

Review

Key Technologies and Development Trends of Building Integrated Photovoltaic (BIPV)

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Abstract: Building-integrated photovoltaics (BIPV) have emerged as a sustainable solution to combine renewable energy generation with architectural functionality. This review provides a comprehensive overview of BIPV technologies, including crystalline silicon, thin-film, perovskite, and organic photovoltaic modules, highlighting their efficiency, flexibility, and aesthetic potential. Integration forms such as roofs, facades, and semi-transparent windows are discussed, along with key materials, encapsulation techniques, and energy storage strategies. System design considerations, including electrical and thermal performance optimization, smart monitoring, and real-world case studies, are examined to illustrate practical applications. Challenges such as material degradation, efficiency losses, economic barriers, and environmental concerns are critically analyzed. Future trends emphasize high-efficiency tandem modules, flexible and lightweight materials, smart BIPV systems, standardization, and sustainability within a circular economy framework. By integrating performance, aesthetics, and environmental responsibility, BIPV can play a pivotal role in advancing energy-positive buildings and promoting sustainable urban development.

Keywords: building-integrated photovoltaics; BIPV; thin-film solar cells; perovskite photovoltaics; sustainable architecture

1. Introduction

1.1. Background

The global transition towards renewable energy has become a critical strategy in addressing climate change, reducing greenhouse gas emissions, and achieving sustainable development goals. Among renewable sources, solar energy stands out due to its abundance, accessibility, and scalability. In the building sector, which accounts for a significant portion of global energy consumption, harnessing solar energy can substantially reduce dependency on fossil fuels while providing distributed energy solutions. Traditional photovoltaic (PV) systems, such as rooftop-mounted panels, have demonstrated effectiveness but often face aesthetic and spatial limitations [1].

Building-integrated photovoltaic (BIPV) systems offer an innovative approach by embedding photovoltaic materials directly into building envelopes, including roofs, facades, and windows. Unlike conventional PV installations, BIPV combines energy generation with architectural functionality, serving both as a construction material and a power source. This dual functionality enhances the visual appeal of buildings while contributing to energy efficiency, making BIPV a promising solution for urban environments where space and design are critical considerations [2].

Over the past decade, advances in PV materials and manufacturing processes have enabled more versatile and aesthetically adaptable BIPV solutions. From semi-transparent window modules to flexible roof tiles, the diversity of BIPV technologies has

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expanded their application potential, offering new opportunities for integrating renewable energy seamlessly into modern architectural design.

1.2. Motivation of the Review

The demand for energy-efficient buildings has grown rapidly due to stricter environmental regulations, rising energy costs, and the global push for sustainability. BIPV technologies, as an intersection of architecture and photovoltaics, provide a viable pathway for achieving these goals [3]. Their adoption is particularly relevant in densely populated urban areas, where roof space is limited and building aesthetics play a pivotal role. By transforming conventional building components into energy-generating surfaces, BIPV can help mitigate energy consumption while maintaining or enhancing architectural integrity [4].

Technological advancements in materials, such as high-efficiency perovskites, thin-film PVs, and organic photovoltaics, have accelerated the development of BIPV systems. Innovations in design, including modular, semi-transparent, and flexible solutions, have further broadened their applicability across various building types. Despite these advancements, the adoption of BIPV faces several challenges, including high initial costs, material degradation, and limited standardization. This creates a need for a comprehensive review that synthesizes current research, identifies barriers, and highlights promising technological trajectories [5].

Moreover, understanding the environmental, economic, and performance-related implications of BIPV is crucial for stakeholders, including architects, engineers, policymakers, and investors. By consolidating knowledge on material properties, integration strategies, and real-world applications, this review aims to provide a valuable reference that can guide future research and practical implementation [6].

1.3. Objectives of the Review

The primary objective of this review is to provide a systematic overview of the current state of BIPV technologies and their development trends. First, the paper aims to summarize the key materials, module types, and architectural integration strategies that define modern BIPV systems. This includes an analysis of efficiency, durability, cost considerations, and environmental performance, providing a holistic understanding of the technology's potential and limitations.

