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Review

Thin-Film Technologies for Sustainable Building-Integrated Photovoltaics

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Abstract: This study investigates the incorporation of thin-film photovoltaic (TFPV) technologies in building-integrated photovoltaics (BIPV) and their contribution to sustainable architecture. The research focuses on three key TFPV materials: amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), examining their composition, efficiency, and BIPV applications. Recent advancements have yielded impressive results, with CdTe and CIGS achieving laboratory efficiencies of 22.10% and 23.35%, respectively. The study also explores the implementation of building energy management systems (BEMS) for optimizing energy use in BIPV-equipped buildings. Financial analysis indicates that despite 10.00–30.00% higher initial costs compared to conventional materials, BIPV systems can generate 50–150 kWh/m^2 annually, with simple payback periods of 5–15 years. The research emphasizes the role of government incentives and innovative financing in promoting BIPV adoption. As BIPV technology progresses, it offers a promising solution for transforming buildings from energy consumers to producers, significantly contributing to sustainable urban development and climate change mitigation.

Keywords: building-integrated photovoltaic (BIPV); thin film photovoltaic (TFPV); building energy management systems (BEMS); smart buildings; energy efficiency

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1. Introduction

The global pursuit of sustainable development and the pressing need to combat climate change have intensified focus on the construction and energy sectors. Buildings account for approximately 40% of global energy consumption and contribute 36% of carbon dioxide emissions [1]. With urbanization advancing rapidly and projections suggesting that 68% of the global population will reside in urban areas by 2050 [2], the demand for energy-efficient and sustainable building solutions has become increasingly critical. In this context, Building-Integrated Photovoltaics (BIPV) has emerged as a promising approach, combining renewable energy generation with architectural functionality. BIPV represents a transformative approach to building design and energy management, enabling structures to transition from passive energy consumers to active energy producers. By incorporating photovoltaic materials into building components such as roofs, facades, and windows, BIPV systems fulfill both energy generation and structural roles [3]. The development of this technology is closely linked to advancements in thin-film photovoltaic (TFPV) technologies, which provide greater flexibility, enhanced aesthetics, and potential cost advantages compared to conventional crystalline silicon solar cells.

This study investigates the interrelationship between BIPV, TFPV technologies, and Building Energy Management Systems (BEMS). BIPV applications are increasingly leveraging advancements in TFPV technologies due to their flexibility and adaptability in integrating renewable energy solutions into building structures. Among TFPV technologies, amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) are the most prominent candidates for BIPV systems.

a-Si stands out for its adaptability to flexible substrates and its superior performance in low-light conditions, despite its lower efficiency compared to crystalline silicon [4]. Efforts to mitigate the Staebler-Wronski effect, a degradation phenomenon, through multi-junction configurations have shown promise in enhancing its stability and efficiency [5]. CdTe has achieved a laboratory efficiency of 22.10% and a commercial module efficiency of 19%, driven by its cost-effectiveness and straightforward manufacturing process [6]. However, concerns over cadmium toxicity have prompted research into safer buffer layers and recycling technologies [7] CIGS has the highest recorded laboratory efficiencies amongst TFPV technologies, achieving figures of 13.40% [8] or 20% [9]. CIGS is noted for its excellent absorption coefficient and suitability for flexible substrates, making it an attractive option for BIPV. Recent research efforts have been focused on enhancing manufacturing processes and exploring tandem structures to achieve even higher efficiencies [10].

The integration of these TFPV technologies into building components has enabled new possibilities in architectural design. Semi-transparent BIPV windows, for example, can generate electricity while providing daylighting and thermal management [11]. BIPV facades are recognized not only for energy production but also for their contributions to insulation and weather protection of buildings [12].

The subsequent phase of the research is focused on scrutinizing the essential function of BEMS in optimizing the operational efficacy of BIPV installations. BEMS are acknowledged as the primary control systems of contemporary buildings, orchestrating various subsystems to attain optimal energy efficiency and occupant comfort.

Advanced BEMS are designed to incorporate machine learning and artificial intelligence to predict and adapt to changing conditions. These systems can optimize the interaction between BIPV generation, energy storage, and building loads, thereby maximizing self-consumption and minimizing dependence on the grid [13]. Recent progress in BEMS has concentrated on incorporating Internet of Things (IoT) devices and cloud computing to improve system responsiveness and data analytical capabilities [14].

The synergy between BIPV and BEMS is considered particularly important in achieving zero or near-zero energy buildings (ZEB or nZEB). By optimizing on-site energy production alongside smart load management, these integrated systems can greatly decrease a building's net energy usage. Research has demonstrated that effectively implemented BEMS can lead to a reduction in energy consumption within buildings [15].

Model Predictive Control (MPC) has been identified as a powerful tool in BEMS, enabling the anticipation of future conditions and the optimization of building operations accordingly. Studies have demonstrated that MPC can enhance energy efficiency compared to rule-based control systems, particularly in buildings equipped with BIPV installations [16].

Figure 1 presents a flowchart outlining key energy efficiency strategies for buildings, providing a structured overview of various methods aimed at optimizing energy use. The flowchart begins with fundamental conservation techniques, such as implementing low-energy lighting and enhancing building insulation to minimize energy waste [17,18]. It then progresses to advanced strategies, including energy recovery systems [19], fuel substitution, and the integration of smart building systems through IoT platforms, which collectively improve energy management [20]. Additional approaches highlighted in the flowchart involve MPC for optimizing energy consumption, with studies showing MPC can reduce energy use by 15–50% and mitigate greenhouse gas (GHG) emissions [21]. Demand response mechanisms allow buildings to adjust energy use in response to real-time pricing signals, thereby enhancing overall efficiency [22]. Thermal Energy Storage (TES), like storing cooling fluids overnight, is another method proven to lessen daytime cooling demands and overall energy use [23]. Lastly, variable speed control technologies, such as variable frequency inverters used in heating, ventilation, and air conditioning (HVAC) systems, are utilized to enhance energy efficiency [24]. These strategies emphasize the potential of BIPV in contributing to ZEB or nZEB, illustrating how advancements in technology and cost reductions can drive the adoption of BIPV as a critical component of sustainable building energy management.

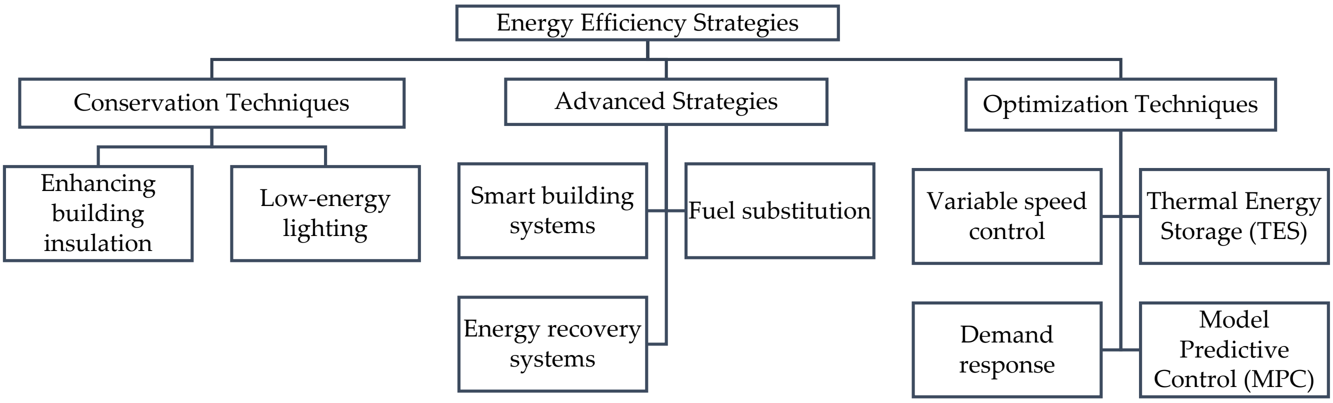

Figure 1. Energy Efficiency Strategies for Buildings.

The last phase of the research flowchart focuses on evaluating the economic and environmental impacts related to the implementation of BIPV. While the initial costs of BIPV systems typically surpass those of standard building materials or conventional photovoltaic systems, the long-term benefits are considered significant.

Recent economic evaluations have revealed encouraging trends regarding the Levelized Cost of Electricity (LCOE) for BIPV systems. It has been determined that LCOE values for BIPV systems in Norway range between 0.08 to 0.13 €/kWh, which are competitive with grid electricity tariffs in numerous regions [25]. The dual functionality of BIPV, serving as both an energy generator and a building material, is acknowledged for mitigating a substantial portion of the initial costs, thereby improving the overall economic proposition [26].

The economic feasibility of BIPV has been significantly shaped by government incentives and supportive policies, including feed-in tariffs, tax credits, and green building certifications, which have been crucial in promoting BIPV adoption across different countries [25]. However, as technology costs continue to decrease, the industry is progressively moving towards models that do not depend on subsidies, focusing instead on the intrinsic value of BIPV systems.

BIPV amalgamate solar energy directly into architectural structures such as facades, windows, and rooftops, facilitating sustainable on-site energy production. However, the manufacturing processes of BIPV are energy-intensive and contribute significant GHG emissions, both directly from production methodologies and indirectly from fossil fuels utilized for energy. Life Cycle Assessment (LCA) is utilized to measure the environmental impacts of BIPV across its entire lifespan, considering a range of materials, including silicon and thin films. The assessment further evaluates BIPV's performance across diverse building applications and geographic locales, alongside the Energy Payback Time (EPBT) to ascertain when the energy savings compensate for the initial energy investment [27]. The outlook for BIPV appears bright, fueled by new technologies such as perovskite solar cells, which could offer higher efficiency and lower costs. Recent advancements in tandem perovskite-silicon cells have achieved efficiencies exceeding 29% [28]. The integration of BIPV with other smart building technologies, such as electrochromic windows and advanced energy storage systems, could lead to highly efficient, adaptive building envelopes [29].

As cities globally work towards lowering their carbon footprint, BIPV is set to become a crucial element in urban energy strategies. The idea of 'prosumer' buildings, which generate and consume energy, is gaining momentum, with BIPV serving as a key enabling technology [25].

While extensive research has been conducted on individual TFPV technologies, a significant research gap persists in the comprehensive, critical evaluation of a-Si, CdTe, and CIGS within the BIPV domain. Previous studies have predominantly focused on isolated technological assessments, often lacking a holistic perspective that integrates technological performance, economic feasibility, and architectural integration potential. The existing literature reveals fragmented knowledge, with limited cross-comparative analyses of these TFPV materials' strengths, limitations, and transformative potential in sustainable architecture. Moreover, current research insufficiently addresses the critical interdependencies between TFPV technologies, BEMS, and design innovations. This study's unprecedented novelty lies in its systematic, multi-dimensional examination that simultaneously evaluates technological efficiency, manufacturing complexities, environmental implications, and economic viability of a-Si, CdTe, and CIGS technologies. By synthesizing technological advancements, policy frameworks, and emerging design paradigms, this research provides a comprehensive roadmap for understanding TFPV's role in transitioning towards zero-energy buildings. The study's unique contribution extends beyond a mere technological review; it offers a strategic framework for interdisciplinary stakeholders—including researchers, architects, policymakers, and industry practitioners—to make informed decisions about BIPV implementation. By critically analyzing the gaps between current technological capabilities and sustainable architectural requirements, this research aims to accelerate the integration of renewable energy technologies into the built environment, ultimately supporting global decarbonization efforts and urban sustainability strategies.

Methodology

To investigate thin-film technologies for sustainable BIPV, a systematic literature review was conducted, focusing exclusively on peer-reviewed studies. A protocol-driven methodology was employed to minimize researcher bias and ensure the thorough identification, synthesis, and evaluation of existing evidence [30]. The review process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring transparency and rigor throughout the research process [30,31].

Figure 2 illustrates the annual trends in publications related to thin-film photovoltaic technologies from 2016 to 2024, categorized by publication type, including articles, book chapters, and books. The literature search was performed across multiple databases, yielding 31,675 documents. These documents were initially screened based on their titles, abstracts, and keywords, narrowing the selection to 440 relevant studies. Further inclusion and exclusion criteria were applied, resulting in the removal of 215 papers and leaving 225 articles for final analysis. Figure 3 outlines the criteria used to filter the literature, including factors such as full-text availability and publication language (English). This figure highlights the systematic process of narrowing the pool of documents for final inclusion in the review. The selected studies were categorized systematically according to various parameters, such as authorship, publication year, type of publication, journal or conference, and their relevance to thin-film technologies in sustainable BIPV systems. This structured approach provided a comprehensive overview of current trends and advancements, offering critical insights into the development and application of thin-film photovoltaic technologies within the BIPV context.

