	Location			Renovation	New construction	Test module	Full-scale/on-site experiment	Simulation	Monitor		
Double-skin or/ ventilated façade	[62]	--	Hot climate zone-Dubai		Ventilated PV curtain wall	●			●		●	PV: CIGS and c-Si	Energy performance and temperature analysis of PV
	[67]	Commercial building	Australia		Ventilated PV façade			●	●	●		Transparent PV	Energy performance and thermal comfort
	[68]	Test module	Itay		Ventilated PV curtain wall			●	●	●	●	Bifacial and monofacial ventilated PV façade	The performance of the BIPV façade naturally ventilated
	[69]	Test module	Iran		Photovoltaic Trombe Wall					●		PV	Thermal comfort

● ● ●

								●					
	[70]	Test module	China		Ventilated PV wall	●			●		●	PV	Electrical output and energy efficiency
	[71]	--	China		Ventilated PV wall	●			●	●	●	amorphous silicon photovoltaic	Energy performance
Framed modular wall	[72]	--	--		PV panels attached to prefabricated wood construction	●		●	●		●	PV	Energy performance
	[73]	--	--		PV system using racking-based attachment	●				●		PV	Topology optimization of PV panel connectors
	[63]	--	Europe		Modular PV wall with multi-layer panel system			●		●		Unglazed solar thermal (UST) façade	Energy performance and cost effectiveness
	[74]	--	Europe		Modular PV wall with hybrid solar harvesting system							Hybird panel (PVT); solar collector system	Energy performance, indoor environment comfort
	[59]	Commercial building; residential building	Switzerland		Modular BIPV system used for façade retrofitting							Crystalline-based technology	Design, optimization, and deployment of PV systems

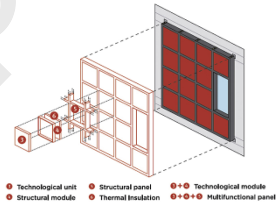
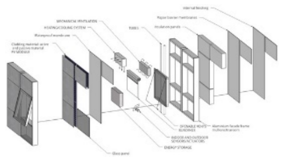
					●				●			in urban environments
[75]	Residential building	America		Transparent wall with PV-integrated polycarbonate sheathing			●	●		●	Thin-film PV; glazing integrated photovoltaic	Cost effectiveness and increased thermal insulation
[76]	Residential building	Germany		Prefabricated smart wall	●			●		●	Embodied HVAC system	Energy performance and heating demand reduction
[77]	Residential building	Spain		Plug and play modular BIPV construction system	●			●		●	BIPV system; HVAC system	Energy performance and economic savings
[32]	Test module	Switzerland		Adaptive solar façade (ASF) racking-based attachment			●	●	●	●	Thin-film adaptive PV	Energy performance
[64]	Test module	Cyprus		BIPV/T system with ventilation flaps			●		●		hybrid photovoltaic/thermal (PV/T) solar system	Energy performance, life cycle cost analysis, and comfort performance
[78]	Non-residential buildings	Italy		Post EV battery integration with the electric grid							Transparent BIPV	Energy performance

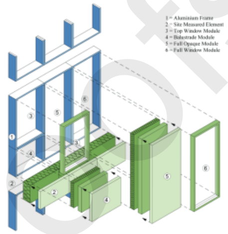
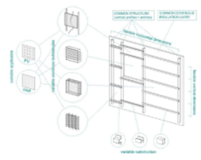
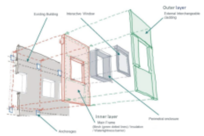
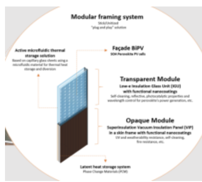
						●		●			
	[79]	Test module	Italy		Adaptive, active, and multifunctional façade	●	●		●	HVAC systems, dynamic blinds, and PV systems	Indoor environmental quality
Adhesive or sealant connection	[34]	Test module	China		Thin-film PV adhered to lightweight panels	●		●		PV	Thermal analysis of PV
	[80]	Test room (office room)	Egypt		PV-integrated prefabricated façade using adhesive bonding	●	●	●	●	transparent PV	Energy performance, visual comfort, and heat transfer

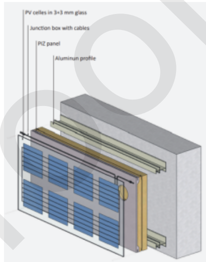
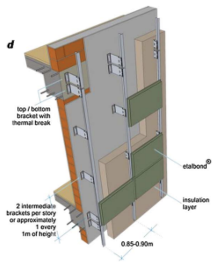
4.1.2 Funded research project-based analysis of APF technology

