International Journal of Energy Production and Management
Vol. 10, No. 2, June, 2025, pp. 231-246
Journal homepage: http://iieta.org/journals/ijepm

Comprehensive Review of Building Integrated Photovoltaic and Thermal Systems (BIPV/T)

Samah Mehira*, Aicha Boussoualim

Laboratory Architecture and Environnement (LAE), Polytechnic School of Architecture and Urbanism (EPAU), Algiers 16200, Algeria

Corresponding Author Email: s.mehira@epau-alger.edu.dz

https://doi.org/10.18280/ijepm.100207

Received: 1 April 2025
Revised: 15 May 2025
Accepted: 15 June 2025
Available online: 30 June 2025

Keywords:
building integrated photovoltaic and thermal systems (BIPV/T), nearly zero-energy buildings (NZEBs), solar technologies, energy efficiency, building codes

ABSTRACT

The increasing worldwide energy requirements, combined with sustainable urban growth, drive the need for inventive building technologies. Building integrated photovoltaic and thermal systems (BIPV/T) generate both electricity and thermal energy while enabling nearly zero-energy buildings (NZEBs) to achieve their energy goals. Our analysis examines the technological, economic, and environmental aspects of BIPV/T systems and their application within building elements such as roofs, facades, and glazing areas. The review also examines supportive policy frameworks for BIPV/T implementation while pinpointing adoption barriers like steep initial investments and incomplete regional policies. The present review is based on a systematic literature review from January 2010 to March 2025 from the Scopus, Web of Science, and IEEE Xplore databases. A search string consisting of the combination of the keywords building integrated photovoltaic and thermal systems (BIPV/T), nearly zero-energy buildings (NZEBs), solar technologies, Aesthetic and Architectural Integration, Energy Efficiency, and Building codes. A total of 75 articles were selected after screening and eligibility assessment. This study seeks to provide guidance for researchers, architects, and policymakers to progress BIPV/T integration towards sustainable urban development.

1. INTRODUCTION

According to the International Energy Agency (IEA) (2021), the building sector consumes about 40% of global energy and produces 36% of carbon dioxide emissions. The substantial environmental effect of buildings has led to the creation of sustainable methods that aim to lower their ecological footprint. The adoption of nearly zero-energy buildings (NZEBs) represents one of the most effective strategies because these buildings strive to achieve energy equilibrium by generating renewable energy on-site [1]. Building Integrated Photovoltaic and Thermal systems (BIPV/T) stand out among renewable energy options because they can both generate electrical power and provide thermal energy during their integration into building elements like facades, roofs, and windows [2].

BIPV/T systems function as multifunctional replacements for conventional building materials while reducing material costs and enhancing energy efficiency, unlike standalone PV systems and green roofs [3]. Urban environments benefit from BIPV/T systems because they provide a practical renewable energy solution where traditional installations struggle with limited space availability [4]. Integrating BIPV/T systems into building envelopes optimizes energy generation and improves both thermal insulation and aesthetics, which promotes sustainable urban development [5].

The purpose of this paper is to examine the state of BIPV/T technologies, performance parameters, economics, environmental and sustainability impact and policy scenarios in various regions and to analyze the integration issues and potential approaches to improve their uptake in NZEB projects.

For that purpose, the following research questions were set up:

- What are the major technical elements and types of BIPV/T technologies used in building applications?
- How BIPV/T technologies perform against other traditional PV systems in terms of cost, payback period and profitability?
- What are the environmental and sustainability benefits that BIPV/T technologies bring throughout the life cycle?
- What are the regional and global policies driving BIPV/T technology uptake and which gaps exist?
- What are the future research trends and innovations to support BIPV/T implementation in building applications?

The questions above were examined in this review by utilizing a literature review method. On one hand, BIPV/T offers both energy production and sustainability benefits, but on the other hand, these systems have a slow uptake due to high costs, environmental sensitivity, and unstable regulations [6]. Asia-Pacific has made significant progress in terms of deployment due to incentives, but other regions lack a standard policy and financial assistance [7].

In addition, the review investigates the evolution of photovoltaic technologies, including: first-generation crystalline silicon (c-Si) (≈20% efficiency [8]), thin-film (10-12% [9]), and perovskite cells (>25% [6]). The paper also evaluates the economics of BIPV/T and demonstrates payback periods ranging from 5 to 15 years depending on the local situation [1]. Feed-in tariffs, net metering, and green building codes are evaluated as policy instruments to support BIPV/T implementation [2], as well as the need for regional economic assessments and complete life cycle analyses [10].

The study aims to provide useful information for researchers, designers, and policymakers in terms of effectively promoting BIPV/T implementation in green buildings.

2. METHODOLOGY OF THE COMPREHENSIVE REVIEW

This Comprehensive review was conducted according to PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) principles to guarantee a transparent and replicable process. In Scopus, Web of Science and IEEE Xplore databases were searched for papers published between January 2010 and March 2025.

Search string: ("BIPV" OR "BIPV/T" OR "Building Integrated Photovoltaic" OR "Building Integrated Photovoltaic and Thermal systems") AND ("Solar Technologies" OR "Energy efficiency") AND ("NZEB" OR "Nearly Zero Energy Building") AND ("Aesthetic Integration" OR " Architectural Integration ").

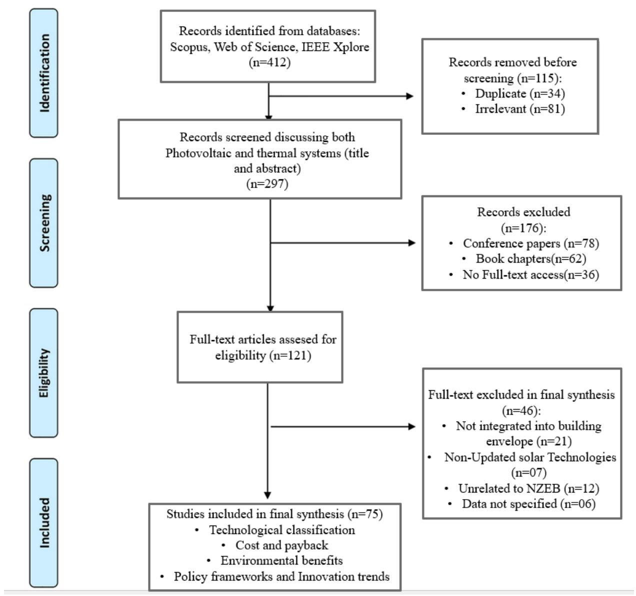

Figure 1. A PRISMA flow diagram of the comprehensive review

Inclusion Criteria:

- Published in peer-reviewed journals, in English;
- BIPV or BIPV/T technology with architectural, technical, economic or environmental implications;
- Intervention in residential, commercial or institutional buildings.

Exclusion Criteria:

- Conference papers, editorials, book chapters;
- PV or solar thermal technologies without integrated concepts;
- No full text access.

Results of Search and Screening:

- Number of studies initially identified: 412
- Number of duplicates: 115
- Number of records screened (titles and abstracts): 297
- Number of full-text articles assessed for eligibility: 121
- Number of studies excluded after full-text review (not meeting the criteria): 46
- Number of studies included in the final synthesis: 75

Articles selected according to the following classification: (1) technological classification, (2) cost and payback, (3) environmental benefits, (4) policy frameworks, and (5) innovation trends.

A PRISMA flow diagram (Figure 1) summarizes the selection process.

3. LITERATURE REVIEW

3.1 BIPV/T technology overview

The diagram in Figure 2 provides a systematic breakdown of the essential components that characterize BIPV/T. The diagram categorizes the system into four essential dimensions: The system structure includes four fundamental parts: Application, Solar Cells, Product Types, and Energy Storage Options. The four dimensions of BIPV/T systems play key roles in shaping design decisions and determining both the system's efficiency and its integration into building structures. It categorizes solar cells based on their generations: Solar cells are classified into three generations, which include first-generation c-Si cells, followed by second-generation thin-film cells and third-generation emerging technologies such as organic and perovskite cells. This classification presents the evolutionary progress and technological diversity found in solar cell types.

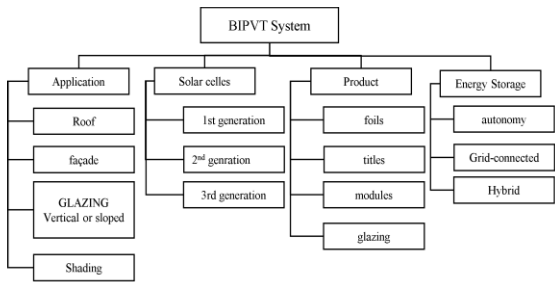

Figure 2. PV system categorization

BIPV/T products exist in multiple forms including foils, tiles, modules and glazing which allows them to address diverse architectural requirements. The diagram demonstrates energy storage options through distinctions made between autonomous systems, grid-connected systems, and hybrid systems.

The understanding of this aspect is essential for determining how these systems can optimize energy management and usage. This introduction provides basic knowledge about BIPV/T system integration while preparing readers for a detailed examination of their components and benefits which improve building performance and energy efficiency in later sections.

3.1.1 Definition and history

Since the 1970s solar photovoltaic (PV) systems for buildings have developed a substantial historical background, photovoltaic modules were originally developed to power buildings that operated independently from the electrical grid. The earliest photovoltaic systems consisted of aluminum-framed modules installed on building exteriors in isolated locations [2]. During the 1980s, rooftop PV installations became more prevalent, particularly in areas connected to centralized power plants enabling solar systems to blend better into urban areas [2].