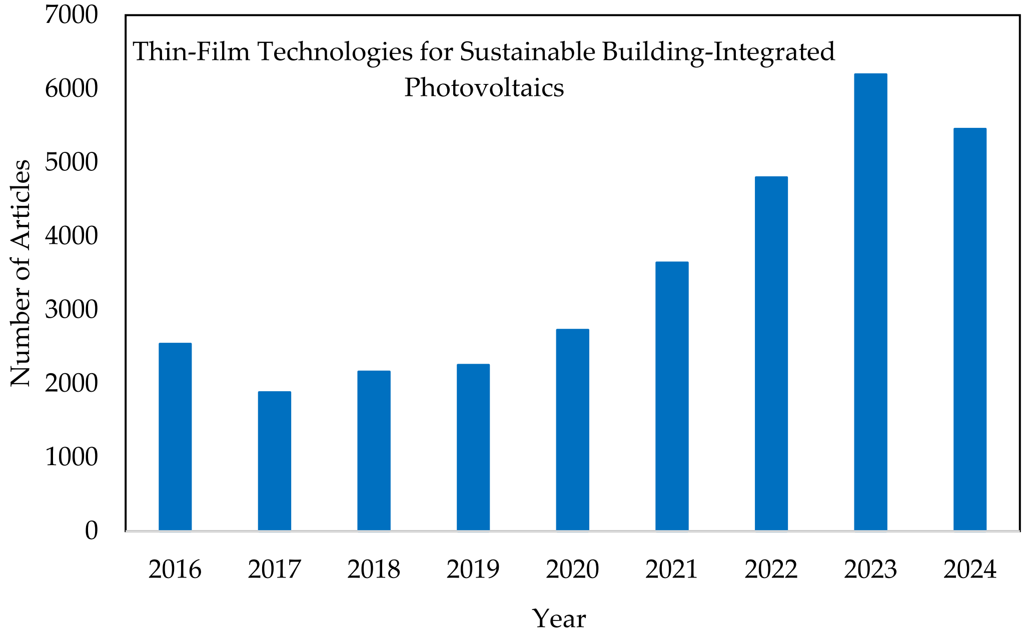

Figure 2. Annual Trends in Publications on Thin-Film Photovoltaic Technologies for BIPV (2016–2024).

Initial Search: "TFPV", "BIPV", "a-Si", "CdTe", "CIGS", and 30 combinations of keywords. A total of 31,675 documents were identified.

Title/Abstract Screening: Exclude irrelevant topics. 25,000 documents removed.

Language Filter: Keep only English papers. 1000 documents removed.

First filter: Screened based on titles, abstracts, and keywords. 5235 documents removed.

Focus Filter: Papers on AV applications only. 240 documents removed.

Peer-Reviewed Filter: Include only peer-reviewed sources. 200 documents identified.

Figure 3. Criteria for Filtering Literature in the Systematic Review of Thin-Film Photovoltaic Technologies.

2. Smart or Eco Buildings

The electrical distribution sector faces mounting pressure to meet the power demands of businesses and the public sector while achieving a net-zero carbon footprint. Smart or eco-friendly buildings have emerged as a promising solution to this challenge. Research has demonstrated considerable potential for energy savings within such edifices, with findings suggesting "possible reductions in energy costs by as much as 40%" when juxtaposing energy-efficient residences with those of average efficiency [32]. Smart Energy International estimates similar savings, ranging from 30–40% [33].

The growing popularity of smart and eco-buildings is largely attributed to their perceived role in the zero-net carbon revolution. It is crucial to understand that these buildings do not primarily seek to limit energy usage. Rather, they emphasize providing comfortable living and working spaces while making the most efficient use of available energy resources [34].

The concept of energy-efficient buildings is not new. As early as 1979, Hunt observed that lighting patterns in buildings were directly related to occupancy, with lights often remaining on until the last person left multi-occupied rooms, even when natural light levels increased [35]. This observation highlighted the need for more sophisticated control systems to manage building energy use effectively.

Modern smart buildings incorporate advanced lighting control systems as an integral part of their overall energy management strategy. These systems use occupancy sensors, daylight harvesting, and automated dimming to maintain adequate lighting levels while minimizing energy waste [36].

The evolution of smart home technology has gone far beyond simple smartphone-controlled lighting. Modern smart home systems combine multiple subsystems to oversee every facet of a building's operation. The IoT has been instrumental in this evolution, facilitating the connectivity and management of security systems, appliances, and various other functions within the building [37].

By monitoring occupant behavior and establishing specific routines, smart buildings can proactively adjust room temperature and lighting levels to match anticipated occupancy periods [38]. Additionally, automated control of curtains and blinds can help regulate solar heat gain, further improving energy efficiency [25].

The implementation of avant-garde domestic technologies facilitates the proficient regulation of these diverse systems, culminating in a notable decrease in overall energy consumption. Nevertheless, it is imperative to acknowledge that while these control systems are crucial for fulfilling net-zero energy mandates, they themselves require energy consumption. To counterbalance this demand and attain authentic net-zero status, edifices frequently integrate renewable energy sources, including solar power systems. These systems may be classified as either building-attached (BA) or building-integrated (BI) systems [39,40].

In accordance with all construction endeavors, both smart and eco-friendly buildings must comply with pertinent regulations and codes of practice. Such regulations extend beyond the physical structure to include the utilities and control systems operating within the premises [41]. The intricate nature of smart building systems frequently necessitates specialized expertise and skills for their proper installation and maintenance, thereby underscoring the necessity for updated training and certification initiatives within the construction sector [42].

The emergence of smart and eco-friendly buildings has engendered the notion of the "prosumer"—individuals who simultaneously consume and generate energy [43]. This phenomenon delineates two prospective pathways towards low-carbon energy frameworks: one wherein prosumers proactively generate their own energy through intelligent prosumer networks, and another wherein they function as both suppliers and consumers of the main power grid [44].

As the construction industry progresses, the incorporation of intelligent technologies and sustainable design practices will become increasingly vital for meeting global sustainability objectives. The ongoing development of more efficient and cost-effective solutions promises to make smart and eco-buildings more accessible and widespread in the coming years.

3. Standards for BIPV and Their Role in Enhancing Building Energy Efficiency

Various international standards regulate the design, performance, and safety of BIPV systems, positioning them as a key technology in creating energy-efficient buildings. These standards aim to ensure that BIPV systems operate reliably while meeting strict safety and performance benchmarks. For instance, guidelines such as EN 50583 and IEC 63092 comprehensively address essential aspects of BIPV modules and systems, including mechanical durability, weather resistance, and electrical safety [45,46]. By establishing clear requirements, these standards build trust among architects, builders, and developers, thereby encouraging the adoption of renewable energy technologies in both new and existing structures.

A significant advantage of BIPV lies in its contribution to the concept of nZEBs. These buildings are designed to deliver outstanding energy performance, meeting most of their energy needs through renewable sources, typically generated on-site. BIPV systems serve as a cornerstone of this concept, enabling buildings to produce a substantial share of their energy requirements via integrated facades, roofs, or windows. This approach not only supports energy efficiency goals but also enhances a building's aesthetic appeal by seamlessly blending functionality with design [47,48].

Standards such as ISO/TS 18178 play a vital role in ensuring that BIPV systems meet rigorous performance requirements while mitigating potential risks. For example, ISO/TS 18178 outlines specifications for laminated solar photovoltaic glass, a material widely used in BIPV applications, ensuring both energy efficiency and structural integrity in the design [49].

While BIPV technology continues to advance rapidly, with improved efficiency rates and innovative applications, the practical implementation faces significant challenges at the intersection of technology and regulation. The complex web of international standards, while necessary for safety and performance, can create barriers to adoption due to varying requirements across jurisdictions and the need for extensive stakeholder education. For instance, architects and developers must navigate multiple technical standards while also considering local building codes, energy regulations, and aesthetic requirements [50]. This regulatory complexity, combined with the need for specialized knowledge in both construction and photovoltaic systems [51,52], can slow down adoption despite BIPV's proven benefits in energy generation and building sustainability [53]. Bridging this gap requires not only continued technological advancement but also streamlined regulatory frameworks and improved stakeholder awareness programs that can help translate BIPV's theoretical potential into practical, widespread implementation [54,55]. Recent studies have shown that integrated approaches to regulatory compliance and stakeholder engagement can reduce implementation barriers, highlighting the importance of addressing both technical and organizational challenges in BIPV adoption [56,57].

Table 1 briefly summarizes the main standards and regulations that regulate the implementation of BIPV, emphasizing their scope and key requirements.

Table 1. Summary of Key Standards and Regulations.

Standard	Focus Area	Key Findings	Place of Validity	Relevance to BIPV
EN 50583-1/2:2016 [45]	BIPV modules and systems	Specifies requirements for electrical safety, mechanical strength, weather resistance, and durability.	European Union	Ensures that modules meet both energy generation and structural safety. Facilitates effective installation and compliance with energy regulations.
IEC 63092-1/2:2020 [46]	BIPV modules and systems	Focuses on mechanical resistance, thermal performance, and fire safety, acknowledging the dual role of BIPV.	International	Provides a global standard for BIPV module requirements. Critical for ensuring compatibility with building electrical systems.
ISO/TS 18178:2018 [49]	Photovoltaic glass	Outlines specifications for laminated solar photovoltaic glass, ensuring durability and aesthetic appeal.	International	Essential for BIPV applications using glass components.

Table 1. *Cont.*

Standard	Focus Area	Key Findings	Place of Validity	Relevance to BIPV
IEC 61730-1/2:2016 [58]	Safety	Establishes safety and defines testing requirements for the construction of photovoltaic modules, focusing on electrical insulation and risk mitigation.	International	Ensures BIPV modules are safe for use in various building applications. Supports BIPV modules in passing essential safety tests.
BS/EN 61215:2016 [59]	Design qualification	Details testing procedures to confirm the durability and performance of terrestrial photovoltaic modules.	European Union	Provides a benchmark for performance evaluation of BIPV modules.
IEC 61215:2021 [60]	Design qualification	Updates performance criteria for photovoltaic modules, including mechanical load tests and thermal cycling assessments.	International	Ensures BIPV modules are resilient and reliable over their lifespan.

4. Building-Integrated Photovoltaics

BIPV represents a significant leap forward in sustainable architecture, integrating renewable energy generation with the building's functional elements. As the global community moves toward climate neutrality, BIPV offers a valuable opportunity to reduce the carbon footprint of buildings while maintaining their visual appeal.

Despite continuous technological advancements and the transfer of technology in renewable energy sectors, BIPV has yet to achieve mainstream status in building practices. This lag in adoption persists even though BIPV systems offer numerous advantages, including flexibility in design, integration into various building components, and the ability to be rigid, semi-transparent, or colored [61].

BIPV systems possess the remarkable capability of being seamlessly integrated into various components of a structure, with building facades emerging as an exceptionally advantageous area for such integration endeavors. The implementation of semi-transparent thin-film or crystalline solar panels can serve the dual purpose of either replacing existing glass elements within their frames or providing a protective covering over them, thereby enhancing the aesthetic and functional aspects of the building's exterior [62]. While facade-integrated panels may not produce as much electricity as rooftop installations due to their orientation, the sheer size of facade surface areas on commercial buildings can lead to comparable energy generation levels [63,64].

One of the foremost benefits associated with BIPV technology is its unique capacity to generate renewable electrical energy, particularly in densely populated urban environments where the availability of rooftop space is severely constrained, and the cost of land is prohibitively high. BIPV roofing materials are categorized primarily into two distinct types: single laminated glass panels, which can be applied directly to building surfaces, and solar shingles, which serve as replacements for conventional roof shingles in both residential and commercial sectors, allowing for a harmonious blend of functionality and design [65]. Additionally, skylights often incorporate ultra-thin solar cells that allow light penetration while generating electricity [66].

Four case studies from Milan, six Brazilian cities, Shanghai, and Awali were analyzed to evaluate the impact of societal and environmental factors on the economic feasibility of BIPV systems. The incorporation of these factors into lifecycle cost analysis (LCCA) revealed key insights. For instance, in Brazil, the discounted payback period (DPP) for Belem reduced from 7 to 4 years, while other Brazilian cities saw reductions to under 5 years, except São Paulo, where the DPP decreased from 13 to 6 years due to low electricity tariffs. In Italy, the DPP improved from 13 to 6 years, benefiting from low transmission line losses and favorable carbon costs. In China, the DPP, initially unfeasible, was reduced to 20 years with the proposed method, making the system feasible. However, in Bahrain, despite the high solar potential, the system remained economically unfeasible due to high initial costs and low electricity tariffs, with a DPP exceeding the system's lifecycle. The net present value (NPV) results showed Italy had the highest NPV of 2.711 USD/Wp, while Bahrain had the lowest at 1.739 USD/Wp. These findings underline the importance of integrating societal and environmental benefits into economic assessments, demonstrating the potential for improved feasibility in regions with appropriate tariffs and conditions, and guiding policymaking for BIPV adoption [67].