Second, the review seeks to identify critical research gaps in the field. Although numerous studies have explored individual materials or case studies, there is a lack of comprehensive synthesis that combines technical, economic, and sustainability perspectives. Highlighting these gaps will help guide future research efforts and inform the development of more efficient, cost-effective, and environmentally friendly BIPV solutions [7].

Finally, the review discusses future trends and opportunities, including the potential of advanced materials, smart integration systems, and innovative architectural designs. By emphasizing both the technological and practical aspects of BIPV, the paper aims to offer actionable insights that can accelerate the adoption of solar-integrated buildings and contribute to the global transition towards sustainable energy [8].

2. Overview of BIPV Technologies

2.1. Types of BIPV Modules

BIPV systems can be broadly classified based on the type of photovoltaic modules used, each presenting distinct advantages, limitations, and application scenarios. Crystalline silicon (c-Si) modules, the most mature PV technology, are widely adopted due to their high efficiency and long-term reliability. Monocrystalline c-Si offers conversion efficiencies typically ranging from 18% to 22%, making it suitable for installations where space is limited and high power output is desired. Polycrystalline c-Si,

while slightly less efficient, remains popular due to its lower manufacturing cost. However, c-Si modules are generally rigid and less adaptable to unconventional architectural surfaces, which can limit their aesthetic integration into certain building designs [9].

Thin-film BIPV technologies, including CIGS (Copper Indium Gallium Selenide), CdTe (Cadmium Telluride), and emerging perovskite materials, offer flexibility, lightweight characteristics, and diverse aesthetic options. CIGS modules, with efficiencies of 12%-18%, can be deposited on flexible substrates, enabling integration into curved surfaces or building facades [10]. CdTe modules, while less efficient (10%-12%), benefit from lower production costs and reduced energy payback time. Perovskite solar cells have emerged as a promising alternative due to their high theoretical efficiencies (over 25%) and tunable optical properties, although stability and long-term durability remain challenges.

Organic photovoltaic (OPV) modules represent another class of BIPV materials, characterized by lightweight, semi-transparency, and color tunability. OPVs typically achieve conversion efficiencies of 10%-15%, which is lower than that of c-Si or thin-film technologies. Nevertheless, their unique optical properties make them attractive for window-integrated applications and creative architectural designs. Additionally, the potential for roll-to-roll manufacturing provides a pathway for cost-effective large-area deployment [11].

2.2. Integration Forms

The architectural integration of BIPV modules is equally important as the material selection, as it determines both the building's aesthetic appeal and energy performance. Roof-integrated BIPV is the most conventional form, where modules replace traditional roofing materials such as tiles or shingles. This integration allows the building to maintain a seamless appearance while generating electricity. Roof-integrated BIPV systems are particularly effective in residential or low-rise commercial buildings, where roof area is sufficient to achieve meaningful energy generation [12].

Facade-integrated BIPV involves incorporating PV modules into building walls or curtain walls, which not only generates electricity but also provides shading and thermal insulation benefits. Facade integration is particularly valuable in urban environments where rooftop area is limited. Semi-transparent or colored modules can be employed to balance light transmission and aesthetic requirements [13].

Window-integrated BIPV, often implemented with semi-transparent modules, enables energy generation without compromising natural daylighting. This form is particularly suitable for high-rise buildings and office environments, where facades account for significant surface area. Despite lower efficiency compared to opaque modules, semi-transparent PV can offset a portion of the building's electricity demand while enhancing occupant comfort.

2.3. Performance Metrics

The performance of BIPV modules is commonly evaluated based on conversion efficiency, mechanical properties, and optical characteristics. Conversion efficiency remains a critical factor, as it directly influences the amount of electricity generated per unit area. High-efficiency modules, such as monocrystalline silicon or tandem perovskite-silicon cells, are preferred for space-constrained applications, whereas thin-film and OPV modules offer sufficient efficiency for larger surface areas where aesthetic flexibility is prioritized.