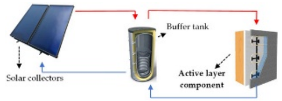
The European Commission has established several policies and targets to enhance the retrofitting of building façades and energy efficiency. The Renovation Wave Strategy (2020) is an initiative aimed at accelerating the retrofit and deep renovation of existing buildings to reduce carbon emissions and improve energy performance. The Energy Performance of Buildings Directive (EPBD) sets standards and requirements for energy performance in buildings across the EU. The 2021 revision emphasizes the need for member states to establish national building renovation plans, introduce minimum energy performance standards, and promote financial mechanisms to support energy-efficient renovations. Within these projects, forty-five research projects have involved the activities of façade developments, modular retrofits, and integration of renewable sources on buildings. A search was conducted on CORDIS for all EU-funded projects related to prefabricated wall panel technology from 2012 to 2024, retrieving a total of 45 relevant projects (Table 6). After reviewing each project, those that only included passive wall panels, lacked specific results, or were not associated with any published research papers were excluded. To be included in the final selection, the projects had to incorporate at least three out of the following four key elements: modular design, façade, enovation, and solar energy. After applying these criteria, 11 funded projects were ultimately included in the analysis. In general, the technological solutions of active prefabricated wall retrofit with Renewable energy technologies have been advanced dramatically over the past decade due to the support from the European Commission and investments from companies. Most of the projects related to this technology have undertaken seven stages of development: conceptual design and decision support, modular façade structure and fastening system, thermal insulation and fixing, renewable module integration, safety testing and regulatory compliance, energy management system and user interface, and finally demonstration and evaluation. Not all projects have completed all seven stages, but they may emphasize on one particular phase of the development due to timing and resources. For example, the early projects have made significant progress in decision-making using dynamic simulation software EnergyPlus to explore the whole system performance. During 2013–2017, the frame material, fastening methods, architectural design, and the selection of renewable modules have become viable. Limited safety testing and regulatory compliance have also been performed internally within these projects. The demonstrations began within a laboratory environment and have gradually been applied to a part of a building, a full building, and multiple buildings. It can be noticed that timber, steel, aluminium, fibre-reinforced polymer, and concrete (with nano additives) have been used as materials for load-bearing in these projects. All of these projects have published their modular façade design concepts in their reports or related journal articles. Their design concepts could be categorised as three types: layer-based modular system, frame-based modular system, and the combination of the two.

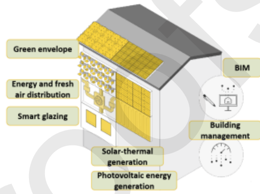
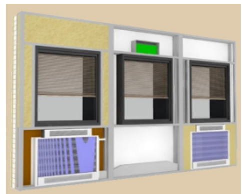
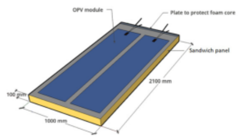
Table 6. List of project-based results (Source: Author self-painted)

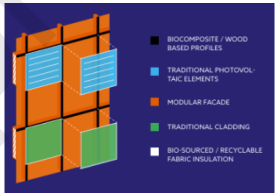
Project name	Project start time /end time	Coordinating country	Related research	Façade concept	Active technology
Meefs Retrofitting	2012-2016	Spain	A structural frame made of a thermoplastic composite material [81]	 Source:https://ec.europa.eu/research/participants/documents	Multi-functional layer (PV + mechanical ventilation)
Adaptiwall	2013-2017	The Nertherlands	Multi-functional light-weight wall panel based on adaptive insulation for energy efficient buildings [79]	 Source:https://ec.europa.eu/research/participants/documents	Mechanical ventilation and heat pumps

Plug-N-Harvest	2017-2022	Greece	Design of the passive and active multi-modal energy systems for energy sufficiency [82]	 Source:https://ec.europa.eu/research/participants/documents	Mechanical ventilation
Bertim	2015-2019	Spain	The innovation of an adaptive multi-layer façade system for retrofitting [83]	 Source:https://ec.europa.eu/research/participants/documents	PV
Ensnare	2021-2025	Spain	A prefabricated and modular façade system to incorporate solar harvesting technologies [74]	 Source:https://ec.europa.eu/research/participants/documents	PV
Powerskin Plus	2019-2024	Portugal	Highly advanced modular integration of storage systems [84]		PV

				Source:https://ec.europa.eu/research/participants/documents	
Bipvboost	2018-2023	Spain	Potential contribution of BIPV system to nearly zero energy building and methodology for project outputs [85]	 Source:https://ec.europa.eu/research/participants/documents	PV
Retrokit	2012-2016	Italy	Develop multifunctional integrated façade elements [86]	 Source:https://ec.europa.eu/research/participants/documents	Solar collector-PV
E2vent	2015-2018	France	Energy efficient ventilated façades for optimal adaptability and heat exchange [87]	 Source:https://ec.europa.eu/research/participants/documents	Machanical ventilation

Renozeb	2017-2022	Spain	A workflow for retrofitting façade systems for indoor human comfort and energy efficiency [77]	 Source:https://ec.europa.eu/research/participants/documents	PV
Plural	2020-2024	Greece	Solar-driven façade active layer system for deep building renovation - ConExWall [11]	 Source:https://ec.europa.eu/research/participants/documents	PV - Machanical ventilation
	2020-2024		Off-site prefabricated hybrid façade systems – smart wall systems [88]	 Source:https://ec.europa.eu/research/participants/documents	Solar thermal collector

