Civil Engineering and Architecture 13(6): 4486-4507, 2025 http://www.hrpub.org
DOI: 10.13189/cea.2025.130627

A Bibliometric Analysis of Research Trends in Achieving Zero-Energy Residential Buildings

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Received April 13, 2025; Revised September 10, 2025; Accepted October 22, 2025

Cite This Paper in the Following Citation Styles

(a): *[1] Ahmed M. El-Sayed, Mustafa Abd El-Hafeez, Marwa Nossier, Shaimaa R. Nosier , "A Bibliometric Analysis of Research Trends in Achieving Zero-Energy Residential Buildings," Civil Engineering and Architecture, Vol. 13, No. 6, pp. 4486 - 4507, 2025. DOI: 10.13189/cea.2025.130627.*

(b): *Ahmed M. El-Sayed, Mustafa Abd El-Hafeez, Marwa Nossier, Shaimaa R. Nosier (2025). A Bibliometric Analysis of Research Trends in Achieving Zero-Energy Residential Buildings. Civil Engineering and Architecture, 13(6), 4486 - 4507. DOI: 10.13189/cea.2025.130627.*

Abstract With growing awareness of the importance of environmental sustainability and the difficulties posed by climate change, there is an urgent need to develop and deploy Zero Energy Residential Buildings (ZERBs) as an innovative approach to minimize energy consumption in the residential sector. This study presents a bibliometric analysis of research on zero energy buildings (ZEBs). This study aims to analyze the academic landscape of Zero Energy Residential Buildings (ZERBs) using bibliometric tools to identify dominant research trends and directions. To reach that goal, the research follows an organized structure that begins with collecting and analyzing studies from the Scopus database for the period from 2014 to 2023, using advanced data analysis tools such as the R package and VOSviewer, to identify prominent trends, determine the most effective strategies, and then identify the ten most scientifically cited research in the field. In addition to identifying the ten most important studies for the year 2023, these studies were analyzed to understand the recent developments in zero energy building (ZEB) technologies. This careful analysis shows that insulating the outer envelope of buildings, which documented 80% of the reviewed studies, is essential for lowering heat loss and improving a building's energy efficiency. It also considers the usage of phase change materials (PCMs), which were cited in 30% of the studies, and the integration of renewable energy sources. These results collectively underscore the necessity of adopting multifaceted approaches to realize practical zero-energy residential buildings.

Keywords Zero Energy Buildings, Zero Energy Residential Buildings, Thermal Insulation, Building Envelopes, Energy Performance, Renewable Energy Sources, Bibliometric Analysis

1. Introduction

Humanity is in danger from climate change; hence, action to reduce greenhouse gas emissions is necessary. According to a 2018 research by the Intergovernmental Panel on Climate Change (IPCC), a temperature increase of more than 1.5 degrees Celsius might have dire future repercussions [1]. The recent report from the International Plant Protection Convention emphasized the significance of curbing demand in the construction industry as an element in strategies to address climate change. Buildings are energy users, so lowering energy consumption can offer opportunities to cut emissions and bolster resilience [2].

The building industry accounts for 40% of the world's energy use [3]. Improving energy management and obtaining a higher proportion of energy from renewable sources are critical tasks for enhancing environmental and economic performance. It forms part of the solutions aligned with the current environmental crisis [4]. In recent years, there has been an increase in interest in Zero Energy Buildings (ZEBs), and many countries have adopted these buildings as future targets to reduce energy consumption

and promote sustainable development [5].

A Zero Energy Building is the pinnacle of a cutting-edge construction method, carefully planned to balance on-site energy output with annual energy use. The combination of energy-efficient building designs, the use of renewable energy sources, and the optimization of energy systems result in this balance. The adoption of ZEBs heralds transformative potential to slash energy demand and curb greenhouse gas emissions dramatically. Moreover, it bolsters energy security and slashes reliance on fossil fuels, as underscored by Li et al. [6] [7]. Zero Energy Residential Buildings (ZERBs) stand as a beacon of hope, presenting an innovative avenue to confront pressing environmental issues while enhancing energy efficiency. Yet, despite their promise, numerous critical facets demand thorough exploration. Venturing into the realm of ZERBs is not merely a step forward; it is a pivotal stride towards tackling climate change head-on and fostering sustainability within our built environment.

Recent studies have advanced the understanding of ZERBs by exploring different yet complementary approaches. Chen et al. [8] focused on optimizing multi-performance parameters such as insulation thickness and window configurations using tools like SketchUp, OpenStudio, and EnergyPlus, aiming to reduce energy demand during the early design stages in cold climate zones in China. Meanwhile, Mejjaouli [9] proposed a retrofitting framework combining mathematical programming, simulation, and Analytic Hierarchy Process (AHP), which proved effective in reducing energy consumption by 30% and achieving a payback period of 2.2 years. On a different front, Sayadi et al. [10] examined the performance of a prototype NZEB in Sweden under future climate scenarios. Their study revealed that traditional climate data underestimate future cooling loads and showed that automatic shading systems could reduce cooling demand by up to 75%. Schwartz and Krarti [11] shifted the focus to the U.S., where they reviewed the adoption of sustainable technologies in the housing sector. They highlighted that while efficiency measures like insulation and LED lighting are commonly implemented due to codes and incentives, advanced technologies such as geothermal and photovoltaic systems face limited uptake due to high costs and lack of awareness. Finally, Wu et al. [12] introduced a parametric optimization model tailored for high-rise buildings in China, using genetic algorithms to simultaneously optimize energy efficiency, PV integration, and economic performance across diverse climatic conditions. Together, these studies underscore the importance of integrating technical design, retrofitting, climate adaptation, and policy-driven adoption to accelerate the realization of zero-energy housing.

Despite significant strides and a myriad of methodologies in the domain of zero-energy buildings, a pivotal challenge persists: crafting efficacious design strategies for ZERBs. This research zeroes in on bridging the gap by synthesizing and applying cutting-edge strategies chronicled in existing literature to realize ZERBs. The crux of the problem lies in the meticulous analysis of an array of prior studies and scholarly works to unearth design strategies that propel the attainment of ZERBs. This endeavor involves a deep dive into the extensive reservoir of research on ZEBs to distill the most effective design strategies for achieving ZERBs. To achieve this, the research is organized into sections: the first part provides an overview of zero-energy buildings, the second part explains the methodology used in the bibliometric analysis, and the third section presents the results derived from a comprehensive literature review on the subject. The fourth section offers detailed a discussion and synthesis of prominent insights from previous research on design strategies for the building envelope, which can contribute to the achievement of ZERBs. Finally, the paper concludes in the fifth section, providing a critical look at the findings and addressing potential challenges in achieving this ambitious goal.

2. Materials and Method

In the pursuit of a deeper understanding of the developments and challenges in designing ZERBs, the study requires a rigorous and precise methodology for data collection and analysis. This section outlines the procedures followed to identify key literature within this field and reviews the bibliometric tools used for the precise analysis of this information. This is presented through Figure 1, which provides an illustrative representation of the methodological foundation employed and the organizational structures of the study.

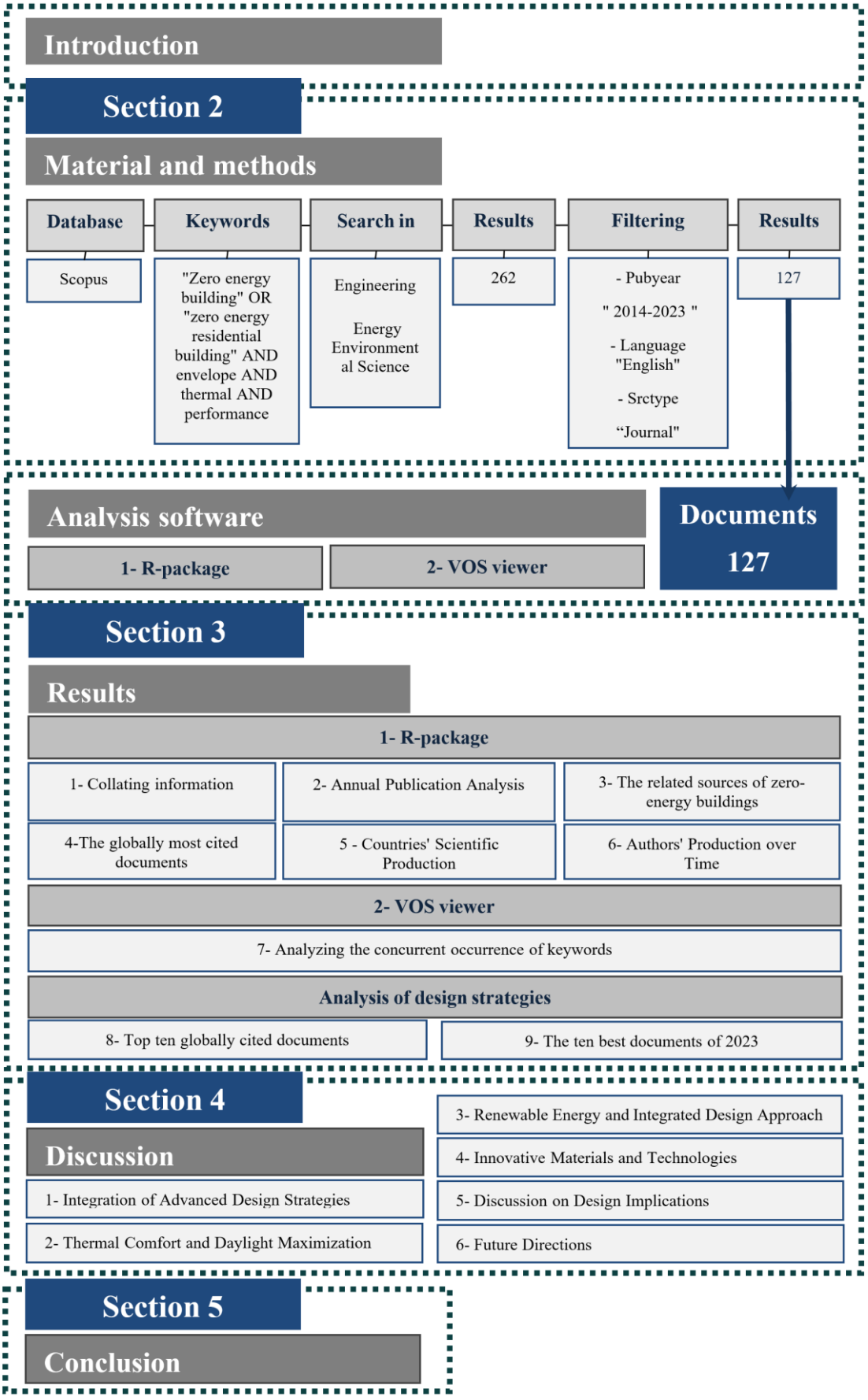


Figure 1. Framework. Source(s): Authors

2.1. Database Development

Bibliometric analysis serves as a cornerstone for gauging academic influence and discerning research trends across myriad studies. The success of such an analysis is intricately tied to the choice of databases, given that each database offers access to a unique spectrum of academic publications. This accessibility empowers researchers to conduct a thorough review and synthesis of information, ensuring their analysis is both robust and reflective of prevailing and nascent trends within their field [13]. Among the many databases available, such as Scopus, Medline, Web of Science (WoS), and Google Scholar, researchers often prefer Scopus due to its distinct advantages over other databases. Scopus is characterized by its multidisciplinary coverage, precise citation tracking, and high-quality indexing, making it an optimal choice for bibliometric analysis and academic research evaluation. These features facilitate a comprehensive understanding of research trends and the academic impact within various fields, enhancing the reliability and depth of research studies.

This review aims to reveal the most important studies that have been conducted in the areas of energy-free residential building research to arrive at the best design strategies for residential building envelopes, which in turn help to reduce energy consumption in buildings. To achieve this, a bibliometric analysis review was conducted in this study. This research was conducted on 16th December 2023. The Scopus database was used in this research. The intel search revealed 262 articles in the zero-energy residential buildings research area. The keywords that were used included "zero energy building" OR "zero energy residential building" AND envelope AND thermal AND performance. This research covered the last 10 years, from 2014 to 2023. This research included LIMIT-TO (DOCTYPE, "article") AND LIMIT-TO (SRCTYPE, "journal"). Finally, the research language used only articles published in English. Moreover, the final articles used in this review were 125 articles in the zero-energy residential buildings research area. Inclusion and exclusion criteria are presented, and in addition, the analysis research framework is illustrated in Figure 1.

2.2. Analysis Software

The R package, conceived and developed by Aria and Cuccurullo, stands as a cornerstone of statistical and scientific map analysis, offering a comprehensive suite of algorithms in the R language. Its evolution has led to recent enhancements, notably the incorporation of Biblioshiny, a user-friendly web interface revolutionizing bibliometric analysis accessibility. Biblioshiny's innovative design empowers researchers regardless of coding proficiency, simplifying the importation of data from databases like Scopus and facilitating nuanced data filtering. Exploiting the bibliometric capabilities inherent in bibliometrix, this study adeptly leveraged the tool's capacity to seamlessly import Scopus data in BibTeX format, optimizing analysis processes through Biblioshiny's intuitive features [14].

VOSviewer stands as a powerful tool in literature review, providing researchers with a dynamic platform for visualizing and understanding the complexity of literature. This software works mainly with bibliometric maps that reveal connections between research institutions such as authors, keywords, or publications. Using sophisticated algorithms, VOSviewer transforms large datasets into flexible visualizations, enabling the identification of patterns, clusters and trends in scholarly publications. With a user-friendly interface and features that allow scalability, researchers can explore the conceptual framework of a field, revealing relationships, collaborations, and emerging themes. VOSviewer's ability to provide complex information in a visual format makes it an indispensable asset in literary studies, empowering researchers to gather valuable insights and navigate the ever-changing field of academic knowledge [15].

3. Result

3.1. Collating Information

Gathering information in the context of bibliometric analysis is essential for understanding the academic and research landscape. It aids in directing research, identifying current trends, and evaluating academic impact, leading to a comprehensive and precise analysis of reference literature, and providing an effective contribution to the field studied. Table 1 offers a comprehensive overview of references related to ZEBs, with a total of 127 entries. Among these references are 122 scientific articles, reflecting in-depth investigations and analyses in this field. Additionally, there are 4 review papers that provide synthesized insights from the existing literature, and one conference paper, contributing a unique perspective on the topic.

The classifications within the table include rows titled (DE) for author keywords and (ID) for Keywords-Plus. The (DE) row shows the number of keywords specifically chosen by the authors within the papers to highlight the focus points of their research, providing insights into the thematic focus of each study. The (ID) row indicates the number of keywords extracted from reference titles using the Scopus system, which were specifically gathered for this study on ZEBs. This row serves as a quantitative indicator, reflecting the number of keywords directly extracted from the titles of the cited references. These keywords are crucial for enhancing understanding of the references, as they offer additional insights into the thematic elements and pivotal points included in the research titles.

Table 1. Succinctly presents primary information and summarizes the dataset

Description	Results
Timespan	2014:2023
Sources (Journals, Books, etc)	48
Documents	127
Annual growth rate %	10.36
Document average Age	4.64
Average citations per doc	22.54
References	5504
Document contents	
Keywords plus (ID)	1029
Author's keywords (DE)	489
Authors	459
Authors of single-authored docs	8
Authors collaboration	
Single-authored docs	9
Co -Authors per Doc	3.9
International co-Authorships %	22.05
Document types	
Article	122
Conference paper	1
Review	4

Source(s): Authors based on biblioshiny tool.

3.2. Annual Publication Analysis

Analysis of the included data for the years 2014 to 2023 reveals a pattern that notes publications on energy-efficient residential buildings (ZERBs). Publications in the earlier years of 2014 and 2015 were much lower, with 6 and 5 cases, respectively. However, there has been a significant increase in recent years, especially in 2022 and 2023, with 21 and 16 cases, respectively, as shown in Figure 2. This marked increase in academic activity indicates a growing interest and focus on zero-energy buildings. The surge in publications may reflect developments in the research landscape, possibly indicating increased awareness and recognition of the importance of sustainable and energy-efficient housing solutions. Further investigation into the content of these articles, their methodologies, and the specific topics they addressed could provide valuable insights into thematic shifts and emerging trends within the field of ZERBs research.

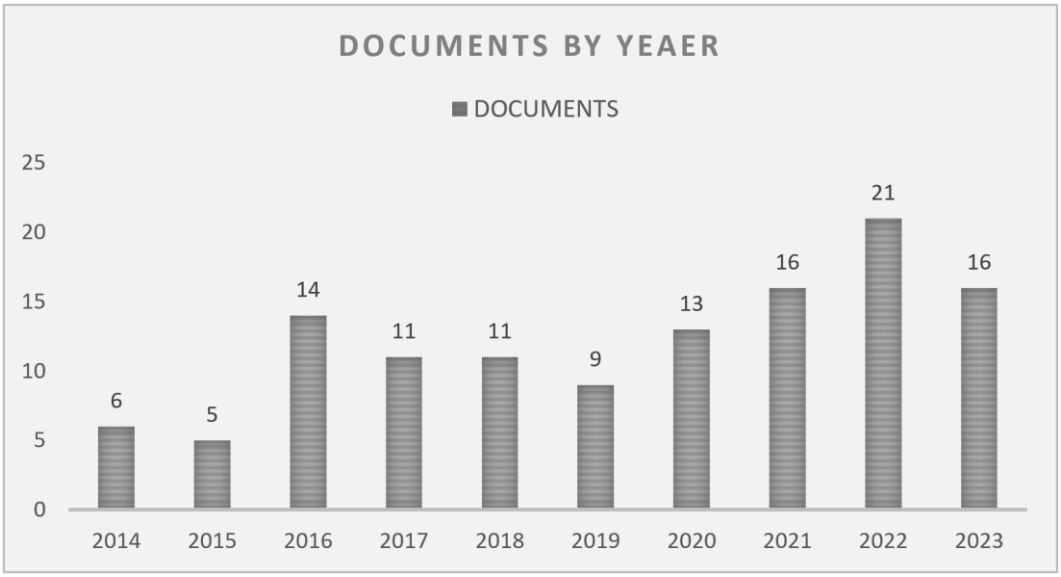
3.3. The Related Sources of Zero-Energy Buildings

The dataset extracted from the model offers valuable insights into the top 10 sources associated with ZEBs, providing a comprehensive understanding of their importance in this subject area. Among these sources, "ENERGY AND BUILDINGS" stands out significantly, contributing a total of 26 articles and boasting an impressive H-index of 17. Its focus on the intersection of building and energy fields indicates strong relevance to the field of ZEBs. Similarly, "ENERGIES" emerges as an important source, with 13 articles and an H-index of 7, emphasizing its notable focus on the broader energy field within the context of ZEBs. Likewise, the "Journal of BUILDING ENGINEERING" is another influential contributor, offering 9 articles and an H-index of 6, showcasing specific interests in electricity, energy, and related issues, as illustrated in Figure 3. These findings collectively highlight the prominence and thematic preferences of these sources in the discourse surrounding ZEBs.

3.4. The Globally Most Cited Documents

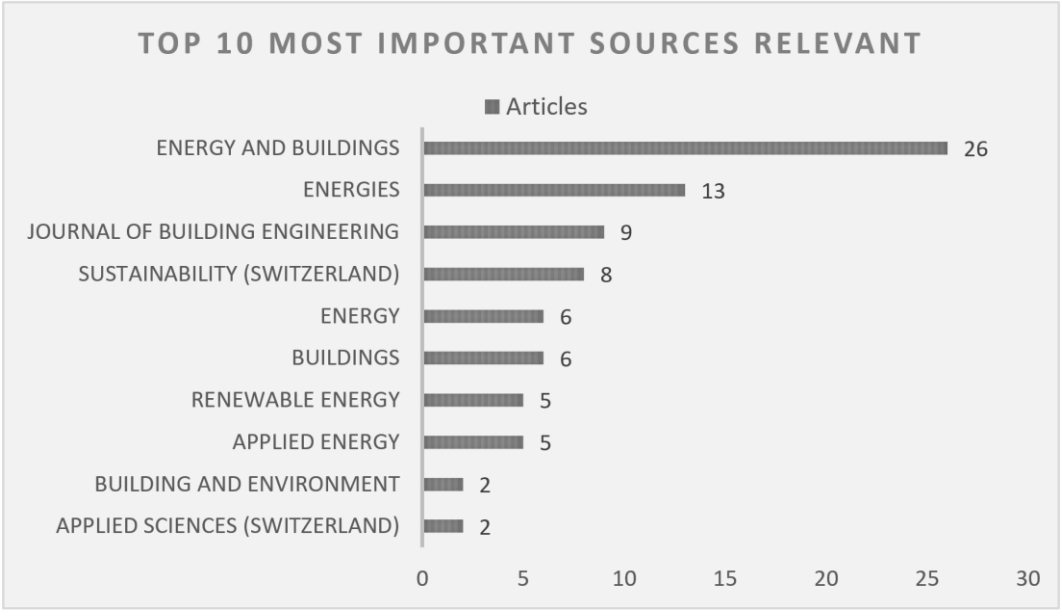
In the field of construction and zero-energy buildings, identifying impactful research works is crucial for guiding future research directions and innovation development. By analyzing documents that have received the highest citation rates, we can explore the ideas and methodologies that have laid the foundation for progress in this area. As shown in Table 2, the principal reference notably stands out with 187

citations. The paper titled "Vacuum Insulation Panel Products: A State-of-the-Art Review and Future Research Pathways" by Edsjø, S., & Petter, B. [16], published in 2014, provides a comprehensive review and outlines prospective pathways for future research in this field. Closely following, with 135 citations, is the paper "Passive Design Strategies and Performance of Net Energy Plus Houses" by Rodriguez-ubinas, E., Montero, C., Porteros, M., & Vega, S. [17]. This paper explores the effectiveness of passive design strategies in achieving net energy plus houses. Additionally, the paper by Marino, C., Nucara, A., & Pietrafesa, M. [18], "Does Window-to-Wall Ratio Have a Significant Effect on the Energy Consumption of Buildings? A Parametric Analysis in Italian Climate Conditions," published in 2017 in the Journal of Building Engineering, holds significant importance in investigating the impact of Window-to-Wall Ratio (WWR) on energy consumption under Italian climate conditions, having received notable citations in this domain. These top ten most-cited documents, detailed in Table 2, provide critical insights into zero-energy buildings, complemented by potential visual representations or insights presented in Figure 4, enhancing the understanding of these pivotal works and their impact on the field.



Source(s): Authors based on biblioshiny tool.

Figure 2. Annual scientific growth of zero-energy buildings



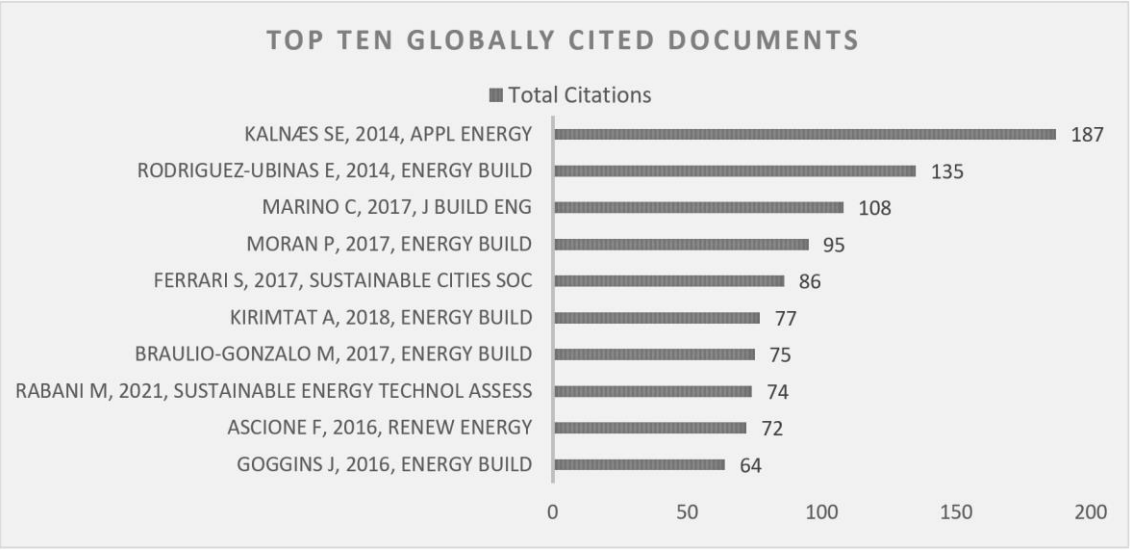
Source(s): Authors based on biblioshiny tool.

Figure 3. Top 10 most important sources relevant to zero-energy buildings

Table 2. Top ten globally cited documents relevant to zero-energy buildings

N	Document title	Authors	Year	Source	Total citations
1	Vacuum insulation panel products: A state-of-the-art review and future research pathways	Edsjø & Petter. [16]	2014	Appl energy	187
2	Passive design strategies and performance of Net Energy Plus Houses	Rodriguez-ubinas et al. [17]	2014	Energy and Buildings	135
3	Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions	Marino et al. [18]	2017	Building Engineering	108
4	Super-insulate or use renewable technology? Life cycle cost, energy, and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate	Moran et al. [19]	2020	Energy and Buildings	95
5	Energy-environmental and cost assessment of a set of strategies for retrofitting a public building toward nearly zero-energy building target	Ferrari & Beccali. [20]	2017	Sustainable Cities and Society journal	86
6	A review of infrared thermography for the investigation of building envelopes: Advances and prospects	Kirimtat & Krejcar. [21]	2018	Energy & Buildings journal	77
7	Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation	Braulio-gonzalo & Bovea. [22]	2017	Energy and Buildings	75
8	Achieving zero-energy building performance with thermal and visual comfort enhancement through optimization of fenestration, envelope, shading device, and energy supply system	Rabani et al. [23]	2021	Sustainable Energy Technologies and Assessments	74
9	Earth-to-air heat exchanger for NZEB in Mediterranean climate	Ascione et al. [24]	2016	Renewable Energy	72
10	Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland	Goggins et al. [25]	2016	Energy and Buildings j	64

Source(s): Authors based on biblioshiny tool.



Source(s): Authors based on biblioshiny tool.

Figure 4. Top ten globally cited documents relevant to zero-energy buildings

3.5. Countries' Scientific Production

The analysis of publications on zero-energy buildings across various countries reveals compelling insights into their research productivity, as depicted in Table 3. Italy stands out as the most prolific contributor in this domain, leading the list with 115 publications. Closely following is China with 83 publications, indicating significant research output in this field. Spain also shows considerable engagement, occupying the third position with 75 publications. Towards the bottom of the list, Greece and Portugal display promising participation, highlighting their contributions to the literature on zero-energy buildings. Simultaneously, Croatia, the United Kingdom, Austria, Canada, and Ireland show varying but noteworthy publication numbers, ranging from 9 to 17, underscoring their active involvement in advancing research on ZEBs. This analysis illuminates the diverse global landscape of contributions in this crucial area of sustainable construction, displaying various levels of engagement and affirming the multifaceted global interest in zero-energy building (ZEB) research.

3.6. Authors' Production over Time in the Field Zero-Energy Building

The thorough scrutiny of research results from over 20 influential authors in the field of ZEBs between 2014 and 2023 highlights the key trends and prominent contributors shaping this domain. "Baglivo, Cristina" emerges as a leading figure, having produced six notable research papers with an impressive H-index of 24. This prolific output reflects Baglivo's deep commitment to constructing zero-energy buildings, particularly evident through her affiliation with the University of Salento in Lecce, Italy, and her ongoing focus on energy-saving methodologies. Similarly, "Congedo, Paolo Maria" stands out with four significant documents and a distinguished H-index of 31 during the period 2013-2023. Congedo's focus on energy saving, supported by five research papers, underscores a strong dedication to renewable energy and conservation within the field of zero-energy building construction. These prominent authors, along with various other active contributors depicted in Figure 5, collectively form the diverse and vibrant landscape of zero-energy building (ZEB) research, emphasizing the significant interest and contributions within this field.

In the context of analyzing the geographic and institutional impact on scientific research in the field of zero-energy buildings, Figure 6 provides a visual representation illustrating the links between authors and their countries through a three-column configuration. The left column identifies the cities associated with the authors, while the middle column highlights the authors themselves. The rightmost column contains the keywords used in the scientific research of these authors. The data within this figure reveal a dense concentration of authors connected to cities in Italy, indicating a prominent presence of Italian scholars in this field. This trend aligns with our previous observations that highlight Baglivo Cristina as a key figure actively engaged in the field of zero-energy buildings.

3.7. Analyzing the Concurrent Occurrence of Keywords

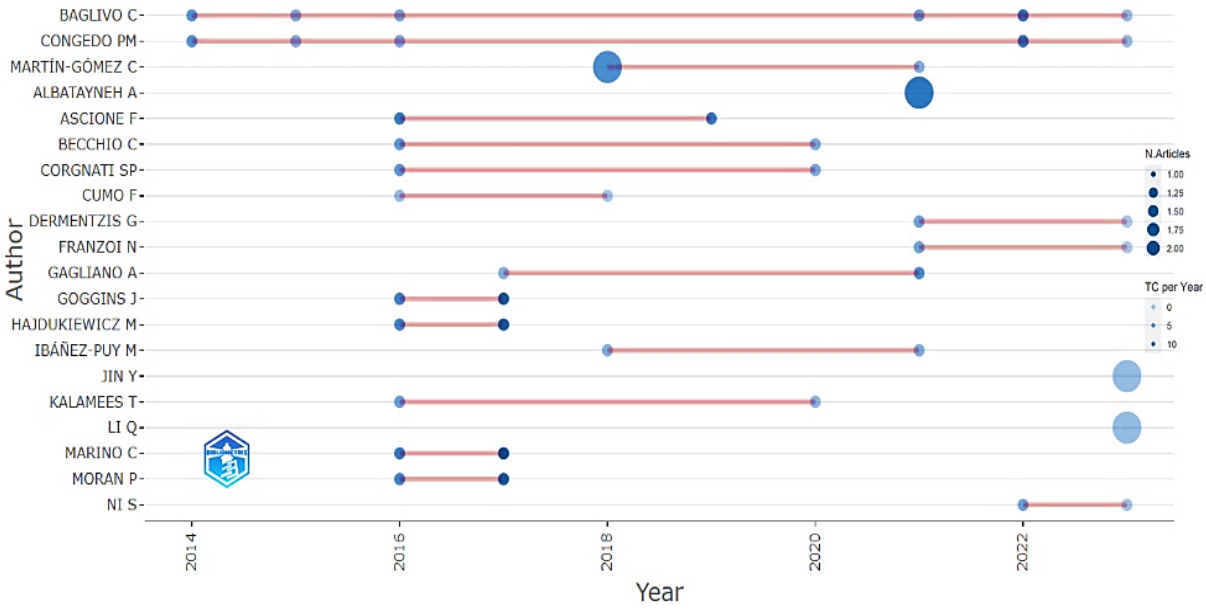
In conducting the bibliometric analysis to identify the most prevalent keywords, the analytical approach of "co-occurrence" was selected, and the unit of analysis was defined as "author keywords." This analytical strategy facilitates the exploration of the interconnections and prevalence of keywords within the scholarly discourse on the subject at hand, depicted in Figure 7.

The previous co-occurrence diagram provides an analysis of the keywords used in references related to zero-energy buildings. This diagram reflects the interconnections and overlaps between different topics and how they are related to each other, offering a comprehensive view of the pivotal points and research trends in this field.

Table 3. The top ten Countries' Scientific Production of the field of study of zero-energy buildings

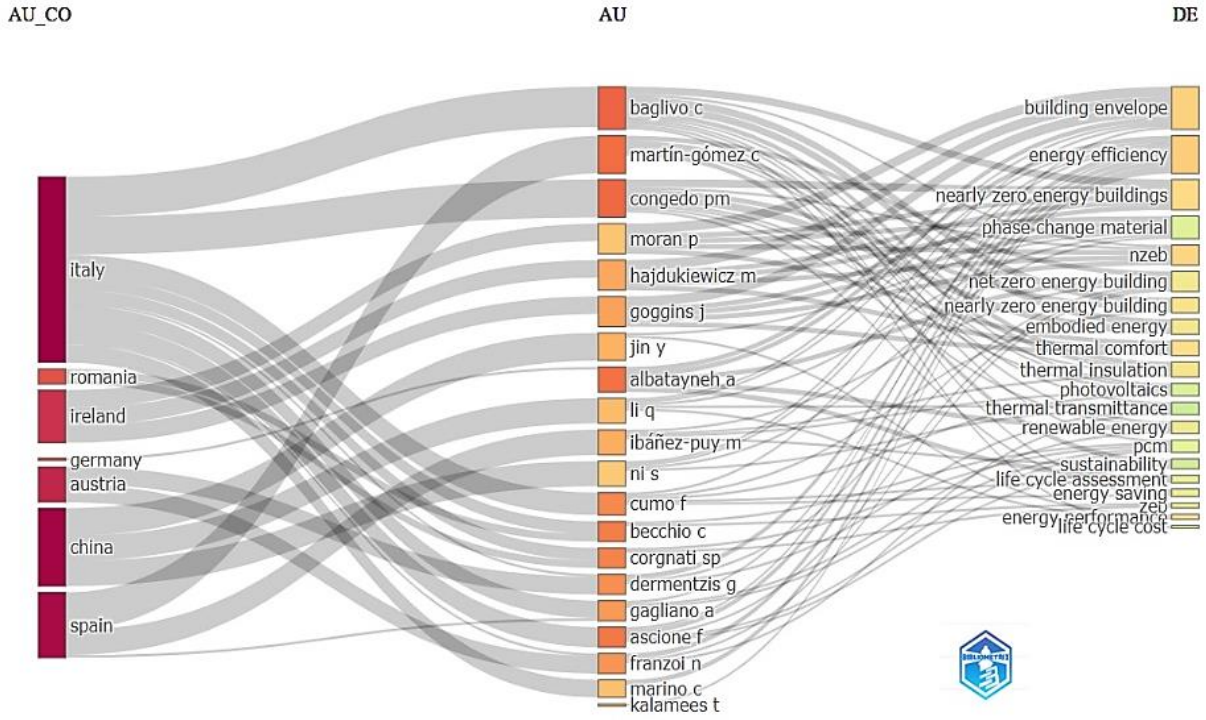
N	Country	Total population
1	ITALY	115
2	CHINA	83
3	SPAIN	75
4	GREECE	17
5	PORTUGAL	12
6	CROATIA	11
7	UK	11
8	AUSTRIA	10
9	CANADA	10
10	IRELAND	9

Source(s): Authors based on biblioshiny tool.