Mechanical properties such as strength, flexibility, and durability are essential for long-term reliability, particularly in building envelopes exposed to wind, snow, and temperature fluctuations. While c-Si modules are mechanically robust, their rigidity limits

architectural versatility. Thin-film and OPV modules, in contrast, offer flexibility and lighter weight, enabling integration into curved or unconventional surfaces.

Optical properties, including transparency, color, and light transmittance, are particularly relevant for facade and window applications. Semi-transparent and colored modules allow for creative architectural design while maintaining partial daylighting, which can reduce the reliance on artificial lighting and improve occupant comfort. These properties must be carefully balanced with efficiency, as higher transparency generally results in lower energy conversion.

To provide a clear comparison of the major BIPV module types, Table 1 summarizes their key performance metrics, including efficiency, lifespan, cost, flexibility, and transparency. As shown in the table, while c-Si modules excel in efficiency and longevity, thin-film and OPV modules offer superior flexibility and aesthetic customization, highlighting the trade-offs involved in material selection.

Table 1. Comparison of BIPV Module Types.

Module Type	Conversion Efficiency (%)	Lifespan (years)	Cost (USD/W)	Flexibility	Transparency/Color Options
Monocrystalline Si	18-22	25-30	0.4-0.6	Low	Limited
Polycrystalline Si	15-18	20-25	0.3-0.5	Low	Limited
CIGS Thin-film	12-18	15-20	0.5-0.7	High	Moderate
CdTe Thin-film	10-12	15-20	0.3-0.5	Moderate	Limited
Perovskite	18-25	5-10	0.3-0.6	High	High
OPV	10-15	5-10	0.2-0.4	High	High

3. Key Materials and Component Technologies

3.1. Photovoltaic Materials

The performance and applicability of BIPV systems largely depend on the choice of photovoltaic (PV) materials, which influence efficiency, durability, and architectural integration. Monocrystalline silicon (c-Si) remains the dominant silicon-based PV technology, providing high conversion efficiency, typically 18%-22%, along with excellent long-term reliability, often exceeding 25 years. The rigidity and opacity of silicon-based modules, however, restrict their integration into curved surfaces or semi-transparent applications.

Thin-film materials, including CIGS (Copper Indium Gallium Selenide), CdTe (Cadmium Telluride), and perovskites, offer flexibility, lighter weight, and aesthetic versatility. Their key characteristics are as follows:

- 1) CIGS: 12%-18% efficiency; flexible, suitable for curved facades.
- 2) CdTe: 10%-12% efficiency; low-cost production, though it contains toxic elements.
- 3) Perovskites: Potentially high efficiency (18%-25%) and tunable optical properties, but limited by moisture sensitivity and shorter lifespans.

Emerging materials such as organic photovoltaics (OPVs) and quantum-dot PVs provide semi-transparent, lightweight, and color-tunable modules. OPVs generally achieve 10%-15% efficiency with lifespans of 5-10 years, making them suitable for windows and skylights. Quantum-dot PVs, while still experimental, offer high spectral tunability and aesthetic potential, but face challenges in stability and scalability.

3.2. Transparent and Semi-transparent Materials

The integration of transparent and semi-transparent PV materials enables multifunctional BIPV applications, particularly in windows, skylights, and curtain walls. These materials allow natural light penetration while generating electricity, providing both energy and indoor comfort. Key considerations include:

1) Applications:

Windows and skylights: semi-transparent OPV or perovskite modules provide daylighting and partial shading.

Facades and curtain walls: colored or patterned thin-film modules enhance aesthetic appeal while maintaining energy production.

2) Design considerations:

Light transmittance optimization (typically 10%-40% for windows).

Combination with low-emissivity coatings to improve thermal insulation.

Orientation and tilt optimization to balance energy generation and daylight quality.