INFINITE	2020-2026	Italy Slovenia France	Social sustainability assessment for stakeholder-centered building retrofit [89]		Multi-functional layer (PV + mechanical ventilation)
	2020-2026	Switzerland	Hidden colored building integrated photovoltaics: technology overview and design challenges [90]		Hidden colored BIPV
REHOUSE	2022-2024	Spain	The importance of renovation and renewable energies for carbon neutral building [91]		Modular multifunctional façade (MF) and adaptable dynamic building envelope
MEZeroE	2021-2026	Italy	Flame spread on an active photovoltaic roof system		PV

POWERSKIN PLUS	2019-2024	Portugal	Combining enhanced insulation and renewable energy technology based on photovoltaics in modular solutions for retrofit in existing curtain walls [78].		PV
AEGIR	2022-2026	Spain	High-yielding, non-intrusive, multifunctional plug-and-play envelope solutions.		PV

The major difference between layer-based and frame-based down to the way that insulation material and renewable components are fixed to the existing façade. The layer-based approach is to attach supporting structure, insulation material, and renewable components one layer by another. The ADAPTIWALL project (Table 6) adopted a layer-based modular system which utilises a concrete layer to bear the structural load [79]. For the frame-based approach, insulation material and renewable components are both surrounded by grid frames. These frames are directly fixed on the existing façade or the levelling concrete layer, which helps deal with uneven surfaces of existing buildings. The ENSNARE, E2VENT, and BIPVBOOST projects (Table 6) have adopted a frame-based system that uses aluminium, fibre reinforced polymer, or timber frames to hold the multi-functional modules that provide warmth and energy generation [74,85,87]. Each type of modular façade retrofit system has its advantages and disadvantages. For example, the layer-based system can avoid the thermal bridge, but its heavyweight feature is not suitable for high-rise building retrofit. The frame-based system could potentially reduce the weight and thickness of the wall; however, depending on the material used, the frame could become a thermal bridge, which reduces the efficiency of the new façade. To avoid the thermal bridge, the PLUG-N-HARVEST project has developed a new aluminium profile that embeds a thermal bridge breaker [82]. A combination of frame and layer-based systems provides a continuous layer of insulation and frames for the assembly of renewable modules. The project BERTIM combined approach enables a continuous insulation layer to be placed between the loading bear frame and the existing façade. This can significantly reduce the contact area between the existing façade and the metal frame, but it still can't eliminate the thermal bridge due to the metal brackets needed for fixing the frame through the insulation layer.

4.1.3 Life Cycle Assessment (LCA) and life-cycle cost assessment (LCCA) in APF technology

Based on the keyword co-occurrence analysis presented in Table 2 of Section 3.1, research on APF in conjunction with life cycle assessment exhibits relatively high betweenness centrality. Therefore, this section analyses APF–BIPV technology from the perspectives of both LCA and LCCA. Over the past decade, LCA investigations of APF-BIPV systems have progressively advanced toward more refined, façade-oriented analyses, capturing both embodied and operational carbon performance across cradle-to-grave boundaries. Currently, a series of LCAs have been performed for different types of PV modules and the outcomes of these investigations can be treated as reference sources for the life-cycle performance of BIPV technologies [92]. Zhang et al. reviewed the Energy Payback Time (EPBT) and greenhouse gas (GHG) emission rate of different types of BIPV. Among them, amorphous Silicon (a-Si) exhibited the longest EPBT, at approximately 3 years, while Cadmium Telluride PV (CdTe) had the shortest, at about 1.5 years. The other cell types, including mono-Si, multi-Si, and Copper Indium Gallium Selenide solar cell (CIGS), showed relatively similar performance, with EPBT values around 2 years. In terms of GHG emission rate, CdTe performed best, whereas the other five cell types exhibited relatively similar results [92]. Frontini et al., within the IEA PVPS Task 15 framework, quantified embodied emissions of approximately 250 kg CO_2-eq/m² for glass–glass crystalline silicon (c-Si) ventilated façades in Central Europe, with operational savings exceeding 900 kg CO_2-eq/m², yielding a strongly negative net balance [93]. Peng et al. conducted a comparative analysis of various PV technologies and found that thin-film technologies exhibit shorter EPBT. Specifically, the EPBT of mono-Si modules ranged from 1.7 to 2.7 years, whereas thin-film PV technologies demonstrated EPBT values in the range of 0.75 to 3.5 years [94]. Jayathissa et al. extended this approach to active solar façade (ASF) elements, revealing that when excluding shading benefits, the ASF exhibits a life-cycle global warming potential (GWP) of 331 g CO_2-eq/kWh, which is marginally higher than that of the orientated static solar façade, measured at 270 g CO_2-eq/kWh, which indicates a slightly higher carbon intensity for ASF under electricity generation alone. However, when the energy savings associated with façade-integrated shading are included, both systems transition to a net carbon reduction profile. Specifically, the GWP decreases to -906 g CO_2-eq/kWh for the ASF and to -773 g CO_2-eq/kWh for the static façade, with the ASF achieving approximately 17% greater net emission mitigation. These results highlight that, while the ASF may not outperform the static configuration in terms of stand-alone PV generation emissions, the integration of dynamic shading yields a substantially superior overall environmental [95]. Fukurozaki et al. conducted a life-cycle evaluation of a 1.2 kWp c-Si rooftop PV system in Brazil, assuming a service life of 30 years for the panel, structure, and cabling, and 15 years for the inverter. The assessment yielded a total life-cycle GWP of 843 kg CO_2-eq, with panel manufacturing and construction identified as the primary emission sources. The energy payback time varied between 2.47 and 3.13 years, depending on the site-specific solar irradiation conditions across different Brazilian locations [96]. Fu et al. evaluated a mc-Si PV system in China, reporting an average EPBT of approximately 3 years, with the highest value reaching 6.05 years depending on regional irradiation. The system's life-cycle GWP was calculated at 50.9g CO_2-eq/kWh, with the production of solar-grade mc-Si identified as the dominant contributor to overall emissions [97]. Akinyele et al. conducted a life-cycle assessment of a 1.5 kW PV system across six climatic regions in Nigeria, reflecting variations in solar resource availability. The analysis indicated an EPBT ranging from 0.82 to 2.3 years, while the total life-cycle GWP spanned from 1,907 to 5,819 kg CO_2-eq [98]. LCCA analysis provides a comprehensive framework to assess the long-term economic performance of BIPV façade panels by integrating capital expenditure, operational savings, maintenance, and end-of-life value. Crystalline silicon technologies remain dominant in façade-integrated applications due to their high energy yield and extended service life, often estimated at 25-30 years with annual degradation rates of 0.3-0.6% [99]. Peng et al. conducted an analysis of the life cycle energy demand (MJ/m²) and GHG emission rates of different photovoltaic technologies. The results indicate that mono-Si systems exhibited the poorest environmental performance, with the highest energy demand ranging from 2860 to 5253 MJ/m², primarily due to the high energy intensity associated with their manufacturing and production processes. The GHG emission rate of mono-Si modules was found to be 29-45 g CO_2-eq/kWh.

