Innovative Infrastructure Solutions (2024) 9:339
https://doi.org/10.1007/s41062-024-01635-x

STATE-OF-THE-ART PAPER

Innovative methods to optimize the integration of passive solar design principles into buildings

Elsayed Salem[1] · Emad Elwakil[1]

Received: 23 February 2024 / Accepted: 18 July 2024 / Published online: 6 August 2024

Abstract

The critical challenge of escalating energy consumption and carbon dioxide emissions in the building sector commands global attention, as it significantly overshadows other sectors regarding environmental impact. Numerous countries are devising strategies to optimize energy usage and reduce carbon footprints, marking a pivotal shift in environmental policy and sustainability efforts. However, there is a lack of studies on adopting passive solar design concepts in the early stages. This paper investigates integrating passive solar design concepts in building techniques to address the current research gap. It evaluates the building industry's readiness for energy optimization, focusing on adopting prefabricated solar panels in building façades, walls, and roofs as a prevalent method. A systematic literature review encompassed papers from 2000 to 2023 in Engineering, Energy, and Building, accessed via the Scopus database, Google Scholar, and the Purdue Library. The research underscores the necessity of incorporating a comprehensive passive solar design approach into buildings. This study is a valuable resource for professionals and academics, fostering innovation and informed decision-making in sustainable building practices.

Keywords Building energy · Passive design · Energy optimization · Solar energy · Renewable energy · Sustainable design · Climate change · Carbon emissions

Introduction

One of the main issues the globe is currently dealing with is the rising demand for homes. The home construction industry uses much energy. The impact is going to get worse as the population and the number of homeowners increase. A wave of green and sustainable techniques is growing to decrease some negative environmental impacts. Construction is a sector that is constantly changing to become more energy-conscious [18, 25, 26] Building-integrated photovoltaics (BIPV) encourage low-energy structures and enable the production of on-site clean energy. According to [12], it is preferable to install BIPV on building façades for rooftop solar systems in densely populated cities, particularly for tall structures with constrained roof space. However, their adoption has been hampered by the market shortage of "plug-and-play" BIPV. In this study, the design concept of BIPV systems will be explored; however, to facilitate the adoption of BIPV in buildings, the study will focus on the prefabrication technology. The innovative BIPV system is renowned for its comprehensive "all-in-one" structure, featuring multiple functional layers enabling autonomous operation of each part. The exceptional design of interlocking joint enables easy installation and ensures compliance with air and water tightness standards. Design methodologies incorporated in this system encompass PV mounting strategies, 2D cross-sectional planning, 3D modelling, in addition to prototype development. Remarkably, the proposed system allows for manual installation on-site within the building by three individuals lacking electrical expertise, eliminating the need for scaffolding because each part is pre-wired and pre-assembled before being brought to the site at the factory. The results in the literature demonstrated the prefabricated BIPV system's potential and usefulness.

The construction industry contributes significantly to CO2 emissions. The building sector consumes 40% of

✉ Elsayed Salem
esalem@purdue.edu

Emad Elwakil
eelwakil@purdue.edu

1 School of Construction Management, Purdue University, Indiana, USA

global energy and generates 36% of global carbon emissions. Construction is an essential industry in a nation's economy. This industry consumes many construction materials and produces much pollution and significant carbon dioxide [27]. According to Belussi et al. [8] the building industry accounts for 40% of the total energy consumption in European countries and the United States.

Most countries have a target to reach Zero Energy Building [5]. The need to change design principles to include renewable energy became vital. There are different ways to include solar panels in buildings; for instance, solar panels can be installed onto roofs or used as roofs or windows and as a building facade. Research literature showed fragmented solutions and guidelines to integrate solar energy in building design. This study will cover this gap by selecting the best methods to integrate solar energy in the early design stage.

This research aims to identify innovative methods to integrate renewable energy production into buildings. The study focuses on including passive solar design principles in early design stages in various building types and climates.

Table 1 Research questions

Question Group	Questions	Sub questions
Historical interest	When did the interest in integrating solar design begin?	How many papers have been published in this issue? What are the top countries? How is the volume of research on building energy compared to other energy fields?
Building Types	What building types are most convenient to include passive solar energy design?	What are the most popular types of buildings convenient for integrating solar design? Can passive solar design be used in residential buildings?
Region and Climate	What is the best climate/location for solar energy?	What are the regions and climates with higher solar energy production? What are the regions and climates with the lowest solar energy production?
Technology	What are the technologies used?	What are the types of technologies? What are the most effective technologies? Is the technology available in most countries? Is the technology expensive? Will the owners accept the technology?
Benefits and drawbacks of	What are the benefits and drawbacks of integrating passive solar design principles into buildings?	What is the feasibility of including solar design? Will the change affect the overall cost?
Passive solar design	Will designers consider the change?	Will the designers accept to include passive solar design in the design stage? Does it need specific experience? Is passive solar design complicated? Which building elements (Roofs/walls/floors) are considered for the change? Is it worth including passive solar design?

Research inquiry framework

This research embarks on a comprehensive investigation, delving into a series of well-defined questions, as shown in Table 1, that collectively aim to enrich the understanding of the topic. The exploration begins with focusing on the historical context, seeking to uncover the historical interest and significance of the subject matter. This involves deep diving into the past and understanding how historical developments have shaped current practices and theories.

Moving forward, the research takes a closer look at various building types. This part of the inquiry centers on examining different architectural forms and styles, assessing their evolution, and understanding their unique characteristics, purposes, and functionalities.

Another critical aspect of this study is the examination of region and climate. Here, the aim is to analyze how geographical factors and climatic conditions influence the subject of study. This involves understanding the interplay between the environment and the subject and how this relationship impacts theory and practice.

The role of technology is also a key focus of this research. This section investigates advancements and integration of technology in the field, exploring how technological innovations have influenced and shaped the current landscape.

Lastly, the research delves into the realm of passive solar design. This segment is dedicated to thoroughly examining the benefits and drawbacks of passive solar design, providing a balanced view of its effectiveness, efficiency, and potential limitations.

Overall, this research is structured to provide a comprehensive and multifaceted understanding of the subject, making significant contributions to the academic field through its investigative depth and breadth.

Study boundaries

The research includes papers published in related areas of interest, for instance, Engineering, Energy, and Building journals. Data was gathered using the Scopus database, Google Scholar, Purdue Library, and Journal websites. The time frame extended from 2000 to 2023. On the other hand,

Table 2 Top 10 countries published on passive solar design from 2000 till 2023

Ranking	Country	Number of publications
1	United Kingdom	48
2	United States	19
3	China	16
4	Italy	10
5	Australia	10
6	Sweden	6
7	Canada	6
8	Switzerland	5
9	Spain	5
10	Norway	5

the Scopus database was used to collect data on the size of publications on passive solar design. The combination of keywords "novel AND method AND design AND solar OR buildings OR houses" was used to filter the search results. Following that, the data results were filtered based on Subject Area "Engineering", Document type "Article", Source "any building or construction-related sources", Publication Stage "Final" and all open access to narrow the results to be more related to the study topic (Table 2).

Bibliographic analysis

To understand the extent of the issue, a review of current literature on passive solar design was conducted through the Scopus database. Figure 1 Shows the number of publications on solar design per year. Different keywords were used to show the lack of research on the main topic.

At first glance, the figure shows that the building industry still has a research gap on solar design. However, with the massive interest in "solar and renewable energy", the building industry comes behind with a few articles on the topic. Figure 2 shows that most countries worked on passive solar design (Fig. 3).

Research methodology

Papers published in similar areas of interest, such as Engineering, Energy, and Building publications, will be included in the research. The Scopus database, Google Scholar, the Purdue Library, and journal websites were used to collect data. The period was extended from 2000 to 2023 (Fig. 4).

The key phrases "novel AND method AND design AND solar OR buildings OR houses" were used to narrow the search results. Following that, the data results were filtered based on Subject area "Engineering", Document type "Article", Source "any building or construction related sources", Publication Stage "Final," and all open access to restrict the findings to be more relevant to the research subject.