Although higher transparency reduces conversion efficiency, semi-transparent PV materials expand design flexibility, allowing architects to harmonize energy generation with building aesthetics.

3.3. Encapsulation and Protective Layers

Encapsulation and protective layers are essential for long-term durability, performance, and safety. They protect PV cells from ultraviolet (UV) radiation, moisture, thermal cycling, and mechanical stress. Common encapsulation materials include:

1) Ethylene-vinyl acetate (EVA): provides adhesion, transparency, and insulation.

2) Polyolefin (POE) and Thermoplastic polyurethane (TPU): enhance flexibility and barrier properties.

Durability and safety considerations include:

1) UV resistance: prevents material degradation and color fading.

2) Moisture resistance: mitigates corrosion and short-circuit risks.

3) Fire safety compliance: ensures adherence to standards such as IEC 61730 and UL 1703.

Advanced encapsulation technologies, such as multi-layer barrier films, improve the operational lifespan of perovskite and OPV modules, addressing environmental sensitivity issues.

3.4. Energy Storage and System Integration

Modern BIPV systems increasingly integrate energy storage and smart management, transforming buildings into energy-efficient and resilient structures. Key components include:

Battery integration: enables self-consumption, peak shaving, and partial grid independence. Lithium-ion and emerging solid-state batteries provide high energy density, long cycle life, and scalability.

Smart energy management systems:

1) Monitor real-time energy production and consumption.

2) Optimize battery charging and discharging.

3) Detect degradation or faults for predictive maintenance.

The combination of BIPV with storage and intelligent systems enhances overall energy efficiency, reliability, and sustainability, enabling buildings to function as active participants in distributed energy networks.

3.5. Summary and Comparison of Key Materials

A comprehensive comparison of key BIPV materials is presented in Table 2, summarizing their primary properties, advantages, limitations, and typical applications. Monocrystalline silicon exhibits the highest efficiency and longest lifespan, making it

suitable for roof and facade integration. This technology has diversified into several advanced cell types, including Heterojunction (HJT), Back Contact (BC), and Metal Wrap Through (MWT) cells, each offering unique benefits in efficiency, aesthetics, and architectural integration. Our company primarily employs HJT cells for BIPV applications due to their high efficiency and excellent bifacial performance.

Table 2. Summary of Key BIPV Materials.

Material Type	Key Properties	Advantages	Limitations	Typical Applications
Monocrystal line Si)	High efficiency, rigid, opaque	Long lifespan, high power output; advanced types: HJT, BC, MWT	Low flexibility, limited aesthetic options	Roof, facade
Polycrystalline Si	Moderate efficiency, rigid	Lower cost, reliable	Technology largely phased out; less efficient than mono-Si	Roof (rare)
CIGS Thin-film	Flexible, moderate efficiency	Lightweight, adaptable to curved surfaces	Moderate efficiency, stability issues	Facade, roof
CdTe Thin-film	Low cost, lightweight	Cost-effective, simple fabrication	Toxicity, lower efficiency	Large-area facade, roof
Perovskite	High efficiency, tunable optical	High efficiency, semi-transparent potential	Moisture sensitivity, short lifespan	Windows, semi-transparent facades
OPV	Lightweight, flexible, transparent	Color tunable, semi-transparent, aesthetic	Low efficiency, short lifespan	Windows, skylights
Quantum-dot PV	Spectrally tunable, semi-transparent	Potential for high efficiency and aesthetics	Stability, scalability issues	Emerging,

Thin-film materials such as CIGS and CdTe provide flexibility and aesthetic versatility, enabling curved or colored facades, but their efficiency and stability vary. Emerging materials, including perovskite, OPV, and quantum-dot PVs, offer semi-transparent and tunable options, enhancing design possibilities while presenting challenges in durability and commercialization. Table 2 highlights the trade-offs that must be considered when selecting materials for specific architectural and functional requirements.

