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Systematic Review

Comparative Performance Analysis of Building-Integrated Photovoltaics and Conventional Envelope Materials: Energy, Economic, and Environmental Assessment

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Abstract

The use of photovoltaic technologies in building envelopes has attracted more and more interest as a promising solution to building sustainability by considering energy efficiency, economic feasibility, and environmental impact issues altogether. This paper will provide an overall comparative analysis on Building-Integrated Photovoltaic (BIPV) systems versus traditional building envelope materials based on a multi-dimensional analysis model. It is demonstrated in the analysis of energy performance that BIPV systems contribute greatly to building energy performance by capturing on-site renewable energy and reducing cooling loads through shading and regulated solar heat gain, in contrast to traditional materials, which only provide passive thermal insulation and energy conservation. Life cycle-based economic analysis shows that despite the higher initial costs of BIPV systems, thematic savings in long-run operations and lower requirements of electricity mean BIPV systems have better economic performance during the life of building services as compared to traditional envelopes, which offer lower upfront costs but have greater cumulative energy costs associated with their application. Environmental performance scorecard BIPV systems are shown to lead to significant reductions in greenhouse gas emissions through the replacement of grid-based electricity, and even though greater energy use is involved in the manufacturing and installation of BIPV systems, the operational carbon savings outweigh these effects in a relatively short time, leading to a net-positive lifecycle environmental impact. The overall multi-criteria comparison established an integrated viewpoint to demonstrate that BIPV systems generally outperform traditional envelope materials in energy, economical, and environmental aspects. The results underline the significance of lifecycle and context-related design approaches to building envelope solution choices in assisting the achievement of energy efficiency, economic stability, and environmental sustainability in the long term.

Keywords: building-integrated photovoltaics; building envelope performance; energy efficiency; lifecycle cost analysis; environmental impact assessment; sustainable building design

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1. Introduction

Fast urbanization, increased population growth, and ever-changing lifestyle trends have all contributed to heightened energy demand in the world, creating pressure on current energy systems as never before [1]. The building sector, in comparison to any other end-use sector, is highly energy-intensive, which is why it represents a large portion of the world energy demand and greenhouse gas emissions [2]. Space heating and cooling, artificial lighting, ventilation, and the increasing reliance on electrical appliances, most of which are fueled by fossil-fuel-based electricity production, constitute a significant portion of this huge energy footprint [3,4]. This has resulted in buildings taking center stage in global initiatives that are geared towards curbing climate change and carbon emissions and ensuring that overall energy consumption is more efficient so that buildings can become sustainable in the long run [5].

To address these issues, the shift to energy-efficient building strategies with the aid of renewable energy systems has been receiving growing popularity both in the academic literature and in practice [6]. With its ubiquity, scalability, and technological maturity, solar energy is globally known to be among the most feasible renewable energy sources of the built environment [7]. Photovoltaic (PV) systems are designed to convert solar radiation directly to electrical energy without combustion reactions and operating emissions to provide a clean and sustainable substitute for traditional energy sources [8,9]. Applied to buildings, PV systems offer the possibility to ensure decentralization of energy production, no reliance on centralized generation networks, and greater autonomy of buildings in terms of energy production [10].

The incorporation of photovoltaic technology into building envelopes was a great development in the design of sustainable architecture and engineering designs [11]. Building-integrated photovoltaic (BIPV) systems are based on essential differences from traditional building-attached PV systems, as BIPV substitutes conventional building envelope elements, including roofs, façades, skylights, and shading systems [12,13]. By performing multiple roles, as structural or envelope-forming features and energy-producing systems at the same time, BIPV proposes a multifunctional design concept [14]. Such integration improves the efficiency of materials, reduces redundancy in construction components, facilitates easy architectural integration, helps in the production of on-site renewable energy, and increases building energy performance [15].

Conventional building materials such as concrete, brick, stone, and glass have been traditionally chosen as building envelope materials according to their structural integrity, durability, thermal property, and aesthetics [16]. The development of material science and methods of construction has enhanced their insulation characteristics and performance, but these materials are mostly passive elements in the building system [17]. Traditionally, building envelopes play a passive role in sustainability; that is, building envelopes regulate heat transfer and improve interior thermal comfort but do not actively contribute to energy production or carbon sequestration [18,19]. BIPV systems, in contrast, are actively involved in building energy dynamics, as these systems generate electricity, reduce net energy demand, and lower greenhouse gas emissions, positioning BIPV as a strategic solution for low-energy and net-zero energy buildings [20].

Although BIPV systems have great benefits, their prevalence is still limited due to a number of technical, economic, and practical issues [21]. Their increased investment cost and initial setup when compared to traditional envelope materials, the lack of technical knowledge amongst architects and engineers, performance variability due to the climatic conditions and orientation, and complexities associated with integration, maintenance, and long-term reliability still hamper wide-scale adoption [22]. Most of the available literature compares the energy, economic, or environmental advantages of BIPV systems in isolation, without a direct, systematic comparison to traditional envelope materials across these dimensions simultaneously [10,13,23]. This gap motivates the need for a comparative evaluation of a systematic and multi-dimensional nature. Accordingly, the objective of this study is to conduct a comparative analysis of building-integrated photovoltaic system

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performance and traditional envelope materials in terms of energy, economics, and environmental impact, and to develop a performance-based assessment framework capable of supporting the informed decision-making of architects, engineers, and policymakers in the design of sustainable and energy-resilient buildings.

There are three distinct ways in which the current study differs from the systematic reviews of BIPVs previously carried out. First, while earlier systematic reviews usually focused on the energy, economic, or environmental performance of BIPV alone, or in some rare cases on all three aspects together but of BIPVs alone, the current study develops a three-dimensional (3E) framework and measures the performance of BIPVs against the performance of conventional, non-photovoltaic envelope materials directly using the same set of indicators. Second, the study comes up with a normalized and weighted multi-criteria performance index (Equations (11) and (12)) for the consolidation of different energy, economic, and environmental indicators that are used to evaluate BIPVs in the available literature, so as to give a reusable evaluation mechanism rather than just reporting of results. Third, it converts the comparative analysis into a situational decision-making guide by linking the choice of a preferred envelope to building type, climatic conditions, and budget. In effect, the three points above make the study a methodological improvement over existing review studies that tend to stop short at comparative analysis of BIPVs versus conventional envelopes.

The following research questions provide a basis for the research undertaken in this study:

RQ1: How do building-integrated photovoltaics (BIPVs) fare against traditional building materials in terms of energy, economic, and environmental performances when they are all considered together in a life-cycle perspective?

RQ2: What kind of synergies and trade-offs are there between these three performance aspects when BIPVs are compared through a standardized multiple criteria approach?

RQ3: What impact does the variation in building type, climate zone, and cost have on the performance superiority of BIPVs?

2. Literature Review

The incorporation of photovoltaic technologies in architectural design is a recent phenomenon and one whose importance has been on the rise in recent studies as an important strategy in the attainment of sustainable and energy-efficient buildings. Figure 1: PRISMA flowchart shows that many articles document that building-integrated photovoltaic (BIPV) systems provide an opportunity to create renewable energy sources on-site and, at the same time, affect the thermal properties of buildings. As external shading features and envelope constituents, BIPV systems help to reduce the cooling loads, especially in hot and humid climatic zones. Together with its capability to produce electricity and enhance thermal performance, this has made BIPV a key element in the design of low-energy buildings and net-zero energy buildings, where a key goal is the reduction in operational energy demand and carbon emissions.

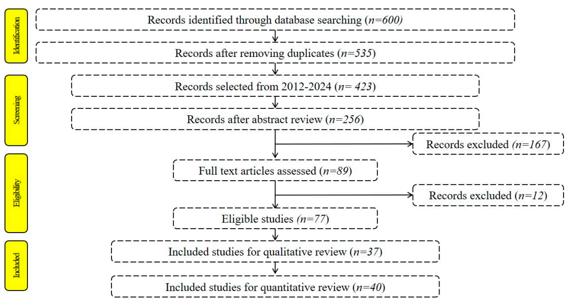

Figure 1. PRISMA flowchart of search results: photovoltaics in building envelope.

3. Inclusion and Exclusion Criteria

3.1. Systematic Review Protocol

This study adopts a structured comparative literature review methodology, focused on synthesizing performance data on building-integrated photovoltaic (BIPV) systems and conventional building envelope materials from a defined body of peer-reviewed literature. Rather than pursuing an exhaustive, multi-database systematic search intended for meta-analytic pooling, this review applies explicit topical, temporal, and data-completeness criteria to identify a focused set of studies from which comparable, traceable performance indicators could be extracted across energy, economic, and environmental dimensions. This approach was selected given the substantial heterogeneity in study design, reporting units, climatic context, and building typology across the BIPV literature, which limits the applicability of a fully pooled, meta-analytic systematic review methodology.

3.2. Search Strategy and Database Selection

A comprehensive search was conducted across multiple databases including the following:

- Web of Science Core Collection;
- Scopus;
- ScienceDirect;
- IEEE Xplore Digital Library;
- Google Scholar.

Search Terms: ("Building-integrated photovoltaics" OR "BIPV" OR "building envelope PV") AND ("commercial building" OR "office building" OR "high-rise") AND ("performance" OR "efficiency" OR "integration")

Inclusion Criteria:

- Peer-reviewed articles published between 2010 and 2024;
- English-language publications;
- Primary focus on BIPV technology and building envelope integration in commercial, institutional, or high-rise building applications;
- Studies addressing residential BIPV applications, retained where they reported performance data directly comparable to the energy, economic, or environmental indicators assessed in this review, providing contextual benchmarks for the typology-based comparative discussion presented in Section 4;
- Empirical studies, reviews, and case studies.

Exclusion Criteria:

- Conference abstracts without full papers;
- Non-English publications;
- Studies with an exclusively residential focus that lack comparative relevance to the commercial-building performance indicators assessed in this review;
- Pure electrical engineering studies without building integration context.

Data Extraction and Analysis Framework

Data extraction focused on the following:

- Technology specifications and performance characteristics;
- Integration methods and building envelope impacts;
- Economic analysis and cost–benefit assessments;
- Environmental performance indicators;
- Case study findings and lessons learned.

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The literature selection process described above (Figure 1) resulted in a final set of 40 studies retained for quantitative comparative synthesis. In addition to their topical relevance to BIPV and conventional envelope performance, these 40 studies were chosen because they each provided at least one quantifiable indicator in a format that was appropriate for extraction and cross-study comparison across the energy, economic, or environmental dimensions evaluated in this review. Although they were not included in the quantitative synthesis that underpins Table 1, Table 2 and Table 3 and the related figures, studies that were found during the more extensive literature search that addressed BIPV technology generally but did not report extractable, comparable quantitative performance data were kept for contextual discussion in the Literature Review.

