RESEARCH ARTICLE

Photovoltaic Integration for Zero Energy Buildings and Architectural Aesthetic Value: A Review

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ABSTRACT

Photovoltaic (PV) integration in architectural design has become pivotal in achieving Zero Energy Buildings (ZEBs) while maintaining aesthetic appeal. This review explores the intersection of PV technology and architectural aesthetics, focusing on advancements, challenges and opportunities. The use of Photovoltaic components in building construction is crucial for achieving ZEB status, which is the onsite generation of a building's annual energy need through a renewable source. PV technology has evolved significantly, moving beyond traditional rooftop installations to incorporate innovative solutions such as Building-Integrated Photovoltaics (BIPV). BIPV seamlessly integrates PV elements into building materials like windows, facades and roofs, thereby enhancing both energy efficiency and visual appeal. Design considerations encompass aspects such as colour, texture, transparency and pattern, which ensure that PV elements harmonize with overall building aesthetics. This study presents the outcome of the review of 28 peer-reviewed journal articles published between 2020 and 2024. Case studies and best practices from around the globe were also used to illustrate successful implementations of PV integration in architectural projects. These examples highlight diverse approaches to balancing energy performance with aesthetic values across different building types and climates. Looking forward, future research directions include enhancing the performance and lifespan of PV materials, integrating smart technologies for optimal energy management and developing standards and guidelines for PV-integrated architectural design. Such advancements will drive the mainstream adoption of ZEBs while enhancing their architectural appeal. In conclusion, PV integration for ZEBs represents a dynamic field where technological innovation intersects with architectural creativity in the development of sustainable buildings that embody both energy efficiency and aesthetic excellence.

Keywords: Architectural aesthetics, Building Integrated Photovoltaics, BIPV, Zero energy, Buildings, ZEB

1.0 Introduction

The significance of Zero Energy Buildings (ZEBs) in lowering carbon emissions and achieving energy independence has been central to built-environment research amidst the growing global awareness of climate change and sustainable building and resource management (Feng et al., 2020). ZEBs are buildings that generate on-site energy that is adequate to meet the building's annual energy need using renewable energy resources, among which is photovoltaic (solar) energy. In the last two decades, photovoltaics (PV) has been a key component of such energy balance. PV systems have always been largely focused on the practicability of energy generation rather than architectural aesthetics, a situation that raises concerns about the architectural value of such buildings. However, owing to technological developments such as Building Integrated Photovoltaics (BIPV), there has been a noticeable significant positive change in the architecture community toward achieving a balance between energy efficiency and aesthetics in buildings.

To contribute to this growing literature, therefore, this work investigates the architectural integration of PV technology into ZEBs with a view to achieving a balance of the technical demands of energy generation with aesthetic and visual appeal. With an emphasis on how developments in materials and design can support architects' aesthetic visions while satisfying energy requirements, the study examines case studies, best practices, obstacles and possible future paths for PV integration in ZEBs. The building industry is responsible for about 40% of global energy consumption (Azami & Sevinc, 2021) and levels of carbon emissions are crucial to reaching sustainability targets in growing global efforts to improve the environment (Saini et al., 2021). Zero Energy Buildings (ZEBs), which typically deploy renewable technology on site to generate a building's annual energy need, have become a key component of sustainable building construction.

The incorporation of renewable energy sources, particularly photovoltaics (PV), which harvest solar energy and transform it into usable power, is essential to ZEB design (Aguacil et al., 2024). PV systems are usually installed as separate rooftop installations in older ZEBs, frequently with little regard for architectural aesthetics. However, new opportunities for smooth PV integration into the very fabric of building designs have been brought about by developments in Building-Integrated Photovoltaics (BIPV). In Building integrated Photovoltaics, PV components can be used, like traditional building materials, for windows, roofs and facades, leading to the simultaneous achievement of structural beauty and energy efficiency (Chandrasekar, 2023).

This review aims to examine the current state of PV integration in ZEBs from an architectural perspective. By exploring recent advancements, aesthetic considerations and technical challenges, this research seeks to provide insights into how PV technology can improve the aesthetic value of buildings while fulfilling energy requirements. The review also includes global case studies to illustrate how PV-integrated ZEBs are being realized across different climates and cultural contexts.

2.0 Literature Review

2.1 History and Development of Photovoltaic (PV) Technology

The origins of photovoltaic technology date back to the discovery of the photovoltaic effect by Edmond Becquerel in 1839 (Lincot, 2017). However, practical applications only emerged in the 20th century with the advent of silicon-based solar cells in the 1950s. Initially developed for space applications, PV technology began to penetrate terrestrial markets in the 1970s, although its adoption remained limited due to high costs and relatively low efficiency.

The use of photovoltaics in buildings has transformed significantly since its early days. Traditional PV installations typically consisted of solar panels mounted on rooftops with little regard for visual impact. However, recent technological advancements have led to the development of BIPV systems that allow PV elements to be incorporated directly into building components such as windows, facades and roofs, offering both functionality and aesthetic flexibility. BIPV advancements include thin-film, dye-sensitized, and perovskite-based solar cells, which provide increased design versatility and adaptability to various architectural forms (Debayan & Sadhu, 2020).

Over the past two decades, PV technology has evolved dramatically, moving beyond traditional rooftop panels to include more innovative solutions like BIPV, which represents a paradigm shift. BIPV enables PV materials to become part of the building envelope itself, thereby enhancing both energy generation and aesthetic integration. Thin-film and organic solar cells have further expanded the design potential for PV integration, as these materials offer greater flexibility and can be adapted to various surfaces and shapes.