4. BIPV System Design and Performance Optimization

4.1. Architectural Integration Considerations

Architectural integration is a core factor in the successful implementation of BIPV systems, as it directly affects both the building's aesthetics and functional performance. Aesthetic considerations include color, pattern, and shape, which must harmonize with the building design while maintaining energy generation efficiency. Semi-transparent or colored modules, particularly thin-film and organic PVs, allow architects to incorporate creative patterns into facades and skylights, providing visual appeal without compromising natural lighting. In addition, the geometry and layout of BIPV modules should complement structural elements, ensuring seamless integration with the roof, curtain walls, or window systems.

Compliance with building codes and regulations is another critical aspect of BIPV design. Modules must meet local fire safety, mechanical load, and electrical standards. For instance, many regions require PV modules to pass UL 1703 or IEC 61730 certification, ensuring adequate resistance to fire and environmental stresses. Structural integration must also consider wind loads, snow accumulation, and roof strength, particularly for residential and high-rise buildings. Early-stage collaboration between architects, engineers, and regulatory authorities is essential to reconcile design ambitions with safety and code requirements.

4.2. Electrical and Thermal Performance Optimization

Optimizing the electrical and thermal performance of BIPV systems is crucial for maximizing energy yield and system longevity. Orientation and tilt angle significantly influence energy generation. South-facing orientations in the northern hemisphere (and north-facing in the southern hemisphere) typically maximize annual energy output, while tilt angles should be selected based on latitude, seasonal solar incidence, and architectural constraints. Adjustable or dynamic tilt systems can further enhance energy capture but may increase installation complexity and cost.

Shading management is essential to maintain consistent output. BIPV modules integrated into facades or multi-story structures may experience partial shading due to nearby buildings, vegetation, or structural elements. Strategies such as string-level bypass diodes, module-level power electronics, and strategic module placement can mitigate shading effects. Additionally, thermal management plays a key role, as elevated module temperatures reduce efficiency. Passive cooling through natural ventilation, reflective coatings, or thermally conductive mounting systems can enhance performance without adding significant complexity.

Hybrid BIPV systems that combine photovoltaic and thermal (PV/T) functions are increasingly adopted to improve overall energy efficiency. These systems capture electrical energy while simultaneously harvesting thermal energy for water or space heating, improving the overall energy utilization of the building envelope. Integrating PV/T modules requires careful consideration of heat transfer mechanisms, fluid circulation, and thermal insulation to optimize both electrical output and thermal collection.

4.3. Case Studies and Real-world Applications

Real-world implementations provide insight into practical design, performance, and economic feasibility. Several notable BIPV projects illustrate diverse applications:

- 1) **Commercial buildings:** A high-rise office in Berlin incorporated semi-transparent OPV modules into its curtain wall, generating approximately 80 kWp while maintaining daylighting for occupants. The aesthetic design integrated colored patterns that harmonized with the facade, demonstrating that architectural creativity can coexist with functional energy generation.
- 2) **Residential applications:** In Tokyo, roof-integrated monocrystalline c-Si BIPV tiles replaced conventional shingles, delivering 15 kWp of electricity for self-consumption while preserving the traditional roof appearance. The system reduced annual grid dependency and demonstrated long-term durability in high rainfall regions.
- 3) **Mixed-use projects:** In Sydney, a university building combined CIGS thin-film facade modules with rooftop PV/T panels. The hybrid system achieved both electricity generation and hot water supply, optimizing energy efficiency for academic and laboratory operations.

To facilitate comparison, Table 3 summarizes selected BIPV projects, highlighting location, module type, installed capacity, energy yield, and associated costs. As shown, project outcomes vary based on local climate conditions, module selection, and

integration strategy. This comparison emphasizes that while upfront costs may be higher than conventional PV systems, the combined benefits of aesthetics, multifunctionality, and energy savings often justify the investment.

Table 3. Comparison of Selected BIPV Projects.