The literature also clearly states that there was a shift in paradigm from the traditional building–fixed photovoltaic systems to a complete embedded photovoltaic system. Early building PV systems were mostly add-on types of systems that were mounted on roofs or facades with no architectural integration. New developments in the field of photovoltaic technologies, including crystalline silicon modules, thin-film photovoltaics, and semi-transparent PV deployments, have facilitated smooth integration into building envelopes. These advances in technology have increased the freedom of design, and PV systems can now be integrated into a facade, a skylight, a roof, and even a shading device without affecting architectural visual appeal. Nevertheless, it is always suggested in research that the effectiveness of BIPV systems is highly determined by factors like the orientation, tilt angles, climatic and solar irradiation levels, material, and system structure, and thus it is important to consider performance evaluation on a case-by-case basis.

Simultaneously, a considerable amount of research conducted on building envelope materials in the conventional building reveals a set of constraints in their long-term sustainability performance. Concrete, brick, stone, and glass are some traditional materials whose primary considerations are structural strength, durability, thermal insulation, and physical appeal. Although some improvements in the thermal efficiency and comfort of the interior created through improvements in facade engineering, high-performance glazing, and insulation materials, these envelope systems are still passive. These systems have limited contributions to sustainability, primarily minimizing heat transfer and energy losses without active involvement in energy generation or carbon mitigation. Consequently, traditional envelope materials have a limited potential in responding to the rising need for the on-site renewable energy of structures.

According to the literature on comparative studies, the incorporation of energy-generating technologies in the building envelope can greatly increase the overall performance of the building, taking into consideration lifecycle effects [24,25]. A number of investigators have shown that BIPV systems, with their high initial cost, can deliver positive lifecycle energy and environmental performance due to less energy usage in operation and lower greenhouse gas emissions. Economic calculations suggest that high capital investments can be compensated by long-term advantages in the form of savings of energy costs, decrease in the material redundancy, and even incentives. Most of the available literature concentrates on individual performance indicators, e.g., energy efficiency, cost evaluation, or environmental impact, without offering a holistic comparison of BIPV systems to conventional envelope materials in several aspects.

In general, the current literature shows that there is a significant gap in the literature on the holistic assessment of building envelope solutions. Although there has been considerable advancement in the understanding of technical and aesthetic aspects of BIPV systems, there was little emphasis on integrated assessment, which evaluates the energy performance, economic viability, and environmental impact simultaneously of the two in comparison to traditional envelope materials. To fill this gap, the current study was based on a multi-dimensional comparative approach that examines building-integrated photovoltaics and traditional building envelope materials. This synthesis of energy, economic, and environmental performance indicators assists in a better understanding of the relative effectiveness of indicators and helps to make informed decisions to design buildings sustainably and develop policies.

The studies included in this review span publications from 2010 to 2024, reflecting a period of substantial technological evolution in BIPV systems. Early studies in this period predominantly examined opaque crystalline-silicon modules in roof- or façade-mounted configurations, while more recent publications (2020–2024) increasingly report on semi-transparent and thin-film technologies, improved module efficiencies, and more sophisticated building-integration strategies. This technological progression should be considered when interpreting the reported performance ranges, as earlier studies may reflect lower baseline efficiencies than more recent installations, contributing in part to the observed variability in reported energy generation and cost figures.

Table 1 shows an illustrative comparison of performance-dimension coverage across a subset of reviewed studies. Note: This table presents 12 representative studies selected from the full 40-study evidence base to illustrate the extent to which the prior literature addresses energy, economic, and environmental performance dimensions in isolation versus in combination. It is not a separate or additional literature sample; all 12 studies shown are included within the 40 studies comprising this review's quantitative synthesis.

To illustrate this fragmentation, Table 1 presents a representative subset of 12 studies drawn from the full 40-study evidence base, categorized according to which performance dimension(s) each addresses.

Table 1. Twelve recent studies against performance dimension(s).

S. No.	Study	Energy	Economic	Environmental	Combined (3E)?	Refs.
1	LCA of textile-integrated flexible PV	—	—	✓	No	[1] Li et al. 2024
2	Thermo-environmental review of envelope panels	✓	—	✓	No	[2] Mohammed et al. 2024
3	BIPV/Thermal system performance	✓	—	—	No	[3] Gagliano et al. 2021
4	Techno-economic + energy assessment of BIPV	✓	✓	—	Partial (2E)	[4] Shankar et al. 2021
5	Economic + LCC analysis of BIPV	—	✓	—	No	[6] Singh et al. 2024
6	Low-carbon design path, green rating systems	—	—	✓	No	[9] Liu et al. 2021
7	Techno-econo-enviro analysis of BIPV types	✓	✓	✓	Yes	[10] Jahangiri et al. 2023

Table 1. *Cont.*

S. No.	Study	Energy	Economic	Environmental	Combined (3E)?	Refs.
8	Energy, economic, environmental of BIPV-TE system	✓	✓	✓	Yes	[13] Luo et al. 2022
9	LCA perspective, environmental impact of BIPV	—	—	✓	No	[15] Al-Janahi & Al-Ghamdi 2021
10	Comparative review, India and globe	✓	—	—	No	[20] Goel et al. 2022
11	"3E" impacts of PV panels vs. windows	✓	✓	✓	Yes	[23] Zhao, Zhang & Ding (n.d.)
12	Techno-economic study, residential BIPV cluster	—	✓	—	No	[24] Quintana et al. 2021

Note: (✓) indicates study represents the particular performance dimension.

This research took a comparative analytical research design, which combined both descriptive and evaluative research designs to investigate the performance nature of building-integrated photovoltaic systems and traditional building envelope materials, as illustrated in Figure 2. The descriptive aspect provided an organized realization of current practices using building envelopes, material characteristics, and plans of photovoltaic integration, whereas the evaluative aspect allowed comparing the proposed strategies on a systematic basis in the context of quantifiable performance indicators [26]. This plan of design made sure that variations in energy performance, economic effects, and ecological performance of BIPV and conventional envelope systems were analyzed in a coordinated and systematic way, which was in tandem with the goals of the research.

The study was based on secondary information sources such as peer-reviewed journal articles, official technical reports, and registered building case studies in the field of photovoltaic integration and envelope material performance. These sources included verified and standardized data on energy production, thermal efficiency, cost variables, and environmental effects [27]. The synthesis and interpretation of the obtained data were conducted with the use of analytical modeling methods and indicators of performance based on the established building energy and sustainability standards. This method has helped perform the analysis based on sound evidence and allowed it to be consistent across building typologies and climatic conditions.

We applied a multi-criteria evaluation framework that supported the concurrent analysis of energy performance, economic viability, and the impact on the environment. Energy indices comprised the potential of electricity production, thermal impact on the building loads, and the general energy efficiency. Economic indicators put into consideration lifecycle aspects of costs such as capital investment, operating costs, and long-term economic gain. Environmental indicators were covered on greenhouse gas emission reduction, embodied energy, and operational carbon savings. A standardized evaluation model allowed a comparative analysis of performance on a variety of aspects, without the need to perform a fragmented or single-criterion assessment.

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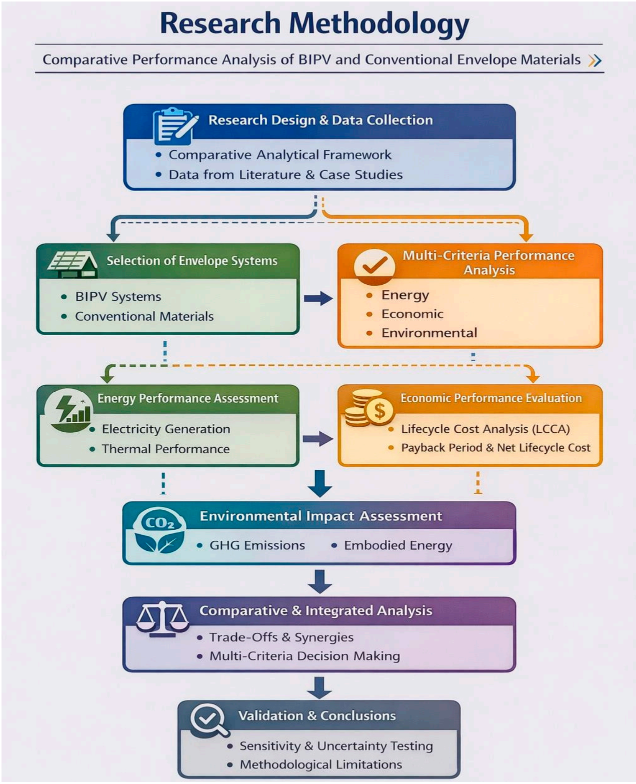

Figure 2. Research methodology flowchart.

The methodological approach of integration made sure that the comparative analysis was more realistic in terms of building performance than independent and theoretical measures. The study was able to describe the interactive nature between building design and performance outcome by including the lifecycle views, climatic effects, and functional properties of envelope systems. This method has enhanced the applicability of the results to sustainable building design because it will have a holistic overview of the performance of BIPV systems and traditional envelope materials under realistic conditions, which will facilitate evidence-based decision-making in the application of energy-efficient and greener building practices.

All quantitative values presented in this manuscript, including those in Figures 3–5 and Tables 2–4, were extracted directly from the reviewed literature rather than generated through original field measurement or laboratory modeling. Reported ranges represent the minimum–maximum values observed across the eligible studies reporting each indicator. A complete mapping of each reported value to its specific source reference(s) is provided in Appendix A (Table A1).

To assess the influence of contextual variability on reported performance outcomes, each of the 40 studies retained for comparative synthesis was characterized according to five contextual variables: climate zone (following the Köppen–Geiger classification), building typology (residential, commercial, or high-rise), photovoltaic technology (crystalline silicon, thin-film, or semi-transparent), façade orientation (where reported), and geographic region.

4. Selection of Building Envelope Systems

The choice of building envelope systems was organized in such a way that it made a clear and objective comparison between the energy-generating and non-generating envelope solutions. Two main types were taken into consideration: building-integrated photovoltaic systems and the traditional building envelope materials [28]. Such a classification enabled the study to clearly compare envelope systems that played an active role in the production of energy on-site with those that were mostly structural, protective, and thermal. This kind of differentiation was necessary in analyzing the performance variability in terms of energy and economic as well as environmental dimensions in the framework of the research.