Green roofs

The excessive consumption of fossil fuel and the rise of carbon emissions in urban cities have heightened the significance of green structures, for instance green roofs, in cityscapes. Addressing this, Mousavi et al. [35] introduced an advanced smart energy-comfort system to enhance the design and functionality of green roofs on buildings. This system incorporates the use of DesignBuilder software, Taguchi method simulations, and integrated machine learning algorithms. The optimization focuses on improving energy efficiency and thermal comfort in green roof buildings. Notably, the most effective solutions compared to

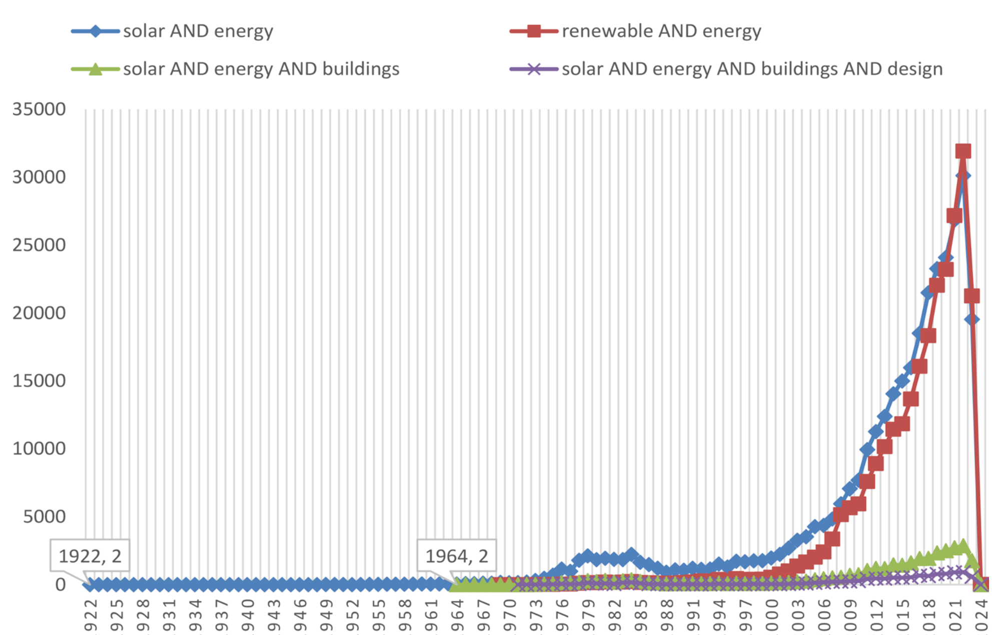


Fig. 1 Number of publications on solar design in buildings (Scopus database)

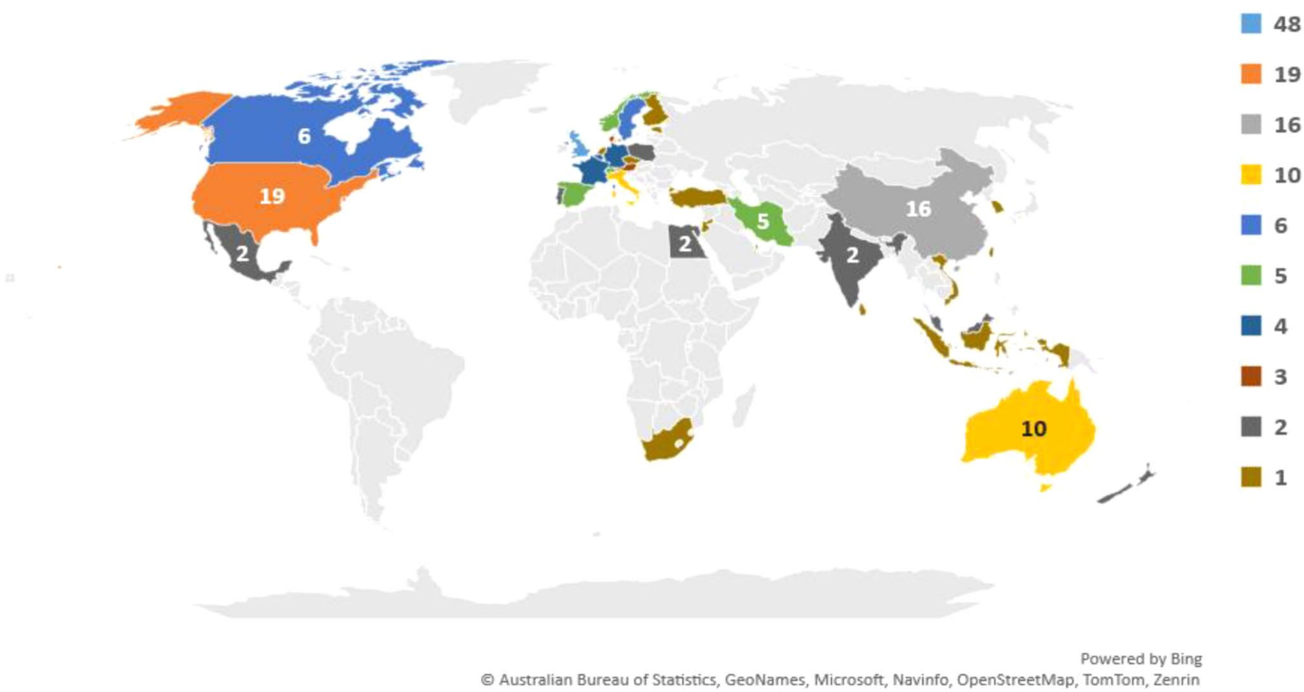


Fig. 2 Countries published on passive solar design from 2000 till 2023. (Scopus database)

Fig. 3 Number of publications on passive solar design per field from 2000 till 2023

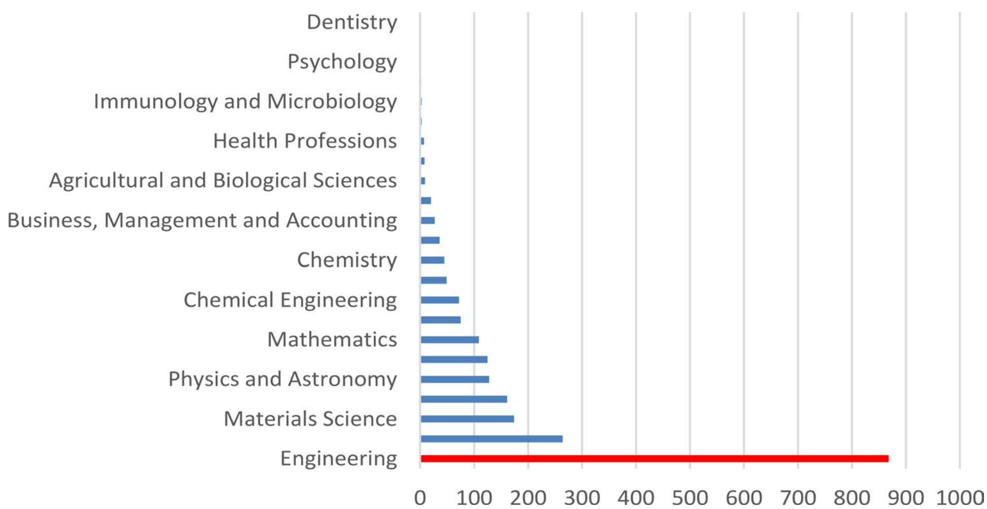
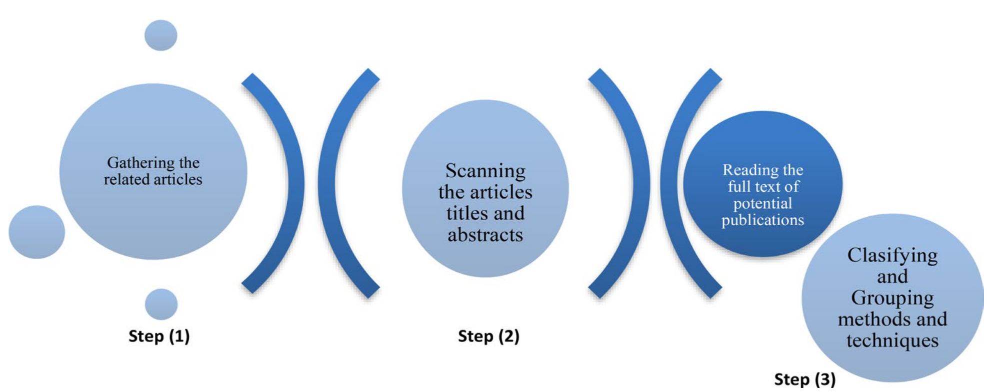


Fig. 4 Research methodology



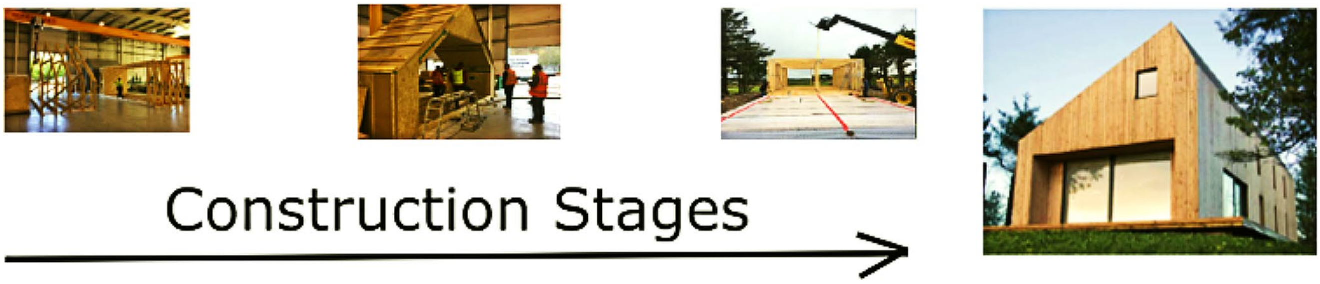


Fig. 5 The construction steps of Integra House. Adapted from [44]

standard scenarios reduced energy consumption by 14%, and increased comfort hours by 12.8%. According to the machine learning results, the adaptive-network-based fuzzy system was the most accurate method for predicting energy and comfort functions. This cutting-edge method represents a significant stride in promoting energy efficiency and thermal comfort in urban environments through intelligent green roof design on buildings.

Low-carbon construction materials

The construction industry significantly impacts climate change, contributing to CO2 emissions and water and soil pollution. Industrial construction, renewable energy use, and heavy civil and highway construction are crucial for managing climate change. Awareness and proactive actions are needed to minimize these impacts and mitigate climate change [17].

One of the most important ways to address the current housing issue and combat climate change is using new construction techniques based on wood. the "Integra House" case study is presented by [44], as a proof of concept for the new truss technology. The project is an excellent example of low-cost and carbon-efficient housing. Utilizing cutting-edge wood truss technology for the house's floor, walls, and roof allows the proposed structure to decrease on-site operations and waste while offering a low-cost, low-carbon emissions design. The model was subject to several stages of development, including design refinement and options analysis, creation and testing of component prototypes in workshops, construction and assessment of full-scale residential prototypes, analysis of both initial and lifecycle costs, and evaluation of environmental impacts. To improve its performance in terms of cost and carbon, it also underwent simulation-based optimization to switch out Rockwool insulation for wood wool insulation and milled timber trusses for whole timber trusses. The best design option (whole timber) has an EC of 261 kg CO2 per m2 and costs £682 per m2, excluding substructure and services. It emits 7.9 kg of CO2 per square meter per year, costing £3.30 to run. Due to being significantly more economical and needing less processing than the milled timber alternative, the design alternative whole timber performed better than milled timber by 30% and 23% in carbon and cost, respectively. This was established by contrasting the two design concepts' carbon footprint and life cycle costs. Figure 5 illustrates the Integra House Construction steps (Fig. 6).

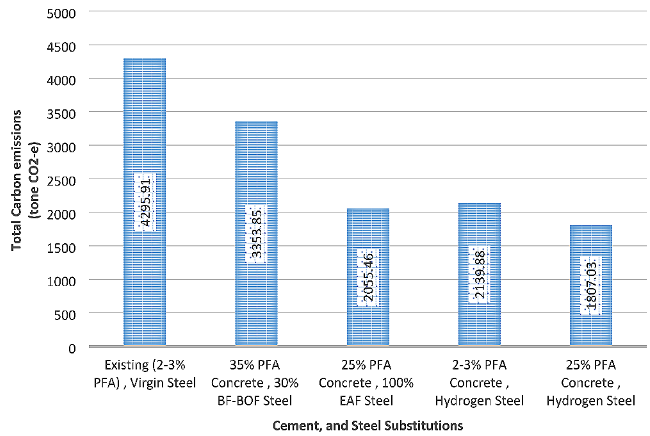


Fig. 6 Impact of substituting existing materials with low-carbon materials on carbon emissions. Adapted from [21]

Gan et al. [21] proposed a BIM-based framework to predict and optimize lifecycle carbon. A suggestion for a standardized approach that uses general formulas to determine embodied carbon. Investigation of parametric modeling with BIM support for enhancing low-carbon alternative design. Investigation of the compatibility of energy simulation and BIM for lifecycle analysis. Due to embodied and operational carbon emissions, resource-intensive residential building construction has a negative environmental impact. The research aims to optimize the performance of the lifecycle carbon of residential buildings by designing and using material alternatives. The project was analyzed, and the carbon emission was predicted using A BIM-based method. Considering 1.5 °C Net-Zero World and 3 °C Hot House World climate scenarios, the BIM model was built to simulate energy and carbon emissions throughout the building lifespan of 50 years. Future residential building projects can benefit from improvements in material selection and operational savings, including using low-carbon building materials like cement substitutes, steel by-products, and green hydrogen steel. This study offers insights into the lifespan performance of residential structures and the potential of using alternate materials to reduce carbon emissions. For instance, cement manufacturing can be replaced with materials such as ground granulated blast-furnace slag (GGBS) at 75% and pulverized fly ash (PFA) at 35%. Green hydrogen steel, a novel low-carbon material, was also explored, converting iron ore into water instead of carbon dioxide. The total carbon emissions can be decreased by up to approximately 42% when substituting existing cement and steel with 25% fly ash and hydrogen steel, as illustrated in Fig. 5.

In 2022, Zuluaga et al. introduced a novel approach that synergistically combines seismic and energy retrofitting. This method leverages wood's mechanical strength and bio-based materials' thermal insulation qualities. Named Strong Thermal and Seismic Backs (STSB), this technique is designed to improve existing masonry structures' seismic resilience and energy efficiency. Seismic-Energy-Retrofitting-Scoreboard (SERS) measures seismic performance, energy efficiency, and carbon footprint to evaluate these improvements. The study explores three retrofitting alternatives: wooden beams, cork, and recycled natural grass, for their energy and seismic retrofitting advantages. Multi-Criteria-Decision-Making (MCDM) process is employed to identify the most effective retrofitting strategy.

In a separate study by Ranjbar et al. [38] DesignBuilder software was utilized on two predominant structural frames: structural steel (SS) and reinforced concrete (RC) frames to assess their environmental impact. This analysis was focused on their respective influences on sustainability criteria. The study found that building with RC-frame have a less negative effect on the environment due to lower carbon emissions and energy consumption. RC-framed construction consumes less electricity and natural gas by 2.3% and 2.7%, respectively. And over a 50-year lifecycle, it can reduce 88 tonnes of CO_2 emissions or more than 5% of the building's overall CO_2 output. This research provides a fresh option for decision-makers to consider sustainability factors during the design process, highlighting the importance of sustainable building frames in reducing environmental impact.

The Indian Concrete Institute (ICI) and industrial colleagues conducted a focus group meeting to address the high demand for sustainable and affordable housing in India. The findings revealed that India's current design methodologies for buildings and structures need improved service life enhancement, real-time monitoring, and whole-life energy consumption. Over 50% of respondents expressed dissatisfaction with current building design rules, as they do not contribute to reducing energy use. High construction speeds exacerbate material inefficiency and lack of durability, highlighting the need for precast elements in modular home construction [9] (Fig. 7).

Building-integrated solar techniques

Photovoltaic systems are increasingly used in modern structures to create zero-energy structures. However, architects still lack understanding of this approach. Celadyn and

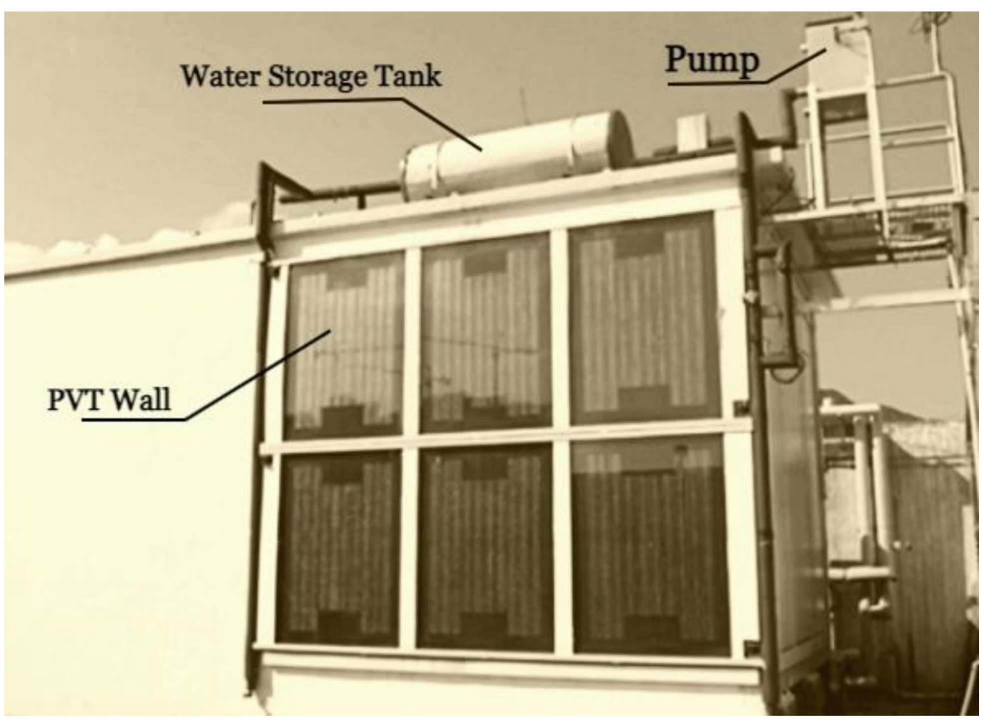


Fig. 7 Building integrated photovoltaic (BIPV) water heating system. Adapted from [14]

Filipek [10] presented the problem according to standard design stages, starting with large-scale urban issues and progressing to building forms and components. Various photovoltaic (PV) system designs were considered based on effectiveness, relationships with building materials, thermal insulation potential, and aesthetic effects. They recommended conducting in-depth studies at the beginning and throughout the design stages to apply these systems properly (Fig. 8).

Building-integrated photovoltaics (BIPV) offer a promising avenue for reducing energy use in structures, yet the current market is deficient in ready-to-install BIPV systems. Chen et al.'s [12] study investigated the development of a prefabricated BIPV wall system that utilizes light gauge steel structure prefabrication technology. This system is characterized by an integrated design incorporating several functional layers, enabling each unit to function independently and facilitating swift installation. The design process covers photovoltaic (PV) mounting strategies, 2D cross-sectional planning, creating system prototypes, and 3D modeling. In a significant advancement, each unit is pre-built and wired at the factory, simplifying installation by a team of three non-electrically trained workers without scaffolding. This study's findings underscore the feasibility and practicality of the prefabricated BIPV system, identify its limitations, and open directions for future research (Fig. 9).

in an office building façade, Pereira and Aelenei [36] investigated the optimization of a BIPV/T-PCM using the Genetic Algorithm technique. Theoretical simulations used an updated mathematical model for the current configuration, including system layers, air cavity width, and ventilation. Field testing validated the model, and the simulated and experimental results were in excellent agreement. The system's total energy efficiency was analyzed for winter and summer conditions, resulting in a total efficiency of 64% and 32% for winter and summer configurations, respectively (Fig. 10).

In 2022, Liu and Wu introduced an innovative BIPV smart window designed to improve energy efficiency besides visual comfort. The innovative system involves a switchable layer made from hydrogel crystalline silicon photovoltaic cells and encased in clear glass. The unique feature of the thermotropic layer is its ability to automatically adjust its visible and optical properties in response to temperature changes. Additionally, the BIPV smart window is engineered to redirect some light, reflected by the thermotropic layer, to its integrated PV cells, thereby generating extra electricity.

A new approach has been developed to predict the performance of the BIPV smart window under various environmental conditions. Using numerical models in a simulated office environment in Nottingham, UK, the study examined

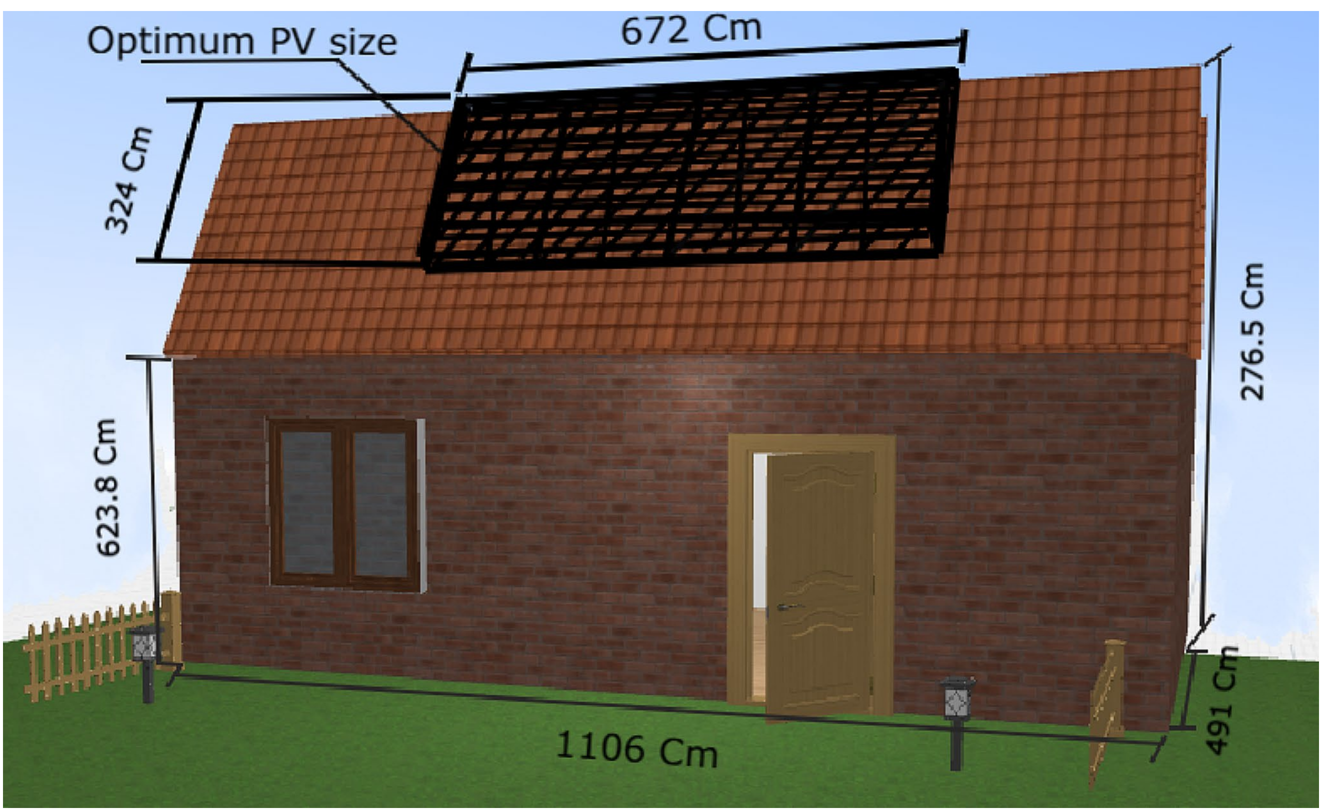


Fig. 8 Building integrated photovoltaics BIPV installed on the building roof. Adapted from [37]

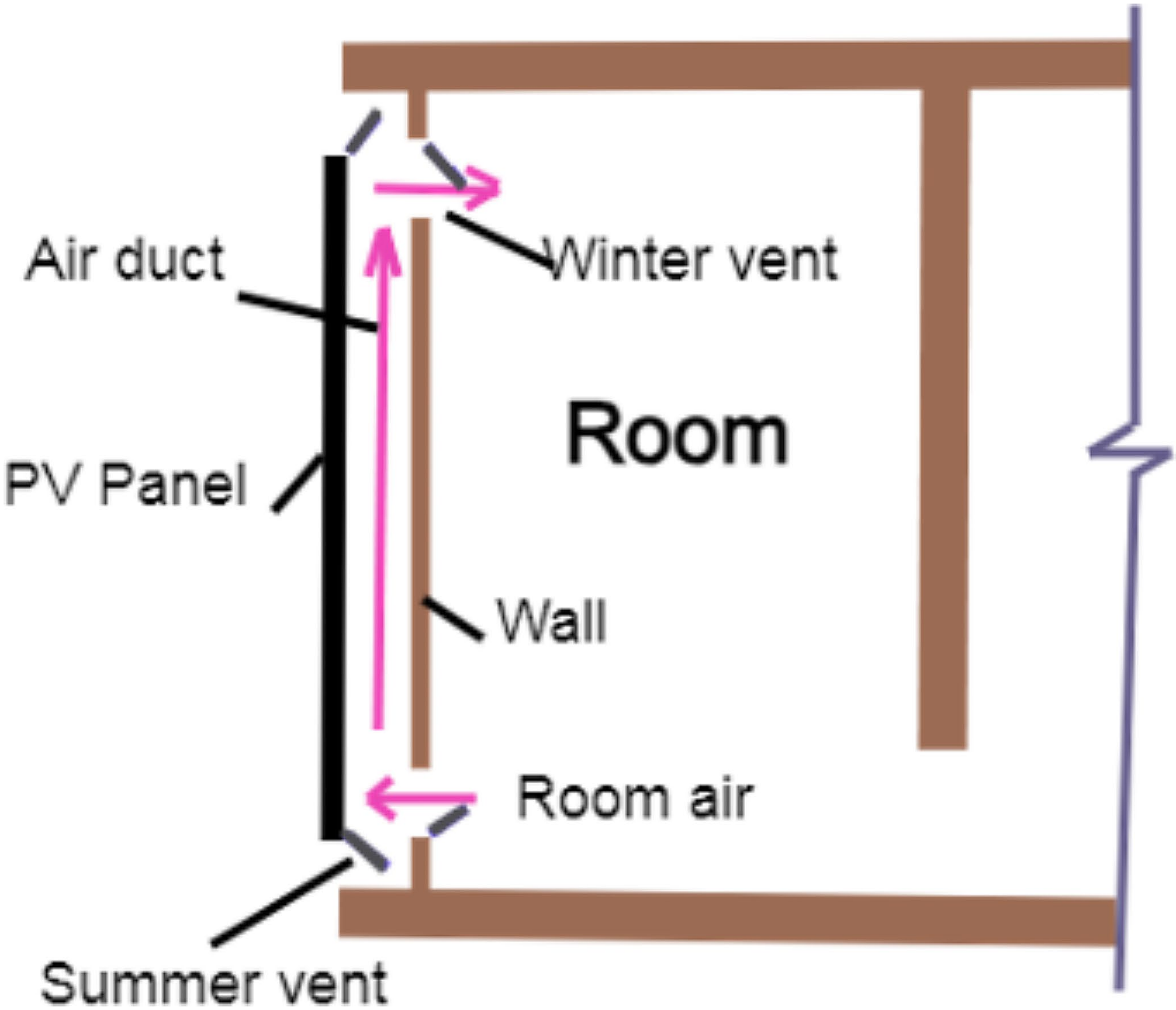


Fig. 9 BIPV system configuration. Adapted from [36]

the impact of different window design parameters, including Window-to-Wall Ratio (WWR), orientation, and transition temperature of the thermotropic layer. The research findings suggest that the BIPV smart window could lead to an annual energy saving of 36.6% and improve indoor lighting quality compared to traditional BIPV windows. Sun et al. [43] introduced a smart window design featuring thermotropic Parallel Slat Transparent Insulation Material for energy conservation and daylight autonomy. The design improves indoor comfort, achieves building energy conservation, and provides dynamic adjustment of solar energy and daylight. The Parallel Slat transparent insulation material (PS-TIM) structure provides additional thermal resistance and automatic daylight and sun adjustment. The study evaluated the system using building energy and daylight simulation software, revealing that thermotropic PS-TIM window systems can increase building energy efficiency and achieve homogeneous daylight distribution, resulting in a 22% savings compared to conventional double-glazed windows. The study offers design recommendations and material development ideas for incorporating this innovative window system into structures.

BIPV systems, primarily designed for roof integration, have gained popularity due to their ability to protect against wind-driven rain. However, there is limited research on their water intrusion capabilities. A novel framework was developed by [19].

to enhance testing methods for BIPV systems, focusing on quantifying water penetration. The study demonstrated that performance-based data can be used to design BIPV systems as climate screens more effectively, demonstrating

Fig. 10 Map and street view of sun sails over the pedestrian zone, Calle Conde de Gondomar, near Plaza de las Tendillas, Cordoba, Andalucia, Spain in 2019. Adapted from [22]

the potential of BIPV systems as a valuable alternative to traditional electricity generators.

In Mediterranean cities, a popular street-scale shading tactic, "Sun sails," significantly reduced cooling requirements for buildings. Finite Element Methods (FEM) were used by [22] to conduct thermal simulations, revealing that the deployment of street sun sails can significantly reduce surface and air temperatures within buildings, reducing cooling requirements by between 12% and 46%. The results offer design recommendations for installing sun sails to maximize their effectiveness.

The Smart Water-filled Glass (SWFG) control system is a novel approach to reducing energy consumption in glass facades. It allows for changing the façade element's opacity over a year in response to seasonal variations. In seven cities from all major climatic zones [24], evaluated the energy performance of a reference office space equipped with a wide-glazed facade. According to climatic conditions and the reusability of the collected heat in the water layer, the simulation research evaluates the overall effectiveness of two operational strategies (insolation-based and storage-based) for modifying water layer settings. The findings support the claim that depending on climate, the impact of SWFG relative to WFG changes; SWFG offers energy savings ranging from 47.41 to 78.01%.

Building energy dynamic modelling

Using machine learning approaches, recent research has begun developing daylight prediction models early in the design stage to better understand building daylighting performance. Most studies significantly restrict the daylight model's potential uses by setting the input parameters for model training the same as the design variation parameters. Lin and Tsay [30] proposed a unique daylight model that pre-processes the design model into "Intermediary features" that serve as input parameters for daylight penetration performance. The daylight model was then trained using a synthetic neural network by projecting the daylight performance of several types of façades. The results revealed that the recommended daylight model would hasten daylighting evaluation by 9 to 10%, compared to the daylighting simulation. It is important to include the assessment within the early design phase.

Table 3 The proposed optimum design parameters of Tehran's multi-objective genetic algorithm optimization approach. Adapted from [15]

Variable	Unit of measure	Baseline Scenario Values	Lighting-based Optimization Values	Cooling-based Optimization Values
Building orientation	(°)	0	0	180
Overhang tilt angle	(°)	90	0	34
Overhang depth	(m)	0.3	0	0.5
Window length	(m)	2	2.99	0.6
Window height	(m)	2	2.99	0.7

Table 4 Optimal objective functions in Tehran. Adapted from [15]

Objective Function	Baseline Value (GJ)	Lighting-based Opt.		Cooling-based Opt.	
		Value (GJ)	Diff. (%)	Value (GJ)	Diff. (%)
Annual lighting electricity	1.89	1.87	−1.5	2.20	+17.5
Annual cooling electricity	2.66	6.03	+126.5	0.62	−76.6
Annual total electricity	4.55	7.90	73.3	2.82	−37.5

Grassie et al. [23] conducted a dynamic modelling study on indoor environmental conditions for future energy retrofit scenarios in UK school buildings. EnergyPlus UK classroom archetype models have been developed to evaluate performance on multiple criteria, considering stock-wide heterogeneity and long-term dynamic changes. Passive ventilation's effectiveness in reducing overheating improved with increased retrofit area, and additional energy demand decreased. However, low ceiling heights in classrooms built between 1945 and 1967 impact the effectiveness of Energy modifications.

The COVID-19 pandemic has heightened the need for fresh air supply in buildings, increasing energy demand. This has necessitated passive cooling methods, such as natural ventilation, to improve indoor air quality. Li et al. [28] developed a novel dual-channel windcatcher desi featuring a rotary wind scoop and a chimney to supply fresh air regardless of wind direction. This design improves thermal performance by integrating heat recovery, passive cooling, and dehumidification technology. A computational fluid dynamic (CFD) model was created and validated to further assess the system's ventilation performance. The outcomes showed that the system could produce enough fresh air even in shifting wind directions.

Genetic algorithm

EnergyPlus is a powerful tool for optimizing building energy performance. By combining a multi-objective genetic algorithm with the EnergyPlus building energy modeling tool, the researchers [15] proposed optimum solutions that improve energy efficiency. The study investigated the impact of architectural elements like building orientation window size on energy consumption in four major climatic areas. The optimization studies reveal that bi-criteria optimization reduces yearly cooling energy usage by 55.8–76.4% in different regions, while yearly lighting electricity demand rises by 1–4.8%. The optimal layout reduces yearly total building energy usage by 23.8–42.2%. The findings highlight the importance of climate and suitable design parameter choices in reducing building energy consumption. The authors concluded that a single solution minimizing two objective functions leads to optimum results. The cooling-based optimization revealed that the optimum room has the northern window with the most extended overhang and the largest window size, reducing annual cooling electricity consumption by 90%—conversely, the lighting-based minimization results in a building with the southern window and no overhang. Tables 3 and 4 introduces the study findings.

According to [13, 34, 48], Pareto proposes one of the most prominent approaches for presenting multi-criteria optimization solutions. The multicriteria method yields a collection of non-dominated solutions known as the Pareto front.

Passive design recommendations for reducing energy consumption

To explore the impact of energy efficiency requirements in building design on energy consumption, investment cost, and thermal comfort in five cities in China, Lin and Yang [31] applied an enhanced multi-objective genetic algorithm (NSGA-II) to building simulation. Compared to a reference building, the optimizations revealed an average AEC reduction of 29.08% and 38.6% with 3.18% greater cost on the original expenditure. The study suggests new rules for building design characteristics to modify key energy efficiency standards. The study offers several key recommendations regarding building energy efficiency. Firstly, it reveals that employing energy-saving measures at the design stage can yield an average energy savings of 29.8% compared to buildings designed as per current standards, with a potential maximum saving of 38.6% for a marginal increase in initial construction costs of 3.18%. Secondly, it identifies discrepancies between current energy efficiency design standards and the Pareto solutions, especially regarding building orientation, suggesting a need for revising these standards across various cities. Thirdly, the study emphasizes that in regions experiencing hot summers and cold winters, roof and exterior wall insulation are crucial factors influencing building energy consumption. Additionally, selecting wall and window types is critical for reducing energy consumption. Finally, the study proposes an optimization approach applicable to the design phase of new buildings and for assessing and enhancing energy savings in existing structures through retrofitting.

Towards zero energy buildings

By reducing building energy consumption while adding some techniques for energy production to buildings, integrating passive solar design in buildings during the design stage accelerates the goal of zero-energy buildings. To reduce energy consumption and greenhouse gas emissions, the construction sector is increasingly adopting net-zero Energy. However, challenges remain, particularly in high-rise residential structures. A study byAlawode and Rajagopalan [2] in Australia examined net zero energy performance delivery methods for these structures using building simulation. Despite some restrictions, NZE performance can be achieved in Australia, particularly in tropical, subtropical, and cold temperate climates. The main barrier to energy production through the façade was the shadowing effects of nearby structures.

Salem and Elwakil [39] studied the obstacles to adopting Zero Energy Buildings. They found that countries plan to convert traditional buildings to Zero Energy, but this is faced with challenges like high initial costs for renewable energy systems compared to overall building costs. According to the authors, the philosophy has gained more interest and support despite these obstacles.

Also, Almutairi et al. [3] explored the potential of zero-energy buildings in Muscat, Oman. The study identified the best locations for solar-absorbing surfaces using climatic data and climate maps and considered unique design aspects. The Solar Radiation model showed that one square meter of solar cells could produce nearly 1710 kWh of energy annually. The 290 m2 building, with a total area of that size, consumed 25,200 kWh of total energy and 19,900 kWh of annual production. To address this energy need, 23 m2 of PV panels were suggested to be installed as canopies at a rate of 61000kWh per year.

Zero Energy Building (ZEB) is gaining popularity as a solution to environmental issues. However, there is a lack of bibliometric analysis for this topic. Souley Agbodjan et al. [42] examined ZEB publications' collaborative networks and subject patterns using tools like VOSviewer and Biblioshiny. Scopus extracted 1051 papers between 1976 and 2020, revealing three stages of research growth: slow from 1076 to 1999, 2000 to 2010, and rapid from 2011 to 2020. The most commonly referenced scholars, most published countries, and widely collaborated scholars are China, the United States, and the United Kingdom. Energy efficiency and life cycle assessment (LCA) are the biggest obstacles to achieving the ZEB goal. Solutions to these issues have been proposed to overcome these obstacles.

Energy retrofits for solid wall homes are crucial in the UK to achieve net-zero goals and combat fuel poverty. Seifhashemi and Elkadi [41] reveal that aesthetics plays a significant role in integrating energy and aesthetics in internal wall insulation (IWI). Over 90% of participants agree that incorporating aesthetics can outweigh drawbacks like cost and loss of internal space. The study suggests changes by the retrofit industry, legislators, and designers to maximize the benefits of aesthetics in Solid Wall Insulation SWI renovation.

To address the challenges of adopting ZEB technology, Salem and Elwakil [40] presented a study to explore the cost barriers preventing countries from implementing Zero Energy Building (ZEB) concepts. The research highlights gaps in energy-saving calculations, comparative studies between NZEB and conventional buildings, life cycle cost analysis, and the high initial cost of ZEB.

The constant issue for governments in the EU and UK is meeting rising housing demand while creating zero-carbon structures. Structurally insulated panels (SIPs) can meet these objectives using a novel conceptual framework and empirical findings. To analyze energy performance using game theory, Finnegan et al. [20] identified potential incentive conflicts between SIP makers and UK/EU regulators. Medium-sized investments are advantageous for both parties, but a commitment from both parties is crucial.

Energy-efficient building design requires an appropriate renewable energy system (RES) design, particularly zero-energy buildings. A novel sizing technique for a single U-tube ground heat exchanger (GHE) is proposed by Baek et al. [6] considering ground temperature recovery and other design factors. Transient simulations for various design situations validate the technique. Results show that the coefficient of variation of root mean square error (CV(RMSE)) is lower than 15% for all ten design situations, allowing for early sizing of a GHE at an early design stage.

The sharp increase in interest in cost-optimal zero-energy building solutions has led to numerous investigations and new techniques [4] provided a methodology using Multi-Objective Parametric Analysis (MOPA) to help choose cost-effective zero-energy buildings. Using a theoretical Reference Building in Belgium, the methodology considers wall, roof, and window alternatives for the building's superstructure. The results show that the design factors for the building envelope are both zero-energy and cost-optimal, expanding the field of roof stacking construction.

Action plans

The EU's energy strategy focuses on reducing energy consumption in buildings by implementing energy efficiency policies. This vital component has been updated over the past half-century with policies like the SAVE Directive. The EU has made significant progress in energy efficiency in buildings over the past 50 years. The policymakers' approach to energy efficiency is influenced by political priorities. The EU's energy strategy aims to save energy from buildings by highlighting the importance of energy efficiency in achieving sustainable development [16].

BIPV performance

The energy performance of a naturally ventilated BIPV system in Limassol, Cyprus, was investigated using theoretical analysis and experimentation [1]. The total energy efficiency was 26.5% and 33.5% at its worst and its best, respectively.

A fan-assisted double skin façades PV integrated office building energy performance were evaluated by [7]. The findings revealed substantial variability in energy performance to climatic variables. It resulted in a power excess in the 'cool' climatic zone. In mild climates, PV-generated power could only cover approximately 30% of the HVAC energy usage. With just 15% of electricity from PV systems, Energy savings were lowest in the 'hot' zone.

Results

The literature review concentrated on examining research on integrating passive solar design in buildings, spanning the years 2000 to 2023. Primarily, the Scopus database served as the foundational source for this investigation. To augment this, additional scholarly articles relevant to the research question were selectively sourced from various other databases, including Google Scholar, Purdue Library, and specific academic journal websites.This study revealed the following results:

Innovative passive design techniques

Table 5 summarizes the innovative techniques used to integrate passive design into buildings.

Potential passive design recommendations for reducing building energy consumption

Utilizing low carbon-low energy material alternatives in construction represents a critical strategy for achieving sustainability in the built environment. This approach prioritizes selecting materials with a minimal carbon footprint and requires low energy for production and utilization. The construction industry can significantly contribute to energy efficiency and environmental sustainability by focusing on such materials. This method addresses the immediate energy conservation needs and aligns with long-term goals for sustainable development.

Integrating plug-and-play solar panels as an alternative to conventional glass in façades is highly recommended in building design, particularly for office and residential buildings. This innovative approach offers a dual benefit:

Table 5 Innovative passive design techniques

Proposed technique	Design method	Simulation and optimization tools	Energy and carbon emissions reduction	Study references
Green roofs	smart energy-comfort system	Integrated machine learning (ML), DesignBuilder (DB) software and Taguchi design computations.	14% reduction in energy consumption compared to the base case.	[35]
Low-carbon alternative materials.	low-carbon materials such as green hydrogen steel, cement substitutes, and steel scraps.	parametric BIM model	carbon emissions can be reduced by over 50% by using hydrogen steel.	[21]
Timber truss (floors, walls, and roofs)	Modern methods of construction based on timber	Prototype house (Pilot case study)	Reducing on-site operations, reducing waste, a low-carbon, and low-cost.	[44]
Wind catcher	A novel design consisting of a rotary wind scoop and a chimney	A Computational Fluid Dynamic model	The dual-channel design results in passive cooling, dehumidification, heat recovery and enhancing thermal performance.	[28]
Prefabricated Building-integrated photovoltaics (BIPV)	The new BIPV wall system is characterized by an "all-in-one" design that allows fast installation due to the independent operation of each unit and an interlocking joint design that		Clean energy on site. Three workers without electrical experience can handle the on-site installation manually from indoors in the building	[1, 29, 33, 36, 37, 45–47]

enhancing the building's energy efficiency while generating renewable energy. Replacing traditional glass with solar panels in building façades and windows reduces the reliance on non-renewable energy sources, thereby contributing to a more sustainable energy ecosystem.

Considering the limitations of current solar technology, it is crucial to incorporate the dimensions of available solar panels during the design stage. Early integration of these considerations ensures that architectural plans are compatible with existing solar technologies, facilitating effective implementation. This foresight is essential for seamlessly incorporating solar energy solutions into building designs, maximizing their efficiency and effectiveness.

The optimization of building orientation, height, and window dimensions using Dynamic Building Information Modelling (BIM) is pivotal for passive solar design. This strategy leverages the capabilities of Dynamic BIM to plan and design buildings precisely that align optimally with solar trajectories. Such planning enhances natural heating, lighting, and ventilation within buildings, contributing significantly to their energy efficiency. This method not only improves the environmental footprint of buildings but also enhances the comfort and well-being of their occupants.

Finally, optimizing the location and street width for passive solar design is essential in city-scale planning. This involves planning urban layouts to maximize solar exposure for buildings and public spaces. Such strategic planning contributes to urban environments' overall energy efficiency and sustainability. By aligning urban design with passive solar design principles, cities can significantly reduce their energy consumption and move towards a more sustainable future.

Conclusion and recommendation for future work

This comprehensive research analysis underscores the urgent global issue of escalating energy demands, focusing on the building sector's substantial energy consumption relative to other industries. Unlike other high-energy industries limited to working hours, residential buildings demonstrate a continuous energy demand throughout the day. This distinction and many residential units highlight the critical need for innovative design strategies.

The study emphasizes the importance of incorporating passive design principles at the initial design stage to significantly reduce energy consumption and augment energy production within the building sector. Solar energy emerges as the most favored alternative energy source. A detailed review of seminal studies [1, 29, 33, 36, 37, 45–47] reveals concerted efforts to assimilate solar passive design in building structures, mainly through the integration of prefabricated Photovoltaics in building facades, walls, and roofs. A critical analysis of these studies indicates a nascent stage in evaluating Photovoltaic system performance, with a notable scarcity of comprehensive assessments on total system (BIPV) performance.

The research underscores that integrating passive solar design into buildings is still in its developmental phase, and significant research is required to realize the goal of zero-energy buildings. The study identifies critical research gaps, including Solar System Performance, Optimizing Solar System Location, and applying passive solar systems at a city scale. To address these gaps, the study advocates for future research focusing on optimizing passive solar design performance and extending the study of passive solar designs to city-wide scales.

This study's scope was confined to open-access papers published between 2000 and 2023, specifically those pertaining to building design. It recommends including research from energy-specific journals in future analyses to broaden the perspective and deepen the understanding of this critical subject.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

References

1 Agathokleous RA, Kalogirou SA, Karellas S (2018) Exergy analysis of a naturally ventilated Building Integrated Photovoltaic/Thermal (BIPV/T) system. Renew Energy. 128:541–552. https://doi.org/10.1016/J.RENENE.2017.06.085. Pergamon

2 Alawode A, Rajagopalan P (2022) Feasibility of net zero energy high rise apartment buildings in Australia. Sol Energy 231:158–174. https://doi.org/10.1016/J.SOLENER.2021.11.030. Elsevier Ltd

3 Almutairi K, Aungkulanon P, Algarni S, Alqahtani T, Keshuov SA (2022) Solar irradiance and efficient use of energy: residential construction toward net-zero energy building. Sustain Energy Technol Assess 53:102550. https://doi.org/10.1016/J.SETA.2022.102550. Elsevier

4 Amer M, Hamdy M, Wortmann T, Mustafa A, Attia S (2020) Methodology for design decision support of cost-optimal zero-energy lightweight construction. Energy Build 223. https://doi.org/10.1016/j.enbuild.2020.110170

5 Ascione F, De Masi RF, De Rossi F, Ruggiero S, Vanoli GP (2017) NZEB target for existing buildings: case study of historical educational building in Mediterranean climate. Energy Procedia 140:194–206. https://doi.org/10.1016/J.EGYPRO.2017.11.135. Elsevier

6 Baek S-H, Lee B-H, Yeo M-S (2021) Novel methodology for sizing a single U-tube ground heat exchanger useful at the early design stage. Buildings 11(12). https://doi.org/10.3390/buildings11120651
7 Barbosa S, Carlo J, Ip K (2019) Energy performance of PV integrated office buildings with fan-assisted double skin façades under tropical climates. Int J Green Energy, 16 (13): 1061–1072. Taylor and Francis Inc. https://doi.org/10.1080/15435075.2019.1653879
8 Belussi L, Barozzi B, Bellazzi A, Danza L, Devitofrancesco A, Fanciulli C, Ghellere M, Guazzi G, Meroni I, Salamone F, Scamoni F, Scrosati C (2019) A review of performance of zero energy buildings and energy efficiency solutions. J Building Eng 25:100772. https://doi.org/10.1016/J.JOBE.2019.100772. Elsevier
9 Bras A, Ravijanya C, de Sande VT, Riley M, Ralegaonkar RV (2020) Sustainable and affordable prefab housing systems with minimal whole life energy use. Energy Build 220. https://doi.org/10.1016/j.enbuild.2020.110030
10 Celadyn W, Filipek P (2020) Investigation of the effective use of photovoltaic modules in architecture. Buildings 10(9). https://doi.org/10.3390/BUILDINGS10090145
11 Chakraborty D, Elhegazy H, Elzarka H, Gutierrez L (2020) A novel construction cost prediction model using hybrid natural and light gradient boosting. Adv Eng Inform 46:101201. https://doi.org/10.1016/J.AEI.2020.101201. Elsevier
12 Chen T, Tai KF, Raharjo GP, Heng CK, Leow SW (2023) A novel design approach to prefabricated BIPV walls for multistorey buildings. J Building Eng 63. https://doi.org/10.1016/j.jobe.2022.105469
13 Cheung BC, Carriveau R, Ting DSK. Multi-objective optimization of an underwater compressed air energy storage system using genetic algorithm., Energy (2014) 74 (C): 396–404. Pergamon. https://doi.org/10.1016/J.ENERGY.2014.07.005
14 Chow TT, He W, Ji J (2007) An experimental study of façade-integrated photovoltaic/water-heating system. Appl Therm Eng 27(1):37–45. https://doi.org/10.1016/J.APPLTHERMALENG.2006.05.015. Pergamon
15 Delgarm N, Sajadi B, Delgarm S, Kowsary F (2016) A novel approach for the simulation-based optimization of the buildings energy consumption using NSGA-II: case study in Iran. Energy Build 127:552–560. https://doi.org/10.1016/j.enbuild.2016.05.052
16 Economidou M, Todeschi V, Bertoldi P, D'Agostino D, Zangheri P, Castellazzi L (2020) Review of 50 years of EU energy efficiency policies for buildings. Energy Build 225:110322. https://doi.org/10.1016/j.enbuild.2020.110322
17 Elhegazy H, Zhang J, Amoudi O, Zaki JN, Yahia M, Eid M, Mahdi I (2022) An exploratory study on the impact of the Construction Industry on Climate Change. J Industrial Integr Manage World Sci. https://doi.org/10.1142/S2424862222500282/ASSET/IMAGES/LARGE/S2424862222500282FIGF7.JPEG
18 Elwakil E, Hegab M (2019) Priority Model for Public-Private Partnership Investment in Energy Projects. 2018 IEEE Conference on Technologies for Sustainability, SusTech 2018. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/SUSTECH.2018.8671372
19 Fedorova A, Jelle BP, Hrynyszyn BD, Geving S (2021) A testing methodology for quantification of wind-driven rain intrusion for building-integrated photovoltaic systems. Build Environ 199. https://doi.org/10.1016/j.buildenv.2021.107917
20 Finnegan S, Edwards R, Al-Derbi B, Campbell I, Fulton M (2022) The potential of structurally insulated panels (SIPs) to Supply Net Zero Carbon Housing. Buildings 12(12). https://doi.org/10.3390/buildings12122081
21 Gan J, Li K, Li X, Mok E, Ho P, Law J, Lau J, Kwok R, Yau R (2023) Parametric BIM-Based lifecycle performance prediction and optimisation for residential buildings using alternative materials and designs. Buildings 13(4). https://doi.org/10.3390/buildings13040904
22 Garcia-Nevado E, Duport N, Bugeat A, Beckers B (2021) Benefits of street sun sails to limit building cooling needs in a mediterranean city. Build Environ 187. https://doi.org/10.1016/j.buildenv.2020.107403
23 Grassie D, Dong J, Schwartz Y, Karakas F, Milner J, Bagkeris E, Chalabi Z, Mavrogianni A, Mumovic D (2023) Dynamic modelling of indoor environmental conditions for future energy retrofit scenarios across the UK school building stock. J Building Eng 63. https://doi.org/10.1016/j.jobe.2022.105536
24 Gutai M, Kheybari AG (2021) Energy consumption of hybrid smart water-filled glass (SWFG) building envelope. Energy Build 230. https://doi.org/10.1016/j.enbuild.2020.110508
25 Hajare A, and E. Elwakil (2020a) Sustain Cities Soc 61:102293. https://doi.org/10.1016/J.SCS.2020.102293. Integration of life cycle cost analysis and energy simulation for building energy-efficient strategies assessmentElsevier
26 Hajare A (2020) and E. Elwakil. Integration of life cycle cost analysis and energy simulation for building energy-efficient strategies assessment. Sustain Cities Soc, 61. Elsevier Ltd. https://doi.org/10.1016/j.scs.2020.102293
27 Li B, Han S, Wang Y, Li J, Wang Y (2020) Feasibility assessment of the carbon emissions peak in China's construction industry: factor decomposition and peak forecast. Sci Total Environ 706:135716. https://doi.org/10.1016/J.SCITOTENV.2019.135716. Elsevier
28 Li J, Calautit J, Jimenez-Bescos C, Riffat S (2023) Experimental and numerical evaluation of a novel dual-channel windcatcher with a rotary scoop for energy-saving technology integration. Build Environ 230. https://doi.org/10.1016/j.buildenv.2023.110018
29 Liang R, Pan Q, Wang P, Zhang J (2018) Experiment research of solar PV/T cogeneration system on the building façade driven by a refrigerant pump. Energy 161:744–752. https://doi.org/10.1016/J.ENERGY.2018.07.189. Pergamon
30 Lin C-H, Tsay Y-S (2021) A metamodel based on intermediary features for daylight performance prediction of façade design. Build Environ 206. https://doi.org/10.1016/j.buildenv.2021.108371
31 Lin Y, Yang W (2018) Application of multi-objective genetic algorithm based simulation for cost-effective building energy efficiency design and thermal comfort improvement. Front Energy Res, 6 (APR): 329510. Frontiers Media S.A. https://doi.org/10.3389/FENRG.2018.00025/BIBTEX
32 Liu X, Wu Y (2022) Numerical evaluation of an optically switchable photovoltaic glazing system for passive daylighting control and energy-efficient building design. Build Environ 219. https://doi.org/10.1016/j.buildenv.2022.109170
33 Luo K, Ji J, Xu L, Li Z (2020) Seasonal experimental study of a hybrid photovoltaic-water/air solar wall system. Appl Therm Eng 169:114853. https://doi.org/10.1016/J.APPLTHERMALENG.2019.114853. Pergamon
34 Machairas V, Tsangrassoulis A, Axarli K (2014) Algorithms for optimization of building design: a review. Renew Sustain Energy Rev 31:101–112. https://doi.org/10.1016/J.RSER.2013.11.036. Pergamon
35 Mousavi S, Gheibi M, Wacławek S, Behzadian K (2023) A novel smart framework for optimal design of green roofs in buildings conforming with energy conservation and thermal comfort. Energy Build 291. https://doi.org/10.1016/j.enbuild.2023.113111
36 Pereira R, Aelenei L (2019) Optimization assessment of the energy performance of a BIPV/T-PCM system using genetic algorithms. Renew Energy 137:157–166. https://doi.org/10.1016/J.RENENE.2018.06.118. Pergamon

37 Rajoria CS, Agrawal S, Chandra S, Tiwari GN, Chauhan DS (2016) A novel investigation of building integrated photovoltaic thermal (BiPVT) system: a comparative study. Sol Energy 131:107–118. https://doi.org/10.1016/J.SOLENER.2016.02.037. Pergamon
38 Ranjbar N, Balali A, Valipour A, Yunusa-Kaltungo A, Edwards R, Pignatta G, Moehler R, Shen W (2021) Investigating the environmental impact of reinforced-concrete and structural-steel frames on sustainability criteria in green buildings. J Building Eng 43. https://doi.org/10.1016/j.jobe.2021.103184
39 Salem E (2023) and E. Elwakil. The Challenges of Transition from Traditional to Net Zero Energy Buildings. 2023 IEEE Conference on Technologies for Sustainability, SusTech 2023, 104–110. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/SUSTECH57309.2023.10129611
40 Salem E (2023) and E. Elwakil. Minimizing the Cost Gap between Net Zero Energy and Conventional Buildings. 2023 IEEE Conference on Technologies for Sustainability, SusTech 2023, 49–54. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/SUSTECH57309.2023.10129570
41 Seifhashemi M, Elkadi H (2022) Aesthetic appealing wall insulation: a novel approach for uptake of solid wall insulation in the UK. Build Environ 224. https://doi.org/10.1016/j.buildenv.2022.109550
42 Souley Agbodjan Y, Wang J, Cui Y, Liu Z, Luo Z (2022) Bibliometric analysis of zero energy building research, challenges and solutions. Sol Energy 244:414–433. https://doi.org/10.1016/j.solener.2022.08.061
43 Sun Y, Wilson R, Liu H, Wu Y (2021) Numerical investigation of a smart window system with thermotropic parallel Slat Transparent Insulation Material for building energy conservation and daylight autonomy. Build Environ 203. https://doi.org/10.1016/j.buildenv.2021.108048
44 Victoria MF, Deveci G, Musau F, Clubb M (2023) Life cycle carbon and cost assessment comparing milled and whole timber truss systems and insulation options for affordable housing. Energy Build 285. https://doi.org/10.1016/j.enbuild.2023.112895
45 Yang T, Athienitis AK (2014) A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets. Sol Energy 104:82–92. https://doi.org/10.1016/J.SOLENER.2014.01.049. Pergamon
46 Yang T, Athienitis AK (2015) Experimental investigation of a two-inlet air-based building integrated photovoltaic/thermal (BIPV/T) system. Appl Energy 159:70–79. https://doi.org/10.1016/J.APENERGY.2015.08.048. Elsevier
47 Yu G, Yang H, Yan Z, Kyeredey Ansah M (2021) A review of designs and performance of façade-based building integrated photovoltaic-thermal (BIPVT) systems. Appl Therm Eng 182:116081. https://doi.org/10.1016/J.APPLTHERMALENG.2020.116081. Pergamon
48 Yusoff Y, Ngadiman MS, Zain AM (2011) Overview of NSGA-II for optimizing machining process parameters. Procedia Eng 15:3978–3983 No longer published by Elsevier. https://doi.org/10.1016/J.PROENG.2011.08.745
49 Zuluaga SS, Kallioras S, Tsiavos A (2022) Optimization of Synergetic Seismic and Energy Retrofitting based on timber beams and Bio-based Infill panels: application to an existing Masonry Building in Switzerland. Buildings 12(8). https://doi.org/10.3390/buildings12081126

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.