Journal of Building Engineering 114 (2025) 114284

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Methods, technologies and challenges of building integrated photovoltaic thermal (BIPV/T) systems to achieve net-zero in high rise buildings: A systematic review

Tahsin Anjum [a], Md Morshed Alam [a,*], Iqbal Hossain [a], Mohamed Gomaa [a], Laveet Kumar [b]

[a] Department of Civil and Construction Engineering, Centre for Sustainable Infrastructure and Digital Construction, Swinburne University of Technology, Melbourne, Australia

[b] Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, Qatar

ARTICLE INFO

Keywords:
BIPV/T system
Net zero energy buildings
Design
Modelling
Architectural integration

ABSTRACT

As the global building sector faces increasing pressure to reduce energy consumption and carbon emissions, achieving net-zero energy performance in buildings has become a critical objective. While rooftop solar photovoltaic (PV) systems are sufficient for low-rise buildings, their effectiveness diminishes in high-rise structures due to limited roof area and high energy demands. The integration of BIPV/T systems in high-rise buildings offers a promising path to achieving net-zero energy goals and decarbonising the building sector. This systematic literature review (SLR) analyses research from January 2014 to January 2025, exploring the role of BIPV/T systems in enabling net-zero energy buildings (nZEB), particularly in high-rise applications. The review identifies key advancements in system design, modelling approaches, thermal storage integration, and architectural adaptability. While water-based BIPV/T systems demonstrate superior thermal performance, air-based systems are more commonly implemented due to simpler integration. Advanced configurations, such as those incorporating phase change materials (PCMs), heat pipes, and concentrators, enhance energy output and thermal regulation, making them highly suitable for dense urban environments. Despite significant advancements in BIPV/T efficiency and design innovations, the review finds that less than 15 % of PV/T research focuses on BIPV/T applications, with even fewer studies targeting high-rise buildings. The review emphasises the importance of integrating BIPV/T systems with heat pumps, thermal storage, and predictive modelling (including AI/ML techniques) to optimise energy performance and reach net-zero goals. It also highlights the role of BIPV/T systems in mitigating the Urban Heat Island (UHI) effect by reducing building surface temperatures and emissions.

Nomenclature

Abbreviation	Meaning	Abbreviations	Meaning
nZEB	Net-zero energy building	CWPVR-PMMA	Curved water-based photovoltaic/thermal roof combined with a polymethyl methacrylate cover

(*continued on next page*)

* Corresponding author.
E-mail address: mmalam@swin.edu.au (M.M. Alam).

https://doi.org/10.1016/j.jobe.2025.114284
Received 10 April 2025; Received in revised form 16 September 2025; Accepted 2 October 2025
Available online 3 October 2025

(*continued*)

PV	Photovoltaic	DHW	Domestic hot water
PV/T	Photovoltaic thermal	TES	Thermal energy storage
BIPV/T	Building integrated photovoltaic/ thermal	HST	Heat storage tank
PCM	Phase change material	TW	Thermal wheel
MDA	Metadata analysis	FEM	Finite element method
AI	Artificial intelligence	HVAC	Heating, ventilation, and air conditioning
ML	Machine learning	MOGA	Multi-objective generic algorithm
ASHP	Air source heat pump	ANN	Artificial neural network
HP	Heat pump	MPC	Model predictive control
SPV/T	Semitransparent photovoltaic/thermal system	BAPV/T	Building applied PV/T
BiSPV/T	Semi-transparent BIPV/T	RSC	Radiative cooling system
CFD	Computational fluid dynamics	EUI	Energy use intensity
DSF	Double skin façade	UHI	Urban heat island
EAHE	Earth air heat exchanger	BIM	Building information modelling
CIGS	Copper indium gallium selenide	LCOE	Levelized cost of electricity
HX	Heat exchanger	TPC	Total primary consumption
AHU	Air handling unit	NPV	Net present value
GSHP	Ground source heat pump	PBP	Payback period
CPV/T	Concentrating photovoltaic/thermal		
EVA	Ethylene vinyl acetate		
CWPVR	Curved water-based photovoltaic/ thermal roof		

1. Introduction

Buildings account for up to 40 % of the world's energy consumption and 33 % of its emissions of greenhouse gases [1]. Even in developed countries like Australia, existing commercial buildings contribute approximately 10 % of the nation's greenhouse gas emissions. According to the Trajectory for Low Energy Buildings report, buildings account for up to 20 % of Australia's total energy consumption and 55 % of its electricity usage [2]. As indicated by the UNEP, the energy intensity in the building sector must decrease by 37 % from 2015 levels by 2030 [3]. This has led to the growing popularity of the Nearly/net-zero energy building (NZEB/nZEB) idea globally. NZEBs/nZEBs are residential or commercial structures with significantly reduced energy demand, where efficiency improvements ensure that the remaining energy requirements can be met through renewable energy technologies [4].

Using a variety of clean energy methods, such as geothermal, solar, wind, biomass, wave, phase-changing materials, hydrogen, and hydropower, zero-energy status in buildings can be achieved [5,6]. Solar energy is one of the most notable of these as a

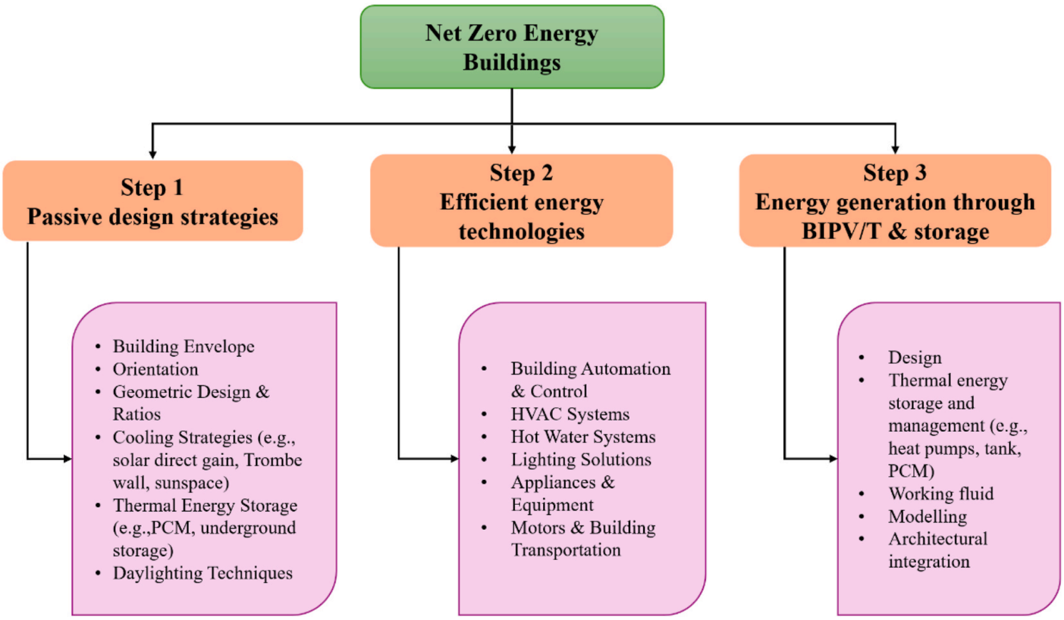

Fig. 1. Key axes for achieving net-zero energy buildings using BIPV/T systems.

well-established and cost-effective solution due to its maturity, scalability, and adaptability to diverse climatic conditions [7]. Research in this field focuses on developing advanced PV technology and integrating PV systems into building designs. Roof and façade-mounted PV systems can significantly cut the requirement of traditional energy sources [8]. Photovoltaic modules can absorb as much as 80 % of the sun's radiant energy, but, depending on their composition, only a fraction is transformed into electricity [9]. Additionally, the surplus energy raises the temperature of the panel surfaces, posing a critical challenge by lowering efficiency and reducing the panels' operational lifespan. In this context, Photovoltaic thermal (PV/T) systems can be included in the exterior walls. This technology, known as building-integrated photovoltaic thermal (BIPV/T), can simultaneously generate both electricity and thermal energy, effectively addressing these limitations. BIPV/T systems offer sustainable energy solutions by supplying both electrical and thermal energy, positioning them as a promising technology for reducing greenhouse gas emissions. In case of architectural integration, two key approaches for incorporating PV/T technology into building structures are Building-Integrated PV/T (BIPV/T) and Building-Applied PV/T (BAPV/T). BAPV/T involves retrofitting the system onto an existing structure, serving as an addition rather than an inherent part of the building's functional elements. This approach typically employs standoff or rack-mounted installation methods. On the other hand, the architectural design process merges PV/T systems within new structures because BIPV/T replaces traditional roofing materials, including slate and metallic surfaces. The installation methods represent the central difference between BIPV/T systems and BAPV/T systems.

Achieving a net-zero energy target is feasible for single-story or small residential houses using conventional rooftop solar PV systems due to their lower energy demand and sufficient rooftop capacity. However, meeting the electricity, heating, and cooling needs of high-rise buildings remains a significant challenge. Space constraints in high-rise buildings can make it challenging to utilise solar energy systems and other renewable energy sources. However, by using building façades to generate energy, this restriction may be avoided. Fig. 1 illustrates three key axes for achieving net-zero energy buildings (nZEBs). The first axis focuses on implementing passive energy technologies, the second emphasises energy-efficient building services, and the third involves energy generation through BIPV/T systems, incorporating optimal design, storage solutions, and integration techniques. This paper addresses the third axis of nZEBs and adopts a distinct methodological approach compared to existing literature, providing a detailed review of its specific contributions and innovations. Over the past decade, reviews on PV/T systems have primarily concentrated on development processes (28 %), equipment (21 %), and materials (19 %), whereas only 15 % have focused on building-integrated PV/T systems [10]. While most review papers primarily emphasise the design perspectives of BIPV/T systems [11–16], this study adopts a narrative approach, outlining the progression toward achieving nZEB targets using BIPV/T systems. For instance, Abdelrazik et al. [11] structured their review by categorising various BIPV/T configurations, such as air-based, water-based, concentrator, and PCM-based systems. Researchers also reviewed various BIPV/T applications [9,14,17] and their associated challenges [9]. Vassiliades et al. [18] reviewed both single and double façade solutions, along with designs where the active system functions as a standalone element of architecture within the building. Table 1 provides a thorough comparison of the scopes of the present reviews with those of earlier reviews on BIPV/T systems. This systematic literature review (SLR) aims to analyse the role of BIPV/T systems in achieving net-zero energy targets for high-rise buildings, focusing on design, modelling, architectural integration, and environmental impact. Recent studies have provided valuable insights into the design and performance of BIPV/T systems. For instance, Abdelrazik et al. [11] presented a detailed comparison of BIPV/T systems employing air, water, phase change materials (PCM), and concentrator-based designs. Similarly, Şirin et al. [19] examined various types of BIPV/T systems, with a particular focus on fluid flow configurations and flow rates, highlighting their influence on both energy and exergy efficiency. Their discussion of the net-zero concept was framed primarily as a proposal and a broad vision for achieving net-zero buildings. Unlike previous studies that typically address either thermal or electrical performance, our review adopts a holistic approach by examining BIPV/T designs, modelling methodologies, and integration with building envelopes, balancing technical performance with aesthetic and functional considerations to achieve a net-zero building. We also examined the limitations of BIPV/T technologies under varying climatic conditions, along with the associated economic and policy implications, thereby providing a holistic framework for understanding their role in achieving net-zero building performance. The study further explores how these systems mitigate urban heat island effects, highlighting both their environmental and aesthetic benefits. Finally, the paper identifies gaps in current research and emphasises the need for real-world applications, offering insights for researchers, engineers, and architects engaged in sustainable urban development.

2. Methodology

The importance of the research area is emphasised using a systematic methodology that includes metadata analysis (MDA). To find pertinent keywords and create a strong search strategy, the procedure started with a thorough brainstorming session. The keywords used for data collection were "building integrated photovoltaic" OR "building integrated solar" OR "BIPV/T″ combined with "thermal" OR "heating" to ensure comprehensive coverage of relevant studies. The Web of Science (WoS) & Scopus database was chosen because of their wide coverage and excellent indexing. A wide variety of technical reviews, original research, and conference papers were found during the first literature search. Duplicate records were eliminated to guarantee the calibre and applicability of the material.

The chosen research was then subjected to a bibliometric analysis, which produced a numerical summary of the research environment. The papers' abstracts were then carefully examined to determine their applicability based on predetermined inclusion and exclusion criteria, considering only articles focused on PV/T system designs and their integration with buildings. Articles that did not address PV/T performance (such as energy or exergy analysis) or design improvements for BIPV/T systems but instead discussed different directions were excluded from this review. To identify key contributors and notable publications in the field, our research analysed authorship patterns, collaboration networks, citation metrics, and publishing trends over time.

A thorough systematic review and meta-analysis of the chosen research studies were carried out after the bibliometric analysis.

Table 1
Summary of previous review articles on the BIPVT system.

Reference	Asefi et al. [12]	Bosu et al. [20]	Verma et al. [21]	Rounis et al. [16]	Yu et al. [22]	Şirin et al. [19]	Abdelrazik et al. [11]	Tiwari et al. [23]	M. Chandrasekar [24]	Riaz et al. [17]	Cheng et al. [14]	Kazem et al. [25]	Present Study
Metadata Analysis	×	×	×	×	×	×	×	×	×	×	×	×	✓
PVT Design Modifications	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Variation of Coolant	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓
Building Architectural Aspects	✓	✓	×	✓	✓	✓	✓	×	✓	×	×	✓	✓
Heat Usage	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓
Efficiency/ Performance	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Indoor Comfort	✓	✓	✓	✓	×	×	✓	×	✓	×	×	×	✓
PV Cell Materials	×	×	✓	×	×	✓	✓	✓	×	×	✓	×	✓
Economic Feasibility	×	×	✓	×	✓	×	✓	×	×	×	×	×	✓
Building Energy Consumption	×	✓	×	×	×	✓	✓	×	×	×	×	×	✓
Limitations/ Challenges	×	×	×	✓	×	✓	✓	×	✓	×	×	✓	✓
Future Prospects	×	✓	✓	✓	✓	✓	✓	×	×	×	✓	✓	✓

Studies were divided into groups according to their kind (numerical or experimental) and topic (advancements in BIPV/T technology, architectural integration, environmental impact). Technical difficulties, recent developments, and potential future study areas were all included in this analysis. Key findings and elements for each area under consideration were highlighted by synthesising and methodically tabulating the results. Fig. 2 presents the study's general approach.

3. Analysis of metadata

This section presents key divisions of research, including leading authors, studies, journals, and countries contributing to BIPV/T research. Additionally, emerging topics and trends are identified through keyword analysis.

3.1. Collecting data

The data collection timeframe spanned publications in English between January 2014 and January 2025. The dataset was obtained from the Web of Science (WoS) and Scopus databases as of January 30, 2025, comprising 218 and 233 peer-reviewed papers, respectively.

A metadata analysis (MDA) was conducted on the compiled dataset to generate critical insights into the research domain [37]. The analysis focused on four core metrics.

- Publication trends
- Geographic and institutional contributions (countries and organisations)
- Prominent authors
- Keyword and source dynamics

Key variables such as author names, publication titles, document types, keywords, journal names, citation counts, publication years, research fields, institutional affiliations, and country-specific contributions were systematically evaluated. To visualise interconnections between countries, organisations, author networks, and research themes within the publications, the Biblioshiny software package (part of the Bibliometrix toolkit in R Studio) was employed.

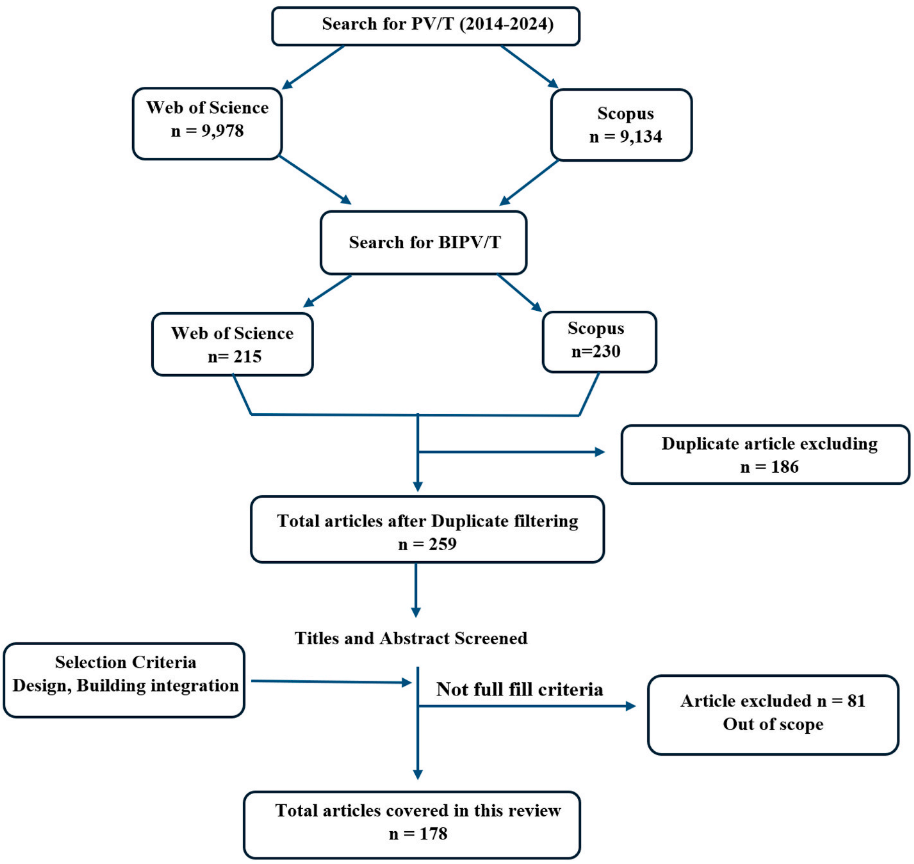

Fig. 2. System literature review (SLR) flow diagram.

3.2. Metadata analysis findings

The Web of Science (WoS) database includes 218 publications focused on Building-Integrated Photovoltaic/Thermal (BIPV/T) systems, covering the period from January 2014 to January 2025. These documents were contributed by a total of 563 authors, with a notable 29.3 % of the publications involving international co-authorship, reflecting a significant level of global collaboration. The average age of the documents is 4.91 years, indicating that the research is relatively recent. The field has experienced an annual growth rate of 8.04 %, demonstrating a steady increase in scholarly output over the decade.

Fig. 3 presents the annual distribution of relevant articles published in high-impact journals indexed in WoS during this period. Additionally, the top ten journals contributing to BIPV/T research include *Renewable Energy*, which leads the field with 25 articles, followed by *Solar Energy* (24 articles) and *Energy* (23 articles). These journals have contributed significantly more original research on BIPV/T compared to others, establishing themselves as key sources of knowledge in this domain.

4. Approach and designs of BIPV/T systems

4.1. Types of investigation

Numerous studies have explored the feasibility of BIPV/T systems. Some researchers have focused on simulation modelling, while others have conducted experimental analyses. Researchers have employed a variety of methods, such as analytical, experimental, numerical, and data-driven (AI/ML) approaches, to investigate BIPV/T systems. The analytical approach involves formulating governing equations to derive specific performance indicators. The experimental approach entails measuring performance parameters directly in a laboratory or real-world setting. In experimental setups, researchers have explored a variety of novel designs. The numerical approach, on the other hand, involves dividing the system into smaller elements and solving the governing equations using computational algorithms. This method is particularly valuable for analysing innovative technologies that may be challenging to model analytically. Moreover, numerical models can be validated through comparison with experimental data, ensuring their accuracy and reliability. Additionally, advanced software tools such as MATLAB, TRNSYS, and ANSYS Fluent are frequently employed for numerical simulations, providing robust frameworks for modelling and performance assessment. TRNSYS offers a user-friendly Unglazed Combined PV/T Solar Collector component (Type 560) that is particularly suitable for researchers. A data-driven approach offers various modelling options, including genetic programming, multipurpose regression models, iterative regression steps, data analysis through collaboration, and automated surface technique research [26]. The tools can adjust to minimise errors on various metrics individually or together. Section 4.5 discusses the modelling approach in detail. Table 2 summarises articles published from 2014 to 2025, highlighting a greater prevalence of simulation studies over experimental ones. In the case of experimental analysis, researchers tested novel design prototypes where modifications were made to the thermal collector and material composition. On the other hand, simulation-based studies have employed specific analytical tools, as illustrated in Fig. 4.