BIPV systems offer a unique benefit compared to non-integrated systems, as they eliminate the need for extra land use or separate photovoltaic installations [40]. This seamless integration into the building envelope renders BIPV an efficient utilization of space and resources.

Notwithstanding its significant potential, BIPV technologies encounter a range of challenges that impede their widespread adoption within the construction industry. Foremost among these challenges is the absence of universally binding standards, coupled with a limited comprehension of the various products and their possible applications among key stakeholders and decision-makers operating within the building sector, which collectively serve to obstruct the path toward mainstream acceptance of BIPV systems [61].

Prominent architects, such as Sir Norman Foster, have recognized the importance of solar architecture in addressing environmental concerns. Foster famously stated, "Solar Architecture is not about fashion, but about survival", highlighting the critical role of sustainable design in modern construction [68].

As architects begin to exploit the vast areas of building facades, BIPV is becoming an increasingly attractive option. Photovoltaic devices can replace traditional building materials like concrete in walls and rooftops, producing fossil-free energy and contributing to a pollution-free environment. Glass is a primary material used in these new facades, allowing daylight to pass into rooms while potentially generating electrical energy [69].

The International Energy Agency (IEA) reports that buildings account for roughly 40% of global energy consumption [70]. BIPV has the potential to significantly reduce this energy usage while providing comfortable environments for occupants. Nevertheless, challenges such as thermal transfer through large, glazed areas and possible shading issues from nearby structures or vegetation must be carefully considered during the installation of BIPV as building facades.

As outlined in the IEA's Photovoltaic Power Systems Programme (PVPS) Task 15 report, BIPV solar photovoltaic modules must fulfill at least two essential roles: they should function as building materials integrated into the structure while also serving as a reliable source of electrical energy generation [71].

In recent years, the investigation into the complex relationship between occupant behavior and energy consumption in buildings has become an important field of research [38]. Standardized occupancy patterns are utilized to determine the service needs for various building functions, including HVAC, domestic hot water (DHW), lighting, and appliance operation [72]. Moreover, cultural variances often result in distinctly unique occupancy patterns, which in turn influence the architectural designs and spatial configurations of buildings [38].

The occupational behavior design gap varies between residential homes and commercial buildings, as well as between nations. Some countries use a full-time space method to determine energy use, assuming constant heat gains from full-time occupancy and appliance use. Others, particularly in hot summer and cold winter zones, employ a part-time space mode based on large-scale or monitored surveys [38].

TFPV systems are particularly advantageous for use within building structures due to their versatility in adapting to various substrates. These can be classified into photovoltaic foils, tiles, modules, and solar cell glazing. The main materials used include silicon wafer-based technologies, thin-film technologies, and some non-silicon alternatives currently in use [40].

When integrating BIPV materials into a building, it is crucial to consider the natural deterioration of these systems, known as the degradation ratio [73]. This factor can significantly affect the durability of the building's exterior, necessitating ongoing maintenance or eventual replacement. However, continuous improvements in solar cell efficiency, open-circuit voltage, short-circuit current, maximum output, and fill factor are expected to enhance the long-term effectiveness and performance of BIPV systems [40].

4.1. Energy Needs of the Buildings

The global push towards sustainable development and lowering carbon emissions has drawn significant attention to the energy consumption of buildings. Both residential and commercial edifices substantially contribute to overall energy utilization, with HVAC systems, lighting, and appliances serving as the principal consumers. As technological advancements progress and our dependence on electrical devices increases, the management of this energy demand becomes ever more critical.

Trends in energy consumption in the United Kingdom from 1970 to 2021 reveal a 4.60% increase, from 1.48×10^6 to 1.55×10^6 million kilowatt-hours (mkWh), between 2020 and 2021, despite overall consumption remaining below pre-pandemic levels. As illustrated in Figure 4, the industrial sector experienced a 4.20% rise in energy use, primarily driven by increased gas consumption across various industries. Residential energy consumption increased by 0.25×10^6 mkWh, largely attributed to higher natural gas usage due to lower average temperatures in 2021. Although primary energy consumption rose by 2.10%, the energy ratio (energy use relative to Gross Domestic Product (GDP)) decreased by 5.0%, continuing a long-term downward trend since 1999. Meanwhile, GDP increased by 7.40%, reflecting the economic recovery following the pandemic [74].

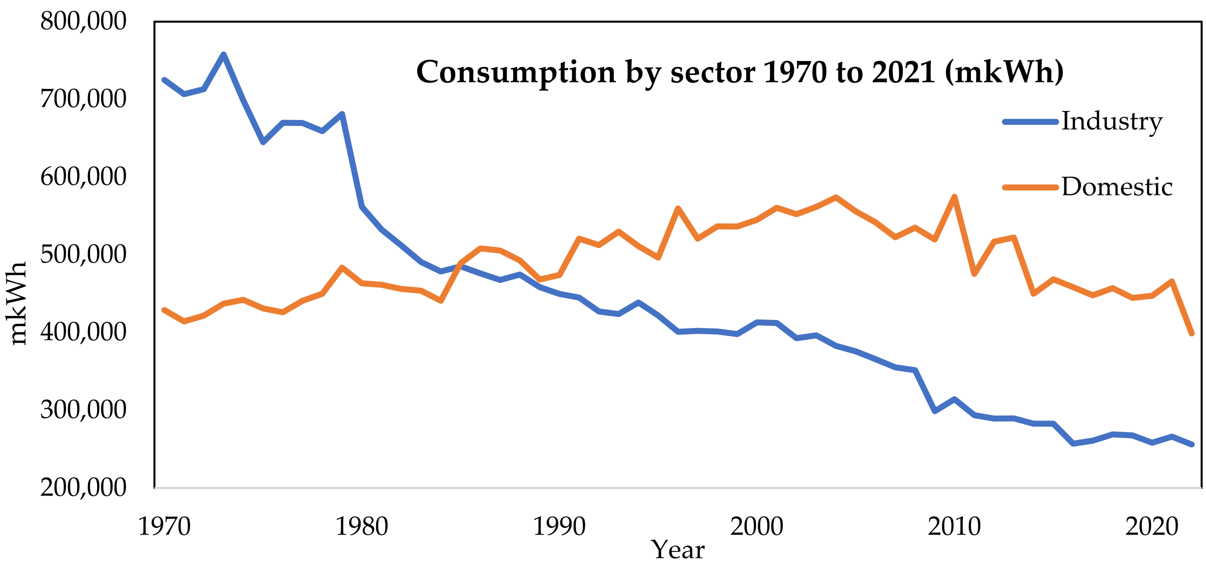

Figure 4. UK Energy Consumption Patterns from 1970 to 2021 [74].

4.1.1. Residential Energy Consumption

In residential settings, energy consumption patterns show significant variability while also revealing common trends across different households. A notable concern is the rising standby power consumption, with Meier's 2001 findings indicating that standby power usage can range from 30 watts in China to 100 watts in the United States, representing about 3–12% of total household electricity use. Although this may seem minor at first, its continuous nature and the cumulative impact of numerous appliances in modern homes make it substantial.

A detailed analysis of the total number of appliances in residential households reveals a significant increase in the Information Technology sector, which grew from just 606 devices in 1980 to an impressive 88,068 by 2019. Despite this growth, improvements in power consumption technology and the shift from traditional desktops to more energy-efficient laptops have led to a substantial reduction in electrical demand, now at approximately 23% of the levels seen in 1979 [75].

In terms of lighting, this category, which previously accounted for about 18% of total household electricity use in 2009, has seen significant reductions thanks to the widespread adoption of energy-efficient LED technology [76]. Interestingly, despite the increased number of lighting fixtures in modern homes, overall electricity consumption for lighting has declined [75].

In 2009, domestic heating systems accounted for around 61.70% of total household energy consumption, with hot water heating contributing an additional 17.60%, and kitchen appliances adding 2.70% [76]. However, the introduction of modern kitchen appliances and the standby modes of many electronic devices, often conveniently connected via Wi-Fi, may distort these statistics in today's context.

Figure 5 illustrates significant shifts in UK domestic energy consumption patterns from 1970 to 2021. Natural gas emerged as the dominant energy source, rising from about 0.10×10^6 mkWh in 1970 to peak at approximately 0.39×10^6 mkWh around 2004, before settling at about 0.32×10^6 mkWh by 2021. Electricity consumption showed a steady growth, increasing from roughly 0.08×10^6 mkWh in 1970 to about 0.11×10^6 mkWh by 2021. In stark contrast, coal consumption plummeted dramatically, starting at nearly 0.17×10^6 mkWh in 1970 and declining to almost zero by 2021. Other energy sources like coke breeze and other solid fuels maintained relatively low and stable consumption levels, generally below 0.05×10^6 mkWh throughout this period. This data illustrates a notable transformation in the UK's domestic energy sector, showcasing a shift from coal to cleaner energy sources, including natural gas and electricity [75].

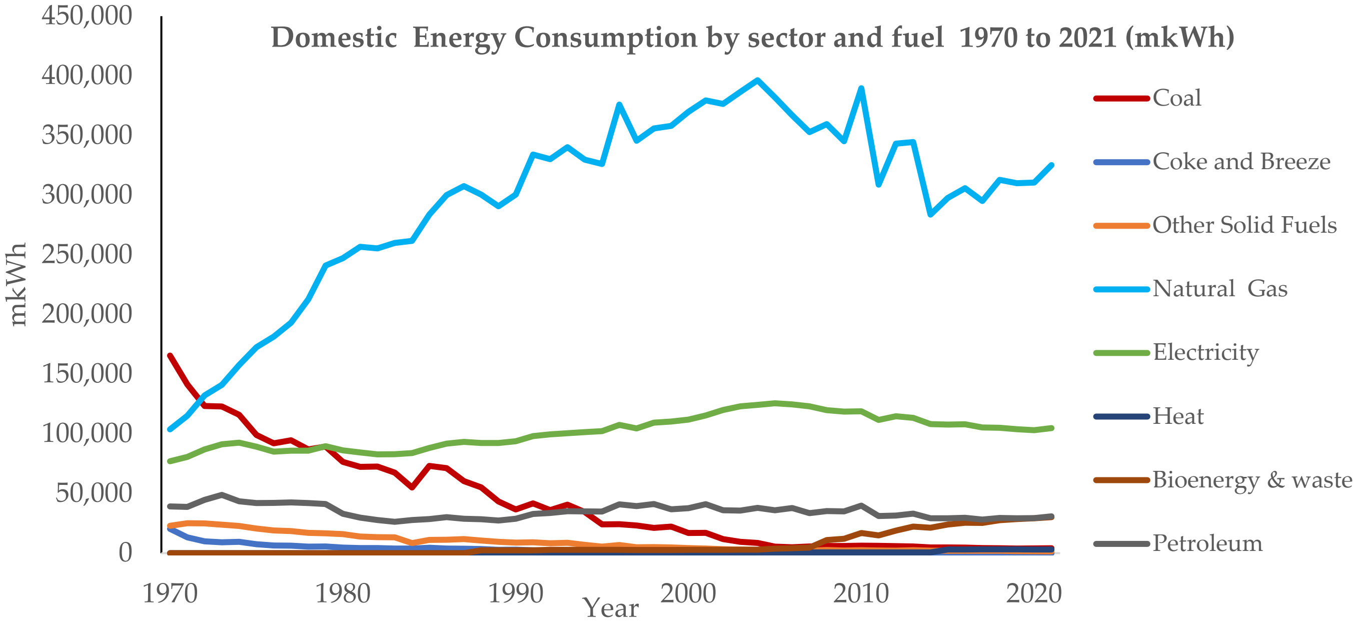

Figure 5. UK Domestic Energy Consumption by Source, 1970–2021 [75].