In contrast, thin-film photovoltaic technologies demonstrated lower GHG emission rates, ranging from 10.5-50 g CO_2-eq/kWh. The study further highlighted that thin-film modules can be fabricated in semi-transparent configurations, offering advantages for BIPV applications requiring light transmittance, whereas mono-Si modules are inherently opaque, limiting their suitability in such contexts [94].In tropical regions, Alhammadi et al. observed that thin-film vertical façades with c-Si due to better performance in diffuse-light conditions, highlighting the climatic dependency of cost-effectiveness [62]. Hybrid and multifunctional BIPV systems, such as BIPV–PCM (phase change material) façades, introduce additional value streams through thermal energy management. Cai et al. found that PCM integration reduced PV operating temperatures by 2–5 °C, improving electrical yield by 3–6% annually, while also lowering building cooling loads [29]. Gholami et al. conducted a comprehensive assessment of the economic feasibility of implementing BIPV systems as a full building envelope solution across varying façade orientations in the capitals of all European Union member states. One of the notable insights from their study is that, when the complete spectrum of environmental and social advantages is considered, even north-facing façades can achieve economic viability in certain European contexts. Furthermore, the findings indicate that the deployment of BIPV systems as continuous building envelopes has the potential not only to recover the entire initial investment but also to generate additional revenue over the system's lifetime, underscoring their value as both an environmental and economic asset in building design [100]. Through the analysis of multiple case studies, Corti et al. examined final yield, Self-Sufficiency Rate (SSR), and Total Life Cycle Costs (TLCC) by simulating the installation of BIPV systems on various building surfaces. The findings reveal that in high-rise buildings, rooftop installations, while achieving higher average annual electricity generation per unit area, are limited in total output due to their small surface area. Conversely, façade installations, despite exhibiting lower average annual yields per unit area, benefit from substantially larger available surfaces and comparatively lower investment costs, thereby offering competitive overall energy and economic performance [101].