4.2. Designs of BIPV/T

The field of BIPV/T research is mostly focused on flat-plate and concentrating systems [94,96,97]. Most studies have investigated either water-based [98] or air-based BIPVT systems. Significant attention is also given to the incorporation of advanced materials such as phase change materials (PCMs), nanofluids, and bifluids [11]. Water-based BIPV/T systems are typically manufactured as single units and either integrated into walls or installed on rooftops. These systems include various designs such as pancake-shaped flow channels, roll-bond absorber, single-glazed, and unglazed configurations. Compared to air-based systems, water-based BIPV/T systems present greater manufacturing complexity due to the need for dedicated water channels and a continuous water flow [99]. Some advanced designs have encountered challenges, such as water leakage from the back of the panel [100]. Still, water-cooled systems

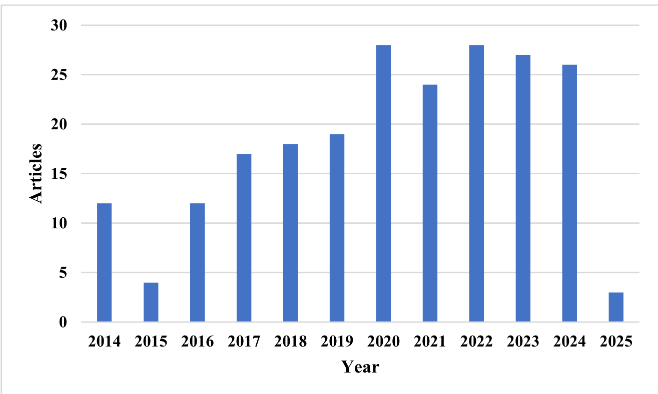

Fig. 3. Yearly research results from 2014 until 2025.

Table 2
Approach of research in BIPV/T across various literatures.

Ref	Author	Year	Experimental	System	Other Methods	Tools	Application Area
[27]	Hu et al.	2014	✓	PV with ethylene tetrafluoroethylene (ETFE) cushion	×	×	Roof
[28]	Ibrahim et al.	2014	✓	PV with Spiral flow absorber	×	×	Roof
[29]	Kamel & Fung	2014	×	BIPV/T-ASHP	Simulation	TRNSYS	Roof
[30]	Kazanci et al.	2014	✓	PV with lateral piping	×	×	Roof
[31]	Li et al.	2014	✓	Semitransparent photovoltaic/thermal system (SPV/T)	×	×	Roof
[32]	Shan et al.	2014	×	Refrigerant-based PV/T	Simulation	MATLAB	Roof
[33]	Yang & Athienitis	2014	✓	BIPV/T glazed air collector	×	×	Roof
[34]	Buker & Riffat	2015	✓	BIPV/T polyethylene heat exchanger	×	×	Roof
[35]	Li et al.	2015	×	Air type BIPV/T	Simulation	TRNSYS	Roof
[36]	Xiang & Gan	2015	✓	PV/T PCM air system	CFD	ANSYS Fluent	Roof
[37]	Yang & Athienitis	2015	✓	Air-based BIPV/T	×	×	Roof
[38]	Buonomano et al.	2016	×	Water-based flat plate BIPV/T	Simulation	TRNSYS	Roof, Façade
[39]	Chen & Yin	2016	✓	Aluminium tube PV/T with functionally graded material (FGM)	×	×	Roof
[40]	Rajoria et al.	2016	×	Solar cell tile (SCT) array & semi-transparent PVT	Mathematical Model	MATLAB	Roof
[41]	Saadon et al.	2016	✓	Double skin air type PV/T	Simulation	TRNSYS	Façade
[42]	Tiwari et al.	2016	×	Air Type BIPV/T	Mathematical Model	MATLAB	Roof
[43]	Wang et al.	2016	✓	BIPV/T heat pipe	×	×	Roof, Façade
[44]	Abdolzadeh et al.	2017	×	BIPV/T ethylene tetrafluoroethylen (ETFE) cushion	CFD	ANSYS Fluent	Roof
[45]	Bigaila & Athienitis	2017	×	PV/T air collector integrated with a small-scale HP with a radiant PCM panel	Simulation	TRNSYS	Façade
[46]	Buonomano et al.	2017	×	Water-based BIPV/T	Simulation	TRNSYS	Roof
[47]	Chialastri & Isaacson	2017	✓	BIPV/T air collector	Simulation	COMSOL Multiphysics	Roof, Façade
[48]	Himanshu Dehra	2017	✓	Air type BIPV/T	×	×	Façade
[49]	Deo et al.	2017	✓	Semi-transparent BIPV/T (BiSPV/T)	Mathematical Model	MATLAB	Roof
[50]	Dahmane et al.	2018	✓	Air type BIPV/T	Mathematical Model	MATLAB	Roof, Façade
[51]	Assoa et al.	2018	×	Air type BIPV/T	Numerical	TRNSYS	Roof
[52]	Shahsavar & Rajabi	2018	×	Air typer BIPV/T	Mathematical Model	MATLAB	Roof
[53]	Athienitis et al.	2018	×	Air open-loop BIPV/T	Numerical	DETECt 2.3 (Written in MATLAB)	Façade
[54]	Dash et al.	2018	×	×	Mathematical Model	MATLAB	Roof
[55]	Ibrahim et al.	2018	✓	BIPV with spiral flow water collector	×	×	Roof
[56,57]	Afrand et al.	2019	×	BIPVT-EAHE system	Mathematical Model	MATLAB	Roof
[58]	Yu et al.	2019	✓	Micro-Channel Loop-Heat-Pipe Photovoltaic/Thermal (MC-LHP-PV/T)	×	×	Roof
[59]	Yu et al.	2019	✓	Air type BIPV/T	CFD	NX Program	Façade
[60]	Yang et al.	2019	×	BIPV/T DSF	Numerical	TRNSYS	Façade
[61]	Tomar et al.	2019	✓	Air type BIPV/T	Theoretical	MATLAB	Roof
[62]	Pereira & Aelenei	2019	✓	Air type BIPV/T-PCM	Mathematical model	MATLAB	Façade
[63]	Yang et al.	2020	×	BIPV/T DSF	Numerical	TRNSYS	Façade
[64,65]	Xu et al.	2020	✓	Air & Water type BIPV/T	Mathematical Model	MATLAB	Façade
[66]	Shakouri et al.	2020	×	BIPV/T-DSF system	Analytical	EES	Façade
[67]	Wajs et al.	2020	✓	Air type BIPV/T	×	×	Roof
[68]	Shakouri et al.	2020	×	BIPV/T-DSF system	Analytical	EES, EnergyPlus, PVsyst, MATLAB	Façade
[69]	Shahsavar et al.	2020	×	BIPV/T Air collector	ML	MATLAB	Roof
[70]	Bot et al.	2020	×	Air type BIPV/T	Numerical	ANSYS Fluent EnergyPlus	Façade
[71]	Barone et al.	2020	×	Water & air cooled BIPV/T	Mathematical Model	DETECt (MATLAB)	South façade

(*continued on next page*)

Table 2 (*continued*)

Ref	Author	Year	Experimental	System	Other Methods	Tools	Application Area
[68]	Shakouri et al.	2020	×	BIPV/T-DSF system	Simulation	TRNSYS, Design Builder, Pvsyst, EES and MATLAB	Façade
[72]	Zhang et al.	2021	✓	Water-based bifacial BIPV/T with a concentration system	×	×	Roof
[73]	Liang et al.	2021	✓	An active PV/T façade technology	Simulation	A WYSIWYG program	Façade
[74]	Ke et al.	2021	✓	A PCM-assisted BIPV/T unit with dual air channels	Simulation	EnergyPlus	Façade
[75]	Ma et al.	2021	×	Air type BIPV/T	Simulation	EnergyPlus	Roof
[76]	Gagliano et al.	2021	×	Water-based BIPV/T	Simulation	TRNSYS	Façade
[77]	Dumoulin et al.	2021	×	Air based BIPV/T-ASHP	Simulation	TRNSYS	Roof, Façade
[78]	Guo et al.	2022	×	BIPV/T unit with air recovery	Numerical	COMSOL	Façade
[79]	Shahsavar et al.	2022	×	BIPV/T – EAHE system	Mathematical Model	MATLAB	Roof
[80]	Ge et al.	2022	✓	CIGS BIPV/T with water-cooled wall	×	×	Façade
[81]	Shahsavar & Khanmohammadi	2022	×	BIPV/T Heat recovery wheel	Numerical	MATLAB	Roof
[82]	Maturo et al.	2022	×	BIPV/T PCM HX	Mathematical Model	MATLAB	Roof
[83]	Kim et al.	2022	✓	Air type BIPV/T	×	×	Roof
[84]	Zhang et al.	2023	✓	PV/T-DSV	Mathematical Model	MATLAB	Window
[85]	Zhao et al.	2023	✓	Air-type BIPVT coupled water-cooled wall	×	×	Façade
[86]	Abdalgadir et al.	2023	×	BIPV/T-AHU	Mathematical Model	MATLAB	Façade
[87]	Su et al.	2023	✓	PV-PCM-Trombe Wall	×	×	Façade
[88]	Ke et al.	2023	✓	CdTe multi-layer PV window system with ventilation enhanced with PCM	×	×	Window
[89]	Ali Sulaiman Alsagri	2024	×	HP-PV/T-PCM	Mathematical Model	MATLAB	Roof
[90]	Wang et al.	2024	×	BIPV/T-energy pile GSHP	Simulation	TRNSYS jEPlus + EA	Roof
[91]	Lukasik & Wajs	2024	✓	BIPV/T roof tile	CFD	ANSYS Fluent	Roof
[92]	Beigi et al.	2024	×	BIPV/T with ground heat exchanger	Simulation	TRNSYS MATLAB	Roof
[93]	Karunyasopon et al.	2024	×	BIPV/T double-skin façades (BIPV/T-DSF)	Simulation	DesignBuilder	Façade
[94]	Liu et al.	2025	✓	Building-integrated concentrating photovoltaic/thermal (CPV/T) solar collector	CFD Mathematical Model	ANSYS Fluent MATLAB	Roof
[95]	Xiao et al.	2025	×	Air type BIPV/T	Simulation	Ladybug Tools	Façade

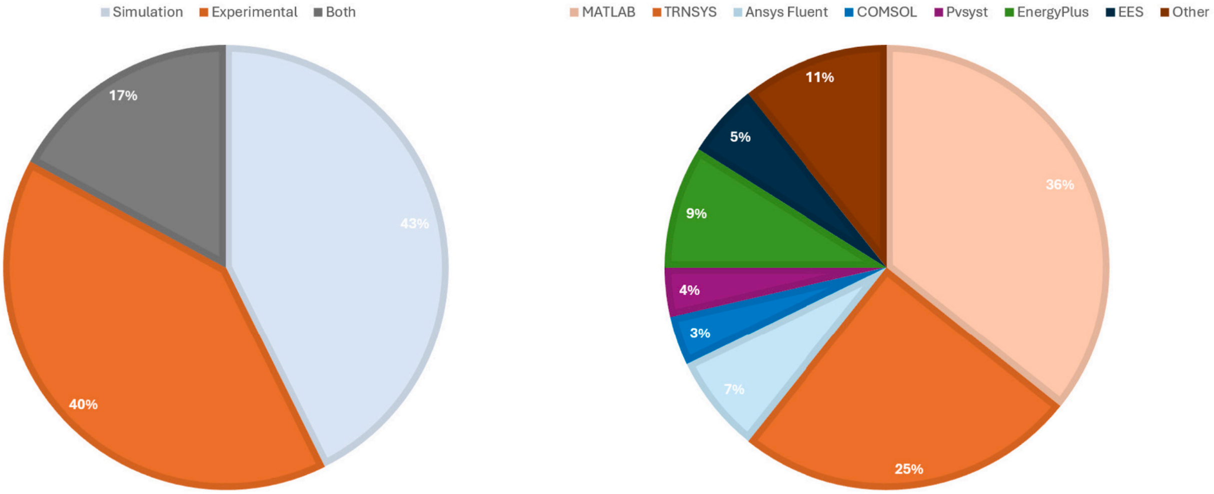

Fig. 4. Types of studies and distribution of tools used.

demonstrate better thermal performance than air-cooled systems, but at higher costs [11]. Additionally, researchers have explored various circulation mechanisms, with a predominant focus on either forced or natural circulation methods. Current BIPV/T solar collectors primarily feature cooling channels on the rear surface, enabling PV modules to capture thermal energy through heat transfer from the back of the panels, rather than directly from the sunlight itself. Spiral flow solar collectors, serpentine tube systems, and aluminium tube-plate cooling designs are typical combinations.

A recent study developed a concentrating photovoltaic/thermal (CPV/T) solar collector that comprised six Fresnel collector units, each of which had a separate photovoltaic and photothermal module [94]. The experimental optical efficiency (43.35 %) is much less than the theoretical prediction (74.29 %), which arises largely from suboptimal optical components such as Fresnel lenses and such split-spectrum splitting elements. Such a performance gap could be bridged by enhancing material selection through the use of anti-reflective coatings, high-precision Fresnel lenses, and manufacturing tolerances. Although the system is built for use in buildings, there have been no experimental tests conducted to determine its suitability for use in applications, e.g., on a building façade or rooftop. This limitation is frequently noted in several studies.

Zadshir et al. [101] developed a unique solar panel design featuring a protective glass layer on top and a sandwiching layer of ethylene vinyl acetate (EVA) around the photovoltaic cells. The panel integrates a foamed aluminium layer at the back with embedded aluminium tubes, enhancing conductivity. The power output increased by 30.2 % due to the cooling system. However, the experimental time frame lasted 160 min until researchers reached steady-state testing conditions. The analysis of how the BIPV/T system might perform over extended periods was absent from the study because it didn't examine material deterioration, hydronic system clogging, and performance changes over time.

Innovative designs, such as PV/T double-skin façades (PV/T-DSF) [102,103] and PV ventilated windows, integrate BIPVT systems into building envelopes to enhance insulation, regulate indoor temperatures, and optimise energy performance. These systems not only contribute to net-zero energy goals but also maintain aesthetic appeal while improving air quality through natural ventilation. In Ref. [104], authors described the integration of PCMs into a CdTe multi-layer photovoltaic window with ventilation system. Two sets of continuous, full-day experiments were conducted under various operational modes. The findings revealed that this advanced system could efficiently fulfill various roles, such as space heating, electricity generation, thermal insulation, and ventilation cooling. Zhao et al. [105] selected the copper indium gallium selenide (CIGS) PV glass device for their experimental setup, with a 35 mm wide ventilation channel insulated from the indoor space on the back. An outdoor inverter axial fan was employed to uniformly cool the PV modules, featuring an adjustable ventilation flow rate. The BIPV/T façade structure proposed by Yang et al. [106], illustrated in Fig. 5 (a), comprises six key components: a protective glass cover shielding PV cells from dust and moisture, an air gap between the glass and PV panel, a PV module that converts solar energy into electricity, an aluminum refrigerant channel (R410a) for heat transfer, a thermal insulation layer minimising heat loss, and the building's original wall. The system demonstrates high thermal efficiency, with 1 m^2 of the façade generating at least 253.3 kWh of thermal energy per month, sufficient to meet the domestic hot water demand for 389 m^2 of building area.

Enhancing indoor air quality is a critical aspect of achieving optimal indoor comfort, with innovative designs targeting the removal of harmful pollutants like formaldehyde. Human health is adversely affected by indoor formaldehyde; to mitigate this, a thermal-catalytic CdTe PV double-skin ventilated window is proposed as a removal solution the design is shown in Fig. 5(b) [107]. Traditional BIPV/T systems use open-loop cooling with pumps, limiting flexibility, whereas Bu et al. [108] proposed a novel closed-loop, naturally circulating BIPV/T system as shown in Fig. 5(c). This system features a four-layered wall comprising a transparent glazing, a flowing water layer for thermal energy collection, a PV layer attached to a brick wall, and water pipes at the top and bottom for circulation. As solar heat warms the water, density differences drive natural circulation, transferring heat to a heat exchanger, which cools the water for domestic use and sustains continuous heat collection.

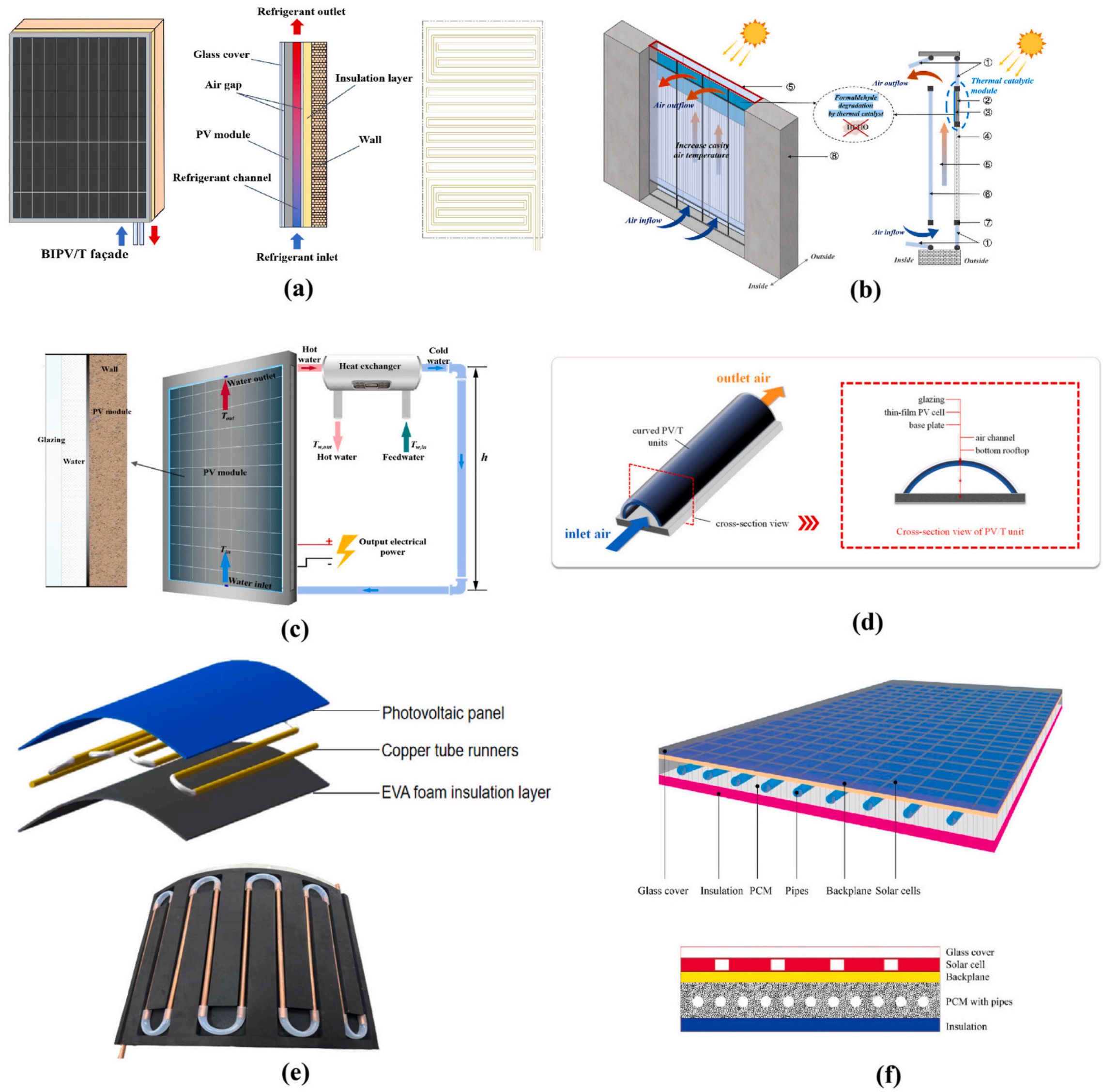

Fig. 5. Some recent BIPV/T Designs adopted from ref [106–115].

Expanding on innovative designs, Tian et al. [109] developed a water-based curved PV/T roof equipped with flexible photovoltaic cells, engineered to produce electricity, deliver hot water during non-heating periods, and maintain the structural integrity of the curved roof design as shown in Fig. 5(d). Similarly, in Ref. [110], the same authors introduced a bent solar balcony integrated with a flexible photovoltaic/thermal (PV/T) system, designed to enable the application of curved PV/T façades that can generate electricity and supply hot water. Another design describes a balcony system primarily composed of curved absorption plates layered with copper pipes, an insulating layer, and flexible thin-film cells. The water circulation module includes copper pipes welded under the absorption plate, main pipes that aggregate water from branch pipes, a water pump, and a storage tank [110]. In Ref. [111], the authors introduce a novel flexible PV/T system designed for installation on building facades with various bend and tilt angles, which enhances both electricity and hot water production, as shown in Fig. 5(e). Demir & Aktacir [112] compared mono-facial and bifacial panels with equal electrical capacity in a BIPV/T system, highlighting the enhancement of rear-side production in bifacial panels using a reflective surface on the building wall. Terashima et al. [113] developed a new panel that incorporates a CIS PV module, featuring an integrated heat exchanger composed of flat aluminium tubes. All components are contained within a panel box, which maintains the dimensions of a standard CIS PV panel. In Ref. [114], the BIPV/T design incorporates a modular hybrid thermo-electric collector into the building envelope, featuring PV glass for electricity, a high-absorptivity absorber plate, and a PCM for energy storage and insulation. An internal heat exchanger within the PCM efficiently heats domestic water, complemented by an insulation layer to minimise energy losses and regulate facade temperature. Shahsavar and Azimi's [115] design consists of a glass cover, PV panel, aluminium plate, PCM compartment, copper pipes embedded in PCM, and insulation as shown in Fig. 5(f). The integration of PCM provides two key

Table 3
Some recent literature on BIPV/T highlights its performance.