Building-integrated photovoltaic systems comprised façade-integrated modules, roof-integrated photovoltaic modules, and semi-transparent photovoltaic modules used in skylights and glazed facades. These systems have been chosen due to their increasing popularity in modern architectural practice and their ability to substitute traditional envelope materials while generating electricity. The incorporation of varied BIPV designs allowed the determination of the variability in the performance based on the orientation, integration type, and use in practice and allowed gaining a better insight into the role of each of these combinations in the context of various building envelope situations.

Traditional material building envelope elements included concrete walls, brick masonry, curtain wall glazing systems, and traditional roofing assemblies. These were building materials that were used in large-scale construction of houses and offices. The materials were selected according to established functions that include thermal protection, structural stability, weather protection, and architectural expression [29]. The study also considered standard envelope materials that have been widely used, which contributed to the comparative analysis of offices that are relevant to the actual construction activities and the accepted building design standards.

Representative envelope constructions were chosen to reflect common construction procedures while also taking into consideration differences in material characteristics, functional requirements, and architectural applications. Issues like thermal behavior, durability, transparency, and structural performance were taken into consideration in order to keep similarity in the chosen envelope systems. This was to provide a fair or balanced comparison, as bias due to unusual design decisions was minimized, which enhanced the validity of the conclusions made concerning the comparative energy, economic, and environmental performance of building-integrated photovoltaic systems and traditional envelope materials.

5. Energy Performance Assessment

The energy performance assessment was set in such a way that it was used to test the effects that various building envelope systems had on both energy demand and energy supply in buildings. The importance of the envelope in controlling thermal behavior was highlighted and viewed as well as its possible role in generating energy at the site. This method was able to determine the overall impact of building-integrated photovoltaic systems and traditional envelope materials on overall building energy performance in similar operating conditions [30].

In building-integrated photovoltaic systems, the evaluation of energy performance was devoted to the fact that this type of system was able to produce electricity directly related to solar radiation. The main indicators were the annual electricity production (energy), the efficiency of photovoltaic conversion, and the ratio of the energy consumed by buildings, which was generated on-site. The interaction of photovoltaic modules with the building envelope and its effect on shading, solar heat gain reduction, and overall energy balance were also taken into account in the analysis. All these elements were indicative of the efficiency of BIPV systems in lowering the use of external sources of energy.

Traditional building envelope materials were evaluated in terms of energy production, but the focus of energy performance was in terms of thermal qualities. Aspects like insulation performance, thermal transmittance, and heat flow resistance were investigated to establish their influence on heating and cooling energy demand [31]. Their capacity to moderate indoor thermal conditions and minimize energy losses was assessed, demonstrating that such systems can be used to reduce operational energy requirements without factoring in energy supply.

In order to facilitate a fair comparison of the two envelope systems, the energy performance of the two envelope systems was normalized to an area of the building envelope. The assessment included climatic conditions, the intensity of solar irradiation, and the orientation and arrangement of the envelope to indicate real operating conditions. This normalization and contexting consideration made sure that the difference in performance was accredited to the nature of the envelope system as opposed to extraneous variables, hence enhancing the validity of the comparative energy performance analysis.

6. Economic Performance Evaluation

A lifecycle cost analysis was used to conduct the economic performance assessment to define the long-term financial impact of various building envelope systems. The methodology permitted the determination of costs and benefits across the service life of the service and not just the initial expenditure [32]. The analysis was able to consider the temporal differences in costs and also to ensure that short-term decisions associated with investment were analyzed on top of long-term financial performance that was applicable in sustainable building development with the lifecycle perspective.

Initial costs of investment and installation were considered in terms of building-integrated photovoltaic systems and the traditional envelope materials. These expenses were the material procurement, complexity of construction, and integration needs of each envelope type. Operation and maintenance costs, such as normal servicing and performance control, were also put into consideration to review the repeated financial obligations. The cost of replacement or refurbishment that was likely to be incurred in the course of the life cycle of the envelope systems was included to present a realistic estimate of the overall ownership costs.

In the case of building-integrated photovoltaics, the analysis was economic to cover not only the spending but also the financial gain related to the generation of electricity on-site. The energy cost savings due to the lesser dependence on electricity on the grid and possible income due to the surplus generation of power were taken into consideration as the overall economic performance. These advantages were also examined concerning the effectiveness of the systems and the duration of their operations in order to see their effect on the counterbalancing of an increase in initial investment demands [33]. Conversely, traditional envelope materials were evaluated based on capital and maintenance expenditures, as no direct energy revenue is generated.

Standardized economic indicators were used to determine the economic feasibility and long-term financial performance. The payback period was intended to estimate the time period during which initial investments were covered, and the cost–benefit ratio presented an idea of the ratio between overall benefits and overall costs. Net lifecycle cost was used to estimate the total financial cost of each envelope system in regard to the service life. The integrated application of such indicators helped to make a comparative evaluation of economic performance organized and thus make informed assessments of the financial feasibility of building-integrated photovoltaic systems with no reference to traditional building envelope materials.

The lifecycle cost model (Equation (4)) applies a discount rate of 6%, consistent with typical values used in building lifecycle cost analyses to account for the time value of money over the assumed 25-year service life; this rate was adopted as a representative mid-range value drawn from the reviewed literature and is varied as part of the sensitivity analysis. Electricity price escalation was assumed at 2.5% per year, based on historical average trends reported. Cost savings were calculated at a constant baseline tariff, which is acknowledged as a simplification. Operation and maintenance (O&M) costs were treated as a fixed percentage of initial capital investment, based on values reported in the literature, recognizing that actual maintenance costs are subject to uncertainty related to system degradation rates, cleaning requirements, and inverter replacement schedules over the building service life. Regional policy incentives, including feed-in tariffs, capital subsidies, and tax credits, were excluded from the baseline economic analysis to preserve cross-regional comparability of the reported cost-benefit and payback period ranges; where such incentives were reported in individual source studies, their potential effect on shortening payback periods is discussed qualitatively in the Discussion section rather than incorporated into the baseline figures.

7. Environmental Impact Assessment

The lifecycle-based evaluation method was used in conducting the environmental impact assessment to look at the environmental implication of the various building envelope systems. This methodology allowed assessing the effects that take place in the production of materials, their construction, operation, and end-of-life phases [34]. The lifecycle gave the analysis the opportunity to have both direct and indirect environmental impacts, hence providing a holistic comparison between building-integrated photovoltaic systems and the conventional building envelope materials in the framework of sustainable building.

The major environmental performance metrics were the potential of reduction in greenhouse gases, embodied energy, and carbon savings in operation. Embodied energy was the sum of energy used in the extraction of materials, their manufacturing, and installation processes, whereas operational carbon savings were the savings in the emission, which occurred during the use of the building. These indicators gave a balanced picture of how well the environment was being performed by considering both the initial environmental costs and the long-term outcomes of the operation of the envelope systems.

In the case of building-integrated photovoltaic systems, a grid of environmental benefits was measured by assessing the offset of the electricity generation provided by the grid by on-site production of renewable energy. The resulting decrease in the emission of greenhouse gases caused by the lowering of dependence on the use of fossil-based sources of power was deemed a major win for the environment [35]. The doubled use of BIPV systems as substitutes for traditional envelope materials that produced clean energy was an added advantage to reducing overall material-related environmental impacts throughout the life cycle of the system.

The traditional building envelope materials were evaluated using their embodied environmental effects as well as their low potential to eliminate operational emissions. Even though these materials were used in thermal regulation and in the conservation of energy, their contribution to the mitigation of direct emissions was limited. The comparative analysis has highlighted the environmental performance of the entire life cycle of the two envelope systems and allowed us to determine the relative strength and limit of both envelope systems in terms of the carbon reduction potential and long-term environmental sustainability.

The environmental performance metrics considered in the present study—embodied energy, embodied emissions, and operational carbon savings—have been identified through the LCA analyses performed in the relevant studies, which typically use the methodology defined by the ISO 14040/14044 standards [36]. The functional unit chosen for the compilation of indicators is 1 m^2 of building envelope surface area in 25-year lifespan/building-year, and system boundaries were restricted to material production, installation, and use stage impacts (cradle-to-use), with no consideration of the end-of-life impact category unless reported. The data from inventories used in the source studies were extracted from, e.g., Ecoinvent, GaBi, or country-specific LCA databases. It should be noted that since different databases and system boundaries were chosen in the various studies, this is recognized as an uncertainty source mentioned in Methodological Limitations.

8. Comparative and Multi-Criteria Analysis

The multi-criteria analysis and comparative analysis were designed in a way that was able to combine the results of the energy, economic, and environmental analyses into one evaluation framework. This methodology allowed the performance findings to be interpreted in a holistic manner as opposed to studying the results of individual indicators [37]. The synthesis of various performance domains made the analysis base a holistic comparison of building-integrated photovoltaic systems and traditional building forms of material in the context of sustainable building design.

The decision analysis methods used to rank and compare the envelope systems of choice in a systematic manner were multi-criteria decision analysis techniques. These methods allowed testing the interaction of complex performance in that both quantitative and qualitative indicators were accommodated. Potential in energy generation, lifecycle cost efficiency, and the reduction in environmental impact were added as primary criteria and enabled the assessment to capture the multidimensional aspect of building envelope performance. This process of evaluation was structured, and transparency and consistency were observed in the comparison process.

The relative weights of performance indicators were determined by the weight of importance to the sustainable building goals. More attention was drawn to indicators to do with long-term energy efficiency, sustainability of the environment, and economic viability, whilst ensuring a balance between all the criteria considered [37]. The weighting procedure facilitated the separation of the envelope systems based on the total contribution made towards sustainability and not hegemony in a particular aspect of performance.

The integrated comparison aided in the establishment of trade-offs, synergies, and performance benefits on both envelope systems in general. The weaknesses and strengths were identified by looking at the impacts of improvements in one area of performance on other areas. This in-depth research provided the informed interpretation of the results and presented a systematic foundation on the relative appropriateness of building-integrated photovoltaic systems and traditional envelope materials in the application to sustainable buildings.

Equal weighting ($wE = wC = wEn \approx 0.33$) was adopted as the baseline configuration for the multi-criteria performance index (Equation (12)), reflecting a neutral prioritization across the energy, economic, and environmental dimensions in the absence of a specific stakeholder perspective (e.g., a developer prioritizing capital cost recovery versus a certification body prioritizing environmental impact). This approach is consistent with common practice in multi-criteria building performance assessments where no single stakeholder priority is assumed a priori. To test whether this weighting choice materially influences the comparative conclusions of this study, a sensitivity analysis was conducted, varying the weighting coefficients by ± 0.10 around this equal-weight baseline. The results indicate that the relative ranking of BIPV systems over conventional envelope materials remains unchanged across all tested weighting configurations, indicating that the study's central comparative finding is not an artifact of the specific weights selected. We note that future studies could strengthen this aspect further through structured expert elicitation methods, such as the Analytic Hierarchy Process (AHP), to derive stakeholder-specific or context-specific weighting coefficients; this is identified as a direction for future research.