2.2 Zero Energy Building Concept

A Zero Energy Building is defined as a building that achieves a net-zero energy balance by producing its annual energy need onsite via renewable energy technology. ZEBs are designed with a combination of passive and active strategies aimed at reducing energy consumption, including high-performance insulation, day lighting, and efficient heating, ventilation, and air conditioning (HVAC) systems. For the remaining energy demand, ZEBs rely on on-site renewable energy sources, particularly PV systems, to meet consumption needs and balance the energy equation.

The concept of ZEBs is embedded in various national and international policies aimed at reducing carbon footprints. The European Union's Energy Performance of Buildings Directive (EPBD) mandates that "all new buildings must be nearly zero-energy buildings by 2021" (Ma et al., 2024). Similar directives exist in the United States, with organizations such as the U.S. Department of Energy promoting ZEB initiatives (Peng et al., 2015).These regulations drive the adoption of PV technology in building design and underscore the importance of harmonizing energy generation with aesthetic considerations (Owen et al., 2014).

2.3 BIPV and ZEB Synergy

The integration of BIPV into ZEBs makes for natural synergy, as both concepts align in their aim to create energy-efficient and sustainable buildings. BIPV systems can be harmonized with ZEB standards through their integration into the building envelope. This synergy is essential for achieving ZEB targets, as BIPV elements can substitute for traditional building materials such as glass and façade cladding, thus contributing to energy generation, insulation and aesthetic appeal (Hamzah & Go, 2023). The architectural potential of BIPV is critical in modern ZEB designs, which must balance technical performance with the aesthetic and functional demands of architectural design. By integrating PV modules into the building envelope, architects can maximize surface area for solar generation without compromising the visual or functional aspects of the building's design.

2.4 Architectural Aesthetic Considerations in PV Integration

2.4.1 Visual Appeal of PV Systems

One of the primary considerations in PV integration is ensuring that the visual impact aligns with the architectural vision of the building. Traditional PV panels are often criticized for their utilitarian appearance, which can detract from the overall aesthetic. With BIPV, architects have a wider array of design choices that include colour customization, transparency options and modular flexibility. These elements allow PV systems to be woven seamlessly into the building's design, thereby enhancing rather than detracting from its visual appeal.

Semi-transparent PV glass can be used in windows or curtain walls, providing daylight penetration and visual connectivity with the outdoor environment while generating electricity. (Wijeratne et. al., 2022) The inclusion of patterned PV modules allows for creative design choices that align with architectural intentions, such as creating unique visual motifs on facades. Many architects are now exploring how PV can enhance a building's visual identity by integrating coloured, patterned, or semi-transparent PV elements, which can make a building visually distinctive while serving functional purposes.

2.4.2 Aesthetic-Functional Balance

The aesthetics of PV materials should not compromise a building's energy efficiency, as achieving a balance between form and function is critical. Advances in PV technology have been aiding architects to achieve this balance, given the availability of materials that are both high-efficiency and customizable in design.

Achieving a balance between form and function is essential in PV-integrated architecture, particularly in urban settings where buildings often need to meet strict aesthetic standards despite space constraints. This balance becomes crucial when integrating PV systems into highly visible parts of a building, especially the facade. While efficiency is a key consideration, architects and designers are increasingly prioritizing the visual coherence of PV elements with the overall architectural language of the structure.

Recent developments in PV material science have led to innovations that support this balance, including colour-tunable and pattern-customizable solar cells. These advancements ensure that PV elements do not stand out as purely functional components but contribute harmoniously to the building's aesthetic narrative (Peng et al., 2015).

2.4.3 Influence of Cultural and Regional Factors

Architectural aesthetics are deeply influenced by cultural and regional factors, which impact how PV systems are accepted and integrated into building designs. In some regions, particularly those with historic architectural styles, PV integration requires a more sensitive approach to preserve cultural heritage while embracing sustainability. The architectural aesthetic of PV-integrated ZEBs must adapt to these regional nuances to ensure cultural acceptance and appeal. In European cities with historic districts, BIPV solutions may be designed to mimic traditional building materials such as clay tiles or stone, blending with the historical context. In contrast, in modern urban centres like Tokyo or New York, PV-integrated skyscrapers might emphasize futuristic aesthetics, using sleek and reflective PV glass to convey modernity and innovation (Awuku et al., 2021).