Ref	PV/T Design	Electrical Efficiency	Thermal Efficiency	
Tian et al. [120]	CIGS curved PV/water-heating CIGS curve PV/air-heating mode	5.59 %	33.38 %	
		5.88 %	40.60 %	
Wang et al. [111]	Flexible PVT	14.71 %		Flowrate
			56.79 %	0.9 l/min
			48.49 %	0.5 l/min
Zhao et al. [105]	Air-type BIPVT	13.1 %		Flowrate
			23.0 %	0.4 m/s
			51.8 %	2.2 m/s
Terashima et al. [113]	PV/T	13.0 %	60.5 %	
Alsagri et al. [89]	HP-PV/T-PCM	9.79 %	46.33 %	
	HP-PV/T	9.62 %	43.06 %	
Ke et al. [88]	PV/T (Heating Season)	7.39 %		
	PV/T (Cooling Season)	6.33 %		
Tian et al. [109]	Curved water-based photovoltaic/thermal roof combined with polymethyl methacrylate cover (CWPVR-PMMA)	4.80 %	56.01 %	
		5.56 %	33.32 %	
	Curved water-based photovoltaic/thermal roof (CWPVR)			
Wajs et al. [67]	Air-cooled PV roof tile	5.8 %		V Flowrate
			27 %	4 m^3/h
				1 m^3/h
Wang et al. [121]	Micro-channel-flat-plate-heat pipe-based BIPV/T	7.9 %	52.9 %	
Shao et al. [122]	Roll-bond PV/T module	7.2 %	69.3 %	
Kim et al. [83]	Air type BIPV/T	13.5 %	23.9 %	
Liang et al. [123]	Inflatable flat plate PV/T with refrigerant pump	8 %	20 %	
Luo et al. [124]	Hybrid photovoltaic water/air solar wall	7.8 %	52.3 %	
Xu et al. [125]	PV/T wall with double air channel & PCM	10.2 %	57.3 %	Summer
		12.3 %	–	Winter
		11.6 %	56 %	Transition
Jalalizadeh et al. [126]	Glazed BIPV/T collectors and an absorption cooling system	12.36 %		Flow Rate
		12.48 %	46.25 %	0.011 kg/s
			47.71 %	0.041 kg/s

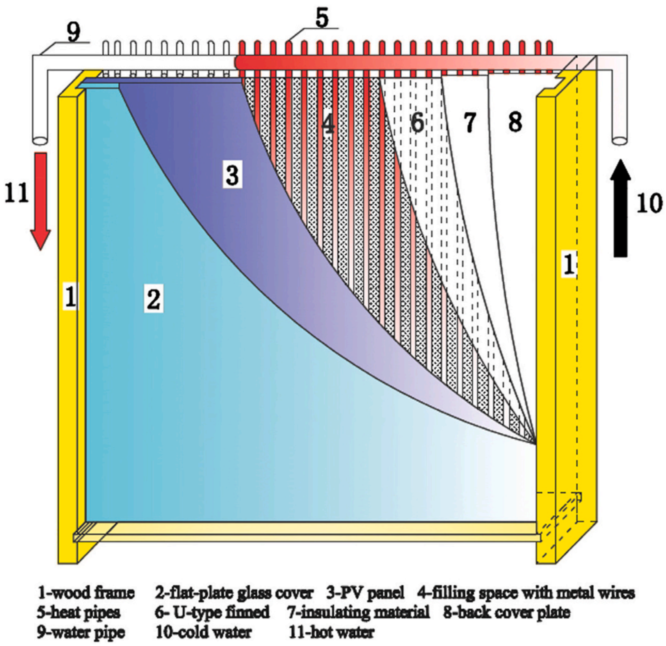

Fig. 6. Schematic heat pipe PV/T module adopted from ref. [43].

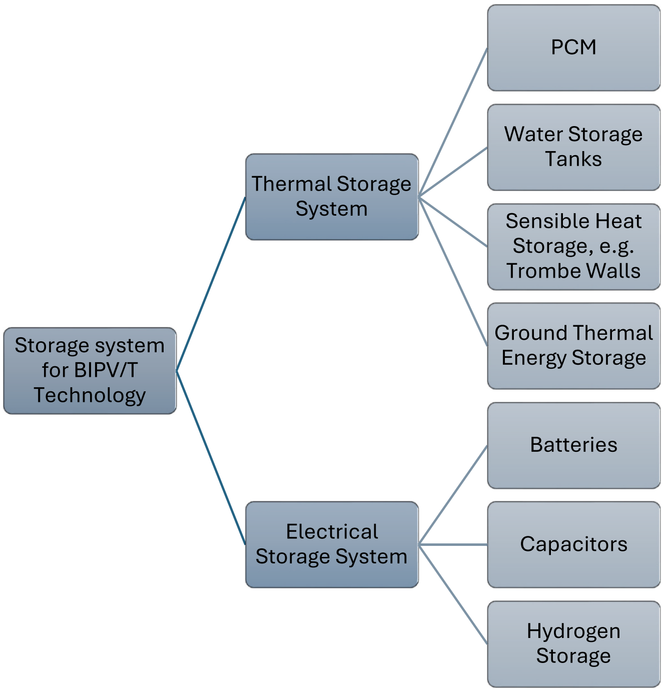

Fig. 7. Frequently utilised energy storage solutions in BIPV/T systems.

advantages: (1) regulating PV panel temperature near ambient levels to improve efficiency and (2) storing thermal energy for post-sunset air heating in the absence of sunlight.

One important factor is that photovoltaic (PV) cells possess distinct characteristics, including their dependence on specific semiconductor materials and their capacity for spectrum conversion. Only the effective spectrum range of PV cells can be utilised for electricity generation. Tomar et al. [116] developed an analytical model to evaluate the temperature-dependent electrical and thermal efficiencies of m-Si, p-Si, a-Si, CdTe, and CIGS photovoltaic modules integrated into insulated test cells, with and without surface water flow. The results indicate that the m-Si module achieved the highest daily average exergy in both scenarios, with and without water flow.

Table 3 presents different literature on BIPV/T and its energy performance. The table shows that the efficiency of PV/T systems can be significantly improved through various configurations, with higher flow rates often enhancing thermal performance. Design innovations, such as PCM integration, hybrid configurations, and optimised airflow channels, enhance thermal efficiency while maintaining moderate electrical efficiency. Performance enhancement strategies for PV/T systems are broadly categorised into three main approaches: geometric modifications, alterations to the working fluid (also changing of flow rates), and the integration of thermal energy storage systems [19]. For instance, in Burdur, Turkey, under identical conditions, including monocrystalline PV cells and the same flow rate, a PV/T air-based system with a foldable geometry [117] demonstrated higher thermal efficiency compared to a system with varying fin designs [118]. While most studies have focused on energy efficiency, many researchers have also examined exergy efficiency. The findings indicate that semi-transparent BIPV/T (BiSPV/T) systems achieve higher energy and exergy efficiency compared to opaque BIPV/T, resulting in lower energy losses and a more positive environmental impact [119].

Early designs attempted to integrate solar thermal panels with photovoltaic (PV) technology by incorporating a liquid-filled energy reservoir heat exchanger box, which was bolted to the underside of the solar PV panel [127]. The liquid was pumped from the house into the box, with a pump regulating flow and outlet temperature. However, these early designs had several drawbacks. Firstly, the heat exchanger typically had an inlet at one end and an outlet at the other, causing a temperature gradient across the panel. The cells closest to the inlet remained cooler than those near the outlet, and due to the interdependent nature of PV cells, the overall panel performance was limited by the hottest cell. Additionally, the liquid needed to be in constant contact with the back of the panel for effective heat dissipation.

In colder climates, antifreeze solutions like glycol are required to prevent the heat exchanger liquid from freezing. Leakage from joints was also a common issue. Furthermore, the complexity of plumbing made installation more challenging and complicated maintenance and repairs. Air- and gas-based PV/T systems addressed these issues; however, water or other liquids offer superior thermal energy capture. The heat pipe-based BIPV/T systems or heat pipe-PCM configurations can achieve superior electrical, thermal, and overall efficiency [89]. Unlike traditional water-based systems, these designs eliminate the need for water to flow across the entire rear surface of the panel, instead transferring heat directly to a condenser for collection (see Fig. 6) [43]. Additionally, by selecting an appropriate working fluid, heat pipe PV/T collectors offer excellent antifreeze properties, making them more effective in cold climates compared to conventional water-based collectors [128]. For air-based PV/T systems, the air box or channel must be designed to be

Table 4
BIPV/Ts with different configurations.

Ref	System	Application Category	Thermal System	Novelty	Application Area	Building Type	Main Findings
Sohani et al. [185]	Air type BIPV/T	Water supply	Cold & Hot water storage	Introducing a solid desiccant for air heat recovery during cooling operations	Façade	1-story	Generating 50 % more electricity while cutting equipment heating and cooling loads by 60 %
Ren et al. [186]	BIPVT- heat pipe	Heating & cooling load	Water Tank	Micro heat pipe array (MHPA)-BIPVT-based multi-energy complementary heat pump system	Rooftop	2-story	This system can supply 61.2 % of the energy needed for year-round refrigeration, heating, and electricity.
Nghana et al. [187]	Air type BIPV/T	Space heating	Boiler, Tank	Attaching transverse ribs to the air channel of the BIPV/T system	Façade	–	Transverse ribs increased heat removal by 2.73 times, lowering PV temperature by 30.5 % and improving efficiency by 11.3 %
Ke et al. [188]	PCM-PV trombe wall	Passive space heating	PCM	Three PCM-PV trombe wall systems with PCM layers in varying positions were proposed	Façade	–	The PV trombe wall, with a PCM layer on the absorber's back, showed the highest electrical but lowest passive heating performance
Karunyasopon et al. [189]	BIPV/T-DSF	Passive heating and cooling	–	Non-ventilated and ventilated cavity BIPV/T-DSF systems, along with an integrated configuration, are presented	Façade	Single room	Offers significant potential for net-zero energy buildings while improving occupant thermal comfort
Karami et al. [190]	BIPVT-based trigeneration systems	Cooling load	Water Tank Boiler	Comparison of trigeneration systems based on BIPVT that use both absorption and vapour compression chillers	Rooftop & Façade	Mid-rise	BIPVT- compression chiller generated more electricity than BIPVT-absorption chiller in colder months, with an average thermal solar fraction 27 % higher
Khanmohammadi et al. [191]	Air-based BIPV/T	Pre-heating/pre-cooling	Thermal Wheel	Developing a novel waste heat recovery system combining an air-based BIPV/T collector with a Thermal Wheel	Rooftop	Mid-rise	BIPV/T-TW system excels in thermal performance, while the BIPV/T system achieves superior electrical performance
Buonomano et al. [192]	Flat-plate PVT solar collectors	Space heating and cooling, DHW	Heat Pump	Exergy and energy analysis of high-rise buildings	South Façade	High-rise	Electricity storage systems average 90 % exergy efficiency, while condensing boilers achieve only 2 %
Erixno et al. [193]	Water Type flat plate PV/T	DHW	Hot-water Tank	Real-time analysis of electricity and heat coverage performance	Rooftop	1-story	System efficiency declined annually: 1.20 % electrical, 1.89 % thermal
Shahsavar et al. [194]	Air type BIPV/T	Heating and cooling	Thermal wheel	The MOGA method was employed to optimise both covered and uncovered BIPVT-SRHX (sensible rotary heat exchanger) systems	Rooftop	2-story	The system with a cover generates slightly more total energy compared to the system without a glass cover
Missoum et al. [195]	Water type BIPV/T	Space heating, Cooling, DHW	Adsorption chiller Water storage tank	Solar polygeneration system (BIPV/T + heat pump + adsorption chiller)	Rooftop	Mid-story	Solar collectors can meet over 56 % of annual heating needs and 72 % of electricity demands
Hasan et al. [196]	Air type BIV/T	Heating	–	An empirical study analysed how ASHP performance varies when paired with an open-loop air-based BIPV/T system	South, east & west Façade	Mid-story	A BIPV/T array can supply the ASHP compressor's power demand in some spring months and reduce it by

(*continued on next page*)

Table 4 (*continued*)

Ref	System	Application Category	Thermal System	Novelty	Application Area	Building Type	Main Findings
							up to 50 % in colder winter months
Gaucher-Loksts et al. [197]	Air type BIPV/T	DHW	Water Heater	Optimising BIPV/T air-source heat pump water heater (HPWH) by determining the ideal thermal storage, building, and heat pump size for maximum system flexibility	Roof	1-story	Using solarium air as a heat pump source reduced energy use by over 80 %, with optimal tank volumes of 300–600 L for a 116 m^2 house

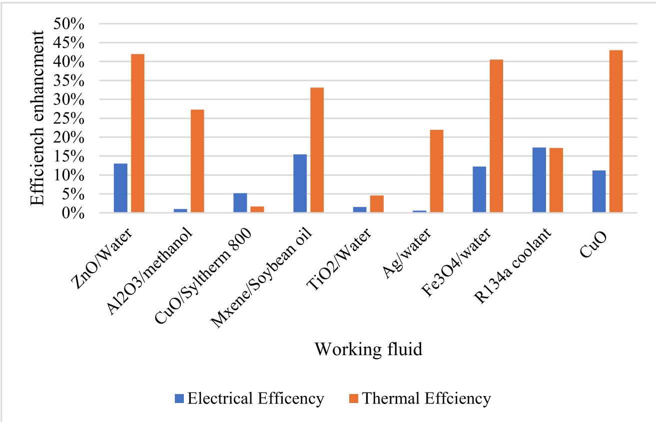

Fig. 8. Performance improvements of different PV/T liquid-based systems [19,58,153].

simple enough for factory installation beneath the solar panel or for retrofitting onto existing rooftop or high-rise façade installations.

Advanced configurations, such as PV thermoelectric systems, demonstrate considerable potential for achieving net-zero energy targets, particularly in building applications such as roofs and façades [129]. A PV thermoelectric system integrates photovoltaic modules with thermoelectric devices, which are solid-state components capable of functioning either as power generators or as cooling devices [130]. In a PV thermoelectric generator system, the thermoelectric devices operate as energy generators, drawing on the thermal heat produced by the photovoltaic module without requiring additional electrical input. In contrast, in a PV thermoelectric cooling system, thermoelectric devices function as cooling units and consume electrical energy to reduce the operating temperature of the photovoltaic module. Moshwan et al. [131] reported that PV thermoelectric generator systems were capable of producing 8 %–38 % more electricity compared to standalone photovoltaic systems, highlighting their strong potential as an effective strategy for advancing net-zero building performance.

Radiative cooling in solar photovoltaic and photovoltaic/thermal systems has advanced significantly in recent years due to progress in material science and related technologies [132]. Although solar energy collection and long-wave heat dissipation (above 3 μm) operate in opposite directions, it is now possible to combine these mechanisms within a single system to maximise energy utilisation [133]. Radiative cooling has been shown to effectively lower the operating temperature of photovoltaic modules, thereby enhancing efficiency, while also extending the operational period of photovoltaic and photovoltaic/thermal collectors into nighttime and colder conditions by introducing a passive cooling mode. Kwan et al. [134] analysed the feasibility of integrating the radiative cooling capacity of standard photovoltaic cells into photovoltaic–thermoelectric cooling systems, demonstrating that this approach can nearly double the equivalent solar-to-cooling coefficient of performance compared to conventional photovoltaic–thermoelectric configurations. More recently, researchers have proposed the comprehensive integration of radiative cooling with photovoltaic and photovoltaic/thermal systems as a pathway toward developing zero-energy buildings. Depending on the working medium, such hybrid systems are generally categorised as air-based, water-based, or heat pump-based designs.

4.2.1. *Thermal energy storage and management equipment*

Heat generated by PV/T systems can either be stored for later use or utilised directly. When directly utilised, the thermal energy can support diverse applications, including indoor radiant floor heating, swimming pool temperature regulation, and thermal support for solar-integrated agricultural systems [39]. Various heat management strategies can be implemented in BIPV/T systems, including fresh air preheating, domestic hot water (DHW) preheating using an air-to-water heat exchanger, combined domestic hot water and space heating through an air-to-water heat pump, and DHW heating utilising a heat pump water heater [135]. Fig. 7 represents various types of storage systems used in BIPV/T technology.

One common method is the use of thermal energy storage (TES) tanks [136], which store heat in insulated tanks containing water or other thermal storage media, providing a reliable source for DHW, space heating, or industrial applications. Additionally, phase change materials (PCMs) are frequently integrated into BIPV/T systems to store latent heat, enabling efficient thermal energy storage and release at nearly constant temperatures, enhancing the system's thermal regulation capabilities. A study determined that the optimal thickness for a phase change material (PCM) applied as a thermal storage layer on the back of a BIPV/T module is 77.2 mm, through dynamic multi-objective optimisation (MOO) [137]. Ground heat storage techniques, such as energy piles or borehole thermal energy storage, are also employed, allowing excess heat to be transferred and stored underground for later use. In architectural integrations, PCM-embedded Trombe walls store heat captured by BIPV/T systems and provide passive heating during colder periods. A Trombe wall is a passive solar technology often referred to as a thermal storage wall or passive solar wall. In Ref. [114], BIPV/T design incorporates a modular hybrid thermo-electric collector into the building envelope, featuring PV glass for electricity, a high-absorptivity absorber plate, and a PCM for energy storage and insulation. An internal heat exchanger within the PCM efficiently heats domestic water, complemented by an insulation layer to minimise energy losses and regulate facade temperature.

Energy pile systems integrate geothermal energy solutions with BIPV/T, utilising structural elements for heat exchange. This approach effectively balances soil thermal loads and enhances energy efficiency in both heating and cooling applications. Researchers proposed a BIPV/T-energy pile GSHP system that both heats and cools buildings, using the energy pile as a heat source in winter and a heat sink in summer [138]. This system also generates electricity, captures and stores solar waste heat in the heat storage tank (HST), and uses low-temperature fluid from energy piles to balance soil temperature and boost electrical efficiency [90]. Integrated heat exchangers, including air-to-water or air-to-air types, efficiently capture heat from the BIPV/T system and distribute it to storage or directly to applications like space heating or DHW. Wang and You [139] introduced a BIPV/T energy pile system aimed at addressing soil thermal imbalances, improving electrical performance, and simultaneously reducing building energy demands. The system captures waste heat from photovoltaic/thermal collectors to regulate ground temperatures, while low-temperature fluid from energy piles cools the collectors, enhancing electricity generation efficiency and minimising heating requirements.

The use of thermal wheel (TW) is also investigated in literature [140–143]. In BIPV/T systems, a thermal wheel transfers heat between incoming and outgoing air streams, enhancing heat recovery and improving thermal efficiency. During summer, the TW cools the exterior warm air by transferring heat with building exhaust as it enters the structure. The BIPVT system guides two separate exhaust air currents, which contribute to PV module cooling for improved performance. In winter, the process is reversed, where the outdoor air receives preheating treatment by absorbing building exhaust heat inside the TW and achieves ongoing heating during its passage through the BIPVT system.