4.1.2. Industrial Energy Use

Figure 6 illustrates substantial shifts in industrial energy use across different sub-sectors in the UK from 2021 to 2022. The chemicals sector experienced the largest overall decrease, with substantial reductions in natural gas (approximately -2.90×10^3 mkWh) and electricity usage (about -1.16×10^3 mkWh), partially offset by an increase in heat consumption (roughly $+0.58 \times 10^3$ mkWh). The paper and printing industry saw a notable increase, primarily driven by bioenergy and waste (about $+1.16 \times 10^3$ mkWh). The iron and steel sector showed a mixed pattern, with a decrease in petroleum use (around -1.16×10^3 mkWh) balanced by an increase in solid fuels (approximately $+0.87 \times 10^3$ mkWh). Other industries and construction sectors displayed relatively small changes, with slight increases in various fuel types. The unclassified category saw decreases in bioenergy & waste and petroleum (each about -1.16×10^3 mkWh). Notably, most sub-sectors showed some level of reduction in natural gas consumption, likely reflecting broader energy market trends or efficiency improvements in 2021–2022 [75].

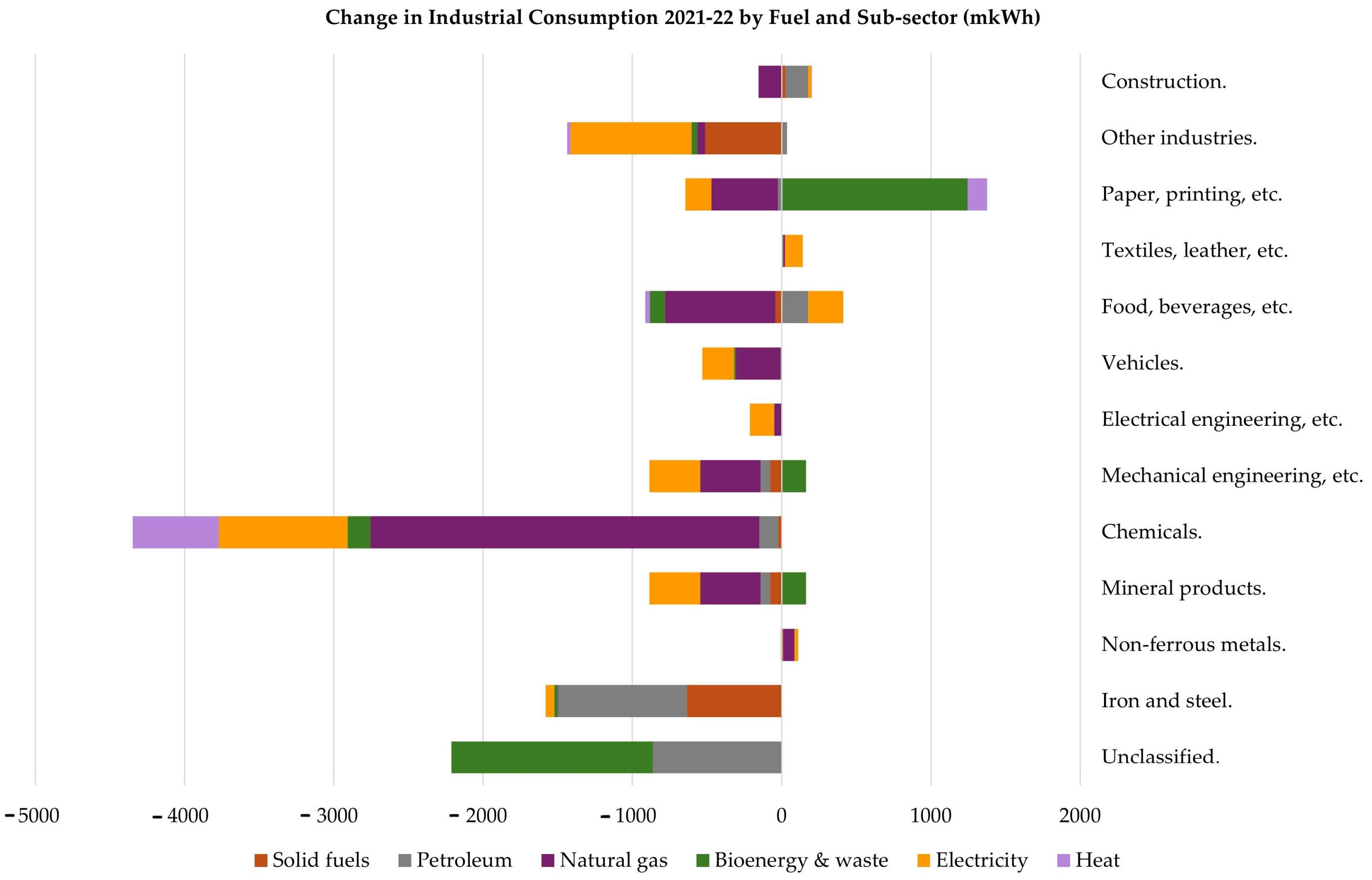

Figure 6. Variations in Energy Consumption by Industrial Sub-Sectors from 2021 to 2022 (mkWh) [75].

High-rise commercial buildings have become prominent features in urban landscapes, primarily due to rising land costs in densely populated areas. These structures often incorporate extensive glazing to maximize natural light, enhancing the interior atmosphere. However, a significant drawback of this design is that, despite using high-performance energy-efficient glazing, there is an increase in internal heat during warmer months and heat loss in cooler months, leading to greater demand for HVAC systems. This demand is essential for maintaining a comfortable and productive work environment [77]. To optimize solar heat gains and ensure adequate light transmission, it is vital to implement appropriate window-to-wall ratios [62].

Research suggests that individuals typically spend around 80% to 90% of their time indoors [78,79]. Similar to homes, commercial structures need to provide a comfortable environment for occupants to boost their well-being and productivity, which in turn enhances overall performance outcomes [79].

Energy consumption from HVAC systems can be reduced through several strategic approaches. The first involves increasing awareness of peak demand for financial benefits. Demand charges refer to the maximum electrical power used at a specific point in time. By predicting peak temperature times, it is possible to initiate cooling earlier, effectively lowering peak demand charges typically recorded every 15 min.

The second strategy focuses on regulating ventilation airflow with advanced energy management systems (EMS) that account for maximum occupancy levels, which will be discussed further [80]. A third method gaining traction is TES, which circulates a coolant throughout the building that is chilled during nighttime hours [81].

Improving energy efficiency can be accomplished by precisely controlling the speeds of HVAC motors with variable frequency inverters. This technology optimizes the operational speeds of pumps, compressors, and fans, resulting in decreased costs and lower energy consumption.

Table 2 presents a summarized view of important insights regarding energy use in buildings and energy management strategies, which include photovoltaic integration. The data is organized into three categories: residential energy consumption, energy use in commercial buildings, and various energy management approaches.

Table 2. Key Findings and Trends in Energy Consumption for Residential and Commercial Sectors.

Key Findings	Category	Source
Standby power usage: 30 W (China) to 100 W (USA), 3–12% of household electricity use.	Residential energy consumption	[82]
IT devices increased from 606 (1980) to 88,068 (2019), but overall electrical demand decreased to 23% of 1979 levels.		[75]
Lighting: Accounted for 18% of household electrical use in 2009, but this consumption has been declining due to the adoption of energy-efficient LED technology. Heating: This represents the largest portion of household energy consumption, at 61.70%. Hot Water: Constitutes 17.60% of overall household energy use.		[76]
Energy consumption increases by ~2.40% per story in high-rise buildings. There is a 31% increase in emissions between low- and high-rise buildings.	Commercial building energy use	[83]
A total of 77% of surveyed London buildings consumed > 45 kWh/m^2 for HVAC.		[84]
MPC has the potential to decrease energy consumption by 15–50%.		[21]

4.1.3. Energy Management Strategies

In recent years, energy management strategies have undergone considerable evolution, incorporating diverse methods aimed at enhancing energy efficiency and minimizing environmental effects. Traditional methods such as conservation, energy recovery systems, and fuel substitution remain fundamental. Conservation focuses on eliminating waste through rational use and economical practices, including simple actions like turning off unused lights and improving building insulation. Energy recovery systems, including those that capture waste heat, lower total energy needs by utilizing byproducts. Replacing harmful fuels with cleaner options remains vital for cutting carbon emissions and advancing the implementation of comprehensive EMS [85,86].

The effectiveness of modern EMS relies heavily on sophisticated control systems and diverse data inputs. These inputs include overall system energy consumption, specific consumption patterns of connected equipment, occupant behavior, energy usage patterns, utility time-of-use charges, and weather data [87,88]. The integration of IoT-based platforms has significantly enhanced understanding and control capabilities, allowing for more precise and responsive energy management [88]. Recent developments have introduced machine learning algorithms for proactive energy management, allowing systems to forecast and enhance energy consumption by analyzing historical data alongside real-time information [89]. Additionally, blockchain technology is being explored for decentralized energy trading and management, offering new possibilities for peer-to-peer energy transactions and grid optimization [90].

New trends in energy management are transforming sustainable building and urban design. The combination of renewable energy sources with smart grid technology is evolving, enabling more efficient distribution and use of clean energy [91]. Digital twin technology is being applied to energy system optimization, providing detailed virtual models of physical systems for analysis and improvement [92]. Edge computing is gaining traction for real-time energy management in smart buildings, enabling faster processing of data and more immediate responses to changing conditions [93]. These developments, along with continuous enhancements in energy storage solutions and grid systems, are facilitating the creation of more robust, efficient, and sustainable energy infrastructures across residential, commercial, and industrial domains.

4.1.4. Model Predictive Control (MPC) for Buildings

The main benefit of MPC in buildings lies in its ability to decrease GHG emissions and lower energy consumption by 15–50%. However, practical implementations of MPC remain inadequately comprehended despite substantial research efforts [21]. Economically speaking, it is important to understand that reducing energy use does not always translate to lower utility expenses; in some cases, storing thermal or electrical energy when prices are low for later use could be more cost-effective [94]. One method for managing HVAC systems involves using price signals from the grid, which can enhance the functionality of smart meters in both residential and commercial properties by facilitating hourly price comparisons [95].

Despite these challenges, BIPV holds great promise for realizing ZEB or nZEB. With ongoing technological progress and decreasing costs, BIPV alongside passive cooling systems is anticipated to be vital in fulfilling the energy requirements of buildings while advancing sustainability objectives. To maximize BIPV benefits and address overall building energy needs, various management strategies can be employed [96].

Table 3 highlights a range of energy management strategies designed to enhance the energy efficiency and sustainability of buildings. Passive cooling systems utilize phase change materials (PCM), which absorb and release latent heat during phase transitions to manage temperature, thereby reducing energy consumption—PCM walls delay heat transfer, while PCM windows cut heat transfer by 66%, and PCM combined with natural ventilation can save up to 90% of energy in hot climates [96]. Conservation strategies focus on eliminating waste through efficient practices such as using low-energy lighting and improving insulation [97]. Energy recovery systems capture waste heat from various processes and repurpose it as energy inputs for other systems, reducing overall consumption [98]. Fuel substitution involves replacing harmful fuels with more environmentally friendly alternatives to cut carbon emissions and promote eco-friendly energy management solutions [19]. Smart buildings leverage IoT platforms to monitor and optimize energy usage, leading to better understanding and control of energy consumption patterns [99]. MPC algorithms predict and adjust energy needs, reducing consumption and lowering greenhouse gas emissions [100]. Demand response enables buildings to adjust energy use based on real-time pricing signals, allowing for more dynamic and cost-effective energy consumption [101]. Thermal energy storage involves chilling coolant during off-peak hours and utilizing it to reduce daytime cooling loads, thus saving energy and reducing costs [102]. Lastly, Variable Speed Control optimizes the energy use of HVAC systems by adjusting motor speeds through variable frequency drives, ensuring that energy consumption is matched to demand [103]. Each of these strategies aims to improve energy efficiency while contributing to sustainable building practices.

Table 3. Strategies for Enhancing BIPV Benefits and Optimizing Building Energy Management.

Strategy	Description	Source
Passive cooling system	Passive cooling systems, such as using PCM, utilize latent heat absorption and release during phase transitions for energy-efficient cooling, enhancing solar control, ventilation, radiative cooling, and more, with PCM walls delaying heat transfer, PCM windows reducing heat transfer by 66%, and PCM with natural ventilation saving up to 90% energy in hot climates	[96]
Conservation	Eliminating waste through rational use and economy, such as using low-energy lighting and ensuring proper insulation.	[97]
Energy recovery systems	Systems like waste heat recovery allow byproducts to be used as inputs for other energy sources.	[98]
Fuel substitution	Substituting harmful fuels with more environmentally friendly options can help decrease carbon emissions and promote the adoption of EMS.	[19]
Smart building	IoT-based platforms that improve understanding and control of energy usage patterns.	[99]
MPC	Implementing MPC for buildings can lower energy consumption and alleviate GHG emissions.	[100]
Demand response	Modifying a building's energy usage in response to current pricing data.	[101]
Thermal energy storage	Chilling coolant overnight to reduce daytime cooling loads, thus reducing energy use and costs.	[102]
Variable speed control	Implementing variable frequency inverters for HVAC motors to optimize energy consumption.	[103]

4.2. The Interplay Between Climate Change and Energy Use in Buildings

Climate change is creating a complex relationship with building energy systems, particularly affecting both energy demand patterns and renewable energy generation through BIPV systems. Studies across Europe and other regions have revealed several important trends and implications for the future of building energy systems.