9. Sensitivity and Robustness Analysis

The sensitivity analysis was performed to confirm the strength and the dependability of the comparative findings of the building envelope system performance assessment. This step was aimed at the investigation of the stability of the results under different conditions of the main influencing parameters [38]. With the inclusion of validation processes, the analysis made sure that the comparative inferences made on building-integrated photovoltaic systems and the traditional envelope materials will be consistent across various assumptions as well as operating conditions.

Systematic variation of parameters critical in the production of the energy, economic, and environmental performance outcomes was performed through sensitivity analysis. Such factors as the cost of energy, efficiency of the photovoltaic systems, and the weather conditions varied within reasonable limits, and their impact on the total performance ranking was determined. It has allowed identifying the parameters that cause the most significant changes to comparative outcomes and also clarified the level to which performance patterns might be varied by the uncertainty in envelope systems.

The analysis also analyzed the effect of variation in the external environment on the long-term economic and environmental performance. The differences in energy tariffs had an impact on the lifecycle cost savings related to building-integrated photovoltaic systems, whereas the results of the study of climatic conditions affected electricity generation potential and thermal performance. The assessment of such interactions promoted insights into the resilience of the envelope system operation under varying operational conditions and geographic locations.

The methodological framework was designed in a way that provides flexibility and reproducibility of the approach to different types of buildings and in different regions. Through the ability to make the evaluation parameters flexible, the framework enabled a further extension of the analysis to residential buildings, commercial buildings, or institutional buildings in another climatic zone. This flexibility reinforced the applicability of the results and helped in their use in more generalized contexts of sustainable building design and policy making.

10. Methodological Limitations

The methodological limitations were found to ensure transparency on the scope and applicability of the comparative analysis. Although the developed framework allowed conducting the assessment of the building-integrated photovoltaic systems and traditional building envelope materials in a systematic manner, it was mostly based on the secondary data sources and modeled performance indicators [39]. Consequently, the results mirrored overall performance patterns as opposed to the site-specific results, which can be different in a real-life construction and operation process.

The secondary data provided limits on the data availability and consistency as well as relevance in terms of context. The values of performance described in the literature were usually based on the varying climatic zones, typologies of buildings, and design assumptions. This variability may have contributed to the incompatibility of the findings, especially in the translation of modeled energy and economic and environmental indicators into practice. These limitations were taken into account in the analysis so as to reduce the misinterpretation of comparative results.

The difference in the building methods, quality of materials, and ways of installation were other sources of uncertainty. Disagreements in workmanship, integration, and maintenance approaches have a great impact on the performance of the two BIPV systems and traditional envelope materials in a real-world scenario. In addition, the different regulations, building codes, and incentive structures were not harmonized, and this may have affected economic and environmental performance within certain regions.

Actual building performance was also affected by site-specific issues like orientation, shading, microclimatic conditions, and behavior of the user; these were not effectively represented in the modeled assessment framework. These aspects restricted the pure generalization of the findings to any building setting. Based on this, the results were interpreted within the stipulated research framework, and it was concluded that subsequent research involving primary data collection and site analysis would contribute to the improvement and validation of the comparative inferences [24].

A formal statistical meta-analysis (e.g., pooled effect size estimation) was not performed, given the substantial heterogeneity in building typology, climatic context, photovoltaic technology, and reporting units across the included studies, which precludes meaningful statistical pooling without introducing significant bias. Instead, this review reports literature-derived ranges and applies a normalized multi-criteria synthesis framework (Equations (11) and (12)) to enable comparative interpretation across studies. Future research employing standardized reporting protocols (see Section 13) would enable a formal meta-analytic synthesis in subsequent reviews.

This review did not apply a formal, scoring-based quality assessment tool for the included papers as these were designed for randomized and non-randomized intervention studies for intervention purposes and would need considerable modifications to become applicable for the current body of literature based on case studies, and techno-economic modeling, which is typical in the field of BIPV. Inclusion and exclusion decisions were made according to specific criteria of topical relevance and data completeness, and all values used have been attributed to their source papers through Appendix A.

11. Result and Discussion

Table 2 provides an overview comparison of the energy-related performance of building-integrated photovoltaic systems and conventional building envelope materials with an emphasis on their radically different functions in the building energy dynamics. The most notable difference, as pointed out in the table, was that the BIPV systems have the capability of producing on-site energy with an annual energy production of between 120 and 220 kWh/m^2/year, unlike the conventional materials that do not produce energy directly. This difference was a sign of a shift from the role of a purely protective envelope to an active component of the energy-generating buildings, which consequently affects the energy balance of the building in general.

Table 2. Energy performance comparison of BIPV and conventional envelope materials.

Performance Indicator	BIPV Systems	Conventional Materials	Observed Outcome	Source References
Annual Energy Generation (kWh/m^2/year)	120–220	0	BIPV actively generates on-site electricity	[3] Gagliano et al. 2021; [7] Tina et al. 2021; [11] Wei et al. 2024; [33] Aguacil et al. 2024
Cooling Load Reduction (%)	8–15	0–5	Higher reduction due to shading and solar control	[3] Gagliano et al. 2021; [29] Alhammadi et al. 2022; [37] Wang et al. 2023; [2] Mohammed et al. 2024; [26] Moghaddam et al. 2023

Table 2. *Cont.*

Performance Indicator	BIPV Systems	Conventional Materials	Observed Outcome	Source References
Grid Electricity Reduction (%)	20–30	5–10	Significant reduction with BIPV	[4] Shankar et al. 2021; [19] El Samanoudy et al. 2024; [2] Mohammed et al. 2024; [16] Alassaf 2024
Total Energy Savings (%)	20–25	5–7	BIPV shows superior net energy impact	[10] Jahangiri et al. 2023; [14] Dehwah & Krarti 2021
Net Energy Contribution	Active	Passive	BIPV transforms envelope into energy producer	

The table also provides a difference in cooling load reduction, which was gained by the two envelope systems. The systems based on the use of BIPV are associated with increasing cooling load reductions because of the presence of the photovoltaic shading, decreased solar heat gain, and enhanced performance of the facade. Compared to conventional materials, conventional materials obtain reductions of moderate magnitude mainly by the effects of insulation and thermal mass. Although these passive measures help in achieving thermal comfort and energy savings, such measures do not generate outcomes comparable to those achieved by integrating active and passive energies through BIPV integration.

Table 2 supports the indicator of better energy performance of BIPV systems in relation to operational energy savings by grid electricity reduction and total energy savings. The BIPV systems will greatly help in saving on the reliance on outside grid supply, especially in buildings with high power consumption owing to the fact that the renewable electricity was generated on-site. Although conventional envelope materials can mitigate heating and cooling loads to some degree, such materials remain completely dependent on external energy sources and therefore contribute only a marginal reduction in total electricity consumption.

Comprehensively, Table 2 illustrates that BIPV systems have energy conservation and energy production advantages, which makes the net energy contribution significantly greater than that of the traditional envelope materials. The comparative indicators distinctly indicate that conventional materials continue to be effective in thermal control but remain passive in nature; therefore, these materials are constrained in their impact on long-term energy performance. On the contrary, BIPV systems actively minimize operational energy consumption and contribute to energy-efficient building plans, which explains their importance in high-technology sustainable building design.

Table 3 shows a comparative analysis of the economic performance of the BIPV systems against the traditional building envelope materials, with the focus on being aware of the financial feasibility of the whole building lifecycle as opposed to taking a one-sided view of the initial investment costs. The table shows that the initial capital per unit area in BIPV systems was higher because these systems combine photovoltaic modules, electrical components, and complex installation requirements. Conversely, traditional materials exhibit lower start-up expenses, and this in most cases makes them preferable in projects whereby short-term budget constraints form the major decision-making factor.

Table 3 shows a change in the economic results when the lifecycle costs are taken over the period of 25 years of assessment. Even though the initial cost of BIPV systems was high, the overall lifecycle cost of the product was less compared to the traditional envelope materials. This was mainly because it will have constant savings since on-site electricity generation will offset the cost of buying grid electricity during the operation period. Although conventional materials are cost-effective in the short term, these materials incur increased costs in the long run because their energy consumption lacks a direct mechanism for cost recovery.

Table 3. Economic performance and lifecycle cost assessment.

Economic Indicator	BIPV Systems	Conventional Materials	Comparative Insight	Source References
Initial Investment ($\$/m^2$)	140–160	70–90	Higher upfront cost for BIPV	[6] Singh et al. 2024; [8] Singh et al. 2023; [24] Quintana et al. 2021; [2] Mohammed et al. 2024
Lifecycle Cost (25 years) ($\$/m^2$)	120–180	140–200	Lower long-term cost for BIPV	[6] Singh et al. 2024; [32] Yang et al. 2023; [16] Alassaf 2024; [26] Moghaddam et al. 2023
Payback Period (years)	7–12	Not applicable	Only BIPV recovers investment	[4] Shankar et al. 2021; [8] Singh et al. 2023; [24] Quintana et al. 2021
Cost-Benefit Ratio	1.25–1.45	<1.0	Long-term economic advantage for BIPV	[6] Singh et al. 2024; [23] Edmund & Go 2022
Electricity Cost Savings	High	Low	BIPV offsets grid dependence	

The payback period indicator also explains the long-term financial behavior of envelope selection. The BIPV systems have a specified payback period in the life cycle of the structure, and this means that the initial cost of the building can be recouped by the savings in operations. Traditional envelope materials fail to demonstrate a payback period because these materials do not generate revenue or significant cost savings beyond incremental energy savings. This distinction brings out the completely different economic functions of the active and passive systems of the envelope.

The cost–benefit ratio presented in Table 3 represents a combined criterion of the economic viability. BIPV systems have a ratio more than one, thus supporting the idea that long-term financial outcomes prevail over start-up expenses. The conventional materials have a ratio that was less than one, showing poor economic returns compared to time. Taken together, Table 3 emphasizes the fact that the economic performance was highly dependent on the timeframe to be considered and supports the applicability of the lifecycle-based financial analysis when comparing the long-term value of BIPV systems with traditional building envelope materials.

The integrated assessment used in Figure 3 involves energy efficiency, economic viability, and environmental impact, all in a single comparative system. The visual indicators show BIPV systems are well able to perform at a higher level in all three dimensions, which indicates their functionality as a multifunctional component of the building envelope. In comparison with traditional materials, which are supposed to act as a passive element only, BIPV systems also play a dual role of generating energy, recovering costs, and reducing emissions, which in turn makes them a more powerful performer in terms of overall performance when considered through a variety of parameters.