4.2 Integration technology of APF-BIPV

Traditional Passive Prefabricated Façade (PPF) panels are non-energy-generating façade components designed to provide thermal insulation, weather protection, and aesthetic finishes. Their performance is limited to passive functions, without any direct energy output. By contrast, a APF-BIPV integrates BIPV modules as the finishing layer of the panel. In this configuration, the outer skin is not merely decorative or protective, but also generates electricity while retaining the conventional functions of weatherproofing and insulation [15]. BIPV finishing layers for APF panels exhibit diverse technological options that balance energy performance, architectural integration, and durability. C-Si technology remains the benchmark for APF-BIPV applications, with module efficiencies up to 25% (Table 7). At present, in terms of material types, the mainstream material selection trends include crystalline silicon photovoltaics and thin film photovoltaics. Mono-Si and CIGS thin films were the most suitable photovoltaic panel materials for dynamic photovoltaic shading. First, the crystalline silicon photovoltaic power conversion rate is high but is greatly affected by temperature [102]. Crystalline silicon photovoltaics have an absolute advantage in the global photovoltaic cell market (90%) [103]. Compared with polycrystalline and amorphous silicon, monocrystalline silicon has a higher performance ratio and panel power generation efficiency [104]. The conversion rate of thin-film photovoltaics (CIGS) is low [105] and inert to temperature [106]. Defaix et al. forecast a 17% increase in thin-film technology efficiency by 2030 [107]. Singh et al. showed that CIGS solar cells have lower material and energy requirements and better processing costs [108]. Based on both availability and constructability considerations, CIGS technology has been identified as a suitable photovoltaic material for future BIPV [109]; the first is from a usability perspective, thin-film photovoltaics are more resistant to shadow effects and high temperatures. The production of CdTe solar cells requires the use of toxic substances, such as cadmium and tellurium, which are potentially harmful [110]. Therefore, CdTe solar cells are not suitable for BIPV applications. From a constructability perspective, CdTe is exceptionally heavy, whereas CIGS is relatively light, enhancing its applicability in shading systems, whose structures are generally less load-bearing than a roof- and façade-integrated PV system. In terms of the panel size, with modular building integration, the market is clearly geared towards opaque or translucent rectangular modules [111]. Thin-film technology is widely used because of its size flexibility. The CIGS film has no size limitations and is relatively flexible. As the film is attached to the surface of the photovoltaic panel, it can be set according to the size of the single-crystal silicon. Merging BIPV–PCM hybrids represents a multifunctional approach, leveraging phase change materials to stabilise PV operating temperature, enhance annual yield. Karthick et al. enhanced BIPV system performance by optimising the combination ratio of PCM materials and conducting experiments. Results indicated that incorporating PCM reduced the instantaneous peak temperature by up to 12 °C compared to the non-PCM configuration. Furthermore, the annual electricity generation increased by approximately 8% with the use of PCM [112]. Overall, the selection of the BIPV layer within APF systems exhibits a high degree of context dependency, constrained by factors such as product availability, installation location, and investment budget.

Table 7. List of Different BIPV Integration Layers (Source: Author self-painted)

	BIPV layer type	Typical structure	Key advantages	Main limitations	Typical façade applications
Crystalline Silicon (C-Si) BIPV modules	**Glass–glass crystalline silicon**	PV cells laminated between two tempered glass sheets with EVA/PVB encapsulant	High durability, moisture resistance, structural rigidity, opaque or semi-transparent	High weight, higher cost	High-rise façades, spandrel panels, and ventilated cladding requiring high fire resistance
	Glass–backsheet crystalline silicon	PV cells laminated between tempered glass and polymeric backsheet	Lower weight, good efficiency	Lower fire rating; backsheet UV degradation risk	Lightweight prefabricated façades, retrofits
Thin-film BIPV modules	**CIGS thin-film**	CIGS absorber on glass or flexible substrate	Uniform colour, flexible formats, better diffuse-light performance	Lower efficiency, moisture sensitivity	Coloured façades, lightweight panels
	CdTe thin-film	CdTe absorber layer on glass substrate	Good thermal stability, low temperature coefficient	Cadmium toxicity; lower efficiency	Large-format panels in hot climates
	Amorphous silicon (a-Si)	a-Si absorber on glass or polymer	Semi-transparent; low-light performance	Low efficiency; initial degradation	Atriums, shading devices, transparent façades
Special-surface BIPV modules	**Colour-modified BIPV**	Coloured glass, pigmented encapsulant, or ceramic frit applied over PV cells	Architectural integration in heritage contexts	Reduced efficiency from colour filtering	Heritage façades, design-driven projects
	Semi-transparent BIPV glazing	Cell spacing or laser patterning in glass–glass modules	Combines daylighting + power	Lower yield	Curtain wall vision zones, double-skin façades
	Flexible BIPV laminates	PV on lightweight polymer substrate (CIGS, a-Si)	Lightweight, adaptable to curves	Lower mechanical resistance, shorter lifespan	Curved façades, lightweight retrofits
Hybrid BIPV modules	**BIPV–PCM hybrid**	PV laminate integrated with a PCM layer behind	Reduces PV cell temperature, adds thermal storage	Added complexity; PCM fire safety	Hot climates, façades needing peak-load shifting