Climate change impacts on solar PV power generation in Europe are projected to be relatively modest, with changes ranging from −14% to +2% by the end of the century. The most significant decreases are expected in Northern European countries, particularly in Scandinavian areas where reductions of 10–12% in PV production are projected. However, southern European regions show a more optimistic outlook, with slight increases in both mean PV supply and daily stability [104].

BIPV systems are becoming increasingly important in the context of climate change mitigation. A novel BIPV climatic design framework that considers local climate conditions categorizes regions into four zones based on global horizontal irradiation (GHI): cold (low GHI), moderate (medium GHI), warm (high GHI), and hot (very high GHI). This framework aims to optimize BIPV implementation across 127 cities globally, considering local climate conditions to maximize building energy performance [105].

The economic implications of climate change on PV systems are significant. PV systems in most Australian cities would require a 10–20% increase in economic costs between 2030 and 2050 climate scenarios. This study employed the morphing method to predict future hourly mean global solar irradiation data for 2030, 2050, and 2070, revealing a nearly linear correlation between increases in average external air temperature and solar irradiation [106].

A comprehensive study in Turkey examined the lifetime energy demand and PV energy generation predictions across 81 cities, considering climate change impacts. The findings revealed significant shifts in building energy demands over a 60-year lifetime:

Cooling demand increased substantially, with the warmest regions showing an average increase of 0.5 MWh/m^2.

Heating demand decreased, with the coldest regions experiencing an average reduction of 0.4 MWh/m^2.

PV energy generation showed a limited impact of climate change, with an all-city average increase of 0.02 MWh/m^2 over the building lifetime.

The shift from heating to cooling resulted in significant environmental and economic impacts, with increases averaging 212 kg CO_2-eq/m^2 and \$27/m^2, respectively, in the warmest regions [107].

The environmental impact of BIPV systems is typically assessed through LCA, with GHG emissions measured in kg CO_2eq as the primary indicator. Key metrics include the GHG emission rate, EPBT, and GHG payback time (GPBT) [108,109].

Despite these challenges, climate change is unlikely to significantly threaten the European PV sector. The expected expansion of PV systems throughout the 21st century, combined with technological improvements and supportive policies, should more than offset any negative impacts from climate change on resource availability [104].

The integration of Productive Building Systems (PBSs) is a valuable approach, combining greening and solar energy solutions to reduce environmental impacts and energy consumption in buildings in Egypt. By incorporating systems such as hydroponic gardens and photovoltaic panels, PBSs contribute to both environmental sustainability and energy efficiency, addressing the growing challenges of high energy consumption and environmental degradation in urban buildings. The most purchased PBSs identified were hydroponic systems (75%), planter boxes (50%), raised beds (42%), photovoltaic panels (95%), and solar water heaters (55%). Social and economic motivations for their implementation included enjoying greenery (95%) and reducing energy expenses (100%). However, high initial costs were a major barrier, with 80% of respondents citing it for greening systems and 94% for solar systems. The study highlights the commonalities between greening and solar systems in terms of their applicability, performance, and integration on building envelopes. The combination of these systems offers enhanced energy production and environmental benefits [110].

These findings underscore the importance of considering climate change impacts in building energy system design and planning. While PV systems show resilience to climate change impacts in many regions, the shifting patterns in building energy demand—particularly the increase in cooling requirements—highlight the need for adaptive strategies and continued focus on the decarbonization of the energy sector. The integration of climate-responsive design frameworks, such as those proposed for BIPV systems, will be crucial in optimizing building energy performance and supporting the transition to sustainable buildings in a changing climate.

Impacts on Building Energy Consumption

The intricate repercussions of climate change on buildings necessitate augmented energy consumption to sustain occupant comfort and productivity. Rising global temperatures have led to increased cooling demands in numerous regions, while extreme weather events require more robust building envelopes and HVAC systems [111]. Effective shading and temperature control have become essential, contributing to greater reliance on HVAC systems. Furthermore, the need for adequate lighting levels when using window blinds or tinting to minimize solar heat gain further drives energy demand [112].

In many areas, climate change is expected to increase overall energy consumption. Tropical regions and the southern United States may see energy demand rise by more than 50%, while Southern Europe and China could experience increases over 25%. In contrast, Northern Europe, Russia, western Canada, and certain parts of the United States are likely to face reductions in energy demand [113]. This alarming projection underscores the urgent need for sustainable solutions within the building sector. Additionally, the recent rise in electric vehicle adoption has further escalated building energy consumption due to the demand for charging infrastructure [114].

These factors highlight the growing importance of local energy production, positioning BIPV as an attractive solution. BIPV systems can mitigate rising energy demands while reducing dependence on fossil fuels and alleviating the impacts of climate change.

BIPV technology transforms edifices from mere energy consumers to energy producers, generating clean electricity while serving the primary functions of building components such as roofs, facades, and windows [115].

Recent advancements in BIPV technology have resulted in improved efficiency and aesthetic appeal, promoting wider adoption. For example, perovskite solar cells have demonstrated impressive laboratory efficiencies exceeding 25% [116]. Such advancements hold the potential to revolutionize the BIPV market, offering higher energy yields and better integration options.

4.3. Measurements

The integration of photovoltaic systems within buildings requires careful consideration of various thermal and optical properties. Three critical metrics are particularly significant when evaluating the performance and energy efficiency of BIPV systems: U-Value and G-value.

4.3.1. U-Value

The U-value of a window serves as a crucial parameter for assessing heat transfer through building elements, which includes radiation, convection, and conduction. Measured in watts per square meter per Kelvin (W/m^2K), the U-value indicates the volume of heat lost through the window; higher values denote increased heat loss. The U-value quantifies heat transfer through a structure, calculated as the rate of heat energy transfer divided by the temperature gradient across that structure. The formula $U = 1/R$ elucidates the inverse relationship between U-value and R-value, where R denotes the measurement of heat resistance [117]. Consequently, as the thermal resistance of a window augments, its U-value diminishes, indicating enhanced insulation properties [118].

Different thermal processes—radiation, convection, and conduction—take place at various points within a window assembly. Conduction primarily happens through the glass, while convection occurs on both the inside and outside surfaces, as well as in the spaces between the glazing layers. Understanding this complexity is crucial for analyzing how different window designs affect energy efficiency [119].

Net window U-values can differ significantly from center-of-glass U-values, as the latter only consider the glass area without accounting for the frame and spacers [120]. As building codes increasingly emphasize energy efficiency and carbon neutrality, the adoption of windows with lower U-values is expected to rise. This trend underscores the importance of selecting appropriate window technologies to enhance overall building performance and occupant comfort.

Table 4 presents U-values for various window types and configurations, highlighting differences in thermal performance. Single glazing has the highest heat loss at 5.7 $W/m^2 \cdot K$, making it the least energy-efficient option. In comparison, conventional double glazing provides a U-value of 2.8 $W/m^2 \cdot K$, indicating decent insulation. However, low-emissivity (low-E) double glazing greatly enhances performance, boasting a U-value of 1.2 $W/m^2 \cdot K$. More sophisticated options, like Uncoated triple glazing 16 mm with argon, can reach an impressive U-value of 0.79 $W/m^2 \cdot K$. Double glazing with argon also shows substantial improvements, demonstrating the importance of selecting high-performance windows for energy efficiency [121,122].

Table 4. U-Values of Various Window Types.

Window Type/Configuration	U-Value ($W/m^2 \cdot K$)	Source
Floor	0.25	[39]
Roof	0.16	
External wall	0.30	
Windows	2.00	

Table 4. *Cont.*

Window Type/Configuration	U-Value (W/m^2·K)	Source
Uncoated single glass 6 mm	5.80	[121]
Uncoated double glass 12 mm cavity	2.80	[122]
Uncoated double glass 15 mm air cavity	1.40	
Uncoated double glass 15 mm argon cavity	1.20	
Uncoated triple glass 16 mm with argon	0.79	
Uncoated double glass 22 mm monolithic aerogel	0.65	
Uncoated double glass 33 mm granular aerogel	0.44	

4.3.2. G-Value

The Solar Heat Gain Coefficient (SHGC) quantifies the amount of solar energy that enters a window as heat, measured on a scale from 0 to 1. A value of 0 indicates no heat transfer, while a value of 1 means that all solar heat is transmitted through the window. This linear scale implies that an SHGC of 0.4 allows for double the heat gain compared to a value of 0.2. Typically, buildings with air conditioning prefer windows with a low SHGC, whereas those designed for passive heating benefit from a higher SHGC. This aspect is particularly significant for opaque or semi-translucent TFPV windows, as excessive solar heat gain can increase reliance on air conditioning for temperature control, potentially offsetting the benefits of the photovoltaic windows. Conversely, limiting solar transmittance in passive houses could necessitate additional heating, negatively affecting clean energy savings [69].

Solar transmittance through transparent or translucent materials encompasses both the solar heat transmitted and the heat absorbed by the material, which is subsequently radiated into the interior space. The extent of solar transmittance through glass or analogous materials can considerably influence indoor temperatures under sunny conditions. This temperature increase can be beneficial in winter or during passive heating, but it may become problematic in summer or hot climates, where air conditioning is often needed. Historically, this heat transfer phenomenon has been represented by a shadow coefficient, as previously noted [123].

The determination of G-values at oblique angles of incidence is considered crucial, as windows are seldom exposed to sunlight at a perfect 90-degree angle. Empirical models have been developed that require knowledge of the G-value at normal incidence (g(0)), the type of glazing, and the number of panes. To determine G-values at different angles, the Fresnel equations are used, incorporating spectral optical constants such as refractive indices and extinction coefficients. However, this method can be complex and often requires precise data that is unavailable. To simplify this process, empirical formulas have been developed to estimate G-values based on the characteristics of the glazing, such as its type (clear, tinted, or coated), thickness, and the number of panes used [124].

Figure 7 presents the G-values for clear glazing, showcasing a comparison among single, double, and triple-glazed units based on Fresnel calculations. Figure 7 highlights the variations in SHGC across different glazing configurations, demonstrating how increased panes reduce overall G-values [125].

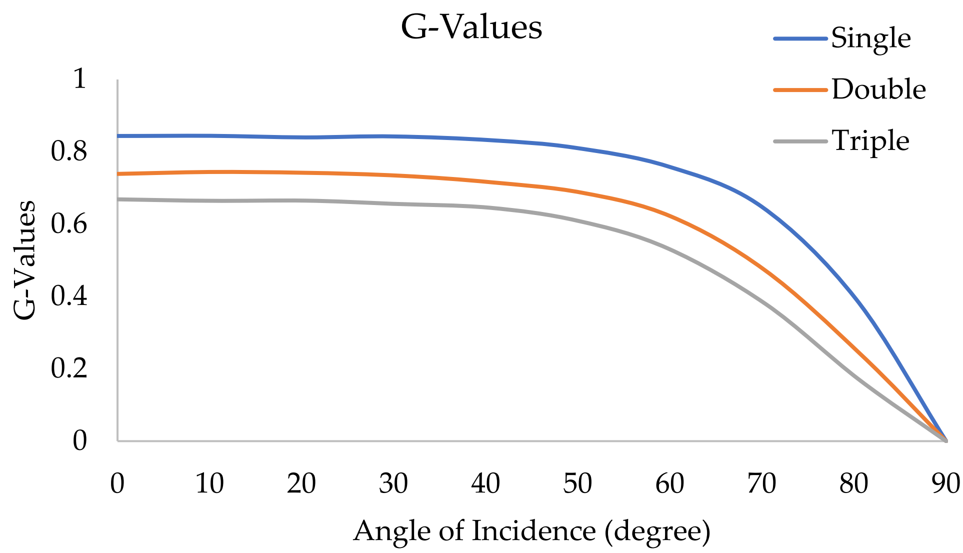

Figure 7. G-Values for clear glazing with Fresnel calculations (single, double, and triple) [125].

5. TFPV Materials

TFPV technologies have gained attention as viable alternatives to traditional crystalline silicon solar cells, offering advantages like flexibility, cost reduction, and adaptability, particularly in BIPV. The three primary thin-film technologies—a-Si, CdTe, and CIGS—are analyzed regarding their structures, benefits, and applications. TFPV cells are much thinner than crystalline silicon, which reduces material costs and enhances design flexibility. These technologies are particularly well-suited for non-traditional applications due to their thin profile [8].