Figure 3 shows an integrated multi-criteria performance comparison of BIPV and conventional building envelope systems. Bars represent normalized performance scores (0–1 scale, per Equation (12)) for each criterion, calculated for both BIPV systems and conventional materials using the ranges reported in Tables 1–3.

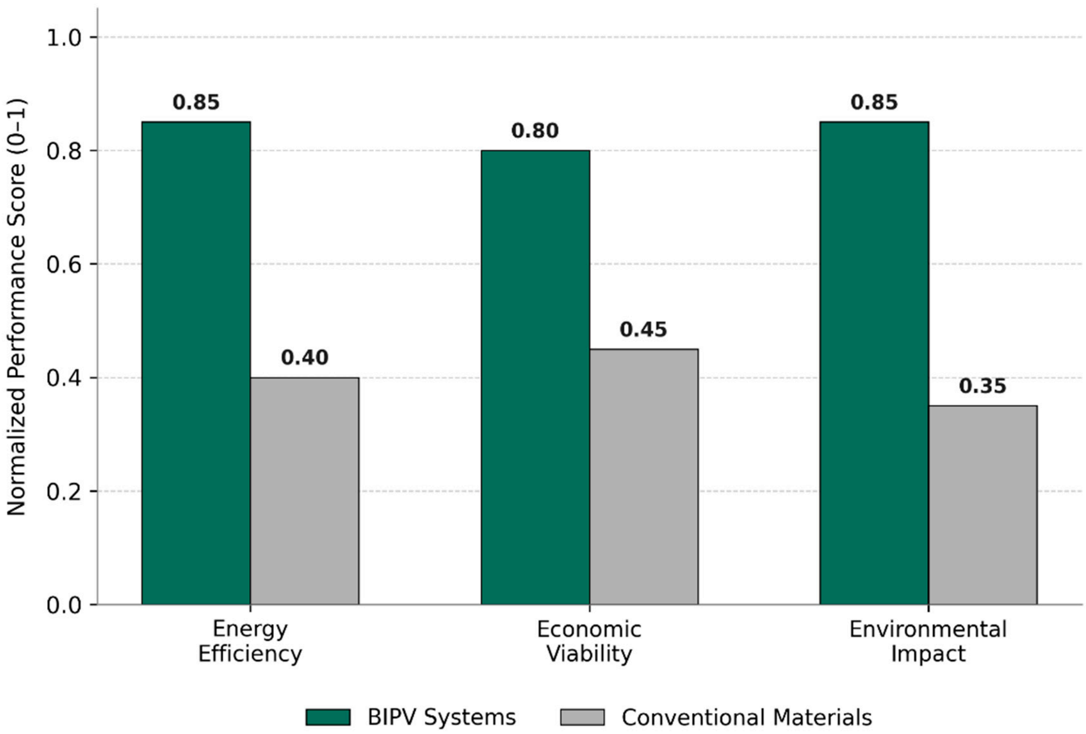

Figure 3. Integrated multi-criteria performance assessment of BIPV and conventional building envelope systems.

The energy efficiency indicator lays emphasis on the fact that BIPV systems are the dominant contribution to building performance. BIPV envelopes have a greater score under the efficiency category owing to the production of on-site renewable electricity and lower cooling costs due to shading and controlled sun exposure, among other reasons, in comparison to traditional materials. The traditional envelope systems are useful in terms of heat transfer reduction but do not have the characteristics of active supply of energy, which restricts their impact on the net building energy balance. This was an illustration of how the use of energy-conserving envelopes has changed to energy-generating building skins.

The economic viability indicator was the financial forecast of the envelope system selected in the long run. The greater outlay investment in the BIPV systems, their capability to cover the electricity bills and generate net savings over the building life cycle makes them better economically performing systems as the building life cycle progresses. The traditional materials exhibit an average economic performance that was dictated by reduced initial costs but limited by a lack of a revenue or cost collection strategy. The visual comparison underpins the significance of the lifecycle-based assessment instead of the short-time assessment of cost as the envelope strategies are compared.

The indicator on environmental impact proves the high contribution of the BIPV system to the mitigation of carbon. Infinite renewable energy production supports the permanent decrease in emissions of greenhouse gases over the lifetime of the building, which overcomes the greater embodied effects of photovoltaic devices. Traditional envelope products have relatively low environmental performance, as the effect on emission reduction was indirect and confined to incremental saving of energy. Taken together, the cumulative analysis presented in Figure 5 depicts the fact that BIPV systems provide multi-dimensional benefits in the energy, economic, and environmental aspects, and the traditional material was playing an increasingly supportive role in the sustainable design and construction of buildings.

$$E_{\mathrm{BIPV},\, m^2} = G \cdot \eta_{\mathrm{PV}} \cdot PR \quad (1)$$

This equation quantifies the amount of electricity produced per unit envelope area through photovoltaic integration. It links solar availability, module efficiency, and system losses into a single performance value. The formulation enables direct comparison with non-generating envelope systems on an area-normalized basis.

$$E_{\text{net}} = E_{\text{gen}} - E_{\text{demand}} \quad (2)$$

This expression evaluates whether the envelope acts as an energy contributor or an energy consumer. Positive values indicate surplus generation, while negative values indicate continued grid dependence. The equation highlights the functional difference between active and passive envelope behavior.

$$\Delta Q_{\text{cool}, m^2} = Q_{\text{conv}, m^2} - Q_{\text{BIPV}, m^2} \quad (3)$$

This relationship measures the reduction in cooling demand achieved through envelope modification. It captures shading effects, reduced solar heat gain, and thermal control improvements. The result reflects indirect energy savings associated with envelope-based design strategies.

$$\text{LLC}_{m^2} = C_{init} + \sum_{t=1}^{n} \frac{C_{O\&M} - S_{energy}}{(1+r)^t} \quad (4)$$

This equation represents total cost accumulation over the service life of the envelope system. It incorporates capital investment, operating expenses, and energy-related financial offsets. The lifecycle formulation reveals long-term cost behavior beyond initial construction expenditure.

$$S_{energy} = E_{\text{BIPV}, m^2} \cdot P_{\text{elec}} \quad (5)$$

This expression converts generated electrical energy into annual monetary savings. It directly links envelope electricity production to prevailing electricity tariffs. The result forms the basis for long-term financial performance evaluation.

$$\text{PBP} = \frac{C_{init}}{S_{annual}} \quad (6)$$

This equation estimates the time required to recover the initial investment. It relates upfront costs to recurring annual savings generated during operation. Shorter payback periods indicate faster financial recovery and improved feasibility.

$$\text{CBR} = \frac{\sum S_{energy}}{C_{init} + \sum C_{O\&M}} \quad (7)$$

This ratio compares total economic benefits against total incurred costs. Values greater than unity indicate that long-term benefits outweigh expenditures. The metric provides a dimensionless indicator of overall economic effectiveness.

$$\Delta \text{CO}_{2,\text{annual}} = E_{\text{BIPV}, m^2} \cdot EF_{\text{grid}} \quad (8)$$

This equation estimates avoided carbon emissions through electricity substitution. It links on-site renewable generation to the carbon intensity of grid electricity. The outcome reflects direct operational emission mitigation.

$$\text{CO}_{2,\text{life}} = \sum \Delta \text{CO}_{2,\text{annual}} - \text{CO}_{2,\text{emb}} \quad (9)$$

This formulation evaluates net carbon performance over the entire service life. It balances operational emission savings against initial embodied emissions. Positive values indicate long-term environmental benefit.

$$CPP = \frac{CO_{2,emb}}{\Delta CO_{2,annual}} \quad (10)$$

This equation defines the time required to offset embodied carbon impacts. It identifies when cumulative operational savings surpass initial emissions. Shorter periods indicate faster transition to net-positive carbon performance.

$$X_{norm} = \frac{X_i - X_{min}}{XX_{min\,max}} \quad (11)$$

This equation standardizes diverse performance metrics onto a common scale. It enables direct comparison across energy, economic, and environmental indicators. Normalization prevents dominance of any single parameter in aggregated evaluation.

$$PI = w_E E_{norm} + w_C C_{norm} + w_{En} En_{norm} \quad (12)$$

This expression integrates multiple performance dimensions into a single index. Weighting factors allow prioritization of specific sustainability objectives. The index supports holistic comparison of envelope system effectiveness.

Table 4 provides a comparative evaluation of the environmental performance of the two envelope systems by looking at the embodied as well as the operational environmental impact. According to the table, BIPV systems will reduce CO_2 emissions per unit area significantly per year compared to traditional envelope materials. This has been improved mostly because we have displaced electricity that was made in grids with renewable energy generated on-site. Although conventional materials help save energy through insulation, such materials can reduce emissions only to a small extent because conventional materials do not truly replace electricity consumption derived from fossil fuels.

Table 4. Environmental performance and carbon impact analysis.

Environmental Metric	BIPV Systems	Conventional Materials	Performance Interpretation	Source References
Annual CO_2 Reduction ($kg/m^2/year$)	18–25	3–5	BIPV provides direct emission mitigation	[9] Liu et al. 2021; [15] Al-Janahi & Al-Ghamdi 2021; [35] Maghrabie et al. 2021; [2] Mohammed et al. 2024
Embodied Energy (GJ/m^2)	3.0–3.5	1.8–2.2	Higher initial impact for BIPV	[1] Li et al. 2024; [15] Al-Janahi & Al-Ghamdi 2021; [34] Hoseinzadeh et al. 2021; [2] Mohammed et al. 2024; [16] Alassaf 2024
Embodied Emissions (kg CO_2/m^2)	~200	~150	Offset during operational phase	[1] Li et al. 2024; [24] Alsaied et al. 2024; [2] Mohammed et al. 2024
Carbon Payback Period (years)	5–7	Not applicable	Faster emission breakeven for BIPV	[9] Liu et al. 2021; [24] Alsaied et al. 2024
Cumulative CO_2 Savings (25 years) (kg/m^2)	450–600	<100	Superior lifecycle environmental benefit	[15] Al-Janahi & Al-Ghamdi 2021; [35] Maghrabie et al. 2021

The embodied energy and embodied emissions indicators in Table 4 point to the first load on the environment in terms of material production and installation. BIPV systems are characterized by greater embodied energy and carbon emissions than conventional envelope materials because of the energy-intensive production of the photovoltaic module and other electrical components required to support the photovoltaic modules. Traditional materials tend to exhibit fewer embodied impacts, which can be traced to simpler processes of production. But these embodied values are one-time effects occurring during the construction phase, and these effects must be analyzed within a full lifecycle context.