2.5 Advancements in PV Technology for Aesthetic Integration

2.5.1 Thin-Film Solar Cells

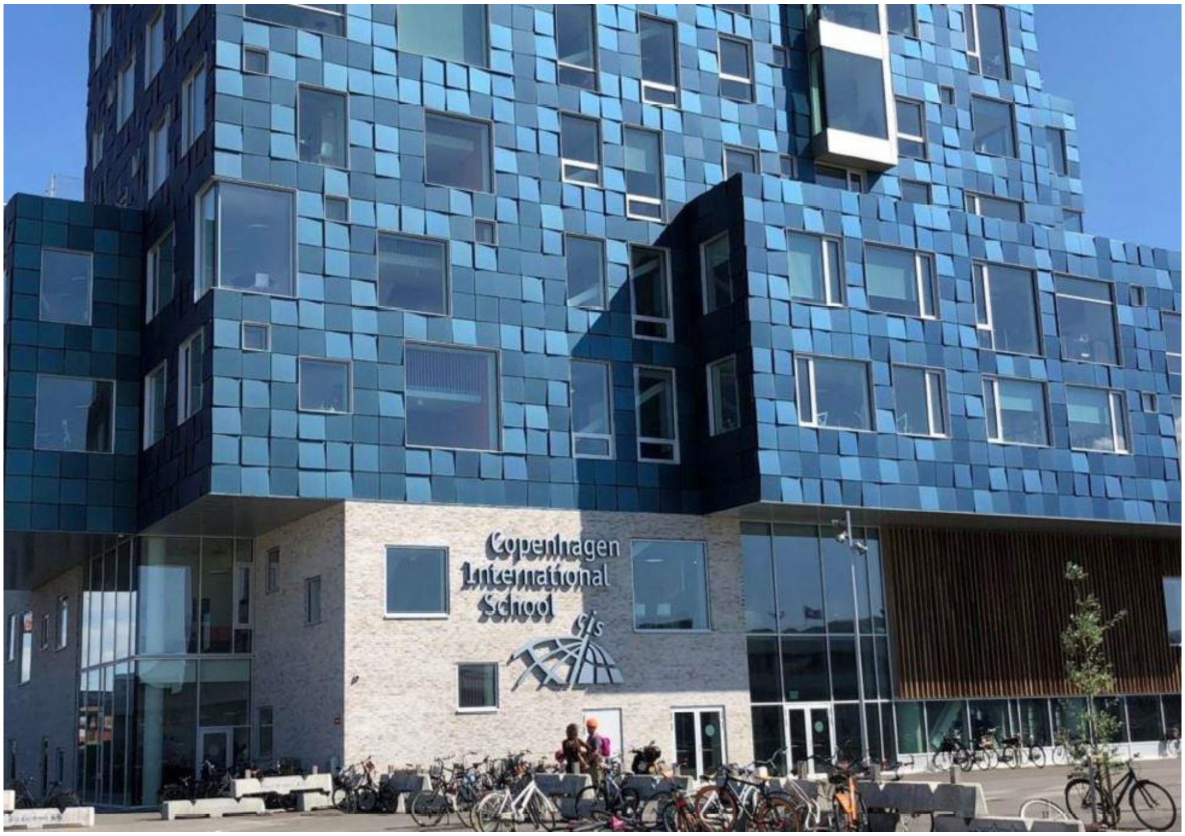
Thin-film solar cells, which include materials like amorphous silicon and cadmium telluride, have revolutionized PV integration by offering increased flexibility and adaptability in design (Jahan et al., 2024). Unlike traditional crystalline silicon panels, thin-film cells can be manufactured on flexible substrates, making them suitable for curved or irregular surfaces (Jahan et al., 2024).

This flexibility allows architects to incorporate PV elements into more complex building geometries, providing a sleek and continuous aesthetic. Thin-film PV cells offer flexibility in design and installation, as they can be manufactured in various shapes and sizes. They are particularly suited for curved surfaces and non-standard architectural forms, enabling seamless integration into a building's envelope. This adaptability is a considerable advantage in architectural aesthetics, as it allows PV systems to follow the design lines of a building without compromising energy efficiency.

2.5.2 Transparent and Semi-Transparent PV Modules

Transparent PV technology, such as organic photovoltaic (OPV) cells and dye-sensitized cells, allows for a high degree of light transmission, making it ideal for applications like windows and skylights (Shi et al., 2024). Semi-transparent PV modules provide the dual benefits of reducing solar gain while generating electricity, thereby enhancing a building's energy efficiency without sacrificing natural lighting.

In Denmark, the Copenhagen International School uses over 12,000 custom-made, blue-tinted solar panels to clad its facade, providing a semi-transparent design that enhances both aesthetics and energy performance. This approach exemplifies how PV can be integrated into a building's design in a way that complements the architectural vision (Copenhagen international school, 2022).



Picture showing the front view of the Copenhagen international school, Copenhagen, Denmark

Source: Copenhagen International School, 2022

Transparent PV modules, including organic and dye-sensitized cells, allow light transmission and are ideal for window applications. Semi-transparent modules can reduce solar gain while generating electricity, making them suitable for façades. Such advancements have significantly widened the design possibilities for PV integration without obstructing natural lighting, thus maintaining both aesthetic and functional qualities.

2.5.3 Colour and Pattern Customization in PV Cells

The development of colour-tunable and patterned PV cells offers architects the ability to match PV elements with the building's design language. Nano-coating techniques and colourization processes have enabled PV modules to be manufactured in various colours without significantly compromising efficiency (Lee et al., 2022).This innovation allows architects to create visually cohesive PV facades that align with the building's exterior colour scheme or pattern.

These panels can be produced in custom colours and patterns, allowing buildings to maintain their unique aesthetic character while achieving ZEB standards. Customizable colours and patterns enable PV cells to be tailored to meet specific architectural visions. Accordingly, researchers have been exploring colourization techniques that do not significantly impact efficiency, such as nano-coating and light-absorbing dyes. These innovations offer architects greater flexibility to incorporate PV in ways that align with the building's intended aesthetic and visual identity.

2.6. Challenges in Photovoltaic Integration for ZEBs

2.6.1 Economic Constraints

The integration of PV technology, particularly BIPV, in ZEBs often presents economic challenges. Traditional rooftop PV installations are increasingly affordable, with costs having significantly declined in recent years owing to economies of scale and technological advancements. However, BIPV systems remain more costly because of specialized manufacturing processes, customizations and installation requirements. Cost-effective solutions are needed to increase the adoption of aesthetically integrated PV (Corti et al., 2024).

One key factor affecting cost is the use of photovoltaic materials with conventional building components, such as glass or façade cladding, which requires additional labour and materials. According to recent market analyses, BIPV can cost substantially more than conventional building materials (Corti et al., 2024).Government incentives and subsidies, as well as the potential for long-term energy savings, can help offset these initial costs, but they remain a limiting factor to widespread adoption, notably in developing regions where costs are a primary concern.