TFPV technologies offer several key advantages over traditional crystalline silicon cells:

- Flexibility: The thinness of these cells allows deposition on flexible substrates, enabling integration into curved or irregular surfaces [126].
- Versatility: TFPV can be applied to various materials, such as glass, metal, and plastic, expanding its potential applications [127].
- Low-light performance: TFPV technologies, particularly a-Si, offer better performance in low-light conditions compared to traditional silicon cells [128].
- Aesthetics: Their thin and semi-transparent nature makes them ideal for architectural integration in BIPV systems [39].

However, TFPV technologies face challenges, particularly in efficiency, with some technologies still lagging behind crystalline silicon in terms of energy conversion rates. Environmental concerns and the competitive pricing of crystalline silicon technologies further hinder widespread adoption. Despite these obstacles, the growing recognition of TFPV's potential positions them as a key player in the future of solar energy.

5.1. Amorphous Thin-Film Silicon (a-Si)

a-Si solar cells, typically 1-µm thick, are fabricated using a layered method starting with a silicon dioxide substrate and p-type tin oxide (SnO_2) contact. a-Si is deposited by decomposing silane gas (SiH_4), creating dangling bonds passivated by hydrogen [129]. However, this hydrogenation contributes to the Staebler-Wronski light degradation effect [130,131]. The a-Si layer, placed between p-doped and n-doped layers, forms a p-i-n junction, complemented by an aluminum rear contact [132]. Although second-generation, a-Si is often grouped with first-generation silicon-based technologies [133].

Figure 8 illustrates the structure of a-Si solar cell, which consists of multiple layers. The top glass substrate absorbs sunlight while providing structural support. The front electrode, made from SnO_2, is transparent, allowing sunlight to pass through while collecting electrons. Below this, the p-type silicon layer acts as a hole acceptor. The intrinsic silicon layer, typically 500-nm to 1-μm thick, absorbs light and generates charge carriers. The n-type silicon layer directs electrons toward the front electrode, while the rear contact enables efficient charge collection and current flow.

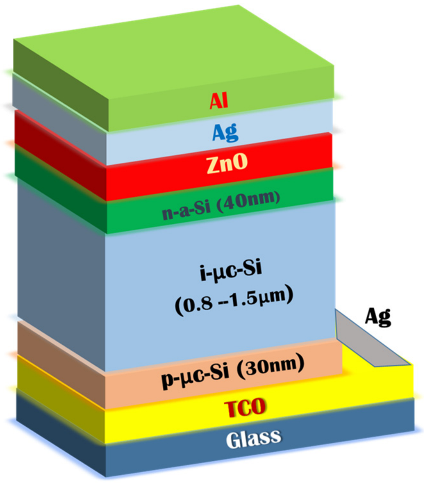

Figure 8. Structure of an Amorphous thin-film silicon (a-Si) Solar Cell.

a-Si solar cells use approximately 1% of the material compared to crystalline silicon, with a higher bandgap of 1.7 eV versus 1.1 eV. Despite requiring less energy to manufacture, a-Si's efficiency is lower, around 10%, making it ideal for applications prioritizing cost over efficiency, such as consumer electronics [134,135]. To enhance efficiency, a-Si has been combined with nanocrystalline silicon, achieving about 12% efficiency and reduced degradation [8]. a-Si has advantages over other thin-film technologies, such as CdTe and CIGS, due to its lower silicon usage and non-toxic nature [131]. It also allows the development of tandem cells using nanocrystalline silicon or a-Si-germanium alloys, without lattice-matching constraints [136]. However, a-Si is affected by the Staebler-Wronski effect, which causes light-induced degradation [137]. Despite these benefits, crystalline silicon-based BIPV currently dominates the market due to its superior durability and efficiency.

5.2. Cadmium Telluride (CdTe)

CdTe has become a leading TFPV technology, gaining market dominance due to its cost-effectiveness and improving efficiency. Its fabrication is simple and cost-efficient, using methods like electrodeposition or vapor transport deposition. A typical CdTe solar cell consists of several layers: a transparent conductive oxide layer (fluorine-doped tin oxide or indium tin oxide), an n-type cadmium sulfide (CdS) buffer layer, a p-type CdTe active layer, and a back contact layer. Recent advancements have focused on optimizing these layers, including reducing CdS thickness and exploring alternative buffer materials [138,139].

Figure 9 illustrates the structure of a CdTe solar cell, comprising several key layers. Sunlight is absorbed by a glass cover, with a transparent SnO_2 front electrode facilitating charge collection. A 100 nm CdS buffer layer enhances junction formation with the photo absorber. The CdTe photo absorber, 3- to 7-μm thick, converts sunlight into electricity, while a rear contact layer completes the electrical circuit.

CdTe technology has made significant advancements in efficiency, with recent reports highlighting an efficiency of 22.10% in laboratory conditions by the National Renewable Energy Laboratory (NREL) in 2016, while commercial modules reached 19% efficiency by 2021 [6]. This efficiency improvement, combined with low production costs, has made CdTe a highly competitive photovoltaic technology. However, the use of cadmium, a toxic metal, raises environmental concerns. Despite this, research suggests that the environmental impact of CdTe is comparable to, or even lower than, that of silicon-based modules when considering their entire lifecycle [140,141]. The optical quality of the CdS buffer layer is vital for CdTe-based solar cells. High-quality CdS epitaxial layers show intense excitonic emissions, with biexciton dominance at high excitation. The results reveal for the first time Te atom diffusion from the CdTe substrate into the CdS layer during CVD growth, causing autodoping [142]. Growing CdTe on a suitable buffer layer, like ZnTe, is crucial for improving structural quality. Studies of ZnTe/GaAs heterostructures show that interface defects and residual strain significantly affect epilayer quality, with threading dislocations and strain gradients observed along the growth direction, emphasizing the importance of buffer layer selection [143]. Recent innovations have focused on enhancing CdTe's performance, such as incorporating novel back contact buffer layers to improve stability [144]. Additionally, tandem configurations, like the perovskite/CdTe tandem cell, have reached a combined efficiency of 24.20% [145]. In the realm of building-integrated photovoltaics (BIPV), semi-transparent CdTe modules have shown promise, with experiments demonstrating transmission rates of 12% for solar radiation and 25% for visible light, indicating their potential integration into building facades and windows [146]. This development opens new avenues for integrating solar energy production within urban architecture, contributing to sustainable building designs.

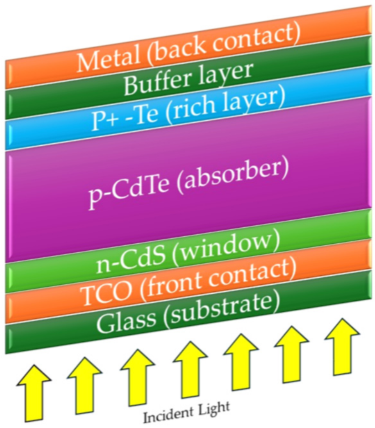

Figure 9. Structure of a CdTe Solar Cell.

5.3. Copper Indium Gallium Selenide (CIGS)

CIGS has become a highly promising TFPV technology due to its superior efficiency and adaptability. CIGS solar cells utilize a compound semiconductor with a direct bandgap ranging from 1.1 to 1.2 eV, which can be adjusted by varying the proportions of indium and gallium. This tunability enhances light absorption across the solar spectrum, contributing to higher efficiency. Moreover, CIGS cells exhibit exceptional resistance to radiation, making them ideal for space applications [147]. A typical CIGS solar cell consists of multiple layers applied to a soda-lime glass substrate. It includes a molybdenum rear contact, a p-type CIGS absorber layer (2–2.5-µm thick), an n-type CdS buffer layer, and a transparent conductive oxide front contact, typically aluminum-doped zinc oxide. Recent research has focused on replacing CdS with alternative buffer materials to improve performance and reduce toxicity [8]. Despite its high efficiency, CIGS technology faces challenges due to high manufacturing costs, stemming from the need for precise control of the multi-element compound and the use of rare materials like indium. However, innovations such as enhanced deposition techniques and roll-to-roll production methods are helping to reduce costs and improve scalability [148]. Figure 10 illustrates the structure of a CIGS solar cell, comprising several key layers.

Table 5 outlines the performance attributes of different thin-film solar cells, such as a-Si, CdTe, and CIGS. a-Si cells offer flexibility and low toxicity, although they have lower efficiency. CdTe cells offer high absorption and low costs, yet harbor toxicity concerns. Conversely, CIGS cells present the highest efficiency and radiation resistance, although they are comparatively expensive, illustrating distinct trade-offs inherent among these technologies.

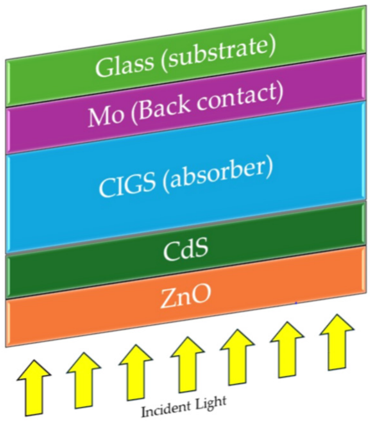

Figure 10. Structure of a CIGS Solar Cell.

Table 5. Best performance of various thin-film solar cells [8].

Characteristics	a-Si	CdTe	CIGS
Thickness	~1 µm	3–7 µm	2–2.5 µm
Bandgap	1.7 eV	1.45 eV	1.1–1.2 eV
Efficiency (%)	~12	~10.70	~13.40
Area (cm^2)	100	4874	3459
V_{oc} (V)	12.5	26.21	31.2
I_{sc} (A)	1.3	3.205	2.16
Fill factor (%)	73.5	62.3	68.9
Main Advantages	Low toxicity, Flexible	High absorption, Low cost	High efficiency, Radiation resistant
Main Disadvantages	Low efficiency	Toxicity concerns	Relatively expensive

6. Building Energy Management Systems (BEMS)

BEMS have emerged as crucial tools in the ongoing effort to optimize energy consumption in both residential and commercial structures. As society's lifestyle has shifted towards a 24/7 continuous power consumption cycle, the need for efficient energy management has become more pressing than ever [149]. BEMS play a vital role in this context, offering sophisticated solutions to monitor, control, and reduce energy usage in buildings [150].

At its core, a BEMS is designed to control the energy requirements of a building, primarily focusing on systems such as lighting and HVAC (Heating, Ventilation, and Air Conditioning). This distinguishes it from the broader Building Management Systems (BMS), which often encompass additional aspects like security, entrance control, and CCTV cameras. However, in larger or more complex buildings, the lines between BEMS and BMS can blur, with energy control integrated into the overall building management framework [151].

The development of BEMS has been characterized by considerable technological progress. Recent developments have seen the integration of IoT technologies [152], giving rise to what is known as the Internet of Energy (IoE) [153]. These advancements have enhanced the accessibility and applicability of BEMS for smaller buildings and residential environments, thereby broadening their potential influence on overall energy consumption trends.

Energy management through BEMS typically falls into three main categories: conservation, recovery, and substitution [154]. Energy conservation focuses on eliminating waste, often resulting in lower electricity bills. Energy recovery involves using the by-products of one process as input for another, maximizing efficiency. Energy substitution refers to replacing traditional energy sources with more sustainable alternatives. A well-designed BEMS combines these elements to create a comprehensive energy management strategy.

The efficiency of a BEMS largely depends on its capacity to collect and analyze diverse data inputs. This encompasses the overall energy usage of the building and its equipment, patterns of occupant behavior, seasonal variations, weather conditions, and utility charges based on time of use [155]. By continuously monitoring these factors in real time, a BEMS can adjust connected power sources for optimal performance while maintaining the required environmental conditions for human comfort. Modern BEMSs' predictive capability allows them to analyze data, anticipate issues, inform maintenance, and trigger alarms for timely action [156]. This proactive approach not only ensures consistent performance but also helps in reducing downtime and maintenance costs.

External environmental determinants significantly affect both the energy consumption of buildings and the comfort of their occupants. Elements such as wind pressure, humidity, temperature, and solar radiation collectively influence the internal conditions of the structure and, by extension, its energy consumption.

While these same environmental conditions can be harnessed for renewable energy production, accurately predicting and accounting for them remains a challenge. Ideally, local microclimate conditions would be measured for each building, but this is often prohibitively expensive. As a result, many BEMS rely on third-party geospatial data, which can introduce errors as large as 40% for synthesized weather data [157].