The difference in the performance between the two envelope approaches was clearly shown by the operational carbon savings over the lifespan of the building. Table 4 indicates that BIPV systems produce high cumulative CO_2 savings in 25 years because of constant generation of renewable electricity. These operation savings gradually compensate for the increase in embodied emission, and net-positive environmental performance was attained. Conversely, traditional envelope covering materials are relatively poor at cumulative carbon savings because their environmental contribution is only indirect: these materials reduce energy demand but do not directly displace emissions.

The long-term environmental benefit of BIPV systems was further supported by the carbon payback period of this technology, as in Table 4. The payback period shows how long operations can effectively reduce the emissions to cover the initial embodied carbon footprint. This breakeven point was achieved relatively soon in the building service life of BIPV systems, and once this was achieved, sustained net emission reductions are provided. This is because the conventional envelope materials do not show a similar payback period because of the lack of active carbon offset mechanisms. On the whole, the table highlights the significance of environmental evaluation that was based on lifecycle in the process of determining the actual level of sustainability performance of building envelope systems.

The significant trade-offs that were identified during the comparative analysis of the building-integrated photovoltaic systems are presented in Figure 4, which focuses on the balance that needs to be attained between the economic, environmental, energy, and comfort-related considerations. The former section points out a trade-off between the economy and the environment, as the initial cost of BIPV modules was higher, but the benefits of using this type of technology are appropriated over time. Though initial expenditure was more than the conventional materials, the long-term energy efficiency and immense carbon emission offsets throughout the building life cycle change the equation towards a better environmental performance and even financial performance. The visualization supports the value of the decision-making process that was lifecycle-oriented and not based on the short-term minimization of costs.

The second one deals with the connection between the energy performance and climate sensitivity. The number indicates that the energy production and other related CO_2 reductions in BIPV systems are extremely reliant on the contextual aspects of the buildings, including building orientation, shading, and solar radiation levels in the regions. Although this sensitivity gives a variability in the performance outcomes, it also indicates the possibility of optimization due to site-specific careful design. The opportunity cost we see here was that the greatest benefits of integrating BIPV can only be achieved at the time when the architectural design and climatic conditions are strongly matched.

The third part was on the compromise between thermal comfort and power production, especially under the use of semi-transparent photovoltaic facades. The number shows that although this kind of system can have a minor effect on natural daylight penetration, it has a positive impact on cooling performance by reducing unnecessary solar heat transfer. It was a compromise between aesthetics and thermal performance, in which moderate losses in the availability of daylight can provide significant savings in cooling energy use, particularly in warm and mixed climates.

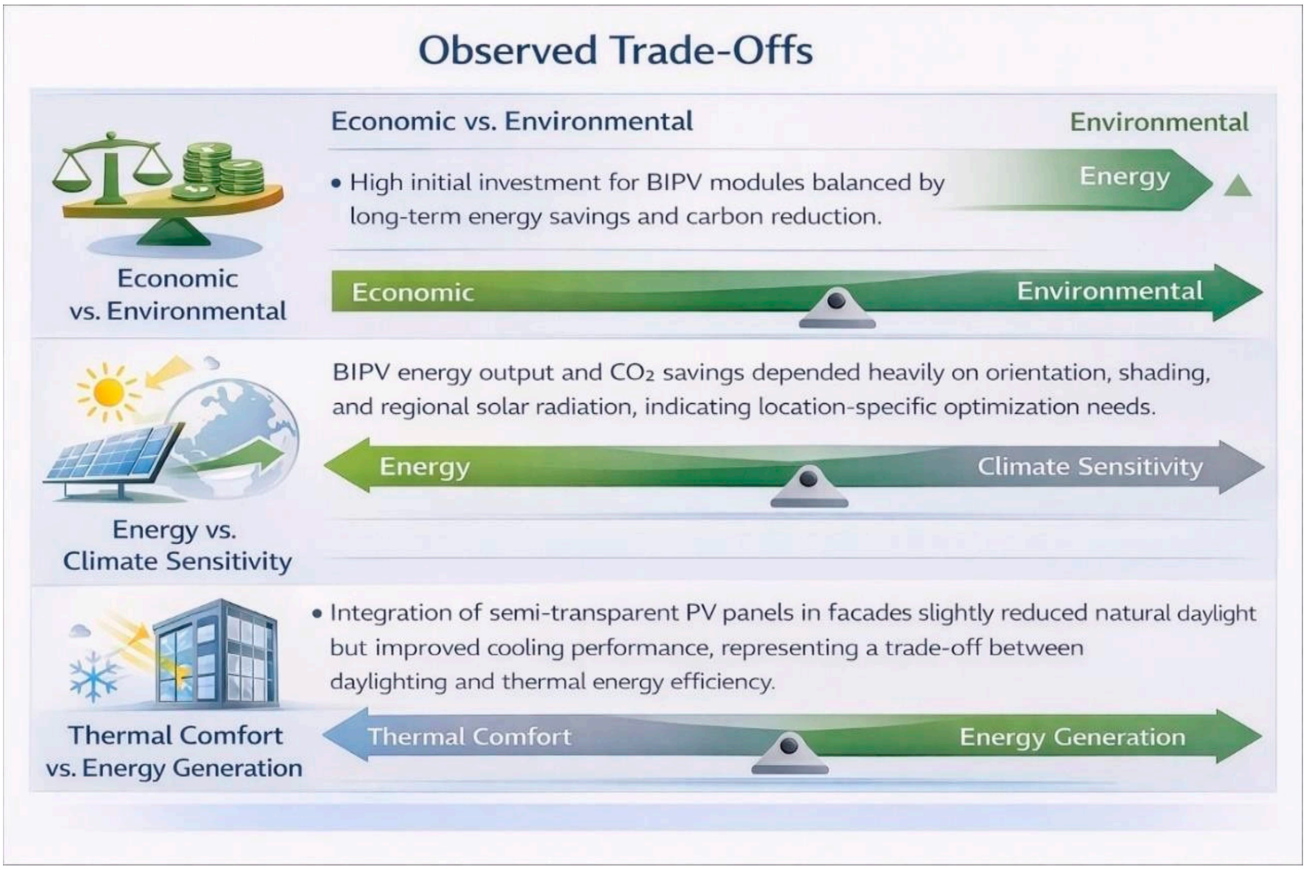

Figure 4. Observed trade-offs in performance dimensions of BIPV systems.

In general, Figure 4 will help to combine these trade-offs to demonstrate that the performance of BIPV systems cannot be assessed in one criterion. Rather, it must have a combined approach that addresses economic investment, environmental gain, climatic sensitivity, and occupant comfort. The visual comparison emphasizes that although BIPV systems add complexity to the design and increase costs, these systems offer multifunctional advantages that support building performance in a more balanced and robust way, provided that the trade-offs are effectively addressed.

Table 5 is an overall comparison of BIPV systems and conventional building envelope materials, whereby energy efficiency, economic feasibility, environmental impact, and functionality role have been recorded together in one evaluation system. Instead of taking the metrics of performance of each of the envelopes separately, the table shows the performance of each envelope system in the presence of several sustainability criteria. This holism was a manifestation of real-world choices in building construction wherein energy, cost, and environmental considerations are balanced to yield long-term performance goals.

Table 5 provides the criterion of energy efficiency that illustrates an evident difference between the two envelope approaches. BIPV systems are categorized as highly energy-efficient systems, as these systems can generate on-site electricity and also support passive thermal management through shading and solar control. Widely used materials, though useful in heat reduction and enhancement of thermal comfort, can only conserve passive energy. Such a difference highlights the benefit of BIPV systems to affect global building energy balance instead of only minimizing energy losses.

Table 5. Multi-criteria performance evaluation summary.

Criterion	BIPV Systems	Conventional Materials	Relative Performance
Energy Efficiency	High	Moderate	BIPV dominant
Economic Viability (Lifecycle)	High	Moderate	BIPV favorable
Environmental Impact	High	Low–Moderate	BIPV superior
Functional Role	Active + Passive	Passive only	BIPV multifunctional
Contribution to Net-Zero Buildings	Strong	Limited	BIPV preferred

The two systems, when considered through the lifecycle perspective of economic viability, further distinguish them. According to Table 5, BIPV systems are highly economically viable on a long-term basis due to energy savings of operation and possible electricity generation revenue. The traditional materials exhibit an average economic performance, most of which was due to the fact that their advantages are limited to the reduction in the initial costs and the certainty of maintenance costs. The comparison underlines the fact that short-term affordability does not always result in long-term financial efficiency when operation energy costs are considered.

The multi-criteria comparison shown in Table 5 was complete with the environmental impact and functional contribution. The high environmental performance of BIPV systems was the result of the long-term decrease in greenhouse gas emissions throughout the life of the building, as opposed to the less than commendable environmental benefits of conventional building materials based on indirect energy savings. BIPV systems can play the active and passive functions of providing structural enclosure and renewable energy, in addition to their functionality. Traditional materials are passive components, the main contribution of which was enclosure performance. Taken altogether, Table 5 illustrates that BIPV systems give a more solid contribution to the aims of sustainable buildings, whereas the conventional materials become more and more complementary in integrated envelope approaches.

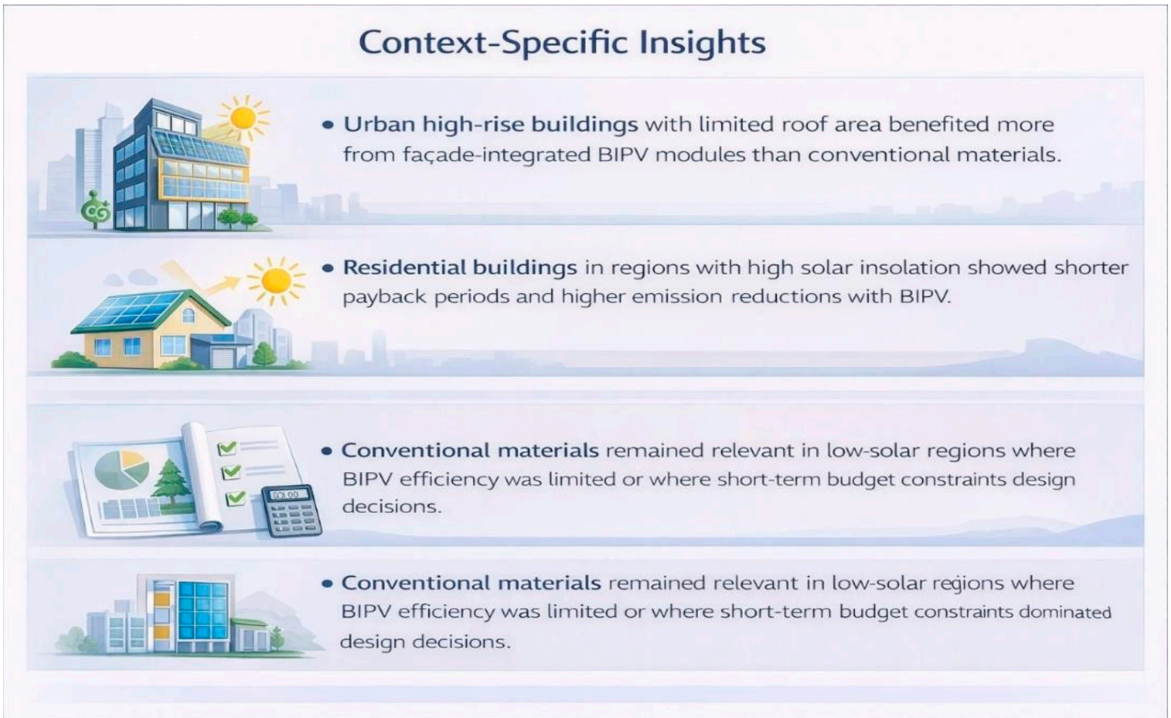

Figure 5. Context-specific performance insights for BIPV and conventional envelope applications.