Building-integrated photovoltaics (BIPV) first emerged in the 1990s to revolutionize solar technology. BIPV systems moved beyond rooftop solar panel installations by becoming essential components of building structures with integration into roofs, facades, and glazing. This innovation allowed these systems to serve dual purposes: generating energy and providing essential structural support. BIPV systems decreased buildings' total energy needs and substituted typical construction materials to offer urban developers both appealing and practical solutions [11, 12].

BIPV technology stands as an essential solution for reaching NZEB goals since it produces on-site electricity and reduces material and installation expenses through the substitution of traditional building materials [1]. The international BIPV market expanded significantly throughout 2014 to 2020, with the Asia-Pacific region reporting growth rates that exceeded Europe's by 10%. The importance of technology becomes evident from this trend which shows a particular significance in developing countries [7].

Building-applied photovoltaics (BAPV) systems offer a unique method for integrating solar energy solutions into architectural designs. BAPV systems differ from BIPV because they mount photovoltaic modules directly onto a building's existing structure rather than embedding them into the building envelope. BAPV systems utilize this installation method because it allows buildings to generate electricity in retrofit projects without changing the original architectural design or structural integrity [13].

The placement of BAPV systems on rooftops or facades usually necessitates additional mounting frameworks such as racks or frames to hold the solar panels. BAPV systems offer a simpler and more affordable installation process but they lack the ability to improve both thermal efficiency and aesthetic value as BIPV systems can provide. Architects and builders must understand this distinction to choose sustainable building practices and energy generation options effectively.

Understanding modern architecture requires familiarity with the essential differences between BIPV and BAPV systems. BIPV systems merge into buildings' architectural structures to provide energy generation through roofing, facades and windows. This combined system generates electricity while improving insulation and weather defense and lowers building expenses by substituting conventional materials.

BAPV systems function as additional energy sources when they are installed atop existing structures. BAPV systems require less installation effort and maintenance yet fail to match BIPV systems in terms of aesthetic cohesion and functional integration. The decision to select one system over another depends on how integrated the solution needs to be and the specific requirements of the building.

Table 1 provides a detailed comparison that helps clarify how each system affects building functionality and design choices for sustainable architecture decision-making.

Table 1. Comparison between BIPV and BAPV

Feature	BIPV	BAPV
Integration with building	Highly integrated into the building envelope (roof, facade, etc.)	Mounted on the building structure but not integrated
Aesthetic appeal	High - Can enhance the appearance of the building	Lower - Added onto existing structures
Cost	Generally higher due to integration	Generally lower due to a more straightforward installation
Installation complexity	Complex - Involves integration into the building structure	Simpler - Mounted on existing structures
Maintenance	Moderate - Requires maintenance of both the PV system and building components	Low - Easier to maintain as separate units
Structural impact	Direct impact on building functions (e.g., insulation, protection)	No direct impact on building functions
Primary purpose	Generate electricity and replace conventional building materials	Primarily to generate electricity

Notes: The data in Table 1 were compiled from peer-reviewed studies [1, 3, 14], which compare BIPV and BAPV systems in terms of efficiency, aesthetics, and integration cost. Values represent typical ranges derived from case study syntheses, offering generalized insight rather than specific measurements.

Table 1 demonstrates that BIPV and BAPV systems both generate renewable energy but differ substantially in their application areas and their impact on cost and building design. New constructions and major renovations that target high architectural integration and sustainability goals like NZEBs find BIPV systems to be ideal solutions. BAPV systems provide existing structures with a more economical and adaptable photovoltaic option that delivers fewer multifunctional advantages. When architects, engineers and policymakers grasp the distinctions between photovoltaic systems they can choose the most appropriate solutions in line with project necessities and financial limits while meeting sustainability targets.

BIPV and BIPV/T systems have evolved from standard solar installations to integrated systems that improve both building energy production and functional performance. The surge in renewable energy interest has driven more widespread use of BIPV technology leading to both economic and environmental benefits.

We have chosen to move forward with the BIPV system following a comprehensive analysis of our options. We selected the BIPV system because it integrates seamlessly with the building envelope which includes both the roof and façade resulting in improved aesthetic appeal and overall design. The higher costs and installation complexity of BIPV systems are offset by their dual function as standard building materials and electricity generators.

BIPV systems deliver aesthetic value along with enhanced insulation properties and building protection that meet our long-term goals. BAPV systems require easier installation procedures and fewer maintenance demands. BIPV is more suitable for our project requirements because BAPV's poor aesthetic rating and architectural integration issues limit their effectiveness.

Figure 3 depicts the technology roadmap for BIPV/T system development from 2000 to 2025. Key dates are highlighted along with the development of BIPV/T systems such as hybrid collectors, the first BIPV/T ventilated façade, thin film technology and the beginning of research on smart materials, AI and IoT as well as its application in the BIPV/T system. Recent developments in perovskite materials and multi-functional BIPV/T system development are expected to improve system performance and facilitate the improved integration of BIPV/T.

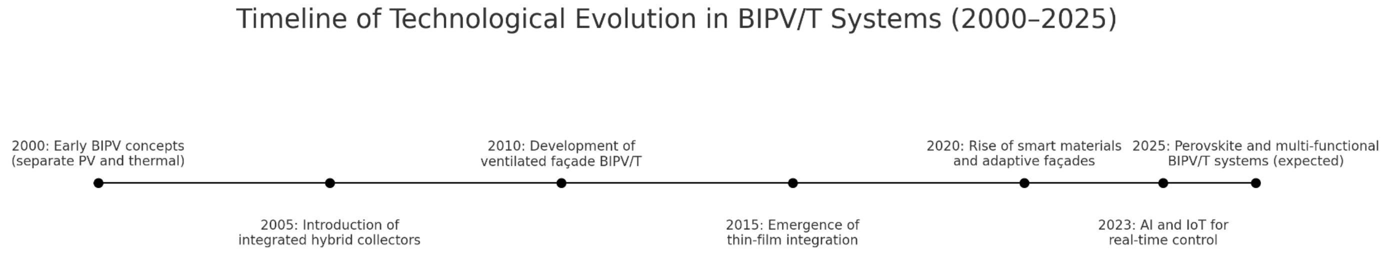

Figure 3. Timeline illustrating key milestones in the technological evolution of BIPV/T systems between 2000 and 2025

3.1.2 System components and types

Full Building-Integrated Photovoltaic and Thermal systems provide an advanced method of solar energy capture by embedding these technologies into construction components. This integration functions effectively while enhancing the aesthetic qualities of architectural design.

BIPV/T systems consist of solar cells essential for sunlight conversion to electricity, along with mounting systems for installation and securing elements as well as energy storage systems which use harvested solar power effectively. BIPV/T system components come in multiple designs, including modules, tiles, foils, and solar glazing products that adapt to architectural needs while optimizing energy production.

Through combined advancements in design and technology, BIPV/T systems advance building sustainability and diminish dependence on conventional energy sources which establishes them as a major breakthrough for renewable energy in architecture.

a. Policy and economic analysis

BIPV/T have gained worldwide attention but their adoption rates differ across regions because of varying policy frameworks along with economic incentives and market dynamics.

(1) Global market overview: The worldwide BIPV market witnessed strong expansion as projections show growth from a $14.0 billion valuation in 2020 to an expected $86.7 billion in 2030 which translates to a compound annual growth rate (CAGR) of 20.1% [15]. The growth surge results from heightened renewable energy awareness combined with government support and technological advancements in photovoltaics.

(2) Regional adoption variations:

- Europe: Europe maintains its position at the forefront of BIPV implementation thanks to rigorous environmental laws combined with significant financial incentives. Through policies that encourage sustainable construction, Switzerland achieved a 10% BIPV rate in its photovoltaic installations [16].
- North America: The U.S. market shows significant growth projected at a CAGR of 22.1% throughout the period between 2024 and 2030. Federal tax credits and state-specific incentives, together with consumer interest in energy-efficient solutions, drive market growth [17].
- Asia-Pacific: China and Japan are experiencing fast-paced growth in BIPV adoption. The Chinese market is expected to grow to $4.1 billion by 2026 through governmental support and urban development patterns [18]. Japan's push towards energy self-sufficiency has sped up the incorporation of BIPV in new building projects.
- Middle East and Africa: Although solar potential is high in the region, the adoption rates stay low primarily because of economic limitations along with insufficient policy backing. New initiatives designed to expand energy source diversity point toward impending market expansion.

Regional policies and economic conditions serve as primary drivers behind the variation in BIPV/T adoption rates across different areas. Regions that implement full-scope renewable energy policies along with financial incentives and awareness campaigns show increased adoption rates. Regions that do not benefit from support systems experience diminished growth rates.

b. Solar cells

PV cells which convert solar energy into electricity, serve as the essential component of BIPV/T systems. The performance of PV cells determines the entire system's effectiveness and efficiency. Throughout history various solar cell generations have developed which exhibited unique combinations of efficiency and cost-effectiveness. The development of solar technologies demonstrates why continuous research and development must focus on increasing energy production and lowering manufacturing expenses.

(1) First generation c-Si cells: Building

Integrated Photovoltaics (BIPV) systems primarily use c-Si because of its exceptional efficiency up to 20% and long-lasting performance [8]. This classification includes both monocrystalline cells and polycrystalline cells made from silicon. Monocrystalline cells provide higher efficiency but polycrystalline cells present a less expensive solution. Their superior performance makes them ideal for BIPV roofing applications but they can be used in multiple building integration forms as well [6].

(2) Second generation thin-film solar cells: Thin-film

Photovoltaic cells that use materials like cadmium telluride (CdTe) and amorphous silicon (a-Si) belong to the second generation of solar technology [9]. Thin-film solar cells offer greater flexibility and affordability compared to c-Si cells, yet their lower efficiency makes them perfect for BIPV foil applications where lightweight materials and adaptability matter. These cells yield less energy but are selected when prioritizing aesthetic value alongside flexible integration instead of peak efficiency [19].