Heat pumps (HPs) have emerged as a dominant technology in the building energy sector. The adoption of air-source heat pumps (ASHPs) in energy systems for nZEBs is experiencing significant growth. Moreover, the performance of heat pumps can be significantly enhanced when coupled with solar energy. This can be achieved by integrating BIPV/Ts into the building's façade, which can reduce energy consumption by approximately 9–10 % [11]. The efficiency gains can be further increased with the addition of a thermal storage system, enabling even greater energy savings. In a case study in Madrid, Spain, a residential building consisting of 54 dwellings

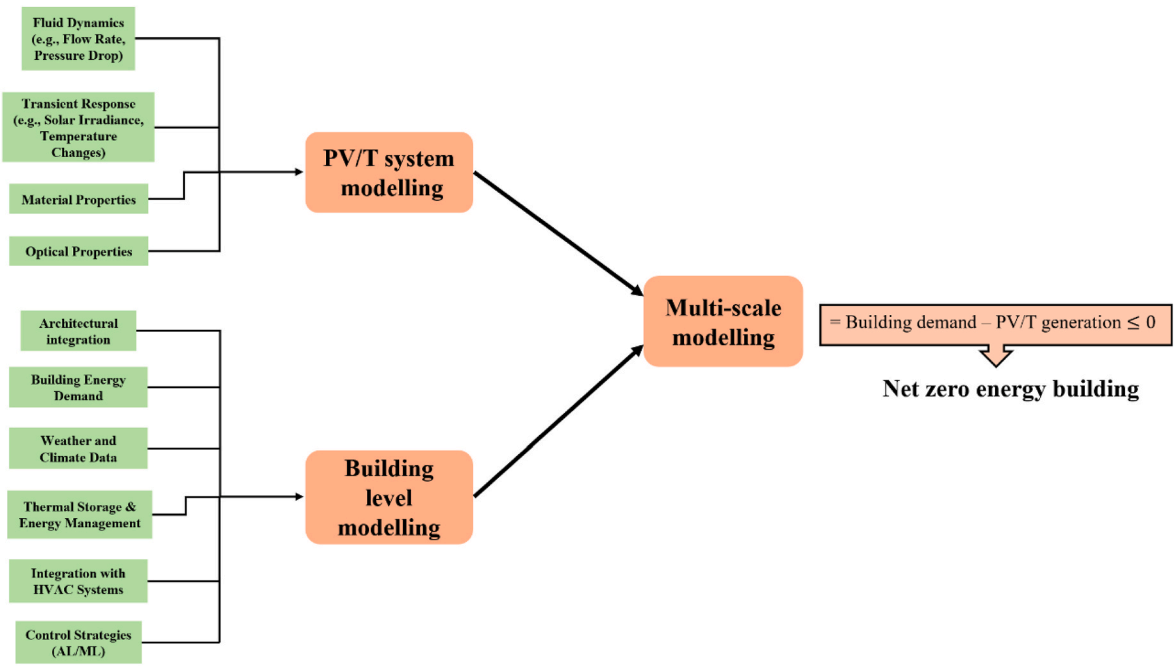

Fig. 9. Modelling framework for BIPV/T systems.

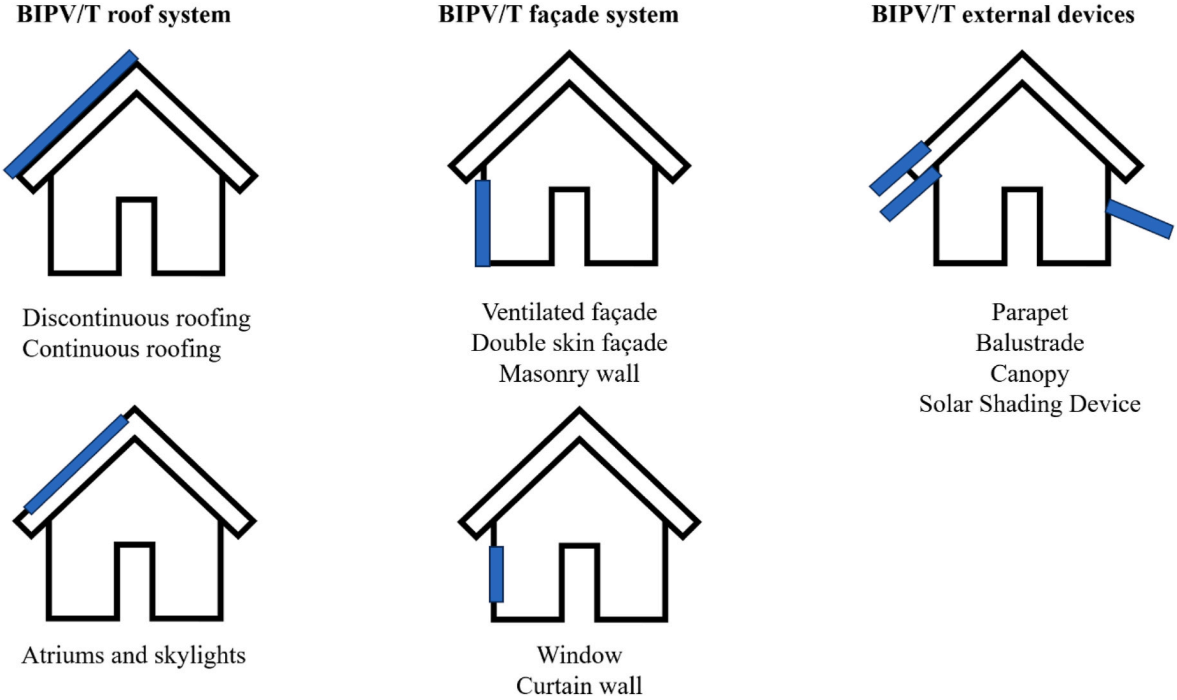

Fig. 10. Potential locations for integrating PV/T modules within a building.

received two heat pump systems installed for space heating and domestic hot water requirements [144]. A combination of PV/T systems integrated with heat pumps and underfloor heating synergistically decreased heating energy usage by a minimum of 19.9 %. With the integration of photovoltaic-based exterior power generation, the total yearly energy use declined by a minimum of 20.7 % during annual performance measurements. The fusion of renewable energy technologies effectively maximises residential building energy efficiency according to experimental findings. Ground-source heat pumps (GSHPs) offer higher energy efficiency but face significant barriers to adoption due to their high initial costs [145]. Beyond heating, heat pumps also play a crucial role in cooling applications within buildings. Table 4 categorises various thermal applications based on different BIPV/T designs.

Karami & Jalalizadeh [146], identified a significant issue with BIPV/T systems in cold winter, where heat loss and low water temperature fail to meet building heating standards. Their study proposes a novel façade-mounted photovoltaic/thermal-heat pump system (BIPV/T-HP) and develops a numerical model to evaluate its heating performance in high-rise buildings. Elevated flow

Fig. 11. The SOLAR XXI building's integrated BIPV/T system [171].

velocities reduce water outlet temperatures, which enables extended heat pump functionality for increased thermal capacity, although backup air-source heat pumps assess system performance in low solar intensity zones. This research presents numerical models for BIPV/T-HP system analysis, but does not perform experimental result validation or conduct actual field tests on these systems.

BIPV/T air-handling units (AUH) facilitate the distribution of preheated air, making them highly effective for space heating and ventilation in colder climates, thereby reducing reliance on traditional heating systems [147]. This integration enhances indoor thermal comfort while improving overall building energy efficiency. Additionally, coupling BIPV/T AHUs with thermal storage systems can further optimise energy utilisation by storing excess heat for use during periods of low solar availability.

Thermal energy storage tanks are the most common storage solution, effectively meeting domestic hot water demands. However, selecting the appropriate tank size is crucial; additionally, space constraints and thermal leakage remain key challenges. While PCMs handle latent heat storage to boost thermal regulation and electrical performance at steady temperatures, they encounter both installation cost problems and complicated implementation issues [13]. PCM-embedded Trombe walls enable passive heating and structural integration, but struggle in extreme climates, and PCM hazards include flammability and leakage, which should be taken into account when designing, producing, and using BIPV/T systems [19]. Ground heat storage (e.g., energy piles) provides sustainable geothermal balancing, but it requires a high upfront investment and site-specific adaptations. Thermal wheels enhance heat recovery and ventilation efficiency, but they also present challenges related to electric power consumption and airflow management.

Heat pumps, particularly air- and ground-source variants, synergise with BIPV/T to reduce energy use by 9–20 %, but face barriers such as inefficiencies in cold climates. When expenses, energy savings, and incentives or subsidies are taken into account, BIPV/T-integrated HP systems are financially feasible [148]. The absence of thermal demands in BIPV/T systems can result in device overheating, reduced efficiency, and possible stagnation damage, as well as high fluid pressures. Pugsley et al. [149,150] suggested a unique solution that combines BIPV with planar liquid-vapour thermal diodes and integrated collector-storage solar water heater features. The design supports BIPV/T functionality and maintains overnight heat storage while reducing both parasitic heat losses and device temperature overheating. This design framework faces crucial challenges regarding expenses while performing structural loading and maintaining material sustainability. There is significant scope for improvement in hybrid systems (e.g., PCMs with heat pumps), as well as in advanced materials for cost-effective, durable, and data-driven thermal management, and in cold-climate solutions.

4.2.2. Types of working fluid

Different working fluids and coolants have been utilised in the design of PV/T systems to capture thermal energy. Many researchers have employed air as a cooling medium through various designs. Additionally, there are vast instances where water has been used as a

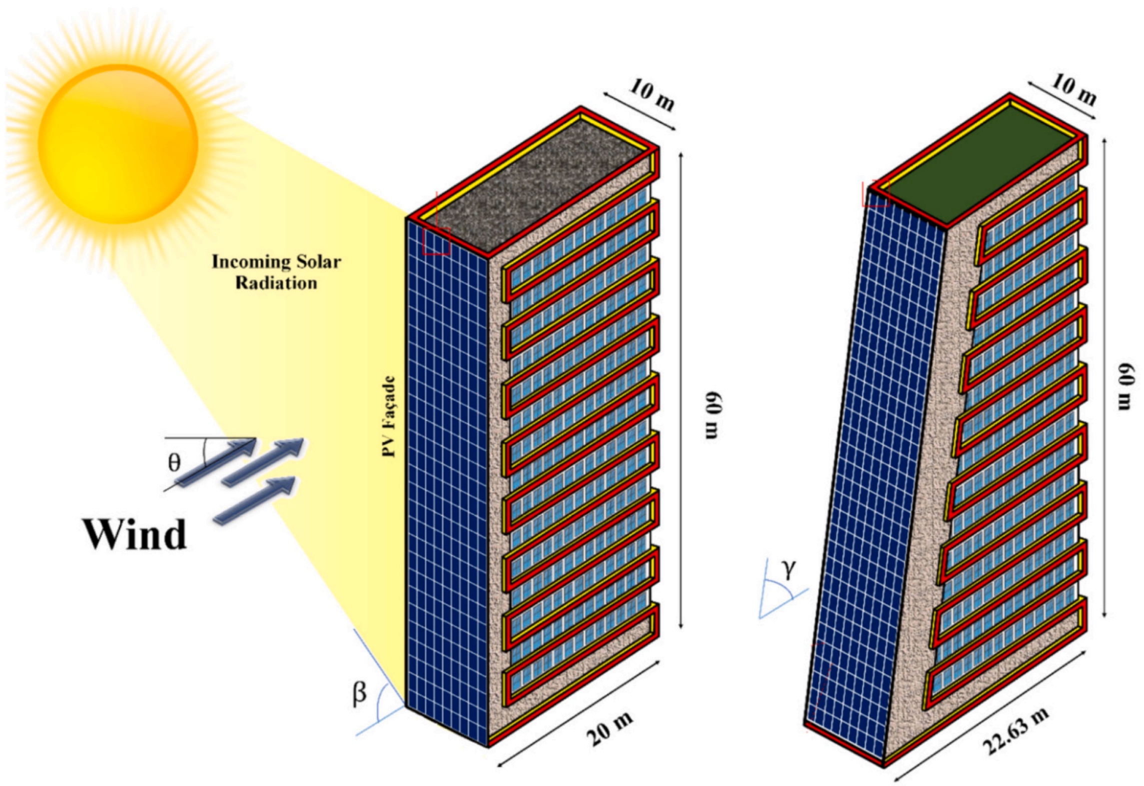

Fig. 12. Schematic of modeled buildings with PV/T façades in both perpendicular and slanted orientations adopted from ref. [180].

heat transfer fluid [113]. Various PCMs, refrigerant [151] and other chemical compounds have also been explored for this purpose. The melting point of the phase change material influences the surface temperature of the photovoltaic cell [65]. Enhancing the water flow rate boosts the rate of heat transfer between the system and the water stream.

A recent review by Kazem et al. [25] examined various types of working fluids used in PV/T systems and highlighted significant improvements in thermal and electrical efficiencies with the incorporation of specific nanoparticles, as reported in the literature. The review further indicated that CuO nanofluid combined with air-based PV/T systems achieves superior thermal and electrical efficiencies compared to water-based or solely air-based PV/T systems. Shan et al. constructed a PV/T collector simulation model that uses R410a as the working fluid to examine the thermal and photovoltaic performance of the system [32]. Sun et al. [152] conducted a numerical study to analyse the exergy efficiency of electricity, thermal energy, and overall performance in a building-integrated photovoltaic thermal (BIPVT) solar collector utilising Al_2O_3/water coolant. The results demonstrated a 60 % enhancement in useful thermal exergy efficiency and a 1.26 % improvement in electrical exergy efficiency. Fig. 8 shows efficiency enhancements for various PV/T liquid systems [19,58,153]. However, it's worth mentioning that this figure shows the comparison of efficiency enhancement in different working fluids only. Design and flow rates are also important factors that vary and are not the same for each experiment.

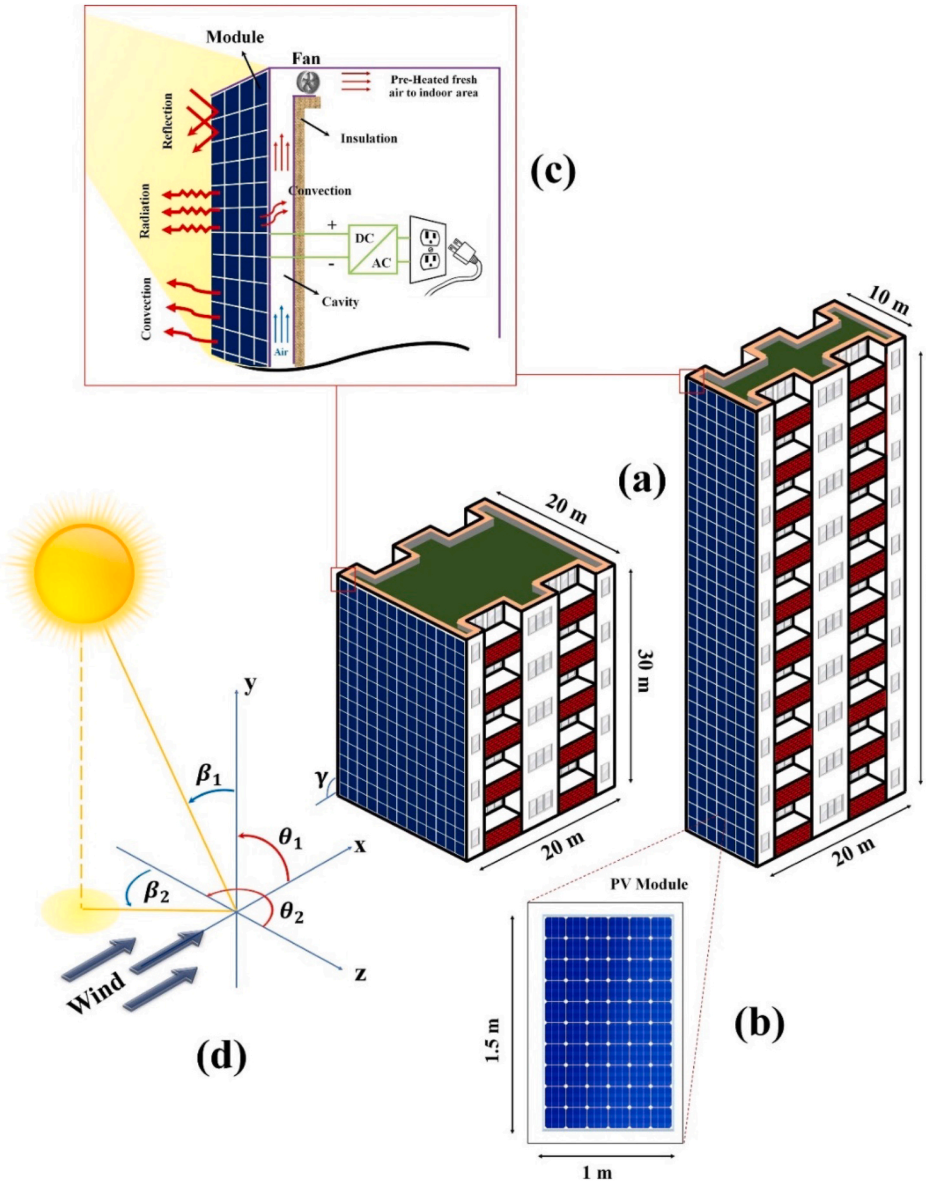

Fig. 13. Schematic design of BIPV/T systems for mid-rise and high-rise buildings (a) PV/T façade-equipped buildings (b) PV cell configuration per module (c) Energy balance of PV/T façade modules (d) Wind direction and sun position relative to buildings adopted from ref. [182].

Fig. 14. Recent designs for integrating PV/T in high-rise building facades (top image), traditional rooftop architecture (middle image), and a two-story building facade (bottom image) [173,180,181].

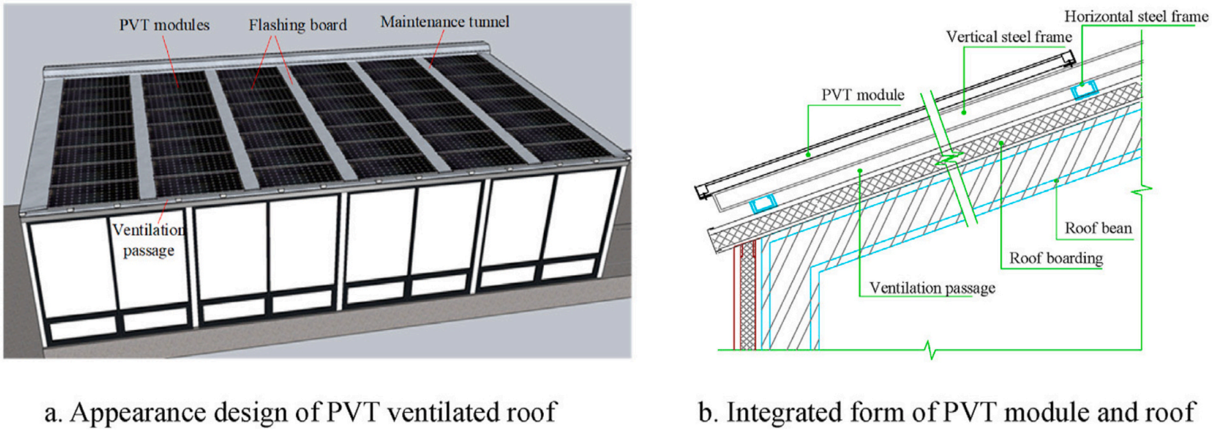

Fig. 15. Design of PV/T ventilated roof adopted from ref. [180].

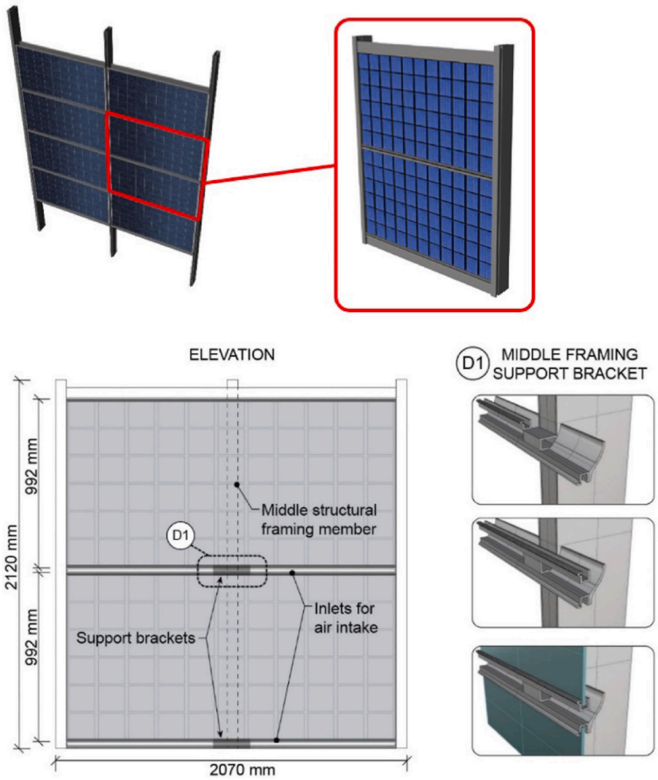

Fig. 16. BIPV/T curtain wall prototype adopted from [184].