Figure 5 was a synthesis of context-specific performance results, which shows the impact of the construction of the typology, climatic conditions, and economic limitations on the proportion of the working efficiency of the BIPV systems and the traditional envelope material. The high-rise buildings are brought to the fore in the upper part, with the scarcity of roof space limiting the use of rooftop photovoltaic systems. Prior studies [21,29] found that façade-integrated BIPV systems had greater functional value because these systems utilize vertical surfaces to generate energy, whereas traditional materials were only passively useful in terms of thermal advantages. This graphical data underlines the strategic value of a BIPV integration in a dense city setting based on the facade.

The second section entails residential structures in areas with high solar insulation. That figure shows that these contexts led to the reduced payback time and greater emission reductions in the cases when BIPV systems were used. There was high solar exposure, which increased electricity generation potential; consequently, the initial investment cost was recovered faster, and more carbon was saved through operations. This strengthens the association between the performance efficiency and climatic suitability, as the BIPV systems provide optimal benefits when the solar resources are favorable.

Although commercial and high-rise building applications are the main focus of this review, a subset of residential BIPV studies that satisfy the inclusion criteria (Section 3.2) are discussed here to show how building typology affects comparative performance, in line with the context-specific decision framework created in this study.

The bottom parts of the picture deal with the circumstances in which traditional envelope materials are still useful. Low-solar areas had low photovoltaic efficiency, which curtailed the energy and environmental benefits of BIPV systems. Projects with limited budgets and short timelines often preferred traditional materials because these materials were less expensive initially, and their performance was accurately predictable. These situations indicate that even though BIPV systems have long-term benefits in their functionality, it was appropriate to note that traditional envelopes are still important in cases where integrating photovoltaics was not feasible due to climatic or economic reasons.

In general, Figure 5 shows that the choice of envelope systems was highly dependent on contextual variables, but not on a blanket design strategy. The graphical comparison highlights the need to match envelope strategies and the building's functionality, sun exposure, and cost. The figure will contribute to performance-driven decision-making by pinpointing these context-based understandings that balance energy production, economic suitability, and the environmental effects of various building applications.

Table 6 presents the main trade-offs that have been determined during the comparative analysis of BIPV systems and traditional building envelope materials. It was worth noting that in selecting an envelope, a variety of often conflicting performance dimensions have to be considered. The initial trade-off emphasizes the association between investment in the economy and environmental gain. Photovoltaic integration and the infrastructure related to it make BIPV systems costly in capital terms; nevertheless, their cost was equalized by tremendous energy savings in the long term and remarkable carbon emissions reduction. The table also solidifies the fact that economic feasibility was greater when the analysis was not limited to the immediate cost but the lifecycle energy and the environmental advantages are taken into consideration too.

The second trade-off that was introduced in Table 6 was that of interaction between climate sensitivity and energy performance. The CO_2 elimination potential and the energy output of BIPV systems were demonstrated to be extremely contingent on aspects like building orientation, shading, and regional solar irradiation levels. This sensitivity creates differences in the result of performance, which means that the effectiveness of BIPV was not consistent across all locations. The development of photovoltaic envelope integration needs to be optimized to make the most of the energy and environmental benefits of the placement location. The third trade-off was between thermal comfort and energy production with special applications in semi-transparent photovoltaic facades. Although such systems will help minimize cooling loads by reducing unnecessary solar heat gains, these systems can also cause a slight decrease in the availability of natural daylight in interior spaces. This trade-off underscores the importance of having a balance between visual comfort and quality of daylight and the thermal and energy efficiency goals, particularly in climates where cooling demand prevails in building energy utilization.

Table 6. Observed trade-offs in envelope system selection.

Trade-Off Category	BIPV Systems	Design Implication
Economic vs. Environmental	Higher initial cost but high carbon savings	Lifecycle-based decision required
Energy vs. Climate Sensitivity	Performance varies with solar exposure	Site-specific optimization needed
Thermal Comfort vs. Energy Generation	Reduced daylight with semi-transparent PV	Balance between cooling and daylighting
Cost vs. Long-Term Performance	Higher capital cost	Improved resilience and savings

In general, Table 6 demonstrates that BIPV systems are associated with design challenges, which need combined decision-making efforts, considering economic, environmental, energy, and comfort factors. As opposed to implying some disadvantages, such trade-offs show the multifunctional nature of BIPV systems and the necessity to adopt the holistic evaluation frameworks. These trade-offs have been optimally used to support the conclusion that under project-specific priorities, climatic conditions, and long-term sustainability goals, optimal envelope performance was realized.

Table 7 indicates a context-based analysis that depicts the degree to which the building envelope systems were more or less suitable depending on the type of building, climatic conditions, and cost. The table highlights that the performance of the various envelopes was not consistent in all the situations and that the best selection of the system had a close association with the circumstances. This practice was indicative of the realities of design, in which envelope strategies have to address the particular conditions of the site instead of betting on one common solution.

Table 7. Context-specific performance suitability.

Building Context	Preferred Envelope Strategy	Reason
Urban High-Rise	Façade-integrated BIPV	Limited roof area, high façade potential
Residential (High Solar Regions)	Roof-integrated BIPV	Shorter payback, high emission reduction
Low-Solar Regions	Conventional Materials	Limited PV efficiency
Budget-Constrained Projects	Conventional Materials	Lower upfront cost

According to the table, the preference for BIPV systems installed on the facades was evident in urban high-rise buildings. The small amount of space available in high-density urban centers limited the possibilities of rooftop photovoltaic systems, and the vertical surface of the building became a better option to generate renewable energy. BIPV systems built on facades enabled the use of large surfaces of the building as sources of electricity and still retained the architectural functionality. The traditional envelope materials, which were structurally sound, had low added value in these situations because they were used passively and did not contribute to energy provision at the site.

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Table 7 illustrates that BIPV systems based on roof integration perform well in residential buildings in areas with high insolation rates of the sun. The high level of solar exposure increased the potential of electricity generation with the result of a reduced payback period and increased cumulative emission reduction. Those circumstances enhanced the economic and environmental results, and proved that BIPV systems provided the greatest benefits under the conditions of climatic suitability and system capabilities. Traditional materials were still operable in these environments but were relatively lower with regard to attaining the long-term objectives of energy and sustainability.

The table also shows the instances in which the traditional envelope materials continued to be useful. The efficiency and economic feasibility of the BIPV systems were lower in regions with low amounts of sun availability as well as in projects with short-term budget constraints. In this situation, the traditional materials supplied were cost-effective and predictable in performance in spite of their low contribution to the generation of energy. Altogether, Table 7 highlights the significance of consideration of contexts in choosing an envelope and informs the use of performance-based decision-making to strike a balance between the energy potential, financial viability, and environmental goals in the widest range of building applications.

The performance ranges reported in Tables 2–4 reflect substantial underlying variability in climate zone, building typology, and photovoltaic technology across the 40 studies comprising the evidence base. Studies conducted in hot–arid and high-solar-irradiance climates (e.g., Gulf region, Iran) generally reported values toward the upper end of the energy generation and CO_2 reduction ranges, while studies from temperate or lower-irradiance contexts contributed values toward the lower end. Similarly, studies employing higher-efficiency crystalline silicon modules tended to report higher energy generation than those examining semi-transparent or thin-film technologies, which typically prioritize daylighting or aesthetic integration over maximum energy yield. This contextual variability should be considered when applying the reported ranges to a specific building project, and reinforces the context-specific decision guidance presented in Table 7.

12. Sensitivity Analysis of Comparative Performance Indicators

In order to analyze the robustness of the comparative results above, a sensitivity analysis was carried out on three parameters having the most significant effect on the obtained results: the electricity price, the photovoltaic efficiency, and the weighting factors included in the multi-criteria performance indicator (Equation (12)). The baseline values for these parameters were estimated as the middle values from the range shown in Tables 2–4. One-by-one sensitivity analysis approach, commonly used in building performance evaluation, was employed in the study.

12.1. Sensitivity to Electricity Tariff

Table 8 presents the effect of a ±20% variation in electricity tariff on the payback period (Equation (6)) and cost–benefit ratio (Equation (7)) of BIPV systems.

Table 8. Sensitivity of economic indicators to electricity tariff variation.

Scenario	Electricity Tariff ($/kWh)	Annual Savings ($/m^2/yr)	Payback Period (Years)	Cost–Benefit Ratio
−20% Tariff	0.074	12.63	11.9	1.08
Baseline	0.093	15.79	9.5	1.35
+20% Tariff	0.112	18.96	7.9	1.62

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As shown in Table 8, for a 20% reduction in electricity tariff, the payback time is increased to 11.9 years from a base value of 9.5 years, whereas a 20% rise brings it down to 7.9 years. Both these figures fall within the earlier estimated payback range of 7–12 years (Table 3). This is because the baseline figure was not a result of a unique tariff situation but has a broader context. It is important to note that, in all cases, the benefit–cost ratio exceeds the breakeven point of 1.0, which means that at even less favorable tariff conditions, BIPVs continue to be more economical than the traditional envelope materials.

12.2. Sensitivity to Photovoltaic Conversion Efficiency

Table 9 presents the effect of a $\pm$ 10% variation in photovoltaic conversion efficiency on annual energy generation (Equation (1)) and annual CO_2 emission reduction (Equation (8)).

Table 9. Sensitivity of energy and environmental indicators to PV efficiency variation.