Efforts to reduce costs include advances in PV manufacturing, such as roll-to-roll processing for flexible PV films and scalable production of transparent PV cells. These innovations are expected to lower the cost of PV materials over the next decade, making BIPV more accessible for broader applications.

2.6.2 Technical and Efficiency Issues

Technical limitations in BIPV technology pose another significant challenge. PV cells integrated into building facades or other less optimal surfaces may not achieve the same efficiency as conventional rooftop installations, as they are often limited by orientation, shading and temperature fluctuations (Yadav & Panda, 2020).For instance, building facades may receive inconsistent sunlight throughout the day, leading to a reduction of their potential energy generation compared to roof-mounted panels.

In addition, the efficiency of PV elements can be affected by design choices. For example, coloured or patterned PV panels may have slightly lower efficiency due to light absorption techniques that prioritize visual aesthetics over maximum energy capture. While high-efficiency materials like perovskite solar cells and multi-junction cells may offer potential solutions to address these efficiency concerns, there is need for further research and testing to ensure long-term durability and performance (Larini et al., 2023).

To address efficiency issues, architects and engineers have also been exploring hybrid PV systems that combine multiple types of PV technologies within a single building. For example, crystalline silicon panels might be installed on roof surfaces for maximum energy capture, while semi-transparent or thin-film photovoltaic cells are used in windows and facades. This approach optimizes energy generation across the building envelope without compromising aesthetic goals.

2.6.3 Regulatory and Standardization Hurdles

The regulatory environment for BIPV remains complex, as many countries have yet to fully establish standards and guidelines for integrating PV into building designs. Existing building codes and zoning regulations, especially in historic areas, may restrict the placement and appearance of PV systems, thus limiting opportunities for architects to implement innovative designs (Wilberforce et al., 2023).

Standardization is essential to ensure the safety, durability and efficiency of PV-integrated buildings. For instance, BIPV materials must meet stringent fire resistance and structural integrity standards while maintaining energy generation capabilities. Local governments and industry bodies are beginning to address these regulatory challenges by developing specific codes and standards for PV-integrated buildings. For example, the European Committee for Standardization (CEN) is working on harmonizing BIPV standards across the European Union, which is expected to streamline the approval process and facilitate broader adoption of BIPV in architectural projects (CEN, 2024).

2.7 Global Case Studies on PV-Integrated ZEBs

This section will analyse case studies from Europe, North America, and Asia, examining how different architectural approaches and climates impact PV integration. Key case studies will include buildings known for their innovation in BIPV, such as the SwissTech Convention Centre in Switzerland, the BIQ House in Germany, and the Solar Decathlon homes. Each case will highlight strategies for harmonizing aesthetics with energy performance in distinct climates and cultural contexts.

2.7.1 Case Study 1: SwissTech Convention Centre, Switzerland

The SwissTech Convention Center at the École Polytechnique Fédérale de Lausanne (EPFL) is a pioneering example of PV integration in an iconic building design. The building features a large BIPV array that is seamlessly integrated into its facade, demonstrating how PV can be used to enhance architectural aesthetics. The BIPV elements are composed of semi-transparent, coloured PV cells that align with the building's curvilinear design, creating a visually dynamic facade that also generates electricity for the building's operations.

Approach view of the SwissTech Convention Centre, Ecublens, Switzerland

Source: Swisstech Convention Centre, 2024

The Centre's BIPV facade produces approximately 300,000 kWh annually, contributing significantly to the building's energy needs while reducing its carbon footprint. This case exemplifies how advanced PV technology can support energy efficiency goals without compromising design innovation.

2.7.2 Case Study 2: BIQ House, Germany

The BIQ House in Hamburg, Germany combines PV technology with an algae-based bio-energy system to achieve ZEB standards. Its unique facade features semi-transparent PV modules that harmonize with the building's algae bio-film panels, allowing natural light to penetrate while generating solar power. The algae panels contribute to the building's insulation and reduce overall energy demand by providing passive shading, while the PV modules enhance energy self-sufficiency.

The Bio Intelligent Quotient Building in Hamburg, Germany

Source: WTWH Media, 2024

The BIQ House illustrates how PV can be integrated with other renewable technologies to achieve two purposes: first is optimization of energy generation and, second is maximisation of every form of aesthetic appeal. By combining PV with bio-energy, the building achieves a sustainable and visually cohesive design that supports ZEB principles.

2.7.3 Case Study 3: Copenhagen International School, Denmark

The Copenhagen International School uses a striking BIPV facade composed of over 12,000 custom-coloured PV panels. Each panel is a unique shade of blue, creating a gradient effect across the building's exterior. The BIPV facade generates approximately 300 MW/h of electricity annually, covering a significant portion of the school's energy needs.

Picture showing a view from the playing grounds at the Copenhagen International School, Copenhagen, Denmark

Source: Copenhagen International School, 2022

This project demonstrates the potential for colour customization in PV cells, allowing architects to achieve visually appealing designs while meeting ZEB requirements. The building's colourful facade has become an iconic feature of Copenhagen's skyline, illustrating how BIPV can enhance both energy performance and urban aesthetics (Copenhagen International School, 2022).

2.7.4. Case Study 4: The Sterling Bank Headquarters, Lagos, Nigeria

Although architectural practices in Nigeria may be considered to be fully abreast of the state-of-the-art in BIPV, there seems to be a near complete absence of the technology's adoption in the completed projects being churned out across the country. The Sterling Bank Headquarters in Lagos was about the only building that came up when a BIPV search was conducted on the Internet as at October 31, 2024. The building, which was designed by FMA Architects – with construction completed in the 1980's (British Council, 2016) – was recently retrofitted with a 3,250-panel (6500m2) 1 Megawatts photovoltaic façade by Architects TLL Consult and Onyx Solar Limited, setting a record as the largest BIPV project in Africa (Onyxsolar, 2023). It is therefore necessary to understand why Nigerian architects seem to be uninterested in deploying the technology in their projects.