In the literature on BIPV-APF systems, the choice of support and anchoring solution is often driven by the original façade substrate, panel format, and installation context. EU smart cities information system reported a series of BIPV retrofit projects, where large-format glass–glass crystalline silicon APF-BIPV panels were mounted using mechanical ventilated façade subframe systems composed of aluminium vertical rails and stainless-steel brackets, allowing precise alignment and rear ventilation [113]. Maturi et al. described an experimental project where direct mechanical fixing was used: BIPV panels incorporating a rigid aluminium perimeter frame were anchored directly to the original laboratory wall using mechanical bolts, eliminating the need for secondary rails [114]. This approach reduced façade depth but required highly accurate substrate preparation and on-site positioning [115]. BILDA company adopts a framework-based anchoring system utilising a bracket-and-strut profile to structurally integrate photovoltaic panels into the building envelope (Figure 14). The system is designed with hinged, openable panel modules, enabling outward rotation to facilitate direct access for inspection, maintenance, and repair of internal components [116]. Dannapfel et al., within the framework of the Plug-N-Harvest project, reported the development of a framework-based anchoring system designed to integrate APF panels while minimising disruption to the existing building envelope. The anchoring configuration consists of pre-installed brackets or anchor plates fixed to the original substrate, typically a reinforced concrete structural wall, serving as the primary support for the vertical or horizontal suspension of APF panels. Each panel is connected according to designated fixed anchoring points, with lower panels generally secured by four anchors and upper panels by two, enabling a sequential, plug-and-play installation process. The system incorporates bi-directional adjustability (horizontal and vertical) through precision micro-grooved bracket interfaces, allowing accurate alignment and compensation for façade surface irregularities. This approach ensures reliable load transfer, including self-weight and wind actions, while significantly improving installation efficiency through prefabrication and modular assembly techniques [117]. For lightweight and small-scaled modules, Kuhn et al. reported the use of structural adhesive systems, particularly structural sealant glazing (SSG) or point fixings to ensure mechanical safety to bond BIPV panels to continuous secondary rails or unitised frames [118]. Hybrid approaches are also reported in the literature. In a retrofit study of a ventilated façade system with an original concrete substrate, Petresevics et al. described an anchoring configuration in which APF panels were secured to the supporting wall using both mechanical fasteners anchored by expansion bolts and adhesive system. The secondary subframe comprised vertical profiles and thermal break isolators to minimise conductive heat transfer, while maintaining a ventilated air gap to enhance the façade's thermal performance [119]. Anchoring strategies are strongly influenced by the original wall material. In concrete retrofits or ventilated BIPV façade retrofitting projects, as previously discussed, framework-based anchoring configurations are commonly employed [116,117]. In steel frame retrofits, bolted cleats are always used to connect APF panels to primary steel columns, often with thermal break isolators to reduce conductive heat losses [114]. Overall, the reviewed literature indicates that APF-BIPV support systems span a spectrum from full mechanical subframes to adhesive-only bonds (Table 8), with intermediate hybrid solutions offering a balance between mechanical redundancy and aesthetic integration. Prefabrication is repeatedly cited as a means to improve anchoring quality, reduce on-site labour, and facilitate integration of electrical components within the support assembly [48,64,88]. However, there remain gaps in comparative performance data, particularly regarding the long-term mechanical behaviour, fatigue resistance, and life cycle environmental impacts of different anchoring strategies, and a need to harmonise anchoring design with BIPV-specific electrical and thermal requirements as well as façade heritage constraints.

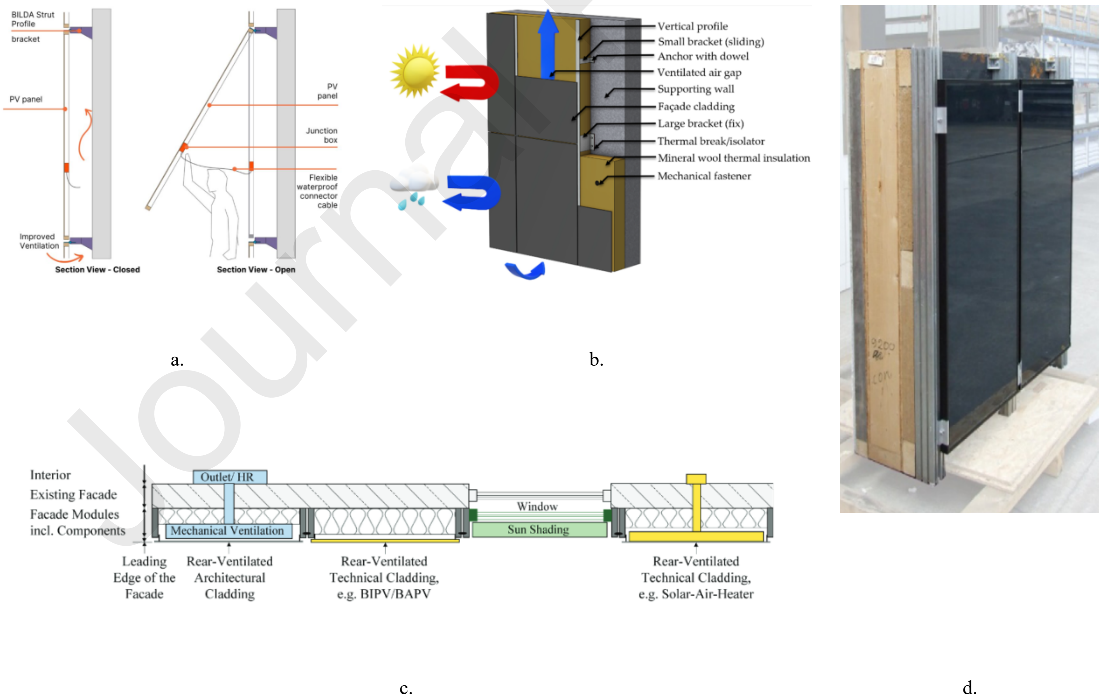


Figure 14. Different APF panel integration technology. a. Flexible framework-based façade system, Source: https://tfire.com.au; b. Ventilated Façade cladding anchoring system, Source: Adapted from [119]; c. Framework-based anchoring system, Source: Adapted from [117]; d. Direct mechanical anchoring system, Source: Adapted from [114]