(3) Third Generation Organic and Perovskite Cells: The newest generation of solar cells features cutting-edge technologies such as organic photovoltaics (OPV) and perovskite solar cells (PSC) [6]. The latest solar technologies demonstrate the ability to operate more efficiently while costing less than traditional silicon-based solar cells. These technologies remain mostly experimental but show capabilities in flexibility and reduced weight while offering manufacturing cost benefits [8]. Recent studies in 2022 and 2023 have demonstrated perovskite solar cells (PSCs) achieving lab-scale efficiencies of over 25%, with continuous progress in stability and scalability—for example, a certified efficiency of 25.1% was achieved in an inverted PSC (NREL certified [20], and peer-reviewed reports confirm efficiencies exceeding 25% using advanced n-i-p architectures [21]. These advancements make perovskite materials promising candidates for integration in BIPV/T applications, particularly in lightweight and semi-transparent modules.

Figure 4 shows the relative efficiency ranges for the first, second, and third-generation PV technologies. First-generation PV technologies are currently available on the market, such as the monocrystalline and polycrystalline silicon cells. The maximum commercial efficiencies range from 15% to 22%. Second-generation thin-film PV technologies such as amorphous silicon and CdTe cells, although having lower efficiencies, may also be attractive for their low material cost and flexibility. Finally, third-generation PV technologies have the greatest potential and already display high-efficiency levels of over 25%, but the technologies are still at an early stage of commercial development.

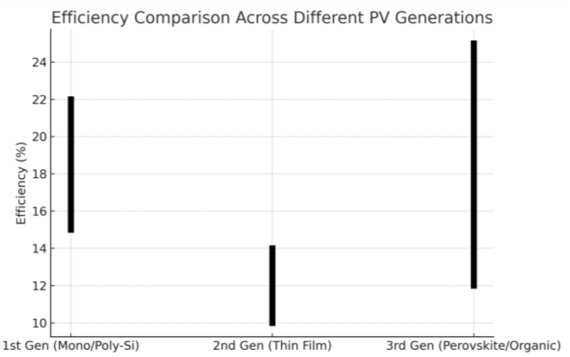

Figure 4. Efficiency comparison of photovoltaic generations
Notes: Ranges represent typical laboratory and commercial values as reported in recent literature

c. Mounting systems

The mounting systems used in BIPV/T installations differ widely according to the building integration type and architectural requirements. These systems play a vital role in attaching PV modules securely to structures and positioning them to capture maximum sunlight exposure.

- Module Mounting Systems: The mounting systems used in BIPV/T installations differ widely according to the building integration type and architectural requirements. These systems play a vital role in attaching PV modules securely to structures and positioning them to capture maximum sunlight exposure.
- Tile Mounting Systems: BIPV tiles function as replacements for traditional roof tiles while generating energy and providing weather protection. These systems come in modular formats that enable integration into existing structures while providing adaptable options for both new builds and refurbishments [3]. BIPV tiles utilize either monocrystalline or polycrystalline cells which produce high fill factors and excellent energy efficiency [9].
- Foil Mounting Systems: The lightweight and flexible BIPV foils enable easy installation across multiple surfaces such as rooftops. Thin-film solar cells enable sufficient energy conversion although their efficiency falls short compared to c-Si cells. BIPV foils attract installation interest because they easily attach to surfaces and blend with non-ventilated roof designs [19].
- Solar Glazing: Semi-transparent PV cells enable solar glazing to generate electricity from windows and glass facades while controlling daylight exposure and solar heat gain [22]. These products offer different levels of transparency and can be customized to meet each building's architectural requirements. These products demonstrate high efficiency in bringing more natural light into buildings while reducing energy usage for both lighting and cooling systems [3]. Selecting the appropriate mounting system for BIPV/T setups plays an essential role in achieving both functional performance and architectural harmony while optimizing energy efficiency to meet structural needs.

d. Categorization of BIPV products

BIPV products encompass a variety of designs that meet specific application needs and provide distinctive visual appeal and functional benefits along with distinct energy production capabilities. This section provides an examination of primary product groups.

- Modules: Traditional photovoltaic panels become part of a building's structural design when they are installed on rooftops or facade surfaces. These products maintain conventional design aesthetics while they produce energy.
- Tiles: Solar tiles take the place of standard roofing materials by providing both electricity generation and protection from weather elements. The tiles integrate flawlessly with roofing design while improving the aesthetic value.
- Foils: Solar foils combine lightness with flexibility in thin-film products to make them ideal for installations on non-ventilated roofs. These materials enable architects to create innovative designs that maintain structural strength.
- Solar Glazing: The category features windows and glass facades with semi-transparent photovoltaic cells built into them. These technologies manage to optimize daylight access while producing energy which leads to improved living conditions and environmental benefits [19].

BIPV/T systems benefit from these components as they establish an all-encompassing energy production solution for buildings. Their performance and aesthetic value improve as they become an innovative selection for sustainable architecture.

3.1.3 Applications of BIPV/T

BIPV/T systems contribute to advances in architectural design while improving energy efficiency. Solar energy technologies incorporated into structural elements like facades and roofs improve both building performance and their visual and functional aspects. Buildings can both utilize solar energy efficiently and preserve their architectural integrity through this dual advantage which provides sustainable urban environment solutions.

BIPV/T systems hold significant value because they decrease dependence on traditional energy sources while reducing operating expenses and possibly enhancing property valuation. Future construction and renovation projects will require careful exploration and implementation of BIPV/T solutions to meet the growing demand for sustainable building practices.

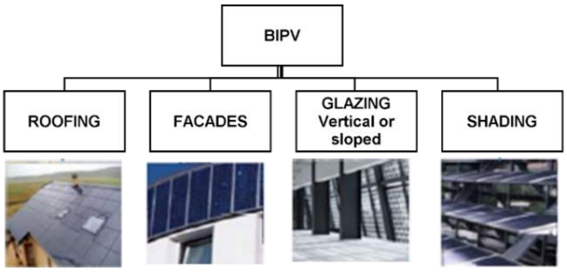

Figure 5. Types of BIPV applications, photos [23]

Different BIPV applications depicted in Figure 5 demonstrate how BIPV technologies maintain adaptability and flexibility across various architectural designs. The figure demonstrates the practical application of BIPV technologies through real-world examples provided by the study [23]. The figure demonstrates how BIPV technology can be effortlessly integrated into building designs while providing both utility and visual appeal.

- Facades: Building facades that integrate photovoltaic systems are becoming more recognized as a way to boost energy efficiency and improve thermal performance. BIPV facade systems serve dual purposes by acting as climate protection barriers and energy-producing units to minimize interior-exterior heat transfer. The study [24] reveals that building-integrated photovoltaic systems can achieve energy savings as high as 37%. BIPV facades function as protective barriers against the weather while they capture energy from sunlight. The integration of photovoltaic technology into building facades can be achieved through two primary methods. BAPV entails attaching PV modules onto existing facade structures while keeping a gap behind the panels to allow for improved air circulation and temperature control [25]. BIPV represents the second method which incorporates PV panels into facades to replace traditional building materials like glass or concrete. This approach combines both energy efficiency and visual appeal by using semi-transparent PV materials that allow natural light entry while generating energy [3].
- Roofs: Due the direct sunlight exposure of roofs makes they are one of the top locations for BIPV system installation. Building-integrated photovoltaic roofing systems offer diverse design options including complete roof replacements with PV materials and partial designs that incorporate PV modules adjacent to traditional roofing materials [6]. These systems boost energy production capability while simultaneously lowering building energy consumption levels. In-roof BIPV systems integrate without disruption into the building's roofing structure while functioning as both energy generators and protection against weather elements. Various photovoltaic technologies remain accessible within the industry, which include monocrystalline and polycrystalline solar cells [9]. Roof orientation and slope determine system efficiency as south-facing and sloped roofs generally achieve superior performance. According to the study [4], residential buildings can achieve substantial benefits from BIPV roofs by using up to 40% of their available roof space.
- Glazing: Windows with BIPV glazing systems integrate photovoltaic cells to enable energy generation while providing daylight control and solar heat gain management for buildings. The application achieves improved fenestration performance through the integration of semi-transparent thin-film solar cells directly into glass surfaces [22]. BIPV glazing systems control sunlight penetration into buildings to minimize heat flow while enhancing thermal comfort and boosting energy efficiency. These systems enable buildings to collect solar power while maintaining access to natural light. The effectiveness of PV cells in glazing depends on both their coverage area and their alignment towards the sun. Findings demonstrate that the size of the PV coverage area has a greater effect on both thermal performance and daylight penetration compared to the PV system's efficiency [22]. Buildings featuring large glass facades benefit greatly from solutions that optimize natural illumination while reducing energy demands for lighting and temperature control.
- Shading Systems: The use of photovoltaic systems within shading devices represents a new and promising development within BIPV technology. BIPV shading systems provide dual benefits by decreasing cooling requirements through shading while producing electricity to improve building performance [26]. The installation of these systems at windows or terraces serves dual functions by providing necessary shading while maintaining optimized sunlight exposure to generate energy. PV-integrated shading systems demand careful design decisions regarding orientation and tilt angle along with photovoltaic technology choices. According to the study [27], buildings equipped with PV-enabled shading devices achieve improved daylight uniformity and experience reduced heating and cooling energy requirements. Building-integrated photovoltaic technology in shading systems results in energy savings without sacrificing architectural flexibility.

The implementation of BIPV/T systems on building facades, roofs, glazing surfaces and shading elements allows for increased energy efficiency while reducing environmental footprint and aiding the creation of almost zero-energy buildings.