Sterling Bank Headquarters, Lagos, Nigeria

Source: Onyxsolar, 2023

Nigerian university campus buildings are largely powered either by electricity from the national grid or individual off-grid solutions. It is common place to find petrol- or diesel-powered electricity generators being used to provide electricity for campus buildings in Nigeria as a substitute to the erratic supply from the grid.

2.8 Lessons Learned from Case Studies

These case studies highlight diverse approaches to balancing energy performance with aesthetic considerations in PV-integrated ZEBs. Key insights from these projects include the importance of customizing PV materials to align with architectural goals, using hybrid renewable systems to optimize efficiency and prioritizing modular designs that adapt to building geometries. Each project underscores the value of BIPV in creating sustainable buildings that are both functionally and visually inspiring.

2.9 Technological Innovations in PV Materials

The future of PV integration in ZEBs will be shaped by ongoing advancements in PV materials and manufacturing techniques. Emerging technologies like perovskite solar cells offer promising efficiency rates and cost advantages, although their durability and long-term stability need further improvement. Organic photovoltaic (OPV) cells are another area of interest due to their flexibility, lightweight characteristics and potential for transparency, making them ideal for window applications.

Nanotechnology also holds potential for enhancing PV efficiency and customization. By manipulating PV materials at the nanoscale, researchers aim to improve light absorption and energy conversion rates while enabling unique colour and transparency features. These advancements could result in PV modules that are nearly indistinguishable from traditional building materials, paving the way for more widespread PV adoption in architectural design.

2.10 Smart Energy Management in PV-Integrated Buildings

The integration of IoT devices and smart energy management systems in ZEBs can optimize the efficiency of PV systems by enabling real-time monitoring of energy production and consumption. Smart systems can dynamically adjust building systems, such as lighting and HVAC, based on energy availability from PV systems, ensuring optimal energy use and reducing reliance on external power sources.

For example, "smart windows" with integrated PV cells can adjust their opacity based on sunlight levels, balancing day lighting needs with energy generation. These innovations can enhance the functionality and efficiency of ZEBs, allowing buildings to operate more autonomously and sustainably.

2.11 Sustainable Manufacturing and Recycling of PV Materials

As PV adoption grows, attention is increasingly being focused on the environmental impact of PV manufacturing and disposal. The production of PV cells, especially silicon-based cells, requires significant energy and resource inputs. Sustainable manufacturing processes, such as those that reduce water and chemical usage, are essential to minimize the environmental footprint of PV materials.

Recycling PV cells at the end of their life cycle is another critical issue. Currently, PV recycling infrastructure is limited, with many PV modules ending up in landfills in a scenario that raises concerns about resource waste and environmental harm. Consequently, research into more sustainable PV materials, including those based on organic and recyclable components, is crucial for creating a circular economy around PV technology in architecture.

3.0 Methodology

3.1 Literature Review Methodology

This study adopts the methodology of systematic literature review to explore the integration of photovoltaic (PV) technology into Zero Energy Buildings (ZEBs) while considering their architectural aesthetic value. The approach aims to synthesize findings from relevant studies published in open-access journals, focusing on recent advancements and trends in the field.

3.2 Selection of Databases

To ensure a comprehensive and relevant selection of literature, the author consulted two primary databases: Elsevier's Science Direct and Taylor & Francis Open. These sources were chosen for their extensive collections of peer-reviewed articles in the fields of renewable energy, sustainable architecture, and building design. The selection criteria were based on the availability of recent publications, open-access availability and the relevance of articles to the themes of PV integration and aesthetic considerations in ZEBs.

3.3 Search Strategy

A structured search strategy was implemented within both databases. The search terms included combinations of keywords such as "photovoltaic integration", "Zero Energy Buildings", "architectural aesthetics", "sustainable architecture" and "renewable energy systems". Boolean operators “AND” and “OR” were employed to narrow down the search and ensure that articles captured a broad spectrum of perspectives and findings related to the integration of PV systems in ZEBs. The initial search yielded a substantial number of articles, which were subsequently filtered based on three inclusion criteria: publication date, open access, and relevance.

Regarding the first criterion, only articles published within the last five years, i.e. 2020 – 2024, were selected in order to ensure that the review focused on the most recent developments in the field. For the second, only open-access articles were selected as a way to ensure unrestricted access to the literature for future researchers and practitioners. Finally, the articles must explicitly address the integration of PV technology in the context of ZEBs and include discussions or evaluations of aesthetic aspects related to architectural design.

3.4 Article Selection

Following the application of the inclusion criteria, a total of 28 articles were selected for this review. The selection process involved reviewing the abstracts and conclusions of potential articles to assess their relevance and contribution to the study’s objectives. The articles included a mix of reviews, experimental studies, surveys, and case studies, providing a well-rounded perspective on the subject matter.

3.5 Data Extraction and Analysis

Data extraction was executed systematically using a structured template to ensure consistency and comprehensiveness. Key information extracted from each selected article includes year of publication, research focus, research methods, country of origin and journal publisher. A summarization of the primary outcomes and conclusions drawn by the authors, as related to both energy performance and aesthetic considerations, was subsequently done with proposed recommendations for practice or future research that emerged from the studies.