Ventilation control is another crucial aspect of BEMS functionality. Many systems use CO_2 level monitoring as a proxy for occupancy levels, adjusting external air intake accordingly [158]. Effective CO_2 conversion technologies, such as carbon dots (C-dots) used in photocatalytic processes, can significantly reduce energy consumption and mitigate excessive CO_2 emissions. Research indicates that PEG1500N-functionalized C-dots coated with gold can convert CO_2 into valuable compounds like acetic acid and formic acid under visible light, highlighting the need for further optimization and investigation of these catalysts for practical applications [159,160]. This approach allows for more efficient use of heating and cooling systems while maintaining air quality standards.

The implementation of BEMS, whether wired or wireless, requires careful design and installation to ensure proper functionality. Regular testing and auditing are essential, particularly for wireless systems used in large buildings to reduce installation costs [161]. These audits should include checks on signal strength and potential interference. Cybersecurity is a growing concern, especially for cloud-based systems in prominent organizations, necessitating robust security measures [162,163].

Maintenance and operation of BEMSs should be designed with simplicity in mind. This includes easy battery replacement, straightforward checks on damper and valve operations, and an accessible human-machine interface (HMI) for continuous fine-tuning and optimization over predefined seasons [164].

While BEMS technology has advanced significantly, its implementation faces several challenges. One notable issue is the limited adoption of advanced control methods like MPC. Despite their potential for superior performance, MPC implementation is often hindered by insufficient training of engineers in modern optimal control methods. As a result, simpler Rule-Based Controls (RBC) remain predominant in most buildings. The challenges associated with MPC implementation include cybersecurity concerns, hardware availability, software compatibility, and the need for user-friendly designs that are computationally efficient for tuning and deployment [21].

An alternative approach that has shown promise is the use of fuzzy logic in BEMS. This method operates with analog digital signals, allowing inputs to vary within a range rather than being strictly on or off. By enabling systems to adjust output levels instead of running at full capacity, fuzzy logic can significantly enhance efficiency. The integration of artificial intelligence in managing these processes offers exciting possibilities for future BEMS developments [165].

As edifices persist in representing a substantial fraction of worldwide energy utilization, the significance of BEMS in fulfilling objectives of energy efficiency and sustainability is paramount. These systems not only help in reducing energy waste and costs but also contribute to broader environmental objectives by minimizing the carbon footprint of buildings.

Looking ahead, the future of BEMS lies in further integration with smart grid technologies, enhanced machine learning capabilities for predictive control, and improved user interfaces for better human-system interaction. As IoT technologies become more prevalent and affordable, we can expect to see more sophisticated BEMS implementations even in smaller residential buildings.

BEMS represent a critical technology in the pursuit of energy-efficient and sustainable buildings. By leveraging advanced sensors, control algorithms, and data analysis techniques, BEMS offer a powerful tool for optimizing energy use, reducing costs, and enhancing occupant comfort. As these systems advance, they are set to become vital in influencing the future of intelligent, sustainable architecture and urban development.

Table 6 summarizes key findings from various studies on BEMS, highlighting their influence on energy consumption, the need for real-time monitoring, and the challenges of implementation.

Table 6. Summary of Key Findings and Scope on BEMS.

Category	Key Findings	Scope	Source
Role of BEMS	BEMS are essential for managing and controlling energy in buildings, supporting the transition to net-zero buildings.	Controls lighting, HVAC, security systems, and more. Also applicable for multi-building sites or complex structures.	[166]
Technological integration	BEMS integrate IoT and Internet of Energy (IoE), especially for smaller and residential buildings.	Advances in technology simplify BEMS and expand their application.	[152,153]
Energy management categories	Energy conservation, recovery, and substitution methods are used to optimize building energy use.	Strategies reduce energy consumption and costs through elimination of waste, energy reuse, and switching to sustainable sources.	[154]
Influences on BEMS	External factors like weather, demand charges, and occupancy patterns affect BEMS efficiency. Real-time and historical data are critical.	Requires comprehensive data to adjust connected power sources and maintain optimal conditions.	[155]
Challenges	Main challenges include cybersecurity, hardware/software compatibility, and limited training in advanced control methods among engineers.	These challenges hinder the widespread adoption of advanced methods like MPC in BEMS.	[21]
Maintenance and operation	BEMS should be regularly tested and audited for performance, especially wireless systems due to potential cyber risks.	Proper maintenance ensures optimal performance and security of the system.	[161–163]
Numerical controls	Fuzzy logic enables efficient control adjustments rather than strict binary on/off operations, enhancing system performance.	Uses AI to dynamically manage processes based on input variability.	[165]
Specific control methods	Predictive controls (MPC) and CO_2-based ventilation adjustments are used for enhanced energy efficiency.	Target specific factors like occupant comfort and optimal energy use.	[158]

Table 6. *Cont.*

Category	Key Findings	Scope	Source
Enhancing energy efficiency	The CO_2-R152a mixture demonstrates an average increase of 12 kJ/kg in cycle-specific work compared to the supercritical CO_2 power cycle in the recompression cycle configuration, and an average increase of 13 kJ/kg in the simple recuperated cycle configuration.	Evaluates the thermodynamic performance of CO_2-R152a and CO_2-based mixtures in power cycles, enhancing energy efficiency and sustainability.	[167]
Efficiency, cost reduction.	The dual recuperated layout with the CO_2 + SO_2 mixture shows an electric efficiency of 39.58% (0.69% higher than the sCO_2 cycle), a decrease in power block CAPEX from 795 $/kWel to 718 $/kWel, and an additional 70 °C of heat recovery from the hot source	Comparative analyses are conducted between transcritical CO_2 + SO_2 and conventional sCO_2 cycles across various plant layouts, focusing on maximizing electric efficiency and cycle-specific work.	[168]
Social acceptance and policy Integration in BIPV	BEMS optimize energy use in buildings, reducing consumption and integrating renewable energy. Social acceptance is driven by ease of implementation, social influence, and trust, rather than cost or energy savings. Sociocultural factors, like education and income, significantly affect adoption.	Focuses on residential and commercial buildings, particularly in urbanizing areas like Egypt, highlighting the need for policy support to enhance adoption.	[169]

6.1. Technological, Urban, and Policy Integration for BIPV

BIPV integration requires a holistic approach combining technological innovation, urban planning, and policy frameworks. Successful implementation demands a multilevel mechanism framework encompassing eleven categories of instruments, with building codes and BIPV-related incentives requiring the highest priority from authorities. Three key sustainability pillars are emphasized through principles like local context compatibility, technical soundness, and economic viability [170].

BIPV integration varies by climatic zone—Southern European cities benefit from rooftop PV on cool roofs and PV shadings, while mid-latitude cities show better results combining rooftop PV with green spaces [171]. There is a critical gap between solar potential and BIPV potential in urban environments, emphasizing the need for comprehensive evaluation platforms integrating solar irradiation data, urban information, and product specifications [172].

To bridge the engineering-policy gap, a focus on semitransparent PV systems that combine energy generation with architectural aesthetics and daylight management is suggested. This approach helps harmonize BIPV with building design while meeting energy goals. Success requires a coordinated effort across building codes, incentive structures, technical standards, and urban planning policies, supported by robust data integration platforms for informed decision-making [173].

6.2. The Role of AI in Building Energy Management Systems

The integration of artificial intelligence (AI) in BEMS represents a significant advancement in achieving energy-efficient buildings. Despite improved building standards and renewable energy adoption, the building sector still faces challenges in meeting Net Zero Emissions (NZE) targets by 2050. A critical issue is the energy performance gap, where operational energy use significantly exceeds design specifications. AI-based BEMS have demonstrated remarkable potential for energy optimization, particularly in commercial buildings. Studies show that offices can achieve up to 37% energy savings through AI-driven HVAC control and optimization. Residential and educational buildings, while showing lower savings potential due to less sophisticated existing BEMS, still achieve significant reductions of up to 23% and 21%, respectively [174].

A notable case study from Istanbul demonstrated how AI-based occupant-centric HVAC control can achieve minimum energy savings of 10% while improving thermal comfort. This system utilized artificial neural networks (ANN) for hourly occupancy prediction and integrated real-time weather forecast information [175].

The integration of multiple technologies has proven crucial for optimal performance. Modern buildings are increasingly becoming complex networked cyber-physical energy systems, incorporating [176]:

- Energy bus systems for transporting heat from renewable sources through pipeline networks.
- Energy hubs that manage multi-energy inputs and outputs.
- IoT devices and sensors for real-time monitoring.
- Big data analytics for system optimization.

IoT plays a vital role in this ecosystem, comprising networked sensors, data storage systems, and analytical engines. The basic implementation includes electrical appliance detection, strategic sensor placement, load distribution, and data processing for optimization [177].

However, challenges remain in implementing AI-based approaches. These systems require extensive training data and need retraining when building parameters change. Additionally, the lack of explicit relationships between physical building parameters and model inputs makes it difficult to extrapolate performance when building operations change [178].

The integration of renewable energy, particularly PV, shows promising synergy with AI-driven systems. PV systems can effectively reduce grid loads during peak demand periods, especially during mid-afternoon peaks and heat waves when air conditioning use is highest [179].

For successful implementation, several factors must be considered:

- The establishment of standardized tests to assess AI system robustness.
- Development of threat-driven procedures to strengthen trust in AI systems.
- Incorporation of occupancy information for improved prediction performance.
- Integration of real-time control mechanisms for supply and demand management.

7. BIPV Financial Analysis

The incorporation of photovoltaic technology into building materials and structures, referred to as BIPV, signifies a noteworthy advancement in sustainable building design and energy generation. This financial analysis will explore the economic aspects of BIPV implementation, considering costs, benefits, and market trends. The upfront costs of BIPV systems are typically higher than those of traditional building materials or conventional rooftop solar installations. The initial investment for BIPV can be 10–30% higher than traditional building envelopes. Nonetheless, this cost gap has been narrowing over time as a result of technological progress and increased production efficiencies [34].

Table 7 shows the cost distribution of photovoltaic system components. Photovoltaic modules account for the largest share, comprising 40–50% of the total cost. Inverters contribute 10–15%, Balance of System (BoS) components make up 15–25%, and installation and labor costs range from 15–30% [26].

Table 7. Cost Distribution of Photovoltaic System Components [26].

Component	From Total Cost
Photovoltaic modules	40–50%
Inverters	10–15%
Balance of System (BoS) components	15–25%
Installation and labor	15–30%

It is essential to recognize that BIPV systems can help offset the expenses of conventional building materials they substitute. For example, BIPV facade systems can take the place of standard cladding materials, which may lower the overall additional cost associated with the BIPV installation [44].

7.1. Levelized Cost of Electricity (LCOE)

LCOE constitutes a vital metric for evaluating the economic feasibility of BIPV systems. It represents the average cost of electricity generated over the system's lifetime and serves as a crucial metric for evaluating the performance of BIPV systems. In contrast to traditional photovoltaic systems, the LCOE for BIPV must account not solely for the benefits of energy generation but also for the value of the substituted building materials, thereby rendering BIPV a dual-purpose investment. Recent studies have highlighted promising trends in BIPV LCOE. For example, in Norway, the LCOE for BIPV systems ranges from 0.08 to 0.13 €/kWh, depending on the system type and location [180]. In the United States, the LCOE for BIPV systems was found to range from 0.06 to 0.12 $/kWh, varying with location and system configuration [181].

BIPV systems are revolutionizing building design by integrating energy generation directly into building skins, such as facades and roofs, allowing on-demand use of generated energy. This integration reduces reliance on grid energy, decreases the demand for large power stations, and minimizes transmission losses [25]. There is growing potential for buildings to act as "prosumers", generating enough energy for their own use and exporting excess energy back to the grid, supported by favorable regulatory conditions [182].

This shift transforms buildings from mere energy consumers into active energy producers, with the potential to replace traditional building materials either fully or partially [25]. While the LCOE remains a primary measure for comparing different energy generation technologies, BIPV systems stand out due to their dual functionality as both energy generators and structural elements. LCOE calculations for BIPV often include the costs of grid-connected photovoltaic systems and Balance of System (BoS) costs, which cover essential components such as module connections, structural elements, and inverters, typically constituting about 50% of the total system cost [133].

Although research on BIPV LCOE is less extensive compared to traditional PV systems, the unique advantages of BIPV—combining energy production with building functionality—highlight its economic and environmental potential. These LCOE values are increasingly competitive with conventional grid electricity prices, especially in the context of rising energy costs and potential future carbon pricing mechanisms. As technology advances and market conditions evolve, BIPV is poised to become an integral component of sustainable building design [25,180].