Table 8. List of different APF panel integration layers (Source: Author self-painted)

	Substrate compatibility	Structural characteristics	Thermal bridging	Applicability assessment
Framework-based system	Concrete, wood, steel	Aluminium or stainless-steel brackets and rails	Point thermal bridges at brackets; mitigated with isolators	Suitable for large, high-load panels; robust and durable
Adhesive system (SSG/ Tape)	Concrete, glass, composite boards	Structural silicone or acrylic foam tapes bonding to secondary rails or frames	Continuous bond line; minimal thermal bridge	Best for lightweight, small panels and high-aesthetic projects
Hybrid (Mechanical plus Adhesive)	Stone, concrete, metal	Concealed undercut anchors or clamps combined with structural adhesive	Adhesive layer reduces thermal bridge	Well-suited to heritage and high-safety projects
Direct mechanical fixing	Concrete, steel	Perimeter-frame bolts or chemical anchors directly installed into the wall	Pronounced point thermal bridges	For small, rigid panels; simple but tolerance-sensitive

4.3 Barriers and challenges for BIPV development

Among the various factors hindering the development of BIPV façades, fire risk has attracted particular attention. BIPV systems must satisfy dual requirements as both electrical components and structural building elements [120]. Cavity spaces in a lot ventilation BIPV façades present particularly severe fire risks. The chimney effect in ventilated façades significantly amplifies these risks, with pressure differentials and re-radiation inside cavities leading to 3-6 times higher mass burning rate, flame height, and temperature [121,122]. Large-scale fire testing of BIPV façade systems has revealed critical failures, including falling objects and vertical flame propagation [123]. The cavity width plays a crucial role, with a critical width range of 13-50 mm identified where maximum vertical fire spread occurs [122]. Meanwhile, an increasing body of research has been devoted to fire safety in BIPV façades. Fire barriers represent essential safety measures, though their effectiveness varies significantly with design and placement [121]. Thermal management strategies have also been proven to be effective for fire control in BIPV façades, including optimizing cavity parameters and implementing fire-resistant materials. Double-skin façade systems show that outer pane tilt angles significantly affect smoke spread, with inward tilted or vertical outer panes creating dangerous conditions for upper floors due to hot smoke adherence [124,125]. Air curtain systems can provide effective fire protection, with jet velocity increases significantly reducing vertical temperature and heat flux on façades [126]. Ventilation design critically influences fire safety outcomes in BIPV façades. Proper venting regimes can limit smoke spread to higher floors, provided vents close during fire events and flashover is prevented. The effectiveness depends on ensuring exterior vents from double-skin façades have a greater effective area than interior vents, directing smoke flow predominantly outside the building [127]. Façade protection regulations also represent a significant regulatory barrier to the deployment of BIPV systems on building façades in Europe, as shown in Table 9, particularly in historic urban centres and culturally sensitive areas. While recent EU directives, such as the recast Energy Performance of Buildings Directive (EPBD, Directive (EU) 2024/1275) [128] and the revised Renewable Energy Directive (RED III, Directive (EU) 2023/2413) [129], promote the integration of solar technologies and aim to simplify permitting procedures, they explicitly allow heritage and landscape protection laws at national and local levels to impose stricter requirements or exemptions for protected buildings and zones (European Commission, 2024a; European Commission, 2023). At the national and municipal level, many Member States enforce façade management policies that require prior approval from cultural heritage authorities when any modification may alter the architectural character, materiality, or visual perception of a building's envelope. These restrictions are particularly stringent for visible façades in conservation areas, surrounding listed monuments, or within UNESCO World Heritage sites.

Approvals often hinge on compliance with aesthetic guidelines, such as colour matching, surface texture, reflectance reduction, and modular alignment (French Ministry of Culture, 2022 [130]; Italian Ministry of Culture, 2024; RCE, 2024 [131]). From a APF-BIPV integration perspective, these regulations create multi-layered challenges, often increasing project complexity, cost, and lead time, discouraging façade-integrated BIPV projects in sensitive contexts despite their potential to contribute to decarbonisation targets.

Table 9. List of different BIPV integration layers (Source: Author self-painted)