4.3. Modelling approaches of BIPV/T systems

In BIPV/T systems, modelling can be categorised into micro-modelling (component-level) and macro-modelling (system-level) [154]. Micro-modelling focuses on capturing detailed physical interactions within individual components [155]. In the BIPV/T system, this modelling approach focuses on the detailed design of PV/T panels, heat exchangers, and fluid channels. It enables a granular analysis of heat transfer mechanisms, such as conduction, convection, and radiation, at the microscale, particularly within PV cell layers, absorber plates, and fluid channels. Computational techniques such as 3D computational fluid dynamics (CFD), the Finite Element Method (FEM), and lumped parameter models are commonly used to simulate airflow patterns, thermal gradients, and optical losses [156]. Additionally, micro-modelling incorporates material-specific properties, such as temperature-dependent PV efficiency and the thermal performance of selective coatings. However, achieving high accuracy requires high-resolution meshing, increasing

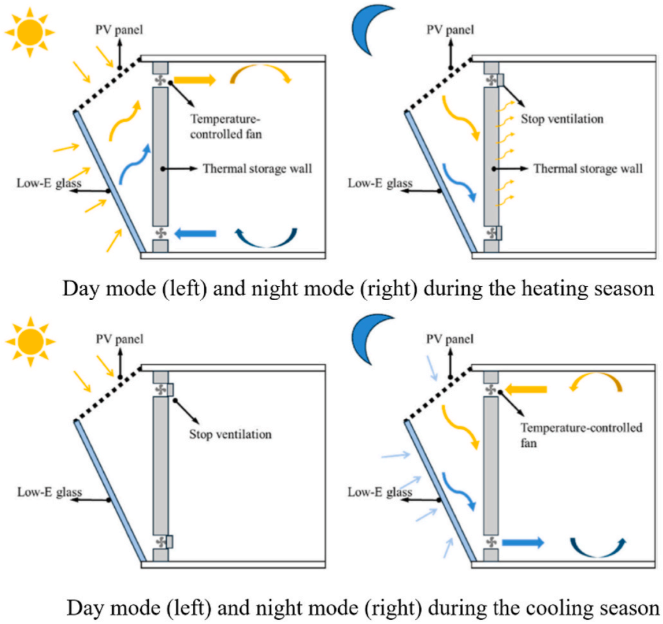

Fig. 17. Design and operational mode for maximising thermal comfort adopted from ref. [95].

computational intensity, and often assumes idealised boundary conditions that may not fully reflect real-world variability.

Macro-modelling evaluates the overall performance of BIPV/T systems within buildings, considering interactions with HVAC systems, thermal storage, and occupant behaviour [157]. It simulates energy flows related to heating, cooling, and electricity consumption, utilising tools such as TRNSYS and EnergyPlus. To enhance accuracy, macro-modelling integrates real-world variables such as weather conditions, occupancy patterns, electricity tariffs, and grid connectivity while also assessing economic and environmental impacts, including lifecycle costs, payback periods, and carbon savings [158]. Methods such as system dynamics simulations track energy flows, machine learning (ML) predicts optimal control strategies, and sensitivity analysis identifies key parameters affecting system performance. Despite its benefits, macro-modelling often simplifies component-level physics and relies on averaged weather data, which may overlook short-term solar fluctuations. Addressing these limitations is essential for improving the accuracy of BIPV/T system simulations and optimising their real-world implementation. Table 2 presents various modelling methods and tools.

Most PV/T models integrated into commercial software packages, such as TRNSYS, are based on the Florschuetz model for PV/T collectors [159]. This model modifies the parameters of the Hottel-Whillier thermal analysis model for flat plate collectors [160] to account for the integration of PV cells into the thermal collector's absorber. Specifically, it adjusts the heat removal factor (FR), the overall heat loss coefficient (UL), and the total incident solar radiation (S). However, these models face challenges as the values for FR and UL are either unavailable due to the absence of standardised testing data or are difficult to calculate accurately, making their application more complex. The Multi-Objective Genetic Algorithm (MOGA) optimisation method integrates input parameters, utilises EnergyPlus to simulate energy performance for each scenario, and delivers optimal solutions.

For more accurate BIPV/T system design, multi-scale modelling integrates micro- and macro-level approaches to enhance system efficiency and performance. In a bottom-up approach, micro-model outputs, such as the impact of temperature on PV efficiency, serve as input parameters for macro-models. Conversely, a top-down approach uses macro-level constraints, such as building energy demand, to refine micro-model optimisations, including heat exchanger design. For instance, a micro-model may predict PV cell temperature rise under specific irradiance. At the same time, the macro-model utilises this data to estimate annual energy savings when integrated into a building. This interconnected approach ensures a more comprehensive and accurate BIPV/T system design, aligning component-level performance with overall building energy efficiency. Fig. 9 shows an overall modelling framework for BIPV/T systems aimed at achieving net-zero energy buildings.

Recent studies emphasise the growing role of AI and machine learning (AI/ML) in optimising BIPV/T systems. Sohani et al. [161, 162] reviewed ML applications in PV systems, highlighting their early-stage adoption and limitations in generalizability, necessitating further research for efficiency improvements. Shboul et al. [163] utilised feed-forward neural networks to predict hourly weather parameters, facilitating dynamic system adaptation. Javadijam et al. [164] applied NSGA-II and TOPSIS algorithms to optimise energy output, heat recovery, and payback periods in BIPV/T thermoelectric systems. Alsarraf et al. [165] enhanced artificial neural network (ANN) predictions for a Kuwaiti BIPV/T system using a PSO-ANN hybrid model, achieving near-perfect accuracy ($R^2 \approx 0.999$). Wang et al. [166] and Sun et al. [152] employed MATLAB-based AI models for geographic performance optimisation and exergy efficiency prediction using Al_2O_3/water coolant. Additionally, Morovat et al. [167] and Sigounis et al. [168] implemented model predictive control (MPC) for air-based BIPV/T integration, improving thermal-electrical synergy in buildings. These studies demonstrate that AI/ML techniques such as neural networks, hybrid optimisation, and MPC are advancing BIPV/T design through predictive modelling, multi-objective optimisation, and real-time control. However, broader validation and scalability remain critical for widespread adoption.

Most models are validated in controlled laboratory environments, with limited field data accounting for real-world factors such as dust accumulation, shading, and microclimatic variability. Although a recent study by Wang and Ji [169] employed multiscale modelling using MATLAB and TRNSYS, it revealed that the total energy benefits of the building decreased by 28.5 % as dust density increased from 0 g/m^2 to 10 g/m^2. Few models incorporate the embodied energy of materials or conduct lifecycle assessments, which are critical for evaluating the sustainability and environmental impact of BIPV/T systems.

4.4. Architectural integration of BIPV/T

BIPV/T systems stand out due to their superior aesthetic appeal, ability to replace traditional building components, and efficient utilisation of solar energy within the structure, making them a more advantageous choice compared to BAPV/T systems. Innovative designs can seamlessly integrate BIPV/T systems into diverse architectural elements, such as rooftops, facades, roof tiles, windows, Trombe walls, shading structures, and skylights, as shown in Fig. 10.

The large and unsightly layout of conventional trombe walls poses significant challenges to their integration into contemporary architectural designs. Researchers are continuously exploring innovative design approaches to address and overcome these limitations. In developing countries, a significant portion of the building stock consists of aging structures, and retrofitting these buildings with PV/T modules on façades or roofs poses many architectural and engineering challenges [170]. Buonomano et al. [38] highlighted that façade-integrated BIPV/T collectors are less favourable compared to roof-integrated systems due to the relatively lower incident solar radiation on vertical surfaces. Their analysis across various Mediterranean climatic zones revealed that roof-mounted BIPV/T configurations consistently proved to be more economically viable than combined façade and roof-integrated systems, emphasising the advantages of roof integration for maximising energy performance and economic returns in BIPV/T applications. The reason is that the façade-mounted PV solar fields have a longer payback period compared to rooftop applications due to lower thermal energy and electricity generation per unit of façade BIPV/T surface area.

SOLAR XXI building demonstrates an example of a low-energy office located within the renewable energy department of the National Institute of Engineering, Technology, and Innovation in Portugal (see Fig. 11) [171]. Through thoughtful design choices, the building increases thermal performance using passive heating methods, and it maximises energy efficiency by incorporating renewable energy technologies [172]. In the SOLAR XXI building, PV/T systems enhance indoor thermal comfort by utilising recovered heat

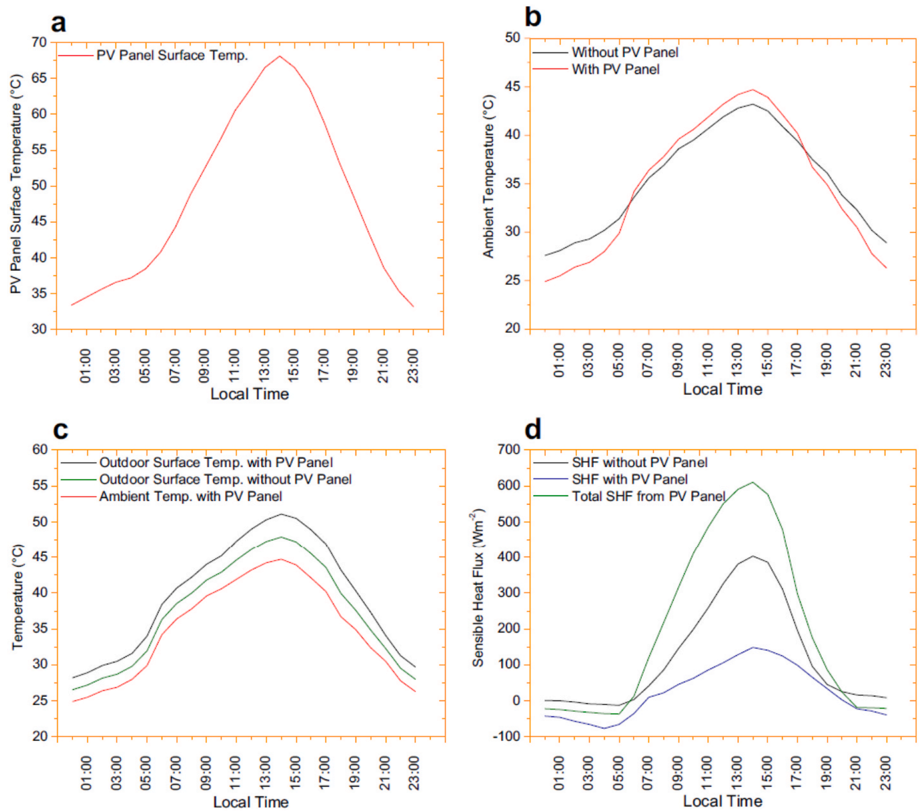

Fig. 18. The two-month average values taken during Sydney's January and February 2017 heat wave are used to demonstrate evidence of local warming in metropolitan settings [210].

Table 5
Summary of literature on the PVHI effect.

Author	Location	Main Findings
Garshasbi et al. [207]	Sydney	Covering 25–100 % of roof areas with PV solar panels can raise ambient air temperatures by 0.6–2.3 °C
H Taha [211]	Los Angeles	0.2 °C drop in summertime midday air temperatures
Ma et al. [212]	Sydney	Peak summer daytime temperatures could drop by 1 °C thanks to urban photovoltaic systems
Berardi & Graham [213]	Ontario	Rooftop photovoltaics may cause urban warming of up to 0.5 °C
Gafford et al. [204]	Southern Arizona	An extensive array of photovoltaic modules caused the air temperature to rise by 1.5 °C during the day and 3–4 °C at night
Broadbent et al. [214]	Southern Arizona	The average daily temperature of the air close to PV arrays was 1.3 °C higher than that of a neighbouring reference location without PV
Khan & Santamouris [210]	Sydney	At the city scale, adding more PV panels can increase surface temperatures by up to 2.3 °C and peak summer ambient temperatures by up to 1.4 °C
Gentle et al. [215]	Sydney	BIPV panels can contribute to the (UHI) effect significantly more than a cool roof

through ventilation. During winter, interior vents are opened to retain warmth, while in summer, exterior vents are opened to prevent overheating. This design increases the system's outlet temperature compared to the inlet temperature, using air from the adjacent thermal zone to support indoor heating [173]. The south wall of this building functions as a PV array, which combines BIPV/T technology to produce 12 MWh per year while fulfilling 67 % of building energy requirements and 70 % of total electrical usage.

A study on nearly zero energy buildings (NZEB) conducted a comparative analysis of different roof configurations and recommended the adoption of a hybrid system [174]. This system integrates BIPV/T panels, which cover 70 % of the roof area, alongside building-integrated solar thermal collectors occupying the remaining 30 %. The reference building consists of three floors and features a rectangular design measuring 15.0 × 24.5 m. Its longitudinal axis is oriented east-west and is divided into ten distinct thermal zones. The examined NZEB meets its entire HVAC energy demand through on-site renewable energy production. Another research indicated that vertical BIPV/T systems integrated into façade applications achieve optimal performance when oriented eastward in Limassol, Cyprus (34.70°N, 33.02°E). This is attributed to the higher incident solar radiation received during morning hours when the sun's rays are nearly perpendicular to the surface [175]. The authors suggested that a 0.1 m air gap in a vertical BIPV/T system is sufficient to prevent PV panel overheating, thereby minimising electrical efficiency losses.

Tian et al. [176,177] proposed replacing the traditional curved south-facing rooftops of Chinese houses with flexible air- or water-based PV/T tiles, integrating modern energy solutions into traditional architectural designs. Zhang et al. [178] proposes an all-focused exterior with a south wall photovoltaic and a north wall sky radiative cooling system (PV-RSC) to enhance summer cooling. The findings of Bezaatpour et al. [179] found that slanted facades which is tilted backward, away from the direct wind direction (for the study tilted angle 85° and 80°) capture more sunlight but generate 4–8 % less energy than perpendicular facades because they retain more heat, leading to higher temperatures that reduce efficiency (see Fig. 12). Their exergy efficiency is also about 2 % lower due to heat retention, even though better wind flow improves cooling. The simulation model was configured for a high-rise building measuring 60 m in height and 10 m in width, incorporating 400 integrated photovoltaic (PV) modules. The BIPV/T system demonstrates greater sustainability under windy conditions, with the perpendicular façade identified as a more favourable option for photovoltaic installations due to its enhanced performance and resilience.

Shao et al. [180] introduced an innovative design for a PV/T ventilated roof that functions as a heat exchanger for a heat pump system. The uniqueness of this design lies in its integrated "sandwich" structure, which combines the PV/T system, heat pump, and building envelope into a seamless unit. This approach eliminates the traditional add-on appearance and enhances the roof's multifunctionality, blending efficiency with aesthetics (see Fig. 15). However, under standard winter weather conditions, the energy-saving performance of the PV/T ventilated roof was found to be limited.

The installation of PV alongside PV/T systems in new buildings enables the accomplishment of nZEB objectives at the design level [181]. Whereas existing building retrofits produce major difficulties during the implementation phase of PV/Ts. A simulation model led by Theokli et al. [173] focused on renovating a 25-year-old multi-story building which stands in the centre of Nicosia, Cyprus. The double façade system incorporated a BIPV/T innovation with an operational Corridor-Type Double Façade solution that operated on separate floors. The research showed that this building retrofit produced both an nZEB-ready structure and budget-effective results.

Fig. 13 illustrates the design by Bezaatpour et al. [182], where 400 PV components are integrated into the façades of both mid & high-rise towers (12,000 m^3 volume, 600 m^2 PV area). The façade is oriented perpendicular to the prevailing wind direction, allowing cold wind (0 °C) to enhance natural cooling and prevent PV overheating, thereby improving system performance. The study evaluates temperature, wind load, and thermal/electrical efficiency for each structure. The system achieves a maximum energy efficiency of 33.28 % and an exergy efficiency of 21.2 % for mid-rise buildings, compared to 37.05 % energy efficiency and 20.9 % exergy efficiency for high-rise buildings. These findings provide valuable insights for future sustainable construction and the optimal design of façade-integrated photovoltaic/thermal systems. Figs. 14–16 provide an overview of various architectural integration designs for BIPV/T systems [95,176,180,183,184]. Additionally, Table 4 summarises literature on design innovations, application areas, and building types. A comparison of application areas between Tables 2 and 4 reveals a significantly higher adoption of rooftop-integrated systems over façade-integrated ones, with limited research on high-rise buildings.

4.4.1. Tilt angle of BIPV/T systems

The tilt angle of a BIPV/T system is a critical parameter for maximising solar irradiance and achieving optimal efficiency. Studies have shown that at lower air mass flow rates, the efficiency difference between a tilt angle of 0° and 90° is substantial [198]. However, at higher air mass flow rates, this efficiency difference becomes negligible. This indicates that air flow rate plays a more important part in the effectiveness of BIPV/T systems compared to tilt angle, emphasising the importance of optimising flow rate in system design. Xiao et al. [95] investigated the influence of tilt angles ranging from 30° to 70° on system performance. Their study revealed that electricity generation peaked at approximately 38°, while the overall system energy use intensity (EUI) reached its minimum between 39° and 41°, as shown in the design shown in Fig. 17. This range was identified as the optimal balance, effectively maximising electricity generation while enhancing solar heat collection during winter and mitigating overheating during summer. This study utilised simulation-based analysis conducted with Ladybug Tools; however, further investigation is required to evaluate its applicability and effectiveness in addressing real-world complexities during implementation. The Ladybug Tools geometric-based analysis workflow does not simulate the electrical behaviour of the entire PV system [199]. Its electrical modelling capabilities are limited and do not support user-defined input for detailed PV system component specifications. However, for thermodynamic simulations, the authors of ref. [95] utilise a custom Python script to modify the EnergyPlus input data file (IDF) for enhanced accuracy. In cases where precise electrical modelling is required, further validation is necessary.

Wang et al. [200] highlighted the impact of frame shadowing on the efficiency of BIPV/T systems. Their findings revealed that the maximum efficiency loss occurs at an azimuthal angle of −45°, where the photovoltaic efficiency of the system is reduced by 2.6 %. In a study, the HDKR/S model (Hay, Davies, Klucher, Reindl/Shadow) was developed as an enhanced version of the HDKR model, incorporating the effects of shading into its mathematical framework [201]. The HDKR model itself is a widely used method for estimating solar radiation on tilted surfaces, integrating direct, diffuse, and reflected solar components to ensure precise energy calculations. The study revealed that for buildings located 10 m horizontally from a BIPV/T system, the optimal tilt angle decreases as the surrounding building's height increases. However, for buildings situated at a horizontal distance exceeding 20 m, the optimal tilt angle remains relatively consistent across all building heights. Another research on the tilt angle of BIPV/T systems revealed that reducing the panel tilt angle enhances shading performance. Taking into account shading, electrical, and thermal efficiencies, the optimal tilt angle is recommended to be between 20° and 28° [202].

5. Impact of BIPV/BIPV-T on the external environment

Currently, nearly half of the world's population lives in urban areas, a figure expected to exceed 60 % by 2030 [203]. The Urban Heat Island (UHI) effect can raise city temperatures by several degrees compared to surrounding rural areas, as urban structures absorb and retain heat. To mitigate global warming, it's clear that reducing fossil fuel use and transitioning to renewable energy sources are essential. Solar PVs are one of the most mature technologies in this transition. However, PV systems also have certain impacts on the built environment that need to be taken into consideration. Studies have reported that the surface temperature of solar panels is often higher than the surrounding ambient air, and on a large scale, this can contribute to an increase in ambient temperature, a phenomenon known as the PV heat island effect [204]. One study observed that nighttime temperatures above a PV plant were consistently 3–4 °C higher than in nearby natural areas, contradicting model-based predictions that PV systems would help cool ambient temperatures [204]. Studies have demonstrated that Building-Integrated Photovoltaics (BIPVs) can elevate the surface temperature of buildings, potentially causing a rise in the temperature of nearby areas [205]. Conversely, BIPVs can also offer shading that may decrease the amount of solar radiation reaching the ground. Large-scale PV panel installations alter the landscape by reducing the albedo, resulting in darker, less reflective surfaces on rooftops [204]. A review article noted that photovoltaic (PV) systems can significantly raise city temperatures during the day, offer some cooling at night, and, in certain climates and building types, may increase energy demand for air conditioning [206].

In another study, using standard roofs, researchers evaluated the influence of PVs on city temperatures in Sydney during the hot months of January and February. The findings indicate that covering 25–100 % of roof areas with PVs could raise surrounding air temperatures by 0.6–2.3 °C [207]. Due to the UHI effect and air pollution in cities, solar panels in urban areas generate approximately 13 % less electricity than those in suburban areas [208]. However, the literature primarily addresses rooftop solar in relation to the urban heat island UHI effect. There is a notable gap in research on how integrating BIPV on façades across multiple buildings in a specific area could impact the urban microclimate. Incorporating cooling mechanisms into photovoltaic systems can effectively lower their surface temperature, thereby mitigating the rise in ambient temperature in large-scale operations. Beyond temperature regulation, BIPV/T systems also significantly reduce GHG emissions. A study demonstrated that integrating an air source heat pump (ASHP) with a PV/T system reduced annual greenhouse gas (GHG) emissions from electricity demand by 225 kg CO_2 [29]. Findings from Asaee et al. [209] reveal that incorporating a PV system results in a 5 % reduction in GHG emissions, whereas implementing a BIPV/T system leads to a 17 % reduction in GHG emissions within the Canadian housing stock. Fig. 18 contains four subplots (a–d) illustrating the impact of PV panels on surface temperature, ambient temperature, outdoor surface temperature, and sensible heat flux over time. The results highlight how PV panels influence temperature distribution by increasing surface temperature (Figure a), affecting ambient conditions (Figure b), modifying outdoor surface temperatures (Figure c), and contributing to sensible heat flux variations (Figure d), demonstrating differences with and without PV panels [210]. Additionally, Table 5 provides a summary of the literature on the PVHI effect.