3.2 Technical aspects of BIPV/T systems

3.2.1 Efficiency and performance

The performance metrics of BIPV/T systems vary greatly depending on the photovoltaic technology used and the environmental conditions they face. PV cell generations exhibit distinct efficiency ratings. c-Si cells generally lead in efficiency among PV technologies, followed by thin-film technologies and organic/perovskite cells. Specific benefits and drawbacks arise when deploying each photovoltaic technology because their effectiveness depends on installation and application circumstances. The optimization of BIPV/T systems across different environments requires a thorough understanding of these technological differences.

Table 2. Summarizing the various solar cell technologies discussed

Generation	1st Generation	2nd Generation	3rd Generation
Category	Silicon-based	Non-silicon-based	Advanced technologies
Cell type	Monocrystalline, polycrystalline	Thin-film	Organic PV, perovskite PV
Material	c-Si	Amorphous silicon, CdTe, CIGS	Various emerging materials
Efficiency	High (up to 20%)	Lower than c-Si	Varies, experimental
Cost	High	Lower than silicon	Potential for low cost
Application	Common in BIPV due to high efficiency	Cost-effective alternative	Under research for future applications

Notes: Table 2. Summary of solar cell technologies used in PV and BIPV systems, including generation type, material composition, typical efficiency, and integration potential. This table was compiled based on scientific reviews and empirical studies published from 2016 to 2023. The given efficiency values are laboratory or reported field data [21, 28].

The highest conversion efficiency reported for first-generation PV cells, which include monocrystalline and polycrystalline silicon cells, reaches 20% as documented by the study [8]. Monocrystalline cells excel in efficiency because of their superior purity but polycrystalline cells provide greater cost savings although they perform slightly less efficiently. BIPV systems use these cells for roofs because high energy production is essential [6]. The performance of these cells depends greatly on multiple factors which involve roof orientation as well as shading and temperature conditions.

Thin-film solar cells as second-generation PV cells deliver conversion efficiencies between 10% and 12% which results in lower efficiency compared to crystalline-based solar cells [9]. Second-generation PV cells offer superior integration flexibility which makes them ideal for applications requiring lightweight and flexible materials such as BIPV foils and shading devices [19]. Thin-film cells demonstrate superior performance in low-light environments compared to crystalline cells despite their sensitivity to shading and environmental conditions [1].

OPV and PSC third-generation PV cells still undergo experimental stages, yet show considerable potential for future BIPV systems. Emerging technologies demonstrate potential for high efficiency and reduced production costs but require additional research to verify their long-term stability and durability [8]. The high efficiency of perovskite cells in transforming sunlight into electricity has made them a focal point of research attention since they might outperform conventional silicon cells under specific conditions according to some studies [6].

The various solar cell technologies discussed in the literature are first summarized in Table 2. The comparison between three generations of PV cells regarding their structural composition, efficiency levels, costs, and practical applications appears in Table 3. First-generation PV cells (c-Si) deliver high efficiency rates (up to 20%) and long-lasting durability though they come with increased expenses. Thin-film solar cells such as a-Si, CdTe and CIGS, lower the price and allow flexible implementation while delivering less power efficiency than their first-generation counterparts. Emerging third-generation PV cells such as perovskite and OPV, achieve efficiencies beyond 25% while providing lightweight and flexible options suitable for next-generation BIPV/T systems. Project needs and energy goals determine the optimal PV technology through this comparison process.

Table 3. Comparison between the three generations of PV cells

Feature	1st Generation PV Cells	2nd Generation PV Cells	3rd Generation PV Cells
Base structure	c-Si	The thin film includes cadmium sulfide (CdS), CdTe, a-Si, etc.	Dye-sensitized solar cells (DSSCs), PSC, OPV
Types	Single crystal (sc-Si), multi-crystalline (me-Si)	a-Si, CdS, CdTe, copper indium selenide (CIS)	DSSCs, PSC, OPV
Introduction	First to be introduced, well-known, and widely used	Developed with advancing technology, generally called thin film	Newer technology, highly efficient, low cost
Durability and health	Durable, non-toxic, no risk to indoor air quality	Less durable, efficiency decreases after extended exposure to the environment	High efficiency, low cost
Cost and Affordability	Initially, high costs decreased significantly over the last decade	More affordable than the first-generation	Low cost
Energy payback time (EPBT)	3-4 years	Shorter than first-generation	Highly efficient, shorter payback time
Efficiency	High	Generally, less efficient than first-generation	Very high efficiency
Application Areas	Standard PV installations	Wide range of applications, including windows and vehicles	Various, including novel applications in different environments
Popularity	Gained popularity between 2000-2008		Emerging technology is gaining traction

The effectiveness of BIPV/T systems depends on multiple environmental and design elements that must be managed to achieve optimal energy production. Here are some key considerations:

- Roof Orientation and Tilt Angle: The effectiveness of photovoltaic systems depends heavily on the roof's directional alignment and its slope. An optimal roof orientation facing south and a tilt of approximately 30 degrees is recommended to achieve maximum sunlight exposure during the day [6]. Suboptimal roof orientation or slope requires adjustments to improve solar energy collection.
- Shading: Shading creates a major obstacle for photovoltaic system performance. The energy production of PV cells arranged in series declines significantly when they experience partial shading. The shading of just one module section can lead to substantial decreases in total energy production. Efficiency losses in BIPV systems can be minimized by performing comprehensive shading analyses throughout both the design and installation stages [9].
- Temperature: The performance of PV cells becomes less effective in high temperatures, particularly for c-Si models. Studies show that c-Si solar arrays lose about 5% of their power output with each 10°C rises in operating temperature [1]. PV system performance requires proper thermal management to maintain optimal efficiency levels, especially when operating in hotter environments.

Designers and engineers can enhance the effectiveness of BIPV/T systems through meticulous examination of these factors for solar energy harnessing.

Table 4. Comparative summary of air-based and water-based BIPV/T systems

Criteria	Air-Based BIPV/T Systems	Water-Based BIPV/T Systems
Working fluid	Air	Water
Typical efficiency	Electrical: 8-12% Thermal: 25-45%	Electrical: 10-14% Thermal: 50-70%
Cost per kW (approx.)	Lower initial cost ~$2500-$4000/kW	Higher initial cost ~$3000-$5000/kW
Thermal storage	Limited thermal storage capability	High thermal storage potential (hot water tanks, buffer tanks)
Maintenance needs	Low – Fewer corrosion risks, simple filters	Moderate to high – Pumps, pipes, and water quality must be monitored
Installation complexity	Simple air ducts and fans, adaptable to retrofits	More complex – Plumbing, heat exchangers required
Applications	Suitable for space heating, pre-heating ventilation air	Suitable for domestic hot water, space heating, and combined systems
Advantages	Lower cost, less weight, easier integration	Higher thermal yield, useful in colder climates
Limitations	Lower thermal efficiency, less suitable for hot water applications	Heavier, more maintenance, complex integration

a. Ventilation and cooling techniques

The effectiveness of Building-Integrated Photovoltaic/Thermal systems hinges on ventilation and cooling techniques because these methods help prevent high temperatures from reducing PV cell efficiency. Building-integrated photovoltaic/thermal systems mount photovoltaic modules into the structure itself which leads to higher operating temperatures than standalone PV systems because airflow is limited.

- Air-based BIPV/T Systems: The implementation of air gaps between PV panels and building surfaces enables these systems to promote natural or forced ventilation which reduces the surface temperature of PV panels. According to the study [6], natural ventilation through panel air gaps helps increase PV module efficiency by up to 9% due to lowered operating temperatures. Forced air cooling provides advantages in systems that deliver space heat through preheated air circulation [6].
- Water-based BIPV/T Systems: Water-based BIPV/T systems operate in two ways by both reducing PV panel temperatures and producing thermal energy for heating spaces and hot water applications. The operation of these systems includes water circulation behind PV panels to capture excess heat which improves energy efficiency. The building's thermal energy requirements are supported by storing heated water which is then used for various heating applications [1].

Table 4 provides a comparative overview of air-based and water-based BIPV/T systems, highlighting their respective advantages, limitations, and suitable applications based on current literature.

Also, Efficient BIPV/T systems require knowledge of ventilation and cooling methods to support sustainable energy solutions in building design.

Various building types have adopted ventilative cooling which uses natural or mechanical ventilation to remove excess heat to improve thermal comfort and decrease energy consumption. Various case studies from real-world applications show how different ventilative cooling methods perform effectively.

- Commercial Building: A real field case in Madrid, Spain retrofitted a BIPV façade with a ventilated air cavity behind the PV modules to prevent overheating. Field results show a ~12°C lower nominal module temperature compared with a non-ventilated configuration, avoiding about 6% power losses at nominal conditions and ~2.5% annual losses thanks to ventilation [29].
- Office Buildings: The University of Oregon's Lillis Business Complex maintains indoor air quality and thermal comfort through a hybrid system that integrates natural ventilation with mechanical support. The hybrid system approach demonstrated substantial energy consumption decreases when compared to standard HVAC systems while showing potential energy savings benefits for commercial environments [30].
- Residential Buildings: Research into multiple passive cooling methods found ventilative cooling to be an effective solution for residential buildings. Through strategic window placement and ventilation shaft installation homeowners can significantly lower indoor temperatures which enhances comfort levels and minimizes air conditioning dependence [31]. Analyses that quantify various cooling methods demonstrate ventilative cooling's superior advantages. A research study comparing energy consumption prediction techniques for residential air conditioning demonstrated substantial energy savings through the

integration of ventilative cooling methods, especially when used with predictive control systems [32].