The data was then organized and analyzed qualitatively, allowing for thematic synthesis of findings across the selected articles. The analysis aimed to identify common themes, trends and gaps in the literature regarding the integration of PV systems in ZEBs and their impact on architectural aesthetics.

3.6 Synthesis of Findings

The final phase of literature review involved synthesizing findings from analyzed articles to draw overarching conclusions about the state of research on PV integration in ZEBs and its impact on architectural aesthetics. This synthesis was framed within the context of existing theoretical frameworks and practical implications, aiming to provide valuable insights for researchers, architects and policymakers interested in advancing the design and implementation of Zero Energy Buildings. Through this comprehensive literature review, this study aims to contribute to ongoing discourse on sustainable building and the place of aesthetic considerations in the adoption of renewable energy.

4.0 Findings and Discussions

SN	Authors (Year)		Research Focus	Research Method	Country of Origin	Journal Publisher
1	Aguacil et al.,	(2024)	BIPV Potential	Case Studies	Switzerland	Elsevier
2	Awuku et al.	(2021)	BIPV Aesthetics	Literature review	United Kingdom	Elsevier
3	Azami & Sevinç	(2021)	BIPV Performance	Experiment	Turkey	Elsevier
4	Chandrasekar	(2023)	BIPV Aesthetics	Literature review	India	Taylor & Francis
5	Corti et al.	(2024)	BIPV cost efficiency	Survey	Switzerland	Elsevier
6	Debayan Sarkar & Sadhu	(2020)	BIPV Performance	Survey	India	Taylor & Francis
7	Dimitrios Rounis et al.	(2022)	BIPV Performance	Experiment	Canada	Elsevier
8	Feng Shi & Hong	(2020)	BIPV Performance	Survey	China	Taylor & Francis
9	Figliola	(2023)	Climatic Resilience	Experiment	Italy	Taylor & Francis
10	Ghosh	(2020)	BIPV Potential	Literature review	United Kingdom	Elsevier
11	Ghosh	(2022)	BIPV Potential	Literature review	United Kingdom	Elsevier
12	Hamzah & Go	(2023)	Climatic Resilience	Experiment	Malaysia	Elsevier
13	Jahan et al.	(2024)	BIPV Material	Experiment	Bangladesh	Elsevier
14	Kryszak & Wang	(2024)	BIPV Aesthetics	Case Studies	Taiwan	Taylor & Francis
15	Kuhn et al.	(2021)	BIPV Aesthetics	Survey	Germany	Elsevier
16	Larini et al.	(2023)	BIPV Material	Experiment	Italy	Elsevier
17	Lee et al.	(2022)	BIPV Performance	Experiment	South Korea	Elsevier
18	Liu et al.	(2021)	BIPV Feasibility	Literature review	China	Elsevier
19	Lohit Saini & Kumar	(2022)	BIPV Feasibility	Literature review	India	Taylor & Francis
20	Ma et al.	(2024)	BIPV Potential	Literature review	China	Elsevier
21	Meng et al.	(2022)	BIPV Material	Literature review	China	Elsevier
22	Reveshti et al.	(2023)	BIPV Potential	Experiment	Iran	Elsevier
23	Samer Quintana & Zhang	(2021)	BIPV Performance	Experiment	Sweden	Taylor & Francis
24	Shi et al.	(2024)	BIPV Material	Experiment	China	Elsevier
25	Tiagarajan & Go	(2024)	BIPV Performance	Experiment	Malaysia	Elsevier
26	Wijeratne et al.	(2022)	BIPV Feasibility	Experiment	Australia	Elsevier
27	Wilberforce et al.	(2023)	BIPV Potential	Literature review	United Kingdom	Elsevier
28	Yadav & Panda	(2020)	BIPV Performance	Experiment	India	Elsevier

Table 1: Characteristics of selected journal articles

4.1 Year of Publication

The analysis of publication years shows a gradual increase in research interest in photovoltaic (PV) integration for Zero Energy Buildings (ZEBs) and aesthetic architectural value. Publications have grown steadily, with the most recent years, 2023 and 2024, contributing the highest number of studies (6 and 7 respectively). This upward trend reflects the expanding focus on the research nexus of BIPV and architectural aesthetics, suggesting that the topic is gaining importance within the research community. The increase aligns with global movements toward renewable energy solutions and aesthetic innovation in building design, indicating heightened awareness and technological advancement in the field.

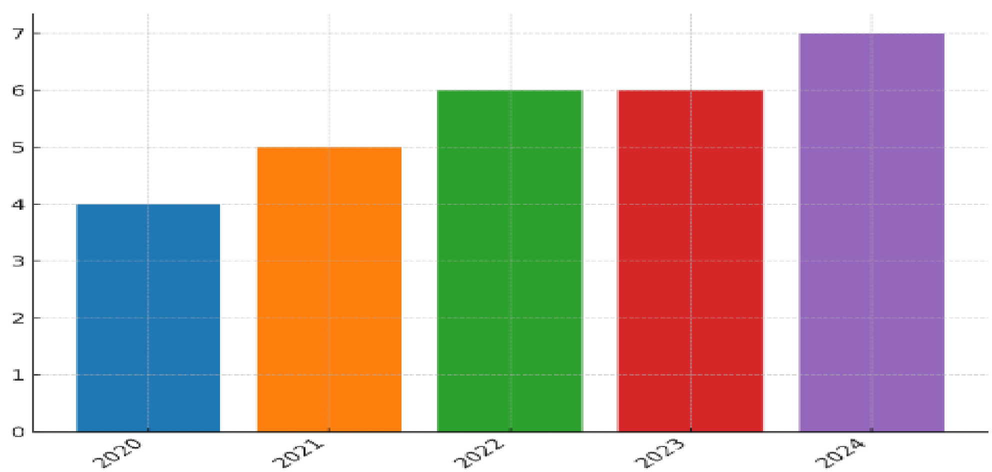


Figure 1: Bar Chart showing frequency of publications per year in the study period