6. Limitations and considerations

A recent review by Bamisile et al. [216] highlighted several environmental constraints that significantly influence the performance of photovoltaic systems. Solar irradiance is one of the most critical factors, as it exhibits strong geographic and temporal variability. Photovoltaic modules perform optimally when sunlight strikes them perpendicularly, and any deviation from this orientation reduces the available surface area for absorption, thereby lowering electricity output [217]. Additionally, as mentioned earlier, rising module temperatures negatively impact efficiency, posing a particular challenge in hot climates. In this context, BIPV/T systems can offer substantial advantages, while specific technologies such as cadmium telluride, which exhibit relatively low temperature coefficients (−0.24 % to −0.26 % per Kelvin), are particularly well-suited for deployment in high-temperature regions compared to other photovoltaic technologies [216]. Atmospheric conditions such as clouds, aerosols, pollutants, and dust can significantly limit output, with cloud cover alone reducing photovoltaic capacity factors by up to 50 % in Northern Europe and 15–30 % in parts of the United States and China [218]. Dust deposition, primarily originating from major desert regions across Africa, Asia, the Americas, and Australia, significantly affects global distribution, with the North Atlantic receiving 43 % (mainly Saharan) and the Indian Ocean 25 % from multiple regional sources [219]. Environmental factors such as high humidity, terrain characteristics (albedo and snow cover), and extreme weather events (wildfires, hailstorms, and solar eclipses) can reduce photovoltaic efficiency, while long-term changes in solar irradiance due to climate change and air pollution present additional challenges for sustained performance [217]. In cold climates, water-based BIPV/T systems face freezing risks, which can be mitigated using antifreeze solutions such as glycol. Apart from climate-related issues, the architectural integration of PV/T panels presents its own set of challenges. Commercially available PV/T panels are relatively heavy, with typical 2 m^2 units weighing around 40 kg when filled with water, presenting challenges for architectural integration on façades and imposing substantial structural loads on buildings [220].

For BIPV/T or BIPV applications in large cities, these environmental challenges are further complicated by urban-specific constraints. High-rise buildings often experience shading effects from adjacent structures, and not all rooftops or façades have optimal orientation, such as unobstructed south-facing exposure for maximising solar energy capture. In a recent study conducted by Shao et al. [221], Building Information Modelling (BIM) was utilised to predict shading effects caused by adjacent structures. The authors identified that, in scenarios involving dynamic shading, the Sudoku-based reconfiguration technique offers the most effective balance between complexity and performance. By implementing suitable reconfiguration strategies, the energy output of BIPV systems can be enhanced by approximately 5–10 %. Careful consideration of technology selection for different climatic zones, combined with strategic urban design measures, is crucial for ensuring a reliable energy yield and supporting the integration of BIPV/T systems in the pursuit of net-zero buildings.

7. Economics and policy implementation

Economic assessments play a crucial role in determining the financial viability and long-term adoption potential of BIPV/T systems. A recent study by Shboul et al. [163] conducted an economic analysis of a BIPV/T (serpentine-shaped water-based collector) system using MATLAB, reporting a levelized cost of electricity (LCOE) of 0.10 USD/kWh under optimal operating conditions. Coca-Ortegón et al. [222] experimentally evaluated the energy performance of a trigeneration system integrating a solar PV/T-assisted heat pump in an industrial building. The thermal storage subsystem for DHW consisted of two tanks, with capacities of 263 L (Tank 1) and 350 L (Tank 2). The study compared the performance of BIPV and BIPV/T systems, reporting LCOE of €0.050/kWh for BIPV and €0.084/kWh for BIPV/T, both of which are substantially lower than the current average grid electricity price of €0.23/kWh at the study site. Based on these costs, the authors identified two primary research directions to enhance the competitiveness of BIPV/T systems: (i) improving the thermal efficiency of BIPV/T collectors, and (ii) optimising manufacturing processes to reduce production costs. Another recent study by Mobayen et al. [223] evaluated the integration of PV/T, heat pumps, electrolysers, fuel cells, reverse osmosis desalination units, and thermal storage tanks for application in zero-energy residential buildings. The authors identified the optimal configuration as incorporating a thermal storage tank volume of 66.25 m^3, which resulted in a total primary consumption (TPC) of 29,145.8 kWh/year and a life cycle cost (LCC) of USD 894,228. Başaran and Koç [224] performed an economic evaluation of a water-based parallel tube PV/T system by considering instantaneous electrical and thermal efficiencies. Their analysis employed net present value (NPV), payback period (PBP), and LCOE as key indicators. For a system with a surface area of 8.96 m^2 and a 25-year operational lifetime, they reported values of 0.091 EUR/kWh for LCOE, 2718.5 EUR for NPV, and 6 years for PBP. From the available literature, it is evident that there remains substantial scope for further research focusing on the techno-economic evaluation of BIPV/T systems in the context of achieving net-zero buildings. While existing studies on BIPV systems provide useful insights, a more comprehensive analysis of BIPV/T technologies is required. For instance, Nam et al. [225] carried out a techno-economic assessment of BIPV systems for zero-energy and zero-emission buildings, reporting LCOE values ranging from 0.117 to 0.348 USD/kWh. In certain cases, where additional ground-mounted photovoltaic capacity was necessary to achieve zero-energy building performance, the LCOE increased by a factor of 1.5–7. LCOE depends on several factors, including installation cost, local weather, and system requirements. Additionally, most of them only provided the LCOE for BIPV/T without comparing it to BIPV, which makes it difficult to conclude the cost-effectiveness of the system. Nonetheless, it is lower than the grid electricity prices.

While techno-economic evaluations highlight the financial feasibility and payback potential of BIPV or BIPV/T systems, translating these economic insights into practice requires supportive policy frameworks to ensure widespread adoption. One of the most effective strategies is the introduction of building codes and mandatory certification schemes for highly energy-efficient or decarbonised buildings [24]. Nearly zero-energy consumption standards or minimum on-site electricity generation requirements for both residential and commercial buildings could further accelerate the uptake of BIPV/T. As highlighted by the International Energy Agency (IEA),

Table 6
Readiness of various BIPV/T technologies and suitability by climatic type.

Technology	Technical readiness of different systems	Climate type	
		Performance in a warm climate	Performance in a cold climate
BIPV/T air system	Medium	Low	High
BIPV/T water system	High	High	High
BIPV/T concentrators	Low	High	Low
BIPV/T-PCM	Medium	High	High
BIPV/T-nanofluid	Low	High	High
BIPV/T-bi fluid	Low	High	High
BIPV/T-heat pipe	Medium	Low	High

policies aligned with scenarios such as Stated Policies (STEPS), Announced Pledges (APS), the Sustainable Development (SDS), and the Net Zero Emissions (NZE) pathway for 2050 can help align building-sector decarbonization with global climate goals [226].

Beyond electricity generation, the integration of thermal batteries represents a promising policy direction [227]. Just as governments provide strong incentives for electrochemical batteries, similar support mechanisms are required for thermal storage technologies. Government-backed research and funding programs could focus on optimising thermal energy usage from BIPV/T systems for space heating and cooling applications, thereby maximising system efficiency and extending their contribution to net-zero buildings.

From the perspective of policymakers, several barriers continue to hinder BIPV/T growth, including inadequate promotion, limited financial incentives, a shortage of technical expertise, and a lack of public readiness. A critical issue highlighted in the literature is the shortage of a sufficiently trained workforce to design, install, and operate BIPV systems. This shortage not only increases costs but also risks poorly implemented projects, which can undermine market confidence. The PVTRIN initiative, supported by the European Commission, addressed this challenge by offering structured training programs and systematically identifying risks across the design, construction, installation, commissioning, and operational phases [228]. Similar workforce development measures will be essential for scaling up BIPV/T deployment.

For long-term sustainability, flexible regulatory instruments are required to reduce dependence on subsidies while maintaining investor and stakeholder confidence. Effective policy mixes should balance technology-driven and demand-driven measures, supported by building codes, certification schemes for energy-efficient buildings, streamlined administrative procedures, and the integration of BIPV/T concepts into both basic education and specialised architectural and engineering curricula [229–231]. Nonetheless, even with such measures, barriers such as insufficient promotion, limited expertise, and public hesitation persist. Importantly, while incentives play a crucial role in early market stages, governments must carefully plan their gradual withdrawal to avoid destabilising the sector [232,233].

Government and institutional support are crucial factors, as seen in the example of the European Union, which is often regarded as one of the most advanced regions in terms of solar thermal development and utilisation due to the significant progress achieved through strong policy and institutional backing [234]. Solar Heat Europe, the European association representing the solar thermal industry, plays a central role in promoting and expanding the use of solar heating technologies for both buildings and industries [235]. The association actively engages in policy and advocacy initiatives to inform EU policymakers about the benefits of renewable heating and cooling solutions, while also working to create a fair and supportive framework for the large-scale deployment of solar heat technologies. The solar thermal sector in Europe is well-established, with hundreds of companies, most of which are small and medium-sized enterprises (SMEs), operating across countries such as Finland, Cyprus, Greece, and Austria. Many of these enterprises are increasingly focusing on PV/T technologies, particularly water-based and concentrator PV/T systems. To further accelerate this progress, Solar Heat Europe has emphasised the importance of directing at least 50 % of EU funds associated with the European Green Deal toward SMEs [236]. In its most recent documentation, the association outlined five key policy recommendations: (1) urgently establish a new Renewable Heating and Cooling strategy for buildings and industry; (2) protect, support, and incentivize EU cleantech SMEs; (3) prioritise the deployment of affordable renewable heating solutions; (4) emphasise positive externalities such as resilience and recyclability; and (5) enable and support the tripling of solar thermal deployment across Europe.

8. Discussion and future research

As outlined earlier in Fig. 1, achieving nearly or net-zero energy through the integration of BIPV/T systems in high-rise buildings requires attention to five critical dimensions: (1) geometrical design and material selection, (2) thermal storage systems, (3) working fluids and system operation, (4) modelling approaches, and (5) architectural integration. The preceding sections reviewed each of these dimensions in detail, and the following discussion synthesises the key insights.

The design of a net-zero energy building incorporating BIPV/T begins with the selection of an appropriate panel configuration. BIPV/T systems can be developed using various PV/T collector types, such as air-based, water-based, dual air–water, heat pipe, and PCM-integrated designs. While dual air-water PV/T collectors offer the combined benefits of both air- and water-based systems, their integration into BIPV/T applications remains relatively complex and requires further research to optimise performance and feasibility. Air-cooled PV roof tiles and BIPV/T DSF systems prioritise simplicity and ease of retrofitting, but exhibit lower efficiencies. The heat exchanger must be designed to achieve maximum efficiency. Aluminium heat exchangers are commonly used due to their exceptional resistance to pressure and harsh weather conditions. Overall, the electrical efficiency ranged from 6 % to a maximum of 15 %, while the thermal efficiency varied between 40 % and 60 %, depending on the specific design and fluid flow velocity. However, there is still room for improvement in their design and performance. Additionally, BIPV/T systems should be optimised to maintain efficiency even under partial shading conditions.

Once a BIPV/T system design is finalised, the next critical step is determining how the captured thermal energy will be utilised. Without efficient thermal energy management, the viability of BIPV/T technology is limited, as the increase in electrical efficiency alone is relatively modest. Therefore, strategic planning for thermal energy utilisation is essential to maximise the overall system performance. Thermal energy can be directly fed into a ducted system for space heating or passed through a heat exchanger to supplement a high-rise building's hot water supply (e.g., for a swimming pool). In an air-based BIPV/T system, a more efficient approach involves harvesting cool air at night when the solar panel surface is cooler than the ambient air [237]. This cooled air can be circulated within apartments to enhance nighttime comfort, particularly in hotter climates. In high-rise buildings equipped with BIPV/T systems, there is significant potential for integration into district heating networks. After meeting the building's own heating demand, excess thermal energy can be supplied to other public buildings. BIPV/T-equipped nZEBs can also be connected to large-scale seasonal storage facilities, enabling heat energy to be preserved for winter and high-demand periods. For example, Denmark utilises pit storage systems insulated with foam to store excess heat collected during the summer, while the Netherlands employs underground aquifers for long-term thermal storage [238,239]. Additionally, heat pump-integrated BIPV/T systems provide an efficient heat supply while also enabling passive cooling. These existing systems can be optimised to enhance energy harvesting from BIPV/T technology, supporting the achievement of nZEB targets.

The selection of an appropriate working fluid is a critical aspect of BIPV/T system design, as it directly influences thermal energy capture and overall system performance. Currently, water-based BIPV/T systems are the most widely adopted due to their availability and suitability for both summer and winter conditions. It is important to note that not all system designs are compatible with every type of working fluid. Among the various configurations, water-based BIPV/T collectors represent the most mature technology, with several companies in Europe and China already offering commercial solutions. By uniformly dispersing nanoparticles with high thermal conductivity into a base fluid, nanofluids can be formulated to enhance the performance of PV/T systems. However, due to their tendency to sediment over time, the practical application of research findings to commercial products remains highly uncertain. In most cases, water is commonly used as the working fluid, while in colder climates, a water-glycol mixture is preferred to prevent freezing. Systems using water or nanofluids consistently achieve higher thermal efficiencies compared to air-based designs, though air systems like the CIGS curved PV/air-heating mode show competitive thermal efficiency with simpler integration.

Before practical deployment, these systems must be modeled under realistic conditions, considering factors such as building architecture, ambient temperature, solar irradiance, shading, energy demand, thermal storage capacity, and the requirements for control and optimisation. Advanced modelling approaches are critical for optimising BIPV/T integration in high-rises, combining micro-modelling (e.g., 3D CFD, FEM) to resolve component-level thermal-electrical interactions and macro-modelling (e.g., TRNSYS, EnergyPlus) to assess system-wide energy flows and grid interactions. Multi-scale frameworks bridge these levels, using micro-scale insights (e.g., PV temperature gradients) to refine macro-level predictions of annual energy savings, ensuring alignment with net-zero targets. Data-driven techniques enhance predictive accuracy and control, enabling dynamic optimisation of flow rates, thermal storage, and demand-response strategies under variable weather and occupancy patterns.

Designing net-zero high-rise buildings with BIPV/T requires the utilisation of both rooftops and façades, as the limited rooftop area alone cannot meet the higher energy demands of tall structures. Consequently, practical implementation demands careful planning of how these systems are integrated architecturally and aesthetically. BIPV/T panels are typically heavier than conventional PV modules due to the additional thermal collector components and circulating working fluids, which impose greater structural loads and necessitate thorough assessment during the design phase. Effective deployment also requires a skilled workforce trained in the installation, operation, and maintenance of such systems. To simplify integration, some researchers have suggested air-based BIPV/T systems, as they eliminate the need for fluid circulation, though at the cost of reduced efficiency. Roof-mounted systems are generally more cost-effective than façades due to higher solar exposure, while optimised tilt angles and airflow rates can further enhance performance by balancing shading, electrical yield, and thermal capture. Slanted façade designs demonstrate improved resilience under windy conditions, and recent innovations such as PV/T–heat pump roofs and perpendicular façades illustrate progress toward multifunctional and visually cohesive solutions. Nevertheless, retrofitting older buildings, particularly in developing regions, remains a significant challenge due to architectural and structural limitations.

Based on the detailed analysis of the BIPV/T systems in this paper, Table 6 outlines the maturity levels of various BIPV/T systems. It is important to clarify that the term "readiness" in this context refers specifically to the technological maturity of BIPV/T systems themselves, rather than the integration of the entire building system. While air- and water-based photovoltaic/thermal systems have been extensively tested and are commercially available, with companies such as Abora, SunMaxx, DualSun, Sunnovate, and Ensun producing panels on a limited scale, other configurations, including systems incorporating phase change materials (PCM), heat pipes, bifluid designs, and concentrators, remain largely at the research stage [235]. Even in water-based systems, while the panels themselves are relatively mature, full-scale deployment on building façades or rooftops, along with operational optimisation for achieving net-zero energy, remains in its infancy. Thus, the overall readiness of BIPV/T systems is still emerging, reflecting ongoing research and early-phase development.

This study identifies the following future research directions to apply the BIPV/T system towards achieving a net-zero building.

- Investigating the appropriate sizing of thermal storage systems and quantifying heat recovery for space heating, cooling, and domestic hot water in high-rise buildings.

- Developing advanced optimisation frameworks and integrating AI/ML-based control algorithms to enhance energy flow management, thermal storage efficiency, and occupant comfort.
- Designing lightweight, modular BIPV/T panels suitable for façades and rooftops, incorporating retrofit strategies, and evaluating their structural, aesthetic, and economic feasibility for large-scale adoption.
- Assessing the influence of BIPV/T façade integration on urban heat island effects and local microclimates, with emphasis on optimising albedo, convective cooling, and thermal regulation.

9. Conclusion

This systematic review has examined the role of BIPV/T systems in achieving net-zero energy performance in high-rise buildings, analysing research published between January 2014 and January 2025. The study examined multiple aspects, including design innovations, modelling approaches, architectural integration strategies, external environmental factors, limitations, and economic and policy implications, with a focus on the holistic implementation of BIPV/T as a complete system rather than as isolated components.

Achieving net-zero buildings with BIPV/T requires five critical dimensions: (1) geometrical design and material selection, (2) thermal storage systems, (3) working fluids and system operation, (4) modelling approaches, and (5) architectural integration. Significant progress has been made in system design, with the potential to select efficient BIPV/T configurations based on climate zones. While the literature abounds with thermal storage studies utilising various media such as air, water, nano-fluids and phase-change materials (PCMs), research on optimally sizing thermal storage in relation to BIPV/T capacity remains scarce. Similarly, the study of working fluids is well-established; however, the optimisation of flow rates based on dynamic environmental conditions, storage capacity, and building demand requires further investigation. Holistic modelling of integrated BIPV/T systems, including thermal storage and auxiliary mechanical systems for meeting heating and cooling loads, has been predominantly conducted using tools like TRNSYS, largely due to its extensive component library and default PVT component. The application of stored thermal energy varies by building type, employing heat pumps, chillers, or boilers. Future work should prioritise comprehensive experimental validation at the full-system level rather than on isolated subsystems. Finally, architectural integration presents a primary obstacle for widespread BIPV/T adoption in net-zero high-rise buildings, where façade integration becomes necessary. Experimental research has largely focused on rooftop installations, with façade-integrated solutions receiving limited real-world validation. Although the LCOE for BIPV/T systems is increasingly competitive with grid electricity, affirming their economic viability, large-scale deployment will require targeted policy support. As cities pursue sustainable solutions to reduce carbon footprints and enhance energy resilience, BIPV/T technology is poised to play a crucial role in the next generation of high-performance buildings.

CRediT authorship contribution statement

Tahsin Anjum: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Md Morshed Alam:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Iqbal Hossain:** Writing – review & editing, Supervision. **Mohamed Gomaa:** Writing – review & editing, Supervision. **Laveet Kumar:** Writing – review & editing, Supervision.

Funding sources

This work was supported by the SUPRA fund from Swinburne University of Technology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] C. Ding, et al., Potential of artificial intelligence in reducing energy and carbon emissions of commercial buildings at scale, Nat. Commun. 15 (1) (2024) 5916.
[2] dcceew, Trajectory for Low Energy BuildingsTrajectory for Low Energy Buildings (2019).
[3] UNEP, Not yet built for purpose: global building sector emissions still high and rising, Available from: https://www.unep.org/news-and-stories/press-release/not-yet-built-purpose-global-building-sector-emissions-still-high#:~:text='%20The%20buildings%20sector%20has%20a,cent%20above%20the%20target%20trajectory, 2024.
[4] D. Brown, et al., A systematic review of barriers to implementing net zero energy buildings in Australia, J. Clean. Prod. (2024) 142910.
[5] M.S. Islam, et al., Techno-economic optimization of a zero emission energy system for a coastal community in Newfoundland, Canada, Energy 220 (2021) 119709.
[6] T. Anjum, A wind energy potential, progress and challenges in Bangladesh: a review, Int. J. Renew. Energy Resour. (2024) 14–35.
[7] T. Anjum, et al., Feasibility analysis of hybrid photovoltaic, wind, and fuel cell systems for on–off-grid applications: a case study of housing project in Bangladesh, Energy Sci. Eng. 12 (8) (2024) 3476–3504.
[8] H.-L. Lou, S.-H. Hsieh, Towards zero: a review on strategies in achieving net-zero-energy and net-zero-carbon buildings, Sustainability 16 (11) (2024) 4735.