7.2. Simple Payback Period and Return on Investment (ROI)

The financial assessment of BIPV systems reveals complex relationships between investment costs and returns across different regions. Analysis of payback periods incorporates both simple and displaced payback calculations, providing crucial insights into investment viability [183].

Simple payback periods are calculated using the formula:

$$\text{Simple Payback Period} = \text{Embodied Energy (MJ)}/\text{Electricity Generated per Annum (MJ)}$$

For a more comprehensive understanding, displaced payback periods are determined by:

$$\text{Displaced Payback Period} = \text{Simple Payback Period}/\text{Overall Efficiency of Electricity Sector}$$

Recent studies have shown promising trends:

- A case study in Italy found simple payback periods ranging from 5 to 12 years for various BIPV configurations [184].
- Research in the UK reported simple payback periods between 7 and 15 years for BIPV systems, with ROI ranging from 2.70% to 7.40% [183].
- In Singapore, calculations showed simple payback periods of 8 to 13 years for BIPV systems, with ROI between 5% and 9% [185].

It is worth noting that these figures can improve significantly when considering the avoided costs of traditional building materials and potential increases in property value.

Regional Performance Factors Affecting ROI:

Several key regional factors significantly influence ROI for solar energy systems [184]:

- Solar insolation: Regions with higher solar exposure experience greater solar insolation, leading to increased energy generation and higher ROI.
- Installation Costs: Geographic differences in construction and setup expenses can impact the overall cost of implementing solar systems, influencing ROI.
- System Efficiency: Local climate conditions, including temperature and weather patterns, affect the performance and efficiency of solar systems, contributing to regional variability in ROI.
- Grid Electricity Costs: The cost of conventional grid electricity varies by region, with higher costs in some areas making solar energy systems more financially attractive and boosting ROI.

Understanding these factors can help in optimizing the design and implementation of solar projects tailored to specific regional characteristics.

Key areas for improvement in solar technologies, including GaAs/Si modules, also highlight the optimization of material use, such as gold and GaAs wafer reusability, and increasing substrate reusability rates, which could enhance ROI. If process efficiencies are optimized, GaAs/Si modules outperform incumbent technologies, like single-Si modules, across all assessed environmental impact categories, including climate change, land use, and human toxicity. Specifically, the Energy Payback Time (EPBT) for GaAs/Si modules ranges from 1.37 to 1.9 years, compared to 1.84 years for single-Si modules. These findings suggest that GaAs/Si modules, if optimized, have the potential to provide significant environmental and economic benefits [186].

7.3. Government Incentives and Policy Support

Current policies for BIPV systems face several challenges that hinder their effectiveness. A key issue is the misalignment between environmental and economic optimization, where policies fail to balance sustainability goals with cost-effectiveness [50]. Limited support for energy self-sufficiency initiatives further restricts the adoption of systems designed for decentralized power generation [187]. Additionally, the incomplete consideration of economies of scale prevents large-scale projects from benefiting fully from cost reductions [188]. Regional disparities in support mechanisms also exacerbate inequalities, making it difficult for some areas to access adequate incentives or resources for BIPV deployment [189].

To address these challenges, policies must incorporate strategies that prioritize environmental maximization while aligning with economic objectives. Enhanced support for self-sufficient installations, such as microgrids or off-grid systems, can promote energy independence and reduce reliance on centralized power [190,191]. Adjusting incentive structures to account for regional variations in solar potential and economic conditions would create a more equitable system [192]. Furthermore, aligning policies with local energy needs can ensure that incentives encourage adoption where they are most impactful. Research highlights that current incentive frameworks, while helpful, require refinement to better promote BIPV adoption across diverse regions [92,193].

Policy stability plays a critical role in influencing long-term investment decisions for BIPV systems, as uncertain regulations can deter potential investors. Regional variations in support mechanisms and solar resources significantly affect system sizing, with different areas requiring tailored approaches [194]. Additionally, incentive structures shape technology choices, guiding stakeholders toward specific solutions that align with policy priorities. Local regulations also impact installation strategies, dictating design and compliance requirements. This analysis underscores the need for future policy development to better align environmental objectives with economic incentives while addressing regional disparities, ultimately fostering more widespread and effective adoption of BIPV systems.

The financial viability of BIPV systems is often enhanced by government incentives and supportive policies. These can include:

- Feed-in Tariffs (FiTs): Many countries offer FiTs for renewable energy generation, including BIPV. For example, in Germany, the FiT for BIPV systems ranges from 0.083 to 0.113 €/kWh as of 2021 [195].
- Tax Incentives: In the United States, the Investment Tax Credit (ITC) offers a 26% federal tax incentive for solar projects, including BIPV systems, that were completed by the end of 2022 [195].

7.4. Financing Options

A variety of financing mechanisms are accessible to facilitate the adoption of BIPV:

- Power Purchase Agreements (PPAs): Within the framework of a PPA, a third-party developer installs, owns, and manages the BIPV system, selling the generated electricity to the building owner at a predetermined rate. This model can effectively eliminate initial costs for building proprietors [34].
- Green Bonds: These fixed-income securities are specifically designed to generate funding for climate and environmental projects, such as BIPV installations. In 2020, the global green bond market reached a remarkable $269.5 billion [196].
- Energy Service Companies (ESCOs): ESCOs can provide comprehensive energy solutions, including BIPV installation and maintenance, often with performance guarantees [197].

8. Results and Discussion

This comprehensive study on BIPV and TFPV technologies has yielded several significant findings that underscore their potential in advancing sustainable architecture and energy management. The results can be categorized into three main areas: technological advancements, energy management integration, and economic viability.

Technological Advancements:

- Efficiency Improvements: The research highlights substantial progress in TFPV efficiencies. CdTe technology has achieved a record 22.10% efficiency in laboratory settings, with commercial modules reaching 19% efficiency. CIGS has demonstrated even higher laboratory efficiencies of up to 23.35%, although commercial modules typically operate at 15–17% efficiency.
- Material Innovations: Recent developments in a-Si technology, including the combination of a-Si with nanocrystalline silicon or a-Si-germanium alloys, have achieved higher efficiency rates of around 12% and reduced degradation over time. This progress addresses the Staebler-Wronski effect, a prominent challenge associated with a-Si cells.

- Application Versatility: TFPV technologies, particularly CIGS, have shown great potential in flexible and lightweight applications, making them ideal for various BIPV implementations beyond traditional solar panels.

Energy Management Integration:

- BEMS Effectiveness: The integration of BEMS has proven crucial in optimizing energy consumption and production in BIPV-equipped structures. BEMS can reduce cooling energy consumption by up to 12% in warm climates when combined with BIPV systems.
- Smart Control Systems: The implementation of MPC in BEMS has shown potential to reduce energy usage by 15–50% and mitigate GHG emissions. However, challenges in implementation, including cybersecurity and training requirements, have been identified.
- IoT Integration: Integrating the IoT and the Internet of Energy (IoE) into BEMS has significantly improved energy management efficiency, particularly in smaller buildings and residential environments.

Economic Viability:

- Cost-Benefit Analysis: While initial BIPV costs are typically 10–30% higher than traditional building materials, these systems can generate between 50–150 kWh/m^2 annually. A case study showed that a BIPV facade installation on a commercial building in Switzerland produced approximately 29,000 kWh annually, covering about 20% of the building's electricity needs.
- LCOE: LCOE for BIPV systems has become more competitive. Research indicates that LCOE ranges from 0.08 to 0.13 €/kWh in Norway and 0.06 to 0.12 $/kWh in the United States, depending on location and system design.
- Simple Payback Period and ROI: Research across different countries has revealed simple payback periods for BIPV systems ranging from 5 to 15 years, with ROIs between 2.70% and 9%. These figures can improve significantly when considering the avoided costs of traditional building materials and potential increases in property value.
- Government Incentives: The study emphasizes the importance of government support in BIPV adoption. For example, Germany supports Building-Integrated Photovoltaic (BIPV) systems with feed-in tariffs (FiTs) ranging from 0.083 to 0.113 €/kWh, while the United States incentivizes solar installations, including BIPV, with a 26% federal tax credit.

In conclusion, this research demonstrates that BIPV, particularly when utilizing advanced TFPV technologies and integrated with smart EMS, presents a viable and promising solution for sustainable building design. The continuous improvements in efficiency, coupled with decreasing costs and supportive government policies, are making BIPV an increasingly attractive option for both new constructions and retrofits.

However, challenges remain, including the need for further efficiency improvements, especially in translating laboratory successes to commercial applications, and addressing environmental concerns associated with some TFPV materials. Additionally, the complexity of BEMS implementation and the higher initial costs of BIPV systems compared to traditional building materials continue to be barriers to widespread adoption.

Despite these challenges, BIPV holds substantial potential to transform buildings from passive energy consumers into active energy producers. As technology progresses and market dynamics shift, BIPV is set to play a vital role in sustainable urban development and global climate change mitigation efforts. Future research should aim to address the current challenges, enhance system efficiencies, and develop more cost-effective and eco-friendlier TFPV materials for BIPV applications.

Table 8 compares the efficiency, flexibility, and applications of a-Si, CdTe, and CIGS TFPV technologies.

Table 8. Comparison of TFPV Technologies (a-Si, CdTe, CIGS).

Aspect	a-Si	CdTe	CIGS
Efficiency	Up to 12% (commercial).	Up to 22.10% (laboratory).	Up to 23.35% (laboratory).
Flexibility	Yes, suitable for curved surfaces.	Limited flexibility.	Moderate flexibility.
Substrate compatibility	Glass, metal, plastic.	Glass, flexible substrates.	Glass, metal, flexible substrates.
Low-light performance	Superior.	Moderate.	Moderate.
Aesthetic appeal	Semi-transparent, flexible.	Limited aesthetic options.	Semi-transparent, flexible.
Cost advantage	Lower material costs.	Lower material costs.	Moderate material costs.
Environmental concerns	Reduced degradation, Staebler-Wronski effect.t	Potential toxicity of cadmium.	Concerns over gallium availability.
Applications	BIPV, flexible applications.	Large-scale installations.	BIPV, flexible applications.
Current challenges	Efficiency, stability issues.	Environmental concerns, efficiency.	Efficiency, material availability.

9. Challenges and Future Outlook

While BIPV and TFPV technologies show great promise, several challenges must be addressed to ensure widespread adoption and maximum effectiveness.

One primary challenge is the need for further efficiency improvements, particularly in translating laboratory successes to commercial applications. While CdTe and CIGS have shown impressive laboratory efficiencies, commercial modules still lag. Bridging this gap will be crucial for enhancing the economic viability of BIPV systems.

Environmental issues related to certain TFPV materials, especially the use of cadmium in CdTe cells, continue to pose major challenges. Future research efforts should prioritize creating eco-friendly alternatives or enhancing recycling methods to address these concerns effectively.

The complexity of BEMS implementation presents another hurdle. Simplifying these systems and providing adequate training for installation and maintenance personnel will be essential for optimal performance and wider adoption.

The higher initial costs of BIPV systems compared to traditional building materials continue to be a barrier to widespread adoption. While government incentives have helped, developing more cost-effective manufacturing processes and innovative financing models will be crucial for market expansion.

The outlook for BIPV is bright, with ongoing advancements in nanotechnology and materials science paving the way for next-generation TFPV materials that boast higher efficiency and reduced environmental impact. Incorporating artificial intelligence and machine learning into BEMS could further enhance energy management, moving us closer to achieving near-zero energy buildings. The push towards sustainable urban development and stricter global building energy codes is expected to accelerate the adoption of BIPV technologies. As cities work to lower their carbon emissions, BIPV has the potential to reshape urban landscapes into networks of distributed energy generation.

In summary, despite current challenges, BIPV holds significant promise for revolutionizing sustainable architecture and energy management. Continued research, technological innovation, and supportive policies will be critical to overcoming existing barriers and unlocking the full potential of this innovative technology.

10. Conclusions

The research demonstrates significant progress in BIPV and TFPV technologies across three key areas. Technologically, efficiency rates have improved substantially, with CdTe reaching 22.10% in labs and CIGS achieving up to 23.35%, while material innovations have enhanced durability and versatility. In energy management, the integration of BEMS has shown remarkable results, reducing cooling energy consumption by up to 12% and overall energy usage by 15–50% when combined with smart control systems. Economically, despite 10–30% higher initial costs than traditional materials, BIPV systems have proven viable with annual generation of 50–150 kWh/m^2, competitive LCOE ranging from 0.06–0.13 €/kWh, and payback periods of 5–15 years. While challenges persist, including efficiency scaling and implementation complexity, BIPV's potential to transform buildings from energy consumers to producers positions it as a crucial technology for sustainable urban development and climate change mitigation.

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