4.2 Research Focus

Research foci within the selected publications reveal diverse aspects of PV integration in ZEBs. The highest frequency is in studies on BIPV (Building-Integrated Photovoltaics) Performance (8 studies), followed by BIPV Potential (6 studies), BIPV Aesthetics (4 studies) and BIPV Material (4 studies). This distribution underscores a strong emphasis on performance metrics as a primary factor for PV integration feasibility, as researchers seek to validate PV systems' energy efficiency and reliability in ZEB applications. Additionally, BIPV potential and aesthetics are central concerns, reflecting the dual pursuit of functionality and visual appeal. Climatic Resilience and BIPV Cost Efficiency are explored to a lesser extent, highlighting the niche but significant need to understand environmental adaptation and economic viability in specific contexts.

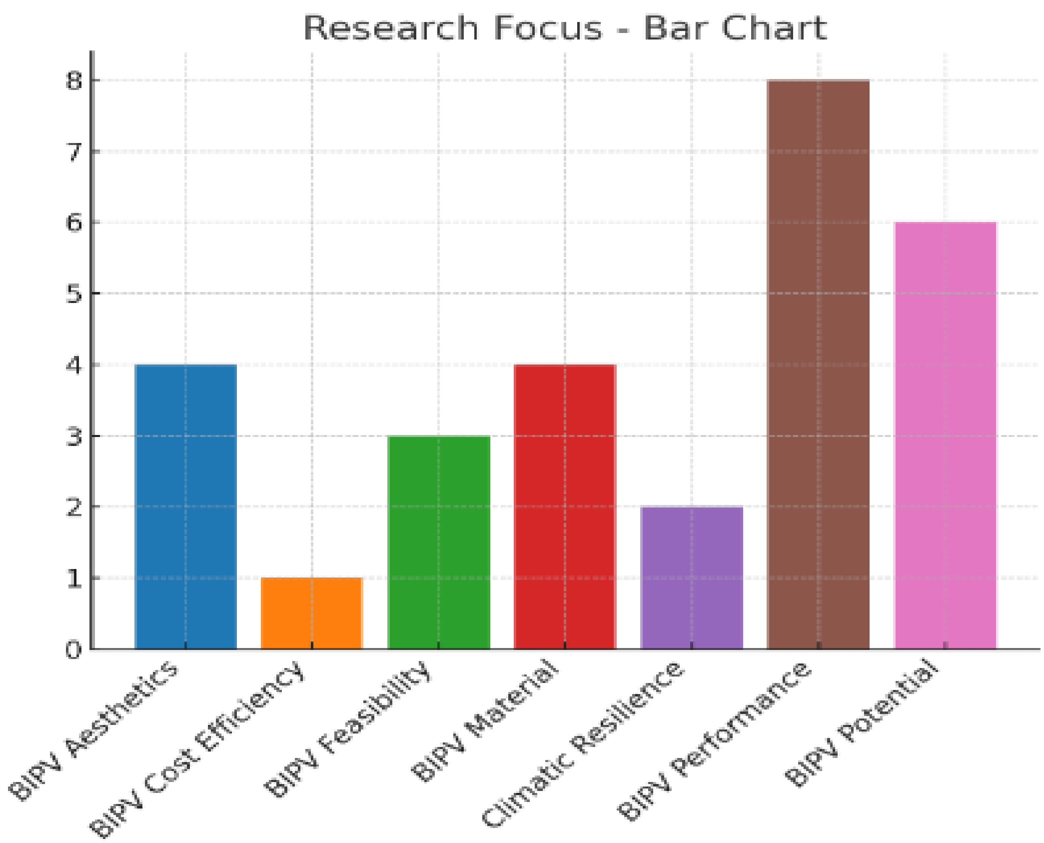


Figure 2: Bar chart illustrating the varying research foci of the reviewed papers

4.3 Research Method

The selected publications employ various research methods, with Experiments being the most frequent approach (13 studies), followed by Literature Review (9 studies), Surveys (4 studies) and Case Studies (2 studies). The predominance of experimental studies indicates a focus on empirical data to substantiate PV technologies in ZEBs, supporting practical and real-world validation. Literature reviews serve as comprehensive assessments that integrate existing findings, which is essential for broadening understanding across methodologies and geographic applications. The lower frequency of surveys and case studies suggests that while empirical insights are valued, broader contextual or qualitative insights, like user and architect perspectives, may be under-represented but could provide complementary insights into PV integration.