Jurisdiction	Regulatory framework/authority	Key restrictions on façade PV	Direct implications for BIPV design and integration
France	Heritage Code & Sites patrimoniaux remarquables (SPR) under Architectes des Bâtiments de France (ABF) [130]	ABF approval mandatory; visible façade PV often refused unless colour/texture harmonised	Requires low-reflectance, colour-matched BIPV modules; alignment with façade patterns; preference for non-visible locations
Italy	Cultural Heritage and Landscape Code (D.Lgs. 42/2004) [131]	Landscape authorisation (autorizzazione paesaggistica) required in protected areas; simplified permits excluded	Favours reversible subframe systems; adhesives/chemical anchors discouraged on historic masonry
Germany (Bavaria)	Bavarian Monument Protection Act (BayDSchG) [132]	Allows PV on heritage buildings under case-by-case review; visible façades highly scrutinised	Coloured/texture-matched BIPV encouraged; mock-ups and visual impact studies often required
Spain	Spanish Historical Heritage (Law 16/1985) [133]	Explicit permit requirement for any work affecting external appearance	Requires reversibility and minimal visual impact; local bylaws may impose stricter aesthetic controls
Netherlands (Amsterdam)	Cultural Heritage Agency (RCE) guidance; municipal heritage policy [134]	Allows PV on monuments under aesthetic integration guidelines; gradual relaxation for visibility	Modular alignment, concealed wiring, and material compatibility critical; heritage canalscape remains sensitive

5 Conclusions

This study presents a comprehensive review of the recent advancements in APF systems integrated with BIPV technology, focusing on their application in energy-efficient building renovation. Through a systematic analysis of academic publications of the last 10 years (2014–2024) and European Commission-funded projects of the last 12 years (2012-2024), the review demonstrates a clear research growth trajectory and increasing practical relevance of this integrated technology. The number of publications in Scopus and Web of Science databases has grown approximately 3.5 times over the past decade, with an average annual growth rate exceeding 12%. In Section 3, the research hotspots in the APF-BIPV field over the past decade were identified, revealing a clear transition in focus that from early-stage attention to fundamental building and PV technologies, to mid-term exploration of energy efficiency and PV integration, and ultimately to current trends toward modular, high-performance, and sustainable building solutions, alongside life-cycle assessment approaches. This evolution underscores the growing significance of high performance and interdisciplinarity in APF research. Accordingly, the analysis in Section 4 places particular emphasis on integration technologies for APF-BIPV and provides a comprehensive review of BIPV from both life-cycle assessment (LCA) and life-cycle cost assessment (LCCA) perspectives. Since most research articles employ simulation or mathematical modelling approaches, Section 4.1 introduces EU-funded projects as a complementary source, summarizing full-scale and on-site experimental initiatives to provide a more comprehensive overview of BIPV technology. At the European level, 45 relevant projects were initially identified, 18 of which were included in the final discussion. In contrast to earlier studies that relied mainly on simulation, recent research increasingly adopts full-scale testing, on-site monitoring, and hybrid evaluation approaches to capture the real-life performance of APF systems. Overall, the field is progressing toward greater standardization, modularity, and replicability, indicating the potential of APF systems to become a mainstream solution for building envelope renovation. However, despite significant progress, the widespread implementation of BIPV-APF systems still faces several critical limitations that must be addressed in future research:

- Limited project scale and low practical transferability:

Although full-scale experimental methods have increased, over 40% of studies remain at the level of simulation or lab façade-scale validation. There is a lack of multi-scale comparative studies and long-term field data to verify system performance under diverse building forms and climate conditions. Most multi-objective optimization approaches are model-based and insufficiently calibrated with empirical data, reducing predictive reliability.

- Incomplete understanding of structural configurations and integration methods: while three dominant integration strategies are frequently cited (double-skin façades, framed modular systems, adhesive/sealant connections), few studies systematically evaluate their differences in structural performance, constructability, or retrofit compatibility. Currently, there is no unified technical standard or product certification framework across the design, manufacturing, and installation stages. This results in a lack of interoperability among systems, making it difficult to replicate technologies across different projects and geographical contexts.

- Insufficient economic feasibility analysis: most existing studies focus on operational energy savings, while only a few systematically evaluate initial investment, life-cycle cost (LCC), long-term performance assessment and degradation, operational and maintenance requirements [58,135].

- Structural and Safety Risks: in multi-story and high-rise buildings, APF systems are exposed to environmental challenges such as wind loads, rainwater infiltration, and long-term thermal stress. However, research on structural safety, fire performance, and thermal stability remains insufficient, particularly in systems that incorporate fire-sensitive material and devices such as PCM and electrical wiring [136,137].

In summary, this study not only outlines the development trends and key integration pathways of APF-BIPV systems in the context of energy-efficient building renovation but also identifies the current technical and construction-related bottlenecks hindering their broader adoption. Through a combined analysis of academic literature and EU-funded projects, the research establishes a systematic knowledge framework encompassing research hotspots, integration strategies, and implementation considerations. This provides a theoretical foundation for future work aimed at targeted technological optimization, standard development, and scenario-based application validation. Looking ahead, the transition of BIPV-APF systems from experimental demonstration to large-scale implementation will require continued efforts in cross-scale performance assessment, life cycle assessment, and the enhancement of safety and reliability. Against the backdrop of a building sector increasingly oriented toward high efficiency and renewable energy integration, APF-BIPV systems are gradually demonstrating both engineering viability and policy alignment potential, particularly in the renovation of existing building façades.

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1. Highlights

- Over the past decade, the number of researches on Active Prefabricated Façades (APF) integrating PV have been increased.
- The combination of PV integrated in modular prefabricated construction holds significant future relevance for building renovation.
- Several EU funded researches have analyzed experimentally the performance of APF in real conditions.