The practical applications and benefits of ventilative cooling across multiple building types become evident through these case studies and comparative analyses. Buildings can achieve improved energy efficiency and thermal comfort through the use of natural airflows while supplementing them with mechanical systems when required.

b. Energy storage

To facilitate continuous solar energy usage with BIPV and BIPV/T, energy storage proves crucial for operation outside daylight hours. The main approach to storing energy involves batteries which save surplus daylight-generated electricity for nighttime or low-sun periods. The performance of these batteries must be optimal because they play a critical role in the operation of BIPV systems which capture renewable energy effectively [2].

Energy management systems must be incorporated into BIPV systems to maximize the efficiency of stored energy use. These systems enable the control of electrical power circulation among photovoltaic panels, storage units and the grid. This strategic method enables buildings to primarily depend on solar power while pulling from grid electricity only when needed. Implementation of these systems leads to decreased energy expenses while advancing sustainability in the energy sector [2].

3.2.2 System design and installation considerations

The implementation of Building-Integrated Photovoltaic and Thermal systems in architectural structures presents technical challenges that require strategic management to achieve optimal performance and maintain sustainable operations over time. Achieving effective BIPV/T system integration demands a complex interaction between architectural design choices and environmental and climatic conditions which together affect energy production efficiency, system durability and aesthetic blending with surrounding structures. The essential elements of roof slope, façade orientation, and prevailing climate conditions all play significant roles in determining the performance and effectiveness of these systems.

- Roof Slope and Orientation: Roof slope combined with orientation serves as basic design components for BIPV systems because these factors determine how much sunlight PV modules capture all day long. To ensure maximum energy production, PV modules or the entire roof structure should face the sun's path. Optimal energy generation requires south-facing roof orientation in the Northern Hemisphere and north-facing roof orientation in the Southern Hemisphere, according to the study [6]. The best tilt angle for solar energy collection typically lies within a range of 20 to 35 degrees. The selected angle optimizes sunlight exposure while reducing shading interference from other building parts and nearby structures [19]. Flat-roofed buildings need extra mounting frameworks to set the PV modules at the proper angle. The process of optimizing energy collection through these modifications leads to higher installation costs and added process complexity [9]. Steeply sloped roofs might eliminate the need for angle adjustment structures but present safety risks during installation and maintenance access challenges that require effective risk management solutions.
- Façade Orientation: The direction of building façades turns into a crucial factor when designing BIPV systems where PV modules must be placed on vertical surfaces. Façade installations face greater shading risks from nearby structures and natural elements compared to roof-mounted PV systems, which usually receive unrestricted sunlight exposure. Energy generation requires careful assessment of building layout and environmental context to minimize shading and maximize solar exposure [19]. In cities with limited rooftop space, dense urban areas, vertical façade-mounted PV systems serve as practical alternatives for solar energy collection. Vertical surfaces demonstrate reduced sunlight absorption efficiency compared to angled surfaces. Facade-based photovoltaic systems produce less energy per square meter as compared to those installed on roofs, according to the study [6]. Maximizing energy density for façade applications requires the use of high-efficiency PV cells like monocrystalline silicon to overcome efficiency deficits.
- Climate and Environmental Factors: Both local climate and existing environmental conditions play a critical role in shaping the design and operational efficiency of BIPV/T systems. The performance and durability of PV modules are impacted by multiple climatic factors such as temperature, humidity, wind speed, and precipitation which demonstrates the importance of choosing appropriate materials and designs based on the installation site's specific conditions [8].
- Temperature: As temperatures increase, c-Si solar cells become less efficient because elevated temperatures negatively impact PV cell performance. For maintaining optimal performance levels in hot climates, PV systems need proper ventilation and cooling measures, including air- or water-cooling systems [1]. Using materials with high thermal conductivity promotes heat release from PV modules, which results in lower operating temperatures and better reliability.
- Humidity and Precipitation: Areas with high humidity levels or frequent rainfall require BIPV systems to use durable waterproofing solutions and materials resistant to corrosion. PV module durability faces considerable risks from moisture penetration. Buildings that integrate PV systems into roofs and façades typically experience a significant reduction in operational lifespan. Protective coatings with waterproofing layers play a critical role in reducing moisture complications and regular maintenance practices ensure continuous system durability [19].
- Wind and Snow Loads: The structural stability of BIPV systems requires careful assessment in areas with frequent strong winds or heavy snowfall conditions. PV modules along with their mounting systems need to resist dynamic wind forces and the extra weight from snow accumulation. Ignoring essential factors could result in harm to both the PV system and the supporting building structure, according to the study [6]. Special situations require reinforced mounting systems or extra structural support to maintain installation safety and stability, which protects both the building structure and its occupants.
- Aesthetic and Architectural Integration: BIPV systems

serve a dual purpose by generating energy while enhancing building aesthetics. The seamless integration of PV modules into building structures remains essential because it enables the creation of attractive designs that simultaneously enhance energy production. The creation of a harmonious integration between building design and functionality demands innovative design approaches alongside strategic material choices that honor both practical needs and aesthetic goals.

Successful implementation of BIPV/T systems demands thorough knowledge of how roof slope interacts with façade orientation and climatic conditions, along with aesthetic considerations. Stakeholders who engage in thorough planning and design to address these factors can improve BIPV installations' efficiency and visual appeal while supporting sustainable building practices and lessening dependency on conventional energy sources.

Besides the technical features and design integration aspects presented above, the economic viability is an important factor for BIPV/T applications to be considered. Besides the technology advancements and optimal design integration approaches, other factors such as the initial investment cost, O&M cost, the ROI and payback period can significantly influence the economics of a BIPV/T application in different climate and policy conditions. In the following part, an overview of the economic analysis reported in the literature will be discussed.

3.3 Economic aspects of BIPV/T systems

3.3.1 Cost and payback time

Building owners and developers face both immediate and extended economic effects when they choose to implement BIPV/T systems. The primary obstacle to broad BIPV/T deployment lies in the elevated initial installation expenses, which surpass those of standard photovoltaic systems. The higher expense of BIPV/T systems results from their ability to generate energy while acting as building materials.

BIPV/T systems function as building materials to replace traditional roofing and facade elements while incorporating photovoltaic technology into the building envelope. Building-integrated photovoltaic systems require unique designs and specific installation methods, which lead to increased initial expenses. According to the study [1]. The cost of BIPV modules can exceed traditional PV systems by 10-30% based on design complexity and the selection of materials as well as installation location, according to the study [1]. The need for specialized labor during BIPV installations raises installation costs even further compared to traditional PV systems that can be installed on existing roofs or structures.

Traditional PV systems provide lower installation costs but do not provide the combination of benefits that BIPV/T systems offer. Traditional PV systems require a building to use separate roofing or facade materials before adding PV modules, while BIPV/T systems provide necessary building components along with power generation. The ability to serve multiple functions in BIPV/T systems leads to lower total expenses for construction materials.

3.3.2 Payback time and long-term financial benefits

The initial high costs of BIPV/T systems are offset by significant long-term financial benefits through energy cost reductions and material savings as well as potential income from excess energy generation. The period required for energy savings to offset the initial investment differs significantly depending on local energy prices, system efficiency levels and government incentives [6].

Under ideal circumstances, the payback period of BIPV systems usually extends between 5 and 15 years according to research findings. The size and complexity of the installation, together with the solar irradiance at the location, determine this variance [2]. The payback duration for BIPV systems becomes notably brief when high solar capacity regions combine with increased energy expenses, since energy cost savings grow faster. Government support programs such as feed-in tariffs combined with tax rebates and renewable energy subsidies can significantly decrease the payback period for BIPV systems, which leads to higher investment attractiveness [1].

Construction costs decrease when BIPV/T systems replace traditional building materials with photovoltaic modules. BIPV roof tiles serve as a replacement for conventional roofing materials such as concrete or ceramic tiles to deliver combined weather protection and energy production from one integrated system. BIPV glass facades can perform structural functions and generate electricity, which reduces the need for additional building materials while delivering long-term savings on materials and maintenance costs [19].

Building owners can generate extra revenue by selling surplus energy produced by BIPV/T systems back to the power grid. Regions implementing net metering and feed-in tariff programs recognize this aspect's significance because building owners receive payments for surplus energy from their BIPV/T systems [6]. Over time, combining energy savings, diminished BIPV market expansion across various global regions, especially Asia/Pacific, has surpassed Europe's market growth. National sustainable development goals and generous financial incentives for renewable energy technologies are the main drivers behind this trend. BIPV technologies have experienced substantial growth because they help meet environmental goals and improve economic viability.

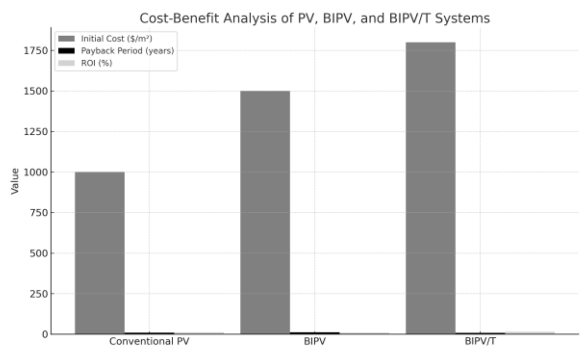

Figure 6. Cost-benefit comparison of PV, BIPV, and BIPV/T systems

Notes: The comparison includes initial cost ($/m²), payback period (years), and ROI (%)

Regional factors play a fundamental role in determining the economic feasibility of BIPV systems. Three crucial factors affect the feasibility of BIPV systems: governmental backing for renewable energy projects, building-specific characteristics at installation sites and current market conditions. Nations that provide strong economic incentives and possess favorable solar energy climates show a greater willingness to adopt BIPV systems across their regions. Users achieve shorter payback periods, which result in substantial financial gains over time. The combination of specific building characteristics and market conditions generates ideal conditions for BIPV development which indicates that regional planning strategies significantly influence solar energy integration in urban environments.