Scenario	Relative Efficiency	Annual Energy Generation (kWh/m^2/yr)	Annual CO_2 Reduction (kg/m^2/yr)
−10% Efficiency	0.90 × baseline	153	19.4
Baseline	1.00 × baseline	170	21.5
+10% Efficiency	1.10 × baseline	187	23.7

As shown in Table 9, both the generation of energy and the emission of CO_2 are within the range initially given (120–220 kWh/m^2/year and 18–25 kg CO_2/m^2/year, respectively; Tables 2 and 4). Thus, one can conclude that the energy/environmental advantage of BIPV systems is not very dependent on the variation of the efficiency of the modules used, which means that the given range is quite representative and general.

12.3. Sensitivity to Multi-Criteria Weighting Coefficients

Table 10 presents the effect of reallocating the weighting coefficients (w_E, w_C, w_En) in the performance index (Equation (12)) by $\pm$0.10 around an equal-weight baseline, using normalized criterion scores derived from the qualitative ratings in Table 5 (Energy Efficiency, Economic Viability, Environmental Impact).

Table 10. Sensitivity of overall performance index ranking to weighting coefficient variation.

Weighting Scenario	w_E	w_C	w_En	PI—BIPV Systems	PI—Conventional Materials	Ranking Outcome
Equal weighting (baseline)	0.34	0.33	0.33	0.834	0.4	BIPV > Conventional
Energy-emphasized	0.44	0.28	0.28	0.836	0.4	BIPV > Conventional
Economic-emphasized	0.28	0.44	0.28	0.828	0.408	BIPV > Conventional
Environmental-emphasized	0.28	0.28	0.44	0.836	0.392	BIPV > Conventional

As shown in Table 10, the performance index of BIPV systems (0.828–0.836) remains substantially higher than that of conventional envelope materials (0.392–0.408) across all four weighting configurations tested. Critically, the relative ranking between the two envelope strategies does not reverse under any tested weighting scenario, indicating that the overall comparative conclusion of this study is not an artifact of the specific weighting assumptions adopted, but instead reflects a consistent performance advantage across plausible prioritization schemes.

12.4. Summary of Sensitivity Findings

Table 11 consolidates the outcomes of the three sensitivity tests, indicating the range of variation observed in each output indicator relative to its originally reported baseline range.

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Table 11. Summary of sensitivity analysis outcomes.

Parameter Varied	Range Tested	Output Indicator(s) Affected	Output Range Under Sensitivity Test	Within Originally Reported Range?
Electricity tariff	±20%	Payback period; cost–benefit ratio	7.9–11.9 yr; CBR 1.08–1.62	Yes
PV conversion efficiency	±10%	Annual energy generation; CO_2 reduction	153–187 kWh/m^2/yr; 19.4–23.7 kg/m^2/yr	Yes
Weighting coefficients	±0.10	Overall performance index (PI)	BIPV 0.828–0.836; Conventional 0.392–0.408	Ranking unchanged

Taking everything into account together, the sensitivity analysis reveals that the outperformance advantage of BIPV systems compared to conventional envelope systems from the energy, economy, and environment points of view still stands up well even when different assumptions about the tariff structure, efficiency of the system, and weights are made. While the level of economic outperformance is lower in case of less favorable tariff regime conditions, the positive finding is consistent under all such scenarios, thus confirming the appropriateness of the comparative framework developed in this research paper.

13. Conclusions

It is vital to emphasize once again that the value of the present research is the synthesis and decision support framework created in the course of the paper, and not the collection of new empirical and/or laboratory data. In consolidating and standardizing the performance metrics taken from the existing literature on BIPV systems into one multicriteria framework, the authors aim at closing the methodological gap as opposed to the data gap: previous studies used to examine the energy performance, economic performance, or environmental performance of BIPV systems separately, or in combination, without a specific comparison with the conventional building envelope materials. The present framework with the normalized performance index and the decision tables tailored to the specific contexts is meant to serve as a working tool for further research on the subject and is to be used and perfected based on the case-specific or site-specific data in future studies.

This paper provided an overall comparative analysis of the building-integrated photovoltaic systems and traditional building envelope materials through the performance analyses of the materials in terms of energy, economic, and environmental aspects. The discussion has shown that the insertion of photovoltaic technology in the building envelope converts the traditionally passive elements into active systems with the capability of producing renewable energy and at the same time performing the roles of structure and architecture. The performance of this multifunctional role made a significant improvement to the overall building performance as compared with the conventional envelope solutions, which majorly depend on the passive thermal regulation.

The energy performance analysis revealed that BIPV systems made significant contributions towards the reduction in energy demand in buildings by generating electricity on-site and other advantages that BIPV systems come with, including shading and control of solar heat gain. Although the traditional envelope materials worked well in mitigating heat loss and enhancing thermal comfort, these materials failed to produce energy, which constrained their overall impact on the total energy consumption of buildings. Normalized comparisons have demonstrated the high ratio of energy that was brought by BIPV systems, especially in buildings where there was a high level of operation energy and a good exposure to sunshine.

On the economic front, the lifecycle-based analysis showed that, in spite of the higher initial investments made on the systems, the economic viability of the BIPV systems was better, as there were long-term economic savings and less reliance on grid power during the building service life. Traditional envelope materials remained competitive because of their lower initial costs; their inability to provide energy-related financial savings results in higher cumulative costs over the long term. These results highlighted the need to utilize the lifecycle cost analysis as opposed to the short-term cost analysis in the analysis of envelope system options.

The environmental evaluation also revealed that the BIPV systems achieved significant reductions in greenhouse gas emissions by offsetting electricity production from the power grid. Although there were more carbon impacts during the manufacturing and installation stage, the carbon savings in the long-term operations offset such initial effects, resulting in net-positive environmental performance throughout its lifecycle. In sum, the multi-criteria assessment indicates that, based on the reviewed literature, BIPV systems generally demonstrate favorable comparative performance relative to traditional envelope materials across energy, economic, and environmental dimensions, although this advantage varies with climatic context, building typology, and underlying economic assumptions, as discussed in the sensitivity analysis and Methodological Limitations. These findings suggest that BIPV systems represent a promising and, in many contexts, preferable solution for the further development of sustainable and energy-resilient building design, while recognizing that conventional envelope materials remain a suitable choice under specific climatic, technological, and budgetary constraints, as outlined in Table 7.

Recommendations:

For practitioners and architects: In the case of tall buildings with limited roof areas, BIPV integrated into the façade system is more preferable compared to rooftop systems as they make the maximum use of the available surfaces for energy production. In the case of high solar residential and low-rise buildings, rooftop BIPV systems are more beneficial in terms of having a short payback period and low emissions. If daylighting is of concern, semi-transparent PV glazing may be a good option to balance lighting and cooling requirements. In all cases, decisions about the building envelope should be made considering lifetime cost and carbon implications instead of capital cost only.

For policymakers: In light of the high initial cost of BIPV, it would be necessary to introduce some financial incentives (subsidies, tax credits, special financing) that will ease the process of adoption. Building codes and green rating systems should include provisions about structural properties of BIPV, and mandatory reporting of embodied energy and carbon of BIPV should be introduced to facilitate comparability across studies.

For future research: Future research should focus on collecting primary data related to various parameters discussed to validate ranges from literature cited herein, using standardized reporting procedures across climatic regions and building types, and developing weightings based on the application of a decision-making tool like the Analytic Hierarchy Process (AHP). This method can be extended to residential, institutional, and mixed-use building types across different climate zones.

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Appendix A

Table A1. Data provenance for quantitative performance indicators reported in Figures 3–5 and Tables 2–4.

Indicator	Reported Range/Value	Applies To	Source Reference(s)	Aggregation Note
Annual Energy Generation (kWh/m^2/yr)	120–220	BIPV	[3,7,11,33]	Min–max across reviewed case studies
Annual Energy Generation (kWh/m^2/yr)	0	Conventional	[2,16]	No direct generation reported
Cooling Load Reduction (%)	8–15	BIPV	[3,29,37]	Min–max across reviewed case studies
Cooling Load Reduction (%)	0–5	Conventional	[2,26]	Attributed to insulation/thermal mass only
Grid Electricity Reduction (%)	20–30	BIPV	[4,19]	Min–max across reviewed case studies
Grid Electricity Reduction (%)	5–10	Conventional	[2,16]	Attributed to passive thermal performance
Total Energy Savings (%)	20–25	BIPV	[10,14]	Min–max across reviewed case studies
Total Energy Savings (%)	5–7	Conventional	[2,26]	Attributed to insulation improvements
Initial Investment ($/m^2)	140–160	BIPV	[6,8,40]	Min–max across reviewed case studies
Initial Investment ($/m^2)	70–90	Conventional	[2]	Min–max across reviewed case studies
Lifecycle Cost, 25 yr ($/m^2)	120–180	BIPV	[6,32]	Discounted cost accumulation, Equation (4) basis
Lifecycle Cost, 25 yr ($/m^2)	140–200	Conventional	[16,26]	Discounted cost accumulation, Equation (4) basis
Payback Period (years)	7–12	BIPV	[4,8,40]	Min–max across reviewed case studies
Payback Period (years)	Not applicable	Conventional	—	No direct energy revenue generated
Cost–Benefit Ratio	1.25–1.45	BIPV	[6,23]	Derived per Equation (7) from underlying cost/savings data

Table A1. *Cont.*

Indicator	Reported Range/Value	Applies To	Source Reference(s)	Aggregation Note
Cost–Benefit Ratio	<1.0	Conventional	[16,26]	Derived per Equation (7) from underlying cost/savings data
Annual CO_2 Reduction ($kg/m^2/yr$)	18–25	BIPV	[9,15,35]	Min–max across reviewed case studies
Annual CO_2 Reduction ($kg/m^2/yr$)	3–5	Conventional	[2]	Indirect, via reduced energy demand
Embodied Energy (GJ/m^2)	3.0–3.5	BIPV	[1,15,34]	Manufacturing + installation phase only
Embodied Energy (GJ/m^2)	1.8–2.2	Conventional	[2,16]	Manufacturing + installation phase only
Embodied Emissions ($kg\ CO_2/m^2$)	~200	BIPV	[1,24]	Single representative value, not a reported range
Embodied Emissions ($kg\ CO_2/m^2$)	~150	Conventional	[2]	Single representative value, not a reported range
Carbon Payback Period (years)	5–7	BIPV	[9,24]	Derived per Equation (10) from embodied/operational data
Carbon Payback Period (years)	Not applicable	Conventional	—	No active carbon offset mechanism
Cumulative CO_2 Savings, 25 yr (kg/m^2)	450–600	BIPV	[15,35]	Min–max across reviewed case studies
Cumulative CO_2 Savings, 25 yr (kg/m^2)	<100	Conventional	[2]	Indirect savings only

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