[9] H.M. Maghrabie, et al., Building-integrated photovoltaic/thermal (BIPVT) systems: applications and challenges, Sustain. Energy Technol. Assessments 45 (2021).
[10] X. Cao, et al., A review of photovoltaic/thermal (PV/T) technology applied in building environment control, Energy Built Environ. (2023).
[11] A.S. Abdelrazik, et al., The recent advancements in the building integrated photovoltaic/thermal (BIPV/T) systems: an updated review, Renew. Sustain. Energy Rev. 170 (2022).
[12] G. Asefi, et al., Thermal management of building-integrated photovoltaic/thermal systems: a comprehensive review, Sol. Energy 216 (2021) 188–210.
[13] G.Q. Yu, et al., A review of designs and performance of facade-based building integrated photovoltaic-thermal (BIPVT) systems, Appl. Therm. Eng. (2021) 182.
[14] X. Cheng, et al., Development and performance of roof-based building-integrated photovoltaic-thermal systems: a review, J. Sol. Energy Eng. Trans. ASME. 143 (4) (2021).
[15] Y.A. Sari, S.M. Said, A review of building integrated photovoltaic-thermal (BIPV/T) systems: current and potential technology development, J. Eng. Sci. Technol. Rev. 14 (4) (2021) 197–206.
[16] E.D. Rounis, A. Athienitis, T. Stathopoulos, Review of air-based PV/T and BIPV/T systems - performance and modelling, Renew. Energy 163 (2021) 1729–1753.
[17] A. Riaz, et al., A review on the application of photovoltaic thermal systems for building facades, Build. Serv. Eng. Res. Tecnol. 41 (1) (2020) 86–107.
[18] C. Vassiliades, et al., Building integration of active solar energy systems: a review of geometrical and architectural characteristics, Renew. Sustain. Energy Rev. (2022) 164.
[19] C. Sirin, J. Goggins, M. Hajdukiewicz, A review on building-integrated photovoltaic/thermal systems for green buildings, Appl. Therm. Eng. (2023) 229.
[20] I. Bosu, et al., Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: a comprehensive review, Sol. Energy 259 (2023) 188–228.
[21] S.K. Verma, et al., A review on futuristic aspects of hybrid photo-voltaic thermal systems (PV/T) in solar energy utilization: engineering and technological approaches, Sustain. Energy Technol. Assessments 53 (2022).
[22] G. Yu, et al., A review of designs and performance of façade-based building integrated photovoltaic-thermal (BIPVT) systems, Appl. Therm. Eng. (2021) 182.
[23] A.K. Tiwari, et al., A comprehensive review of photovoltaic-thermal (PVT) technology: performance evaluation and contemporary development, Energy Rep. 10 (2023) 2655–2679.
[24] M. Chandrasekar, Building-integrated solar photovoltaic thermal (BIPVT) technology: a review on the design innovations, aesthetic values, performance limits, storage options and policies, Adv. Build. Energy Res. 17 (2) (2023) 223–254.
[25] H.A. Kazem, et al., Energy Enhancement of Building-Integrated Photovoltaic/Thermal Systems: a Systematic Review, Solar Compass, 2024 100093.
[26] A. Shahsavar, S.A. Bagherzadeh, M. Afrand, Application of artificial intelligence techniques in prediction of energetic performance of a hybrid system consisting of an earth-air heat exchanger and a building-integrated photovoltaic/thermal system, J. Sol. Energy Eng. Trans. ASME. 143 (5) (2021).
[27] J. Hu, et al., Experimental studies on summer performance and feasibility of a BIPV/T ethylene tetrafluoroethylene (ETFE) cushion structure system, Energy Build. 69 (2014) 394–406.
[28] A. Ibrahim, et al., Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system, Energy Convers. Manag. 77 (2014) 527–534.
[29] R.S. Kamel, A.S. Fung, Modeling, simulation and feasibility analysis of residential BIPV/T+ASHP system in cold climate - canada, Energy Build. 82 (2014) 758–770.
[30] O.B. Kazanci, et al., Sustainable heating, cooling and ventilation of a plus-energy house via photovoltaic/thermal panels, Energy Build. 83 (2014) 122–129.
[31] G.Q. Li, et al., Experiment investigation on electrical and thermal performances of a semitransparent photovoltaic/thermal system with water cooling, Int. J. Photoenergy 2014 (2014).
[32] F. Shan, et al., Dynamic characteristics modeling of a hybrid photovoltaic-thermal solar collector with active cooling in buildings, Energy Build. 78 (2014) 215–221.
[33] T. Yang, A.K. Athienitis, A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets, Sol. Energy 104 (2014) 82–92.
[34] M.S. Buker, B. Mempouo, S.B. Riffat, Experimental investigation of a building integrated photovoltaic/thermal roof collector combined with a liquid desiccant enhanced indirect evaporative cooling system, Energy Convers. Manag. 101 (2015) 239–254.
[35] S. Li, et al., System identification and model-predictive control of office buildings with integrated photovoltaic-thermal collectors, radiant floor heating and active thermal storage, Sol. Energy 113 (2015) 139–157.
[36] Y. Xiang, G. Gan, Optimization of building-integrated photovoltaic thermal air system combined with thermal storage, Int. J. Low Carbon Technol. 10 (2) (2015) 146–156.
[37] T. Yang, A.K. Athienitis, Experimental investigation of a two-inlet air-based building integrated photovoltaic/thermal (BIPV/T) system, Appl. Energy 159 (2015) 70–79.
[38] A. Buonomano, et al., BIPVT systems for residential applications: an energy and economic analysis for European climates, Appl. Energy 184 (2016) 1411–1431.
[39] F. Chen, H. Yin, Fabrication and laboratory-based performance testing of a building-integrated photovoltaic-thermal roofing panel, Appl. Energy 177 (2016) 271–284.
[40] C.S. Rajoria, et al., A novel investigation of building integrated photovoltaic thermal (BiPVT) system: a comparative study, Sol. Energy 131 (2016) 107–118.
[41] S. Saadon, et al., Simulation study of a naturally-ventilated building integrated photovoltaic/thermal (BIPV/T) envelope, Renew. Energy 87 (2016) 517–531.
[42] G.N. Tiwari, et al., Periodic theory of building integrated photovoltaic thermal (BiPVT) system, Sol. Energy 125 (2016) 373–380.
[43] Z.Y. Wang, et al., Experimental investigation of the thermal and electrical performance of the heat pipe BIPV/T system with metal wires, Appl. Energy 170 (2016) 314–323.
[44] M. Abdolzadeh, M. Sadeqkhani, A. Ahmadi, Computational modeling of a BIPV/T ethylene tetrafluoroethylen (ETFE) cushion structure roof, Energy 133 (2017) 998–1012.
[45] E. Bigaila, A.K. Athienitis, Modeling and simulation of a photovoltaic/thermal air collector assisting a facade integrated small scale heat pump with radiant PCM panel, Energy Build. 149 (2017) 298–309.
[46] A. Buonomano, et al., Adsorption chiller operation by recovering low-temperature heat from building integrated photovoltaic thermal collectors: modelling and simulation, Energy Convers. Manag. 149 (2017) 1019–1036.
[47] A. Chialastri, M. Isaacson, Performance and optimization of a BIPV/T solar air collector for building fenestration applications, Energy Build. 150 (2017) 200–210.
[48] H. Dehra, An investigation on energy performance assessment of a photovoltaic solar wall under buoyancy-induced and fan-assisted ventilation system, Appl. Energy 191 (2017) 55–74.
[49] A. Deo, G.K. Mishra, G.N. Tiwari, A thermal periodic theory and experimental validation of building integrated semi-transparent photovoltaic thermal (BiSPVT) system, Sol. Energy 155 (2017) 1021–1032.
[50] M. Ahmed-Dahmane, A. Malek, T. Zitoun, Design and analysis of a BIPV/T system with two applications controlled by an air handling unit, Energy Convers. Manag. 175 (2018) 49–66.
[51] Y.B. Assoa, F. Sauzedde, B. Boillot, Numerical parametric study of the thermal and electrical performance of a BIPV/T hybrid collector for drying applications, Renew. Energy 129 (2018) 121–131.
[52] A. Shahsavar, Y. Rajabi, Exergoeconomic and enviroeconomic study of an air based building integrated photovoltaic/thermal (BIPV/T) system, Energy 144 (2018) 877–886.
[53] A.K. Athienitis, et al., Assessing active and passive effects of façade building integrated photovoltaics/thermal systems: dynamic modelling and simulation, Appl. Energy 209 (2018) 355–382.

[54] A. Dash, et al., Optimization and performance characteristics of building integrated photovoltaic thermal (BIPVT) system in cold climatic conditions, Asian J. Water Environ. Pollut. 15 (3) (2018) 63–72.
[55] A. Ibrahim, et al., Outdoor performance evaluation of building integrated photovoltaic thermal (BIVPT) solar collector with spiral flow absorber configurations, Int. J. Power Electron. Drive Syst. 9 (4) (2018) 1918–1925.
[56] M. Afrand, et al., Energy and exergy analysis of two novel hybrid solar photovoltaic geothermal energy systems incorporating a building integrated photovoltaic thermal system and an Earth air heat exchanger system, Sol. Energy 188 (2019) 83–95.
[57] Z.X. Li, et al., Multi-objective energy and exergy optimization of different configurations of hybrid earth-air heat exchanger and building integrated photovoltaic/thermal system, Energy Convers. Manag. 195 (2019) 1098–1110.
[58] M. Yu, et al., Experimental investigation of a novel solar micro-channel loop-heat-pipe photovoltaic/thermal (MC-LHP-PV/T) system for heat and power generation, Appl. Energy (2019) 256.
[59] J.S. Yu, J.H. Kim, J.T. Kim, A study on the thermal performance of air-type BIPVT collectors applied to demonstration building, Energies 12 (16) (2019).
[60] S. Yang, et al., Numerical simulation study of BIPV/T double-skin facade for various climate zones in Australia: effects on indoor thermal comfort, Build. Simulat. 12 (1) (2019) 51–67.
[61] V. Tomar, B. Norton, G.N. Tiwari, A novel approach towards investigating the performance of different PVT configurations integrated on test cells: an experimental study, Renew. Energy 137 (2019) 93–108.
[62] R. Pereira, L. Aelenei, Optimization assessment of the energy performance of a BIPV/T-PCM system using genetic algorithms, Renew. Energy 137 (2019) 157–166.
[63] S. Yang, et al., Performance assessment of BIPV/T double-skin façade for various climate zones in Australia: effects on energy consumption, Sol. Energy 199 (2020) 377–399.
[64] L. Xu, et al., Study of a hybrid BIPV/T solar wall system, Energy (2020) 193.
[65] L. Xu, et al., Annual analysis of a multi-functional BIPV/T solar wall system in typical cities of China, Energy 197 (2020).
[66] M. Shakouri, A. Noorpoor, H. Ghadamian, Quantification of thermal energy performance improvement for building integrated photovoltaic double-skin façade using analytical method, J. Renew. Energy Environ. 7 (3) (2020) 56–66.
[67] J. Wajs, et al., Air-cooled photovoltaic roof tile as an example of the BIPVT system - an experimental study on the energy and exergy performance, Energy (2020) 197.
[68] M. Shakouri, H. Ghadamian, A. Noorpoor, Quasi-dynamic energy performance analysis of building integrated photovoltaic thermal double skin facade for middle eastern climate case, Appl. Therm. Eng. (2020) 179.
[69] A. Shahsavar, et al., Machine learning predictive models for optimal design of building-integrated photovoltaic-thermal collectors, Int. J. Energy Res. 44 (7) (2020) 5675–5695.
[70] K. Bot, et al., Performance assessment of a building integrated photovoltaic thermal system in Mediterranean Climate-A numerical simulation approach, Energies 13 (11) (2020).
[71] G. Barone, et al., Passive and active performance assessment of building integrated hybrid solar photovoltaic/thermal collector prototypes: energy, comfort, and economic analyses, Energy (2020) 209.
[72] H. Zhang, et al., Performance study of a combined low-concentration bifacial photovoltaic/thermal system with glass channels, Renew. Energy 171 (2021) 947–957.
[73] R. Liang, et al., Real-time monitoring implementation of PV/T façade system based on IoT, J. Build. Eng. 41 (2021) 102451.
[74] W. Ke, et al., Annual performance analysis of a dual-air-channel solar wall system with phase change material in different climate regions of China, Energy 235 (2021).
[75] L. Ma, et al., Optimization of passive solar design and integration of building integrated photovoltaic/thermal (BIPV/T) system in northern housing, Build. Simulat. 14 (5) (2021) 1467–1486.
[76] A. Gagliano, et al., Analysis of the performances of a building-integrated PV/Thermal system, J. Clean. Prod. 320 (2021).
[77] R. Dumoulin, E.D. Rounis, A. Athienitis, Operation and grid interaction modeling of a house with a building integrated photovoltaic thermal (BIPV/T) system coupled to an air-source heat pump, Science and Technology for the Built Environment 27 (9) (2021) 1311–1329.
[78] J. Guo, et al., A quantitative analysis on key factors affecting the thermal performance of the hybrid air-based BIPV/T system, Buildings 12 (8) (2022).
[79] A. Shahsavar, P. Talebizadehsardari, M. Arici, Comparative energy, exergy, environmental, exergoeconomic, and enviroeconomic analysis of building integrated photovoltaic/thermal, earth-air heat exchanger, and hybrid systems, J. Clean. Prod. (2022) 362.
[80] M. Ge, et al., Experimental research on the performance of BIPV/T system with water-cooled wall, Energy Rep. 8 (2022) 454–459.
[81] A. Shahsavar, S. Khanmohammadi, Effects of number of objective functions on the optimization of a hybrid building integrated photovoltaic/thermal-heat recovery wheel unit, Sustain. Energy Technol. Assessments 53 (2022).
[82] A. Maturo, A. Buonomano, A. Athienitis, Design for energy flexibility in smart buildings through solar based and thermal storage systems: modelling, simulation and control for the system optimization, Energy 260 (2022).
[83] J.H. Kim, et al., Performance assessment of an air-type BIPVT collector with perforated baffles through indoor and outdoor experiments, Energies 15 (10) (2022).
[84] C. Zhang, et al., Experimental and numerical studies on the thermal and electrical performance of a CdTe ventilated window integrated with vacuum glazing, Energy 244 (2022).
[85] Y. Zhao, et al., Performance study of air-type BIPVT coupled water-cooled wall, Energy Rep. 8 (2022) 265–270.
[86] Y. Abdalgadir, et al., Daily and annual performance analyses of the BIPV/T system in typical cities of Sudan, Energy Built Environ. 4 (5) (2023) 516–529.
[87] X. Su, et al., Study on impact of photovoltaic power tracking modes on photovoltaic-photothermal performance of PV-PCM-Trombe wall system, Energy Build. 301 (2023).
[88] W. Ke, et al., A seasonal experimental study on a novel CdTe based multi-layer PV ventilated window system integrated with PCM under different operating modes, Energy (2023) 285.
[89] A.S. Alsagri, Thermodynamic investigation of a photovoltaic/thermal heat pipe energy system integrated with phase change material, Arabian J. Sci. Eng. 49 (2) (2024) 2625–2643.
[90] F. Wang, T. You, H. Cui, Multi-objective optimization and evaluation of the building-integrated photovoltaic/thermal-energy pile ground source heat pump system, Appl. Energy 371 (2024).
[91] H.L. Alwan, W.A.M. Al-Shohani, A.Q. Ahmed, Enhancing the performance of photovoltaic using exhausted air from thermal comfort spaces, Proceedings of the Institution of Civil Engineers-Energy 178 (1) (2024) 34–46.
[92] M. Beigi, et al., A novel liquid desiccant-based hybrid system of building integrated photovoltaic-thermal system and ground heat exchanger for buildings in hot and humid climate, Energy Convers. Manag. (2024) 317.
[93] P. Karunyasopon, et al., Performance analysis of transparent BIPV/T double skin façades integrated with the decision-making algorithm for mixed-mode building ventilation, Architect. Eng. Des. Manag. 20 (5) (2024) 1141–1163.
[94] H. Liu, et al., Performance investigation of a building-integrated collector based on spectrum splitting technology, Appl. Therm. Eng. 258 (2025).
[95] Y.L. Xiao, et al., Thermal performance optimization of a novel integrated photovoltaic thermal collector system, Renew. Energy 238 (2025).
[96] M. Piratheepan, T.N. Anderson, Performance of a building integrated photovoltaic/thermal concentrator for facade applications, Sol. Energy 153 (2017) 562–573.
[97] G. Barone, et al., Modelling and simulation of building integrated concentrating photovoltaic/thermal glazing (CoPVTG) systems: comprehensive energy and economic analysis, Renew. Energy 193 (2022) 1121–1131.
[98] X. Xu, L. Zhang, An experimental study on the performance of a hybrid photovoltaic/thermal solar system, Energy Eng. J. Assoc. Energy Eng.: J. Assoc. Energy Eng. 119 (6) (2022) 2319–2345.

[99] A. Basuhaib, et al., Experimental investigation the effect of different operating parameters and optimized the water-based PVT system for domestic applications, Sol. Energy 268 (2024) 112278.
[100] T. Anjum, et al., Performance investigation of tempered glass based photovoltaic panel integrated with back cooling hollow chamber, Energy Sources, Part A Recovery, Util. Environ. Eff. 45 (4) (2023) 11733–11751.
[101] M. Zadshir, et al., Design and performance testing of a novel building integrated photovoltaic thermal roofing panel, Build. Simulat. 16 (10) (2023) 1863–1879.
[102] Z. Ioannidis, et al., Modeling of double skin facades integrating photovoltaic panels and automated roller shades: analysis of the thermal and electrical performance, Energy Build. 154 (2017) 618–632.
[103] K. Martin-Escudero, et al., Solar energy system for heating and domestic hot water supply by means of a heat pump coupled to a photovoltaic ventilated facade, Sol. Energy 183 (2019) 453–462.
[104] W. Ke, et al., Performance analysis of a novel hybrid CdTe-PCM multi-layer ventilated window system for building application: an experimental and numerical study, Energy (2024) 293.
[105] Y. Zhao, et al., Experimental performance of air-type BIPVT systems under different climate conditions, Sustain. Energy Technol. Assessments 60 (2023).
[106] H. Yang, et al., Investigation on the heating performance of a BIPV/T façade coupled with direct-expansion heat pump system in severe cold region, Renew. Energy 232 (2024) 121065.
[107] C. Zhang, et al., Comprehensive performance investigation of a novel thermal catalytic semi-transparent PV double-skin ventilated window integrated with CdTe cells, Energy (2024) 300.
[108] S. Bu, et al., A novel building integrated photovoltaic/thermal wall for hot water-electrical power co-generation, Renew. Energy 239 (2025).
[109] X.Y. Tian, et al., Comparison analysis of the glazed and unglazed curved water-based PV/T roofs in the non-heating season, Renew. Energy 205 (2023) 899–917.
[110] X.Y. Tian, J. Wang, J. Ji, Performance prediction of a curved-type solar balcony combined with the flexible PV/T system during the non-heating season, Energy Convers. Manag. (2023) 292.
[111] J. Wang, et al., Design and experimental study of a novel flexible PV/T structure, Energy (2024) 296.
[112] Y.C. Demir, M.A. Aktacir, Experimental investigation of BIPV/T application in winter season under Şanlıurfa's meteorological conditions, IET Renew. Power Gener. (2024).
[113] K. Terashima, H. Sato, T. Ikaga, PV/T solar panel for supplying residential demands of heating/cooling and hot water with a lower environmental thermal load, Energy Build. 297 (2023).
[114] F.J.G. Gallero, et al., Performance analysis of a novel façade-based building integrated photovoltaic-thermal system with phase change material for domestic hot water, Appl. Therm. Eng. (2024) 240.
[115] A. Shahsavar, N. Azimi, Performance evaluation and multi-objective optimization of a hybrid earth-air heat exchanger and building-integrated photovoltaic/thermal system with phase change material and exhaust air heat recovery, J. Build. Eng. 90 (2024).
[116] V. Tomar, et al., Thermal modeling and experimental evaluation of five different photovoltaic modules integrated on prototype test cells with and without water flow, Energy Convers. Manag. 165 (2018) 219–235.
[117] A.D. uÅ Tuncer, A. Khanlari, S. Adnan, Seasonal energy-exergy analysis of a new foldable photovoltaic-thermal air collector: an experimental and numerical study, Heat Tran. Res. 53 (14) (2022).
[118] E. Çiftçi, et al., Energy and exergy analysis of a photovoltaic thermal (PVT) system used in solar dryer: a numerical and experimental investigation, Renew. Energy 180 (2021) 410–423.
[119] S. Saadon, et al., Exergy, exergoeconomic and enviroeconomic analysis of a building integrated semi-transparent photovoltaic/thermal (BISTPV/T) by natural ventilation, Renew. Energy 150 (2020) 981–989.
[120] X. Tian, et al., A multifunctional curved CIGS photovoltaic/thermal roof system: a numerical and experimental investigation, Energy (2023) 273.
[121] Z. Wang, et al., The integration of solid-solid phase change material with micro-channel flat plate heat pipe-based BIPV/T, Build. Serv. Eng. Res. Tecnol. 39 (6) (2018) 712–732.
[122] N. Shao, L. Ma, J. Zhang, Experimental study on electrical and thermal performance and heat transfer characteristic of PV/T roof in summer, Appl. Therm. Eng. 162 (2019).
[123] R. Liang, et al., Study on the improved electrical and thermal performance of the PV/T façade system, Int. J. Photoenergy 2020 (2020).
[124] K. Luo, et al., Seasonal experimental study of a hybrid photovoltaic-water/air solar wall system, Appl. Therm. Eng. (2020) 169.
[125] L.J. Xu, et al., A hybrid PV thermal (water or air) wall system integrated with double air channel and phase change material: a continuous full-day seasonal experimental research, Renew. Energy 173 (2021) 596–613.
[126] M. Jalalizadeh, et al., Dynamic simulation of a trigeneration system using an absorption cooling system and building integrated photovoltaic thermal solar collectors, J. Build. Eng. 43 (2021).
[127] M. Hossain, et al., Thermal performance analysis of parallel serpentine flow based photovoltaic/thermal (PV/T) system under composite climate of Malaysia, Appl. Therm. Eng. 153 (2019) 861–871.
[128] M. Herrando, et al., A review of solar hybrid photovoltaic-thermal (PV-T) collectors and systems, Prog. Energy Combust. Sci. 97 (2023) 101072.
[129] R. Chandel, et al., Review on thermoelectric systems for enhancing photovoltaic power generation, Sustain. Energy Technol. Assessments 53 (2022) 102585.
[130] D. Cotfas, et al., Critical factors and parameters for hybrid photovoltaic-thermoelectric systems; review, Appl. Therm. Eng. 215 (2022) 118977.
[131] R. Moshwan, et al., Advances and challenges in hybrid photovoltaic-thermoelectric systems for renewable energy, Appl. Energy 380 (2025) 125032.
[132] Y. Li, et al., Radiative sky cooling in low-medium concentration photovoltaic systems, Appl. Therm. Eng. 221 (2023) 119860.
[133] M. Hu, et al., Applications of radiative sky cooling in solar energy systems: progress, challenges, and prospects, Renew. Sustain. Energy Rev. 160 (2022) 112304.
[134] T.H. Kwan, et al., Integration of radiative sky cooling to the photovoltaic and thermoelectric system for improved space cooling, Appl. Therm. Eng. 196 (2021) 117230.
[135] V. Delisle, M. Kummert, Cost-benefit analysis of integrating BIPV-T air systems into energy-efficient homes, Sol. Energy 136 (2016) 385–400.
[136] Y.J. Xie, et al., Numerical investigation of the effect factors on the performance of a novel PV integrated collector storage solar water heater, Renew. Energy 195 (2022) 1354–1367.
[137] A. Sohani, et al., The real-time dynamic multi-objective optimization of a building integrated photovoltaic thermal (BIPV/T) system enhanced by phase change materials, J. Energy Storage 46 (2022).
[138] V. Minea, Y. Chen, A.K. Athienitis, Canadian low-energy housing: national energy context, and a case study of a demonstration house with focus on its ground-source heat pump, Science and Technology for the Built Environment 23 (4) (2017) 651–668.
[139] F. Wang, T. You, Synergetic performance improvement of a novel building integrated photovoltaic/thermal-energy pile system for co-utilization of solar and shallow-geothermal energy, Energy Convers. Manag. (2023) 288.
[140] A. Shahsavar, et al., Performance assessment of an innovative exhaust air energy recovery system based on the PV/T-assisted thermal wheel, Energy 162 (2018) 682–696.
[141] A. Shahsavar, S. Khanmohammadi, Feasibility of a hybrid BIPV/T and thermal wheel system for exhaust air heat recovery: energy and exergy assessment and multi-objective optimization, Appl. Therm. Eng. 146 (2019) 104–122.
[142] S. Khanmohammadi, A. Shahsavar, Comparison of the performance of different designs of a combined system consisting of a photovoltaic thermal unit and a sensible rotary heat exchanger, Sustain. Energy Technol. Assessments 45 (2021).
[143] A. Shahsavar, S. Khanmohammadi, Energy and economic evaluation and multicriteria optimization of different arrangements of integrated photovoltaic thermal and heat recovery wheel system, Int. J. Energy Res. 44 (3) (2020) 1488–1505.