Figure 6 depicts a comparison of the cost, payback period, and ROI of three solar energy systems (conventional PV, BIPV, and BIPV/T), initial cost per m^2, payback period (years), and return on investment ROI (%). While the initial cost of BIPV/T is the highest, its payback period is also the lowest and its ROI the highest, which means that over the long run, BIPV/T can be considered the most cost effective. These numbers are indicative and are calculated from several references from the recent literature.

3.4 Environmental aspects and sustainable impact of BIPV/T systems

3.4.1 Contribution to NZEB

BIPV/T systems serve as essential components for achieving the aims of NZEB. The new dual-output systems both generate electricity and thermal energy which leads to notable reductions in building carbon emissions. BIPV/T solutions match contemporary structure energy requirements while reducing reliance on non-renewable power sources which makes them essential for sustainable construction and CO_2 emissions reduction efforts.

The implementation of BIPV/T systems directly responds to major energy challenges that modern buildings encounter. Buildings consume more than 40% of total energy across several countries, according to the IEA. The figure indicates an immediate necessity to develop solutions because the resulting CO_2 emissions intensify global warming issues. BIPV/T systems stand out as an effective solution because they produce renewable energy through building envelopes while simultaneously improving thermal insulation attributes. The new approach achieves lower heat transfer, which cuts down the need for both electrical and thermal energy [6].

BIPV/T systems excel because they integrate flawlessly with building architecture while maintaining their visual attractiveness. NZEB projects benefit greatly from this characteristic since energy efficiency and sustainability form their central principles. The studies demonstrate that these systems have the potential to reduce CO_2 emissions significantly by lowering dependence on external energy sources. The replacement of standard construction materials with photovoltaic panels that produce electricity while serving as building components demonstrates this concept clearly [3]. The thermal energy recovery feature of these systems allows buildings to minimize their heating and cooling requirements while simultaneously decreasing total energy use and environmental impact [1].

The growing focus on NZEB standards and sustainable development principles will drive a significant increase in the adoption of BIPV/T systems for both new buildings and retrofitting projects. Urban areas benefit greatly from these systems because traditional solar energy installations face significant space limitations in these environments. The application of BIPV/T systems enables optimal utilization of existing building areas such as roofs and facades for enhanced solar energy collection. BIPV/T systems can help achieve net-zero energy targets through proper system design and the consideration of crucial factors like orientation and shading. These systems improve the visual and operational characteristics of contemporary architectural design while maintaining functionality [6].

The integration of BIPV/T systems offers a revolutionary way to address building energy requirements. These systems deliver renewable energy solutions while adding to architectural elegance, which makes them crucial for advancing towards a sustainable, low-carbon future.

3.4.2 Lifecycle and durability

The environmental impact of BIPV/T systems depends greatly on their lifecycle and durability. Within this framework, the lifecycle accounts for the entire environmental cost during manufacturing up until disposal or recycling stages. Durability refers to the ability of the system to endure different weather conditions throughout its lifespan.

(1) Environmental Impact Over Lifecycle: While BIPV/T systems significantly reduce operational emissions, manufacturing processes still involve environmental burdens. According to the study [10], the production of c-Si wafers accounts for over 40% of total embodied energy in PV modules. Their lifecycle assessment reveals that the EPBT ranges between 2 and 4 years, and that emissions during the wafer slicing and doping stages contribute most to the carbon footprint. These findings are essential for understanding the full environmental cost of BIPV/T systems.

BIPV/T systems are designed to operate between 25 and 30 years according to the warranty terms provided by their manufacturers. Recent research shows that technology improvements could enable systems to function for up to 50 years because innovations are extending the resilience and performance of system components [10, 29]. For fully understanding BIPV/T systems' environmental benefits, we need to perform assessments throughout the entire lifecycle of these systems. PV cells require substantial resources and energy to produce but their long-term use compensates for their initial environmental impact. Their operational lifespan shows a substantial decrease in CO_2 emissions, which serves as the main mechanism for achieving this result.

BIPV systems demonstrate beneficial environmental outcomes throughout their life cycle according to life cycle assessments (LCA), even though they require larger initial environmental investments than traditional building materials. BIPV systems take approximately three to four years to produce the amount of energy they consume during manufacturing. Once the system surpasses its initial energy consumption phase, it delivers a net environmental benefit while reducing dependency on fossil fuels.

(2) Durability in Different Climates: The longevity of BIPV/T systems can be affected by varying environmental elements, including temperature changes, moisture levels, and wind pressures, which differ based on the system's installation location. High temperatures decrease photovoltaic module performance which may shorten the system lifespan through thermal stress effects. Studies show that power output from c-Si photovoltaic arrays decreases by about 5% for each 10°C increases in operating temperature [1]. The emergence of hot spots and increased shunt resistance from degradation limits the lifespan of PV modules which can be prevented through proper ventilation and cooling methods.

In colder environments, air-based BIPV/T systems perform well by supplying consistent space heating throughout all seasons. These systems maintain electrical generation efficiency while boosting building thermal insulation through the integration of heating elements into their design [6]. Research on ventilated double-skin facades in Mediterranean environments shows that well-designed systems can maximize energy production and thermal exchange which results in better system durability through temperature control over the full year.

Places that experience intense humidity or regular rainfall need to focus on moisture prevention because water penetration can harm PV systems and reduce their functional lifespan. Applying weatherproof coatings and precise system design allows for risk reduction while maintaining BIPV system performance throughout its expected lifespan.

3.5 Regulatory and policy aspects of BIPV/T systems

3.5.1 Building codes and standards

Tailored policy instruments are important in enabling BIPV/T in developing countries. Micro-credit to allow for small scale implementation, governmental subsidies to reduce the upfront cost, and international climate finance such as the Green Climate Fund, among other means. Also, enabling technical training for local workers and local manufacturing of components can enable better technology penetration and localisation.

Successful integration of BIPV/T systems in buildings requires supportive regulatory frameworks to stimulate their broad adoption. Building codes and standards that include sustainability criteria serve as essential tools to guarantee that BIPV/T systems conform to established best practices in terms of design, installation and operation. These frameworks protect structural strength and energy performance while addressing safety and environmental factors, which enables BIPV/T systems to integrate effectively into both newly constructed buildings and existing structures.

Regional governments have developed several policy tools like feed-in tariffs, net metering, and financial incentives to advance the use of BIPV/T systems. Building owners can benefit from feed-in tariffs by selling excess energy from their systems back to the grid at fixed rates which serves as financial motivation to adopt BIPV technology [3]. Net metering stands as a vital policy tool for integrating grid-connected BIPV systems because it allows building owners to receive credits for surplus electricity that flows into the grid which helps to reduce their power costs [2]. Financial mechanisms help resolve many monetary difficulties that come with BIPV systems and enable wider acceptance of renewable energy technologies.

The BIPV market has experienced significant expansion in regions including Europe and the Asia/Pacific region due to strong economic incentives for renewable energy development. The increase in market adoption is due to subsidies and regulatory support which have enhanced the financial appeal of these systems by reducing payback periods [6]. The lack of uniform policies and incentives in certain regions creates significant obstacles for the growth of BIPV technology.

Building codes serve as essential regulators for the technical specifications of BIPV/T installations beyond economic policy frameworks. Building codes provide essential guidance that maintains BIPV/T system installations within established safety and structural norms and electrical standards which reduces improper installation risks leading to system failures or hazardous conditions [33]. Current national regulations require new construction projects to include renewable energy systems, especially in buildings designed to meet NZEB standards, because BIPV/T systems become essential parts of these buildings.

Multiple regulatory frameworks that include building codes, feed-in tariffs, and net metering have a decisive influence on the economic and technical viability of BIPV/T systems. Essential guidelines and incentives provided by these policies create momentum towards sustainable energy solutions in the building sector.

3.5.2 Barriers to adoption

Multiple regulatory, financial and technical challenges obstruct the broad implementation of BIPV/T systems. The substantial initial investment needed for BIPV/T systems represents one of the primary barriers to their implementation. Custom designs and installations for these systems incur significantly higher initial costs compared to traditional PV systems despite their potential for long-term energy savings. The higher cost-per-kilowatt-hour of produced electricity remains a significant obstacle to broader adoption [6].

The absence of standardized protocols in BIPV/T systems serves as a significant obstacle to their implementation. The adoption of BIPV/T technologies encounters difficulties on a global level because building codes, technical standards, and regulations differ between regions and countries. Policy discrepancies represent a barrier to market cohesion and prevent the realization of economies of scale which would otherwise lower material and installation expenses [3]. The integration of BIPV systems into existing structures faces technical challenges such as roof slope considerations, building orientation, and climate conditions which make implementation more difficult and increase expenses.

Handling maintenance and lifecycle management stands out as a critical area of concern. BIPV systems possess inherent durability but require consistent maintenance to sustain their best performance throughout their lifespan. Potential adopters demonstrate hesitation because there are no standardized maintenance protocols and replacement component availability remains uncertain during the system's lifecycle [1].

BIPV/T systems face substantial challenges due to inconsistent policy and financial backing between different regions. BIPV/T systems become much more financially sustainable when government incentives like feed-in tariffs and net metering exist in a particular area. The lack of economic incentives in certain regions results in high financial barriers that restrict the broad application of BIPV systems [6].

Adopting BIPV/T systems across the building sector requires overcoming all the discussed barriers while using regulatory frameworks and economic mechanisms to drive their implementation.