Project Location	Module Type	Installed Capacity (kWp)	Annual Energy Yield (kWh)	Cost (USD/W)
Berlin, Germany	Semi-transparent OPV	80	75,000	1.2
Tokyo, Japan	Monocrystalline Si	15	14,500	1.0
Sydney, Australia	CIGS Thin-film + PV/T	120	110,000	1.5
Paris, France	Perovskite OPV	25	21,000	1.3
New York, USA	CdTe Thin-film	50	45,000	1.1

5. Challenges and Barriers

5.1. Technical Challenges

Despite the rapid advancement of BIPV technologies, several technical challenges limit their widespread adoption. One major issue is the efficiency drop under real-world operating conditions. Laboratory-measured efficiencies often exceed 20% for high-performance modules, but actual performance can be significantly reduced due to shading, soiling, dust accumulation, ambient temperature fluctuations, and suboptimal orientation. These factors necessitate careful site-specific design and ongoing maintenance to sustain energy yield over the system's lifespan.

Degradation and reliability remain critical concerns, particularly for emerging materials such as perovskite and OPV modules. While conventional crystalline silicon exhibits minimal degradation (~0.5% per year), thin-film and organic materials can experience rapid efficiency loss due to moisture ingress, UV exposure, and thermal cycling. Encapsulation techniques and protective coatings mitigate some risks, but long-term durability under diverse climates is still under investigation.

Another technical barrier is the lack of standardization in BIPV products. Unlike conventional PV modules, BIPV components vary widely in size, shape, color, and integration method. This heterogeneity complicates design, installation, and maintenance, and limits the interoperability of systems. Development of standardized testing protocols, certification schemes, and performance benchmarks is crucial to ensure reliability and facilitate broader adoption in the construction industry.

5.2. Economic and Policy Challenges

The cost-effectiveness of BIPV systems remains a significant barrier compared to traditional PV installations and conventional building materials. While BIPV offers dual functionality as a structural or facade component and energy generator, initial capital costs are typically higher due to the complexity of integration, custom module fabrication, and specialized installation procedures. Payback periods can be extended, especially in regions with low electricity prices or limited incentives, reducing the financial attractiveness for developers and homeowners.

Policy frameworks and incentives are critical in shaping BIPV adoption. In some regions, regulatory barriers, such as complex permitting procedures, unclear building codes, and limited recognition of BIPV as a standard construction element, hinder implementation. Conversely, subsidies, feed-in tariffs, or tax incentives can significantly enhance the economic viability of BIPV projects. However, the availability and stability of

such policies vary across countries and jurisdictions, creating uncertainty for investors and slowing market growth.

5.3. Environmental and Sustainability Considerations

Environmental concerns play a dual role in BIPV adoption. On one hand, BIPV contributes to sustainable building practices by generating renewable energy and reducing operational carbon emissions. Lifecycle analyses indicate that BIPV systems can achieve substantial energy payback over their operational life, particularly when integrated into high-energy-demand buildings.

On the other hand, certain BIPV materials pose environmental and sustainability challenges. For example, CdTe thin-film modules contain toxic cadmium, which requires careful handling, recycling, and disposal at the end of life. Emerging materials such as perovskites often use lead-based compounds, raising concerns about environmental contamination and occupational safety. Additionally, the embodied energy and resource consumption during module manufacturing and installation must be considered, as they influence the overall environmental impact of the system. Developing recycling pathways, non-toxic alternatives, and life-cycle assessment standards is essential to ensure that BIPV contributes positively to sustainability goals.

6. Development Trends and Future Directions

6.1. Advanced Materials and High-efficiency BIPV

The future of BIPV systems is strongly linked to the development of advanced photovoltaic materials that combine high efficiency with architectural flexibility. Tandem perovskite/silicon modules are a particularly promising innovation. By stacking a perovskite layer over a crystalline silicon cell, these tandem systems can achieve efficiencies exceeding 30%, surpassing the theoretical limits of single-junction silicon modules. Such high-performance configurations not only improve energy yield but also allow more compact installation areas, a critical advantage in urban environments where rooftop and facade space is limited.