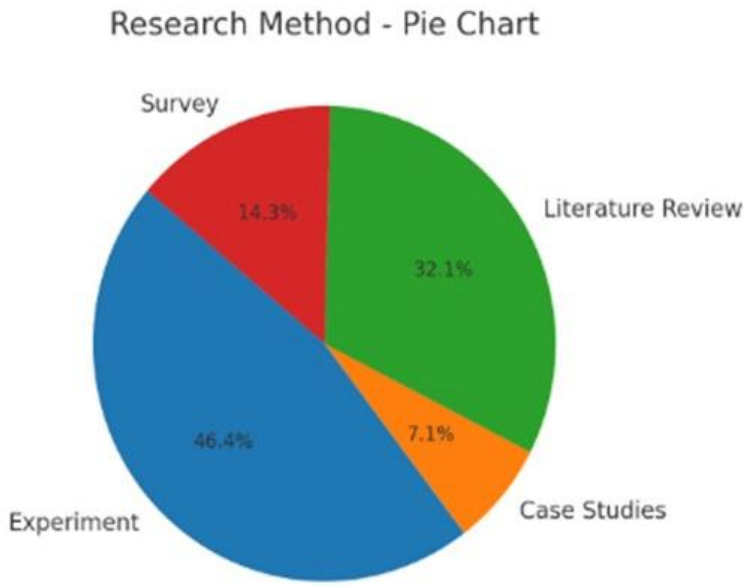


Figure 3: Pie chart showing the research methods employed in the reviewed papers

4.4 Country of Origin

The geographical origins of the publications reveal a concentration of research efforts in China (5 studies), India (4 studies) and the United Kingdom (4 studies), with other countries contributing fewer studies. This distribution indicates that PV integration in ZEBs and aesthetic considerations are of interest across a wide geographic spread, with particular emphasis in regions facing rapid urbanization, high energy demand and environmental challenges. China's prominent contribution may reflect its robust investment in renewable energy research and development. Meanwhile, contributions from diverse countries, including Australia, Germany, Italy, and Malaysia, emphasize the international relevance and adaptability of PV solutions within different architectural and environmental contexts.

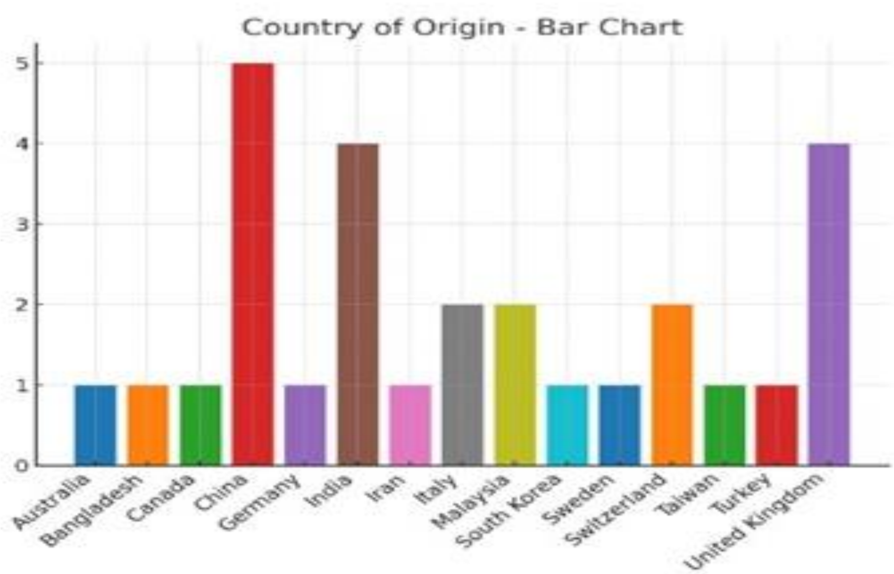


Figure 4: Bar chart showing the countries of origin of the reviewed papers

4.5 Journal Publisher

Most of the publications were sourced from Elsevier (21 studies), while Taylor & Francis accounted for the remaining seven. The predominance of Elsevier as a publisher suggests that journals under this publisher have a strong influence on this field of research, potentially because of their reach and relevance to the engineering, architectural and environmental disciplines.

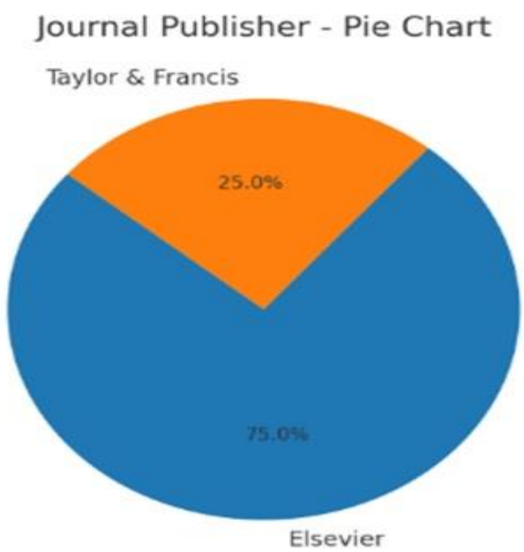


Figure 5: Pie chart showing publishers of the reviewed papers

5.0 Conclusion

In conclusion, PV integration for ZEBs represents a promising yet challenging field at the intersection of energy efficiency, architectural design, and sustainability. While significant progress has been made, further research and technological innovation are needed to overcome existing challenges and ensure that PV integration aligns with both functional and aesthetic goals. The continued development of standards, as well as the emergence of more cost-effective technologies and cross-disciplinary collaboration, will be crucial in driving the mainstream adoption of PV-integrated ZEBs that embody architectural excellence and sustainability.

PV integration for Zero Energy Buildings represents a dynamic and promising area of architectural innovation, where the goal of sustainability intersects with the pursuit of aesthetic excellence. BIPV technology has expanded the possibilities for creating buildings that are both energy-efficient and visually striking, although challenges remain in terms of cost, efficiency, and regulatory adaptation. As PV technology continues to advance, architects, engineers and policymakers must collaborate to develop standards and best practices that support PV integration in ZEBs.

5.1 Future research directions

Future research directions will include improving PV material performance, advancing recycling and sustainable manufacturing, and enhancing the functionality of PV-integrated buildings through smart energy management. By addressing these challenges and leveraging emerging technologies, the architectural field can contribute to a sustainable built environment that embodies both energy efficiency and aesthetic quality.

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