[144] C. García-Gáfaro, et al., A photovoltaic forced ventilated facade (PV-FVF) as heat source for a heat pump: assessing its energetical profit in nZEB buildings, Energy Build. (2022) 261.
[145] B.A. Aljashaami, et al., Recent improvements to heating, ventilation, and cooling technologies for buildings based on renewable energy to achieve zero-energy buildings: a systematic review, Results Eng. (2024) 102769.
[146] C. Zhang, et al., Heat harvesting characteristics of building façades integrated photovoltaic/thermal-heat pump system in winter, Renew. Energy 215 (2023).
[147] M. Khaki, et al., Energy and exergy analysis and multi-objective optimization of an air based building integrated photovoltaic/thermal (BIPV/T) system, Sol. Energy 158 (2017) 380–395.
[148] H.A. Kazem, et al., A systematic review of photovoltaic/thermal applications in heat pumps systems, Sol. Energy 269 (2024) 112299.
[149] A. Pugsley, et al., BIPV/T facades – a new opportunity for integrated collector-storage solar water heaters? Part 1: state-of-the-art, theory and potential, Sol. Energy 207 (2020) 317–335.
[150] A. Pugsley, et al., BIPV/T facades - a new opportunity for integrated collector-storage solar water heaters? Part 2: physical realisation and laboratory testing, Sol. Energy 206 (2020) 751–769.
[151] R. Liang, et al., Experiment research of solar PV/T cogeneration system on the building façade driven by a refrigerant pump, Energy 161 (2018) 744–752.
[152] C. Sun, et al., Numerical examination of exergy performance of a hybrid solar system equipped with a sheet-and-sinusoidal tube collector: developing a predictive function using artificial neural network, Case Stud. Therm. Eng. 53 (2024).
[153] P. Jidhesh, T.V. Arjunan, N. Gunasekar, Thermal modeling and experimental validation of semitransparent photovoltaic- thermal hybrid collector using CuO nanofluid, J. Clean. Prod. (2021) 316.
[154] B. Goss, et al., Modelling and prediction of PV module energy yield, in: The Performance of Photovoltaic (PV) Systems, Elsevier, 2017, pp. 103–132.
[155] Wikipedia, Microsimulation (2025). Available from: https://en.wikipedia.org/wiki/Microsimulation.
[156] A. De Gracia, et al., Numerical modelling of ventilated facades: a review, Renew. Sustain. Energy Rev. 22 (2013) 539–549.
[157] Y. Sun, Sensitivity analysis of macro-parameters in the system design of net zero energy building, Energy Build. 86 (2015) 464–477.
[158] Z. Mao, et al., Macro-model of PV module and its application for partial shading analysis, IET Renew. Power Gener. 12 (15) (2018) 1748–1754.
[159] L. Florschuetz, Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors, Sol. Energy 22 (4) (1979) 361–366.
[160] H. Hottel, A. Whillier, Evaluation of flat-plate solar collector performance, Trans. Conf. Use of Solar Energy (1955).
[161] M. Ibrahim, et al., Building retrofitting towards net zero energy: a review, Energy Build. 322 (2024) 114707.
[162] A. Sohani, et al., Using machine learning in photovoltaics to create smarter and cleaner energy generation systems: a comprehensive review, J. Clean. Prod. 364 (2022).
[163] B. Shboul, et al., Energy and economic analysis of building integrated photovoltaic thermal system: seasonal dynamic modeling assisted with machine learning-aided method and multi-objective genetic optimization, Alex. Eng. J. 94 (2024) 131–148.
[164] R. Javadijam, et al., Artificial intelligent based techno-economic-exergetic optimization of a thermoelectric enhanced building integrated photovoltaic thermal system, J. Build. Eng. 84 (2024).
[165] J. Alsarraf, et al., Application of PSO–ANN modelling for predicting the exergetic performance of a building integrated photovoltaic/thermal system, Eng. Comput. 36 (2) (2020) 633–646.
[166] C. Wang, et al., Investigation on the operation strategy of a hybrid BIPV/T façade in plateau areas: an adaptive regulation method based on artificial neural network, Energy (2022) 239.
[167] N. Morovat, A.K. Athienitis, J.A. Candanedo, Design of a model predictive control methodology for integration of retrofitted air-based PV/T system in school buildings, J. Build. Perform. Simul. (2024).
[168] A.M. Sigounis, C. Vallianos, A. Athienitis, Model predictive control of air-based building integrated PV/T systems for optimal HVAC integration, Renew. Energy 212 (2023) 655–668.
[169] C. Wang, J. Ji, Comprehensive performance analysis of a rural building integrated PV/T wall in hot summer and cold winter region, Energy 282 (2023) 128302.
[170] A. Sohani, et al., Building integrated photovoltaic/thermal technologies in Middle Eastern and North African countries: current trends and future perspectives, Renew. Sustain. Energy Rev. 182 (2023).
[171] design, P.C.I.D.a. Solar XXI. Available from: https://pcidarch.com/solar-xxi-building/.
[172] K. Bot, et al., Performance assessment of a building-integrated photovoltaic thermal system in a mediterranean Climate-An experimental analysis approach, Energies 14 (8) (2021).
[173] C. Theokli, et al., Energy renovation of an existing building in Nicosia Cyprus and investigation of the passive contribution of a BIPV/T double facade system: a case-study, Energy Rep. 7 (2021) 8522–8533.
[174] A. Buonomano, et al., Innovative technologies for NZEBs: an energy and economic analysis tool and a case study of a non-residential building for the Mediterranean climate, Energy Build. 121 (2016) 318–343.
[175] R.A. Agathokleous, S.A. Kalogirou, S. Karellas, Exergy analysis of a naturally ventilated Building Integrated Photovoltaic/Thermal (BIPV/T) system, Renew. Energy 128 (2018) 541–552.
[176] X.Y. Tian, et al., Performance assessment of the curved-type multi-channel PV roof for space-heating and electricity generation in winter, Renew. Energy 231 (2024).
[177] J. Wang, et al., Field experimental investigation of a multifunctional curved CIGS photovoltaic/thermal (PV/T) roof system for traditional Chinese buildings, Energy Convers. Manag. (2022) 271.
[178] C.X. Zhang, et al., Cooling performance of all-orientated building facades integrated with photovoltaic-sky radiative cooling system in summer, Renew. Energy 217 (2023).
[179] J. Bezaatpour, et al., Assessment of merits and demerits of perpendicular and slanted photovoltaic/thermal facades, Sustain. Energy Technol. Assessments 72 (2024).
[180] N.N. Shao, et al., Experimental study on the heat transfer performance of the PVT ventilated roof as heat exchanger for heat pump system, Renew. Energy 187 (2022) 995–1008.
[181] C. Italos, et al., Use of double skin façade with building integrated solar systems for an energy renovation of an existing building in Limassol, Cyprus: energy performance analysis, Energy Rep. 8 (2022) 15144–15161.
[182] J. Bezaatpour, et al., Towards optimal design of photovoltaic/thermal facades: Module-based assessment of thermo-electrical performance, exergy efficiency and wind loads, Appl. Energy 325 (2022).
[183] Y.S. An, et al., Experimental performance analysis of photovoltaic systems applied to an positive energy community based on building renovation, Renew. Energy 219 (2023).
[184] E.D. Rounis, A.K. Athienitis, T. Stathopoulos, BIPV/T curtain wall systems: design, development and testing, J. Build. Eng. 42 (2021).
[185] A. Sohani, et al., Techno-economic evaluation of a hybrid photovoltaic system with hot/cold water storage for poly-generation in a residential building, Appl. Energy 331 (2023).
[186] H. Ren, et al., Performance simulation and analysis of a multi-energy complementary energy supply system for a novel BIPVT nearly zero energy building, Energy Convers. Manag. (2023) 282.
[187] B. Nghana, F. Tariku, G. Bitsuamlak, Numerical study of the impact of transverse ribs on the energy potential of air-based BIPV/T envelope systems, Energies 16 (14) (2023).
[188] W. Ke, et al., Effects of the PCM layer position on the comprehensive performance of a built-middle PV-Trombe wall system for building application in the heating season, Energy (2023) 267.

[189] P. Karunyasopon, et al., Performance analysis of transparent BIPV/T double skin façades integrated with the decision-making algorithm for mixed-mode building ventilation, Architect. Eng. Des. Manag. (2023).
[190] M. Karami, M. Jalalizadeh, Performance comparison and risk assessment of BIPVT-based trigeneration systems using vapor compression and absorption chillers, J. Build. Eng. 69 (2023).
[191] S. Khanmohammadi, A. Shahsavar, Energy analysis and multi-objective optimization of a novel exhaust air heat recovery system consisting of an air-based building integrated photovoltaic/thermal system and a thermal wheel, Energy Convers. Manag. 172 (2018) 595–610.
[192] A. Buonomano, et al., Transient analysis, exergy and thermo-economic modelling of facade integrated photovoltaic/thermal solar collectors, Renew. Energy 137 (2019) 109–126.
[193] O. Erixno, N. Abd Rahim, A techno-environmental assessment of hybrid photovoltaic-thermal based combined heat and power system on a residential home, Renew. Energy 156 (2020) 1186–1202.
[194] A. Shahsavar, M. Arici, Effect of glass cover on the energy and exergy performance of a combined system including a building integrated photovoltaic/thermal system and a sensible rotary heat exchanger, Int. J. Energy Res. 46 (4) (2022) 5050–5066.
[195] M. Missoum, L. Loukarfi, Investigation of a solar polygeneration system for a Multi- storey residential building-dynamic simulation and performance analysis, Int. J. Renew. Energy Dev. -Ijred 10 (3) (2021) 445–458.
[196] J. Hasan, A.S. Fung, M. Horvat, A comparative evaluation on the case for the implementation of building integrated photovoltaic/thermal (BIPV/T) air based systems on a typical mid-rise commercial building in Canadian cities, J. Build. Eng. 44 (2021).
[197] E. Gaucher-Loksts, A. Athienitis, M. Ouf, Design and energy flexibility analysis for building integrated photovoltaics-heat pump combinations in a house, Renew. Energy 195 (2022) 872–884.
[198] M. Tripathy, et al., Performance of building integrated photovoltaic thermal systems for the panels installed at optimum tilt angle, Renew. Energy 113 (2017) 1056–1069.
[199] R.J. Yang, et al., Digitalising BIPV energy simulation: a cross tool investigation, Energy Build. 318 (2024) 114484.
[200] Y. Wang, et al., Performance of a building-integrated photovoltaic/thermal system under frame shadows, Energy Build. 134 (2017) 71–79.
[201] S. Yadav, S.K. Panda, M. Tripathy, Performance of building integrated photovoltaic thermal system with PV module installed at optimum tilt angle and influenced by shadow, Renew. Energy 127 (2018) 11–23.
[202] X. Chen, et al., Performance evaluation and optimization of a building-integrated photovoltaic/thermal solar water heating system for exterior shading: a case study in south China, Appl. Sci. (Basel) 9 (24) (2019).
[203] D. Gu, K. Andreev, M.E. Dupre, Major trends in population growth around the world, China CDC weekly 3 (28) (2021) 604.
[204] G.A. Barron-Gafford, et al., The photovoltaic heat Island effect: larger solar power plants increase local temperatures, Sci. Rep. 6 (1) (2016) 35070.
[205] R. Zhang, P.A. Mirzaei, J. Carmeliet, Prediction of the surface temperature of building-integrated photovoltaics: development of a high accuracy correlation using computational fluid dynamics, Sol. Energy 147 (2017) 151–163.
[206] D. Sailor, J. Anand, R. King, Photovoltaics in the built environment: a critical review, Energy Build. 253 (2021) 111479.
[207] S. Garshasbi, A. Khan, M. Santamouris, On the cooling energy penalty of urban photovoltaics: a case study in Sydney, Australia, Energy Build. 294 (2023) 113259.
[208] Y. Wang, et al., Interactions between building integrated photovoltaics and microclimate in urban environments (2006).
[209] S.R. Asaee, et al., Techno-economic assessment of photovoltaic (PV) and building integrated photovoltaic/thermal (BIPV/T) system retrofits in the Canadian housing stock, Energy Build. 152 (2017) 667–679.
[210] A. Khan, M. Santamouris, On the local warming potential of urban rooftop photovoltaic solar panels in cities, Sci. Rep. 13 (1) (2023) 15623.
[211] H. Taha, The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas, Sol. Energy 91 (2013) 358–367.
[212] S. Ma, et al., Pricing the urban cooling benefits of solar panel deployment in Sydney, Australia, Sci. Rep. 7 (1) (2017) 43938.
[213] U. Berardi, J. Graham, Investigation of the impacts of microclimate on PV energy efficiency and outdoor thermal comfort, Sustain. Cities Soc. 62 (2020) 102402.
[214] A.M. Broadbent, et al., The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance, J. Appl. Meteorol. Climatol. 58 (5) (2019) 989–1006.
[215] A. Gentle, J. Aguilar, G. Smith, Optimized cool roofs: integrating albedo and thermal emittance with R-value, Sol. Energy Mater. Sol. Cell. 95 (12) (2011) 3207–3215.
[216] O. Bamisile, et al., The environmental factors affecting solar photovoltaic output, Renew. Sustain. Energy Rev. 208 (2025) 115073.
[217] K. Hasan, et al., Effects of different environmental and operational factors on the PV performance: a comprehensive review, Energy Sci. Eng. 10 (2) (2022) 656–675.
[218] X. Li, D.L. Mauzerall, M.H. Bergin, Global reduction of solar power generation efficiency due to aerosols and panel soiling, Nat. Sustain. 3 (9) (2020) 720–727.
[219] W. Chen, et al., Progress in dust modelling, global dust budgets, and soil organic carbon dynamics, Land 11 (2) (2022) 176.
[220] Ensun, Solar hybrid pvt, Available from: https://www.ensuntec.com/pvt-system/, 2025.
[221] C. Shao, A. Migan-Dubois, D. Diallo, Performance of BIPV system under partial shading condition, Sol. Energy 283 (2024) 112969.
[222] A. Coca-Ortegon, et al., Operational performance of trigeneration PVT-assisted HP system, Energy Build. 296 (2023) 113383.
[223] S. Mobayen, et al., Dynamic analysis and multi-objective optimization of an integrated solar energy system for Zero-Energy residential complexes, Energy Convers. Manag. 341 (2025) 119924.
[224] K. Başaran, İ. Koç, PV/T system application for renewable heat and electric energy in buildings: performance and techno-economic analysis, Isı Bilimi ve Tekniği Dergisi 44 (2) (2024) 359–373.
[225] K. Nam, et al., Net zero proximity index and techno-economic analysis of BIPV for zero energy and zero emission buildings, J. Build. Eng. 103 (2025) 112188.
[226] IEA Policies. Available from:: https://www.iea.org/reports/global-energy-and-climate-model/policies.
[227] Z. Zeng, B. Zhao, R. Wang, Passive day and night heating for zero energy buildings with solar-based adsorption thermal battery, Cell Rep. Phys. Sci. 2 (9) (2021).
[228] F. Boronuosi, et al., Building-integrated photovoltaic (BIPV) and its application, design, and policy and strategies, in: Natural Energy, Lighting, and Ventilation in Sustainable Buildings, Springer, 2023, pp. 91–109.
[229] M.M.V. Cantarero, Of renewable energy, energy democracy, and sustainable development: a roadmap to accelerate the energy transition in developing countries, Energy Res. Social Sci. 70 (2020) 101716.
[230] D. Hayashi, Harnessing innovation policy for industrial decarbonization: capabilities and manufacturing in the wind and solar power sectors of China and India, Energy Res. Social Sci. 70 (2020) 101644.
[231] H.C. Curtius, The adoption of building-integrated photovoltaics: barriers and facilitators, Renew. Energy 126 (2018) 783–790.
[232] Y. Lu, et al., The implementation of building-integrated photovoltaics in Singapore: drivers versus barriers, Energy 168 (2019) 400–408.
[233] A.K. Shukla, et al., Solar PV and BIPV system: barrier, challenges and policy recommendation in India, Renew. Sustain. Energy Rev. 82 (2018) 3314–3322.
[234] J. Payá, et al., Low-Pressure steam generation with concentrating solar energy and different heat upgrade technologies: potential in the European Industry, Sustainability 16 (5) (2024) 1733.
[235] S.H. Europe, Solar hybrid PVT, Available from: https://solarheateurope.eu/market/our-technologies/solar-hybrid-pvt/, 2025.
[236] S.H. Europe, Policy (2025). https://solarheateurope.eu/policy/.
[237] A. Khan, et al., Rooftop photovoltaic solar panels warm up and cool down cities, Nature Cities 1 (11) (2024) 780–790.
[238] W. Sommer, et al., Optimization and spatial pattern of large-scale aquifer thermal energy storage, Appl. Energy 137 (2015) 322–337.
[239] I. Sifnaios, et al., Dronninglund water pit thermal energy storage dataset, Sol. Energy 251 (2023) 68–76.