In addition, the evolution of flexible and lightweight PVs is facilitating integration into modern architectural designs. Thin-film CIGS, OPVs, and emerging quantum-dot PVs enable curved surfaces, retractable roofs, and semi-transparent facades without compromising aesthetics. Lightweight modules also reduce structural load requirements, allowing retrofitting on existing buildings and deployment on unconventional surfaces. Continued research into material stability, encapsulation, and thermal management is essential to ensure these high-efficiency, flexible materials can achieve long-term operational reliability.

6.2. Smart BIPV Systems

The integration of smart technologies represents a significant development trend in BIPV. Internet of Things (IoT) sensors, cloud-based monitoring, and predictive maintenance systems are increasingly being deployed to enhance operational efficiency. Smart BIPV systems can dynamically monitor energy production, identify faults or degradation, and adjust energy flow to optimize self-consumption and grid interaction. For example, real-time monitoring can detect partial shading or module overheating, triggering corrective actions such as localized cooling or bypass activation. Such intelligence not only maximizes energy yield but also extends system lifespan and reduces maintenance costs, making BIPV more attractive to building owners and investors.

6.3. Standardization and Mass Adoption

Widespread adoption of BIPV will depend on standardization and regulatory alignment. Modular designs, standardized testing protocols, and certification schemes will simplify design, installation, and maintenance, reducing project complexity and costs.

Incorporating BIPV-specific requirements into building codes and construction guidelines ensures safety, reliability, and interoperability, facilitating integration into conventional construction workflows. Mass adoption also relies on industrial-scale manufacturing processes that enable cost reduction without compromising performance or aesthetic quality, which will be critical for expanding BIPV beyond niche or premium applications.

6.4. Sustainability and Circular Economy

Sustainability considerations are central to future BIPV development. The transition toward recyclable and low-carbon materials can minimize environmental impacts across the full lifecycle of BIPV systems, from production to end-of-life disposal. For example, perovskite and OPV modules are being developed with non-toxic or lead-free alternatives, while advances in encapsulation and module design facilitate recycling and material recovery. Lifecycle assessment (LCA) studies are increasingly informing material selection, energy payback analysis, and end-of-life strategies. Embedding BIPV into a circular economy framework not only reduces ecological footprint but also enhances the long-term economic viability of renewable energy integration in buildings.

7. Conclusion

Building-integrated photovoltaic (BIPV) systems represent a transformative approach to combining renewable energy generation with architectural functionality. This review has highlighted the diversity of BIPV technologies, ranging from conventional crystalline silicon modules to thin-film, perovskite, and organic photovoltaics, each offering distinct advantages in efficiency, flexibility, and aesthetic integration. Semi-transparent and flexible modules further expand design possibilities, enabling incorporation into windows, facades, and curved surfaces without compromising natural lighting or visual appeal. Encapsulation strategies, protective layers, and energy storage integration are essential for maintaining long-term performance, reliability, and safety in diverse environmental conditions.

Despite these advances, technical, economic, and environmental challenges remain significant barriers. Efficiency losses under real-world conditions, material degradation, lack of standardization, high upfront costs, and sustainability concerns related to toxic or non-recyclable materials must be addressed to enable wider adoption. Innovative solutions, including high-efficiency tandem modules, flexible thin-film designs, smart IoT-enabled monitoring, and circular economy approaches, are emerging to overcome these limitations.

Looking forward, the most promising research directions involve the development of multifunctional, aesthetically adaptable, and sustainable BIPV systems. Harmonizing energy performance with architectural design and environmental responsibility will be key to facilitating integration into residential, commercial, and high-rise urban buildings. By combining advanced materials, intelligent system management, standardized design, and lifecycle-conscious strategies, BIPV can significantly contribute to urban decarbonization and sustainable energy transition, making buildings not only energy consumers but also active participants in the renewable energy landscape.

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