4. RESULTS

To aid a comparative understanding of the data derived from the literature, a summary table of quantitative indicators regarding the performance and economics of BIPV/T has been prepared. Table 5 presents photovoltaic efficiency by generation, regional payback period, additional costs compared to traditional PV systems, carbon emission reduction, and system lifetime of peer-reviewed research and development data that vary according to technology and location.

Table 5. Summary of key quantitative findings from the literature

Parameter	Range / Value	Notes / Sources
PV efficiency – 1st Gen (Si)	17-21%	Monocrystalline and polycrystalline cells [8]
PV efficiency – 2nd Gen (thin film)	10-12%	CdTe, a-Si, CIGS [9]
PV efficiency – 3rd Gen (perovskite)	23-26% (lab), 15-18% (pilot)	Still in development phase [6]
Payback period – Europe	6-12 years	With policy incentives [16]
Payback period – Asia-Pacific	5-10 years	Due to rapid urban integration and incentives
Payback period – North America	7-15 years	Varies with state-level support
Carbon emission reduction	Up to 40% reduction	Compared to conventional buildings [1]
Additional cost over traditional PV	+10% to +30%	Depends on integration type and labor

In addition to the summary information and comparative table presented above, several commonalities and trends were noted in the data reported across the reviewed literature. The best applications for air-based BIPV/T configurations were found in cold and temperate climates, with preheat efficiencies often reaching above 50% in optimally insulated building façades. Meanwhile, liquid-based systems were more thermally stable and had improved COPs in tropical or humid climates, especially with the incorporation of phase-change materials or stratified storage tanks.

The inclusion of thermal storage elements, whether water tanks or built-in thermal masses, was also seen to provide BIPV/T systems with improved buffering capacity between supply and demand periods and a closer match to building energy loads. Furthermore, research studies that included smart energy management systems with dynamic flow regulation, sensor-based control, and real-time solar tracking showed an average 10–15% increase in overall energy efficiency when compared to fixed-parameter models.

Another noted trend in the reported literature was the effect of building design factors, such as optimal tilt angle, solar orientation, and the inclusion of ventilated double façades, on the overall system performance. Configurations that thermally isolated the PV module from the building envelope, for instance, showed better electrical efficiency under peak solar loads without sacrificing interior comfort.

Overall, these findings underscore the need to consider BIPV/T design holistically with climate adaptation, building typology, and control strategies. As such, multi-criteria optimisation is required to fully realise the performance potential of BIPV/T technologies in various urban and climate settings.

5. DISCUSSION

5.1 Contradictions in the literature

There are several inconsistencies across the literature regarding the thermal efficiency, cost effectiveness, and operation results of BIPV/T. For example, a literature review by the study [2] reports thermal efficiency up to 70% for water-based systems in well-controlled laboratory conditions, but these systems typically perform worse in the field due to factors such as ambient temperature variations, dust buildup, and poor orientation [2, 8]. Electric efficiency ranges from 8% to over 20% depending on cell technology, integration type, and location. These inconsistencies suggest the need for more standardized performance parameters and a greater focus on field validation.

5.2 Methodological limitations of reviewed studies

Several of the reviewed studies use simulation or small-scale prototypes, making them less generalizable. missing information about uncertainty margins, no consensus on lifecycle assessment, and little consideration of degradation and user behaviors over time. Moreover, there is a bias in the geographic coverage of case studies, which mainly consist of projects in temperate climates. These places have less solar potential than many tropical and arid zones, where solar potential is high but challenges in integration differ.

5.3 Implications for policymakers and industry stakeholders

Based on the reviewed evidence, there is a need for policy consistency and financial incentives to drive widespread adoption of BIPV/T. The EU already has strong policies and guidelines for BIPV/T through the EPBD and the associated green building initiatives. In other areas, however, there is no clear guidance. For the industry, an inconsistent supply chain, lack of technical training, and high initial investment costs are still major barriers. Standardization of BIPV/T modules and an improved return-on-investment scenario may help.

5.4 Theoretical perspectives on BIPV/T adoption

To understand BIPV/T adoption, we need an interdisciplinary approach. perceived advantages, compatibility with existing infrastructures, and system complexity will affect the adoption of the technology. Early adopters are typically in institutions or high-income residences, usually located in regions with supportive policy conditions. Future research should explore the interplay between economic models, regulatory structure, and behavioral factors to understand the diffusion pathways.

5.5 Challenges and future directions

5.5.1 Technological advancements

The future development of BIPV/T will rely heavily on digital technology. Artificial intelligence (AI) and machine learning (ML) can leverage real-time data to optimise energy yield, forecast faults and dynamically control system loads. Supervised ML algorithms can be trained using past weather and energy output data to improve PV forecasting and adaptive thermal storage, for instance.

The evolution of BIPV/T systems depends on technological developments in solar cells and energy storage as well as their integration into building designs. Key development domains offer substantial technological progress which will enhance both the performance and usability of BIPV/T systems.

Advancements in solar cell technology stand as the primary driver for boosting the efficiency of Building-Integrated Photovoltaic and Thermal systems. Solar cells come in different types, including monocrystalline and polycrystalline solar cells as well as thin-film solar cells which all exhibit distinct efficiency ratings and financial costs. The advent of third-generation solar cells such as organic and perovskite types, offers chances to achieve superior efficiency alongside diminished production expenses. The new solar cells under investigation show promise for versatile applications in building elements because they can be integrated more easily into materials such as windows and facades.

The development of energy storage systems stands as a significant area for advancement. BIPV/T systems improve their functionality by adding batteries and capacitors for storing surplus energy from photovoltaic systems. Enhancements in battery technology that bring better storage capacity, along with lower costs and longer lifespans, can substantially improve BIPV/T system performance. Energy storage systems must operate efficiently to store peak solar energy so it remains accessible for future use, especially within autonomous setups and areas afflicted by unstable grid connections.

The ongoing improvements to design and functionality will enable better integration of BIPV/T systems within architectural structures. Existing implementations of solar cell glazing in windows and facades are being enhanced through research to improve their efficiency and aesthetic options. Customized glazing that adjusts transparency and color levels creates novel opportunities to incorporate photovoltaic technology into building designs while maintaining architectural aesthetics.

Air-based BIPV/T systems that deliver both electricity and heating show great potential for better energy efficiency in cold climate regions during their developmental stage. These systems use preheated air to meet heating requirements while enhancing energy efficiency and reducing heating expenses. The advancement of BIPV/T systems will lead to wider adoption in urban areas because multifunctional integration offers combined electrical performance with thermal benefits and visual appeal.

5.5.2 Research gaps and opportunities

BIPV/T systems advancement presents multiple research and innovation opportunities focused on advanced materials development and innovative design methodologies along with new applications. Although meaningful progress has been achieved to date, multiple essential research gaps still need focus.

Advanced materials stand out as a leading area for investigation. Existing BIPV systems rely mainly on c-Si solar cells but new materials such as organic and PSC are becoming popular because they offer flexibility and lightweight properties alongside cost-effective manufacturing possibilities. The use of these novel materials will enable BIPV/T systems to integrate more smoothly into building facades and windows which expands their use across different architectural settings. The efficiency and visual appeal of BIPV installations improve with these materials but require further research to resolve durability and performance issues under different weather conditions.

Research opportunities abound in the field of innovative design approaches. Building integration of photovoltaic technology requires solutions that balance energy performance with visual design principles. The study of BIPV systems which produce energy while providing superior insulation and protection against weather conditions, helps to achieve maximum building performance. The thermal performance of buildings can be improved by reducing heat transfer and enhancing energy retention through technological advancements in ventilated façade systems and double-skin facades with integrated BIPV elements.

A growing interest in retrofitting existing buildings with new BIPV/T system applications continues to emerge. Updating traditional structures with modern BIPV systems presents distinct problems yet delivers significant opportunities for energy reduction and sustainability improvement. The development of specialized BIPV solutions for different building types while researching their economic and technical viability remains a critical priority.

Continuous research needs to investigate the long-term durability as well as lifecycle performance of BIPV/T systems, particularly in regions with severe weather conditions. Directing efforts towards these key areas will be critical to achieving resilient and dependable BIPV/T technology performance across various environmental settings.

6. CONCLUSIONS

The extensive analysis of BIPV/T systems establishes their essential contribution to environmental building approaches and the development of NZEBs. BIPV/T systems provide multiple advantages through direct energy generation integration into building envelopes, which meet practical requirements while enhancing visual appeal. The review identified varying efficiency rates across different PV technologies: First-generation c-Si cells reach up to 20% efficiency, whereas second-generation thin-film cells provide 10% to 12% efficiency at reduced cost. Researchers have discovered that PSC represents third-generation technology with lab efficiencies beyond 25% yet commercial application remains unexplored. Initial expenditures for BIPV/T systems exceed traditional PV systems by 10% to 30%, yet their combined benefits as structural materials and long-term financial advantages make them economically attractive. The payback period for BIPV/T systems ranges from 5 to 15 years and depends on regional policies as well as solar exposure and market incentives.

Existing benefits have not overcome certain limitations that still prevent broad adoption. The substantial initial investment costs, combined with complicated installation demands and performance variations due to shading and temperature changes, represent major obstacles. The absence of standardized building codes combined with regulatory inconsistencies creates additional difficulties for BIPV/T system integration in areas lacking well-developed renewable energy policies. The absence of detailed economic analyses specific to each region hinders stakeholders from thoroughly evaluating the future advantages of BIPV/T investments.

Actionable recommendations must be developed to address these challenges for policymakers, architects, and developers. The establishment of supportive regulatory frameworks by policymakers should be a primary goal to boost BIPV/T adoption through standardized building codes and financial incentives, including tax credits as well as feed-in tariffs and net metering programs. Architects and urban planners must focus on integrating BIPV/T systems during the initial design phase to achieve both maximum energy production and visual consistency. Developers need to assess the long-term economic gains of BIPV/T systems despite their upfront costs and investigate combined renewable technology solutions with BIPV/T.

Research efforts going forward should aim to boost the performance and lifespan of emerging solar materials, specifically PSC and OPV, due to their promising applications in flexible and lightweight technologies. Research into advanced thermal regulation methods involving phase change materials and new cooling strategies has the potential to enhance system performance. For the widespread adoption of BIPV/T systems to increase, it is essential to conduct cross-disciplinary research that explores their socio-economic effects and function in urban energy transitions.

BIPV/T systems mark a revolutionary progression towards architecture that combines energy efficiency with sustainability. Through targeted policies together with technological innovation and interdisciplinary research aimed at existing challenges, BIPV/T systems become essential to both decrease carbon emissions and define urban development's future.

REFERENCES

[1] Biyik, E., Araz, M., Hepbasli, A., Shahrestani, M., et al. (2017). A key review of building integrated photovoltaic (BIPV) systems. Engineering Science and Technology, An International Journal, 20(3): 833-858. https://doi.org/10.1016/j.jestch.2017.01.009

[2] Shukla, A.K., Sudhakar, K., Baredar, P. (2016). A comprehensive review on design of building integrated photovoltaic system. Energy and Buildings, 128: 99-110. https://doi.org/10.1016/j.enbuild.2016.06.077

[3] Jelle, B.P. (2015). Building integrated photovoltaics: A concise description of the current state of the art and possible research pathways. Energies, 9(1): 21. https://doi.org/10.3390/en9010021

[4] Defaix, P.R., Van Sark, W.G.J.H.M., Worrell, E., de Visser, E. (2012). Technical potential for photovoltaics on buildings in the EU-27. Solar Energy, 86(9): 2644-2653. https://doi.org/10.1016/j.solener.2012.06.007

[5] Peng, C., Huang, Y., Wu, Z. (2011). Building-integrated photovoltaics (BIPV) in architectural design in China. Energy and Buildings, 43(12): 3592-3598. https://doi.org/10.1016/j.enbuild.2011.09.032

[6] Maghrabie, H.M., Abdelkareem, M.A., Al-Alami, A.H., Ramadan, M., et al. (2021). State-of-the-art technologies for building-integrated photovoltaic systems. Buildings, 11(9): 383. https://doi.org/10.3390/buildings11090383

[7] Tabakovic, M., Fechner, H., Van Sark, W., Louwen, A. (2017). Status and outlook for building integrated photovoltaics (BIPV) in relation to educational needs in the BIPV sector. Energy Procedia, 111: 993-999. https://doi.org/10.1016/j.egypro.2017.03.262

[8] Tyagi, V.V., Rahim, N.A.A., Rahim, N.A., Selvaraj, J.A.L. (2013). Progress in solar PV technology: Research and achievement. Renewable and Sustainable Energy Reviews, 20: 443-461. https://doi.org/10.1016/j.rser.2012.09.028

[9] Taşer, A., Koyunbaba, B.K. (2021). A comprehensive review on building integrated photovoltaic (BIPV) systems. Izmir Institute of Technology. https://www.researchgate.net/publication/352681985.

[10] Azadian, F., Radzi, M.A.M. (2013). A general approach toward building integrated photovoltaic systems and its implementation barriers: A review. Renewable and Sustainable Energy Reviews, 22: 527-538. https://doi.org/10.1016/j.rser.2013.01.056

[11] Hagemann, I. (1996). PV in buildings-the influence of PV on the design and planning process of a building. Renewable Energy, 8(1-4): 467-470. https://doi.org/10.1016/0960-1481(96)88900-2

[12] Clarke, J.A., Hand, J.W., Johnstone, C.M., Kelly, N., et al. (1996). Photovoltaic-integrated building facades. Renewable Energy, 8(1-4): 475-479. https://doi.org/10.1016/0960-1481(96)88902-6

[13] Barkaszi, S.F., Dunlop, J.P. (2001). Discussion of strategies for mounting photovoltaic arrays on rooftops. In Proceedings of the ASME 2001 Solar Engineering: International Solar Energy Conference (FORUM 2001: Solar Energy — The Power to Choose). Solar Engineering 2001: (FORUM 2001: Solar Energy — The Power to Choose), Washington, DC, USA, pp. 333-338. https://doi.org/10.1115/SED2001-142

[14] Tripathy, M., Sadhu, P.K., Panda, S.K. (2016). A critical review on building integrated photovoltaic products and their applications. Renewable and Sustainable Energy Reviews, 61: 451-465. https://doi.org/10.1016/j.rser.2016.04.008

[15] Allied Market Research. Building integrated photovoltaics (BIPV) market. https://www.alliedmarketresearch.com/building-integrated-photovoltaic-market.

[16] Bonomo, P., Frontini, F. (2024). Building integrated photovoltaics (BIPV): Analysis of the technological transfer process and innovation dynamics in the Swiss building sector. Buildings, 14(6): 1510. https://doi.org/10.3390/buildings14061510

[17] Grand View Research. (2024). Building-integrated photovoltaics market size report, 2030. https://www.grandviewresearch.com/industry-analysis/building-integrated-photovoltaics-bipv-market.

[18] Research and Markets. (2022). Global building integrated photovoltaics (BIPV) market report 2022: Market to surpass $20 billion by 2026 - Smart city, the new urban infrastructure model, to steer next wave of growth. https://www.globenewswire.com/news-release/2022/03/18/2406005/28124/en/Global-Building-Integrated-Photovoltaics-BIPV-Market-Report-2022-Market-to-Surpass-20-Billion-by-2026-Smart-City-the-New-Urban-Infrastructure-Model-to-Steer-Next-Wave-of-Growth.html.

[19] Jelle, B.P., Breivik, C. (2012). State-of-the-art building integrated photovoltaics. Energy Procedia, 20: 68-77. https://doi.org/10.1016/j.egypro.2012.03.009

[20] Liu, C., Yang, Y., Chen, H., Xu, J., et al. (2023). Bimolecularly passivated interface enables efficient and stable inverted perovskite solar cells. Science, 382(6672): 810-815. https://doi.org/10.1126/science.adk1633

[21] Liu, S.W., Biju, V.P., Qi, Y.B., Chen, W., Liu, Z.H. (2023). Recent progress in the development of high-efficiency inverted perovskite solar cells. NPG Asia Materials, 15(1): 27. https://doi.org/10.1038/s41427-023-00474-z

[22] Sun, Y.Y., Liu, D.M., Flor, J.F., Shank, K., et al. (2020). Analysis of the daylight performance of window integrated photovoltaics systems. Renewable Energy, 145: 153-163.

https://doi.org/10.1016/j.renene.2019.05.061
[23] Verberne, G., van den Donker, M.N. (2015). BIPV pricing in the Netherlands: 2014 price benchmark report. https://resolver.tno.nl/uuid:406b6380-de69-432b-98ae-b64c3c6557cd.
[24] Shi, S., Zhu, N. (2023). Challenges and optimization of building-integrated photovoltaics (BIPV) windows: A review. Sustainability, 15(22): 15876. https://doi.org/10.3390/su152215876
[25] Alrashidi, H., Ghosh, A., Issa, W., Sellami, N., et al. (2020). Thermal performance of semitransparent CdTe BIPV window at temperate climate. Solar Energy, 195: 536-543. https://doi.org/10.1016/j.solener.2019.11.084
[26] Ma, L., Ge, H., Wang, L., Wang, L.Z. (2021). Optimization of passive solar design and integration of building integrated photovoltaic/thermal (BIPV/T) system in northern housing. Building Simulation, 14(5): 1467-1486. https://doi.org/10.1007/s12273-021-0763-1
[27] Barone, G., Buonomano, A., Forzano, C., Giuzio, G.F., et al. (2020). Passive and active performance assessment of building integrated hybrid solar photovoltaic/thermal collector prototypes: Energy, comfort, and economic analyses. Energy, 209: 118435. https://doi.org/10.1016/j.energy.2020.118435
[28] Green, M.A., Dunlop, E.D., Hohl-Ebinger, J., Yoshita, M., et al. (2022). Solar cell efficiency tables (Version 60). Progress in Photovoltaics, 30(7): 687-701. https://doi.org/10.1002/pip.3595
[29] Martín-Chivelet, N., Gutiérrez, J.C., Alonso-Abella, M., Chenlo, F., Cuenca, J. (2018). Building retrofit with photovoltaics: Construction and performance of a BIPV ventilated façade. Energies, 11(7): 1719. https://doi.org/10.3390/en11071719
[30] Brager, G., Baker, L. (2009). Occupant satisfaction in mixed-mode buildings. Building Research and Information, 37(4): 369-380. https://doi.org/10.1080/09613210902899785
[31] Zhai, Z.J., Previtali, J.M. (2010). Ancient vernacular architecture: Characteristics categorization and energy performance evaluation. Energy and Buildings, 42(3): 357-365. https://doi.org/10.1016/j.enbuild.2009.10.002
[32] Aswani, A., Master, N., Taneja, J., Krioukov, A., et al. (2012). Quantitative methods for comparing different HVAC control schemes. In 6th International ICST Conference on Performance Evaluation Methodologies and Tools, Cargese, France, pp. 326-332. https://doi.org/10.4108/valuetools.2012.250305
[33] Solar, C.A.T.B.I., Kalogirou, S. (2015). Building integrated solar thermal systems. In Design and Applications Handbook (1st ed.). European Cooperation in Science and Technology. https://pure.ulster.ac.uk/ws/portalfiles/portal/71293560/Book_1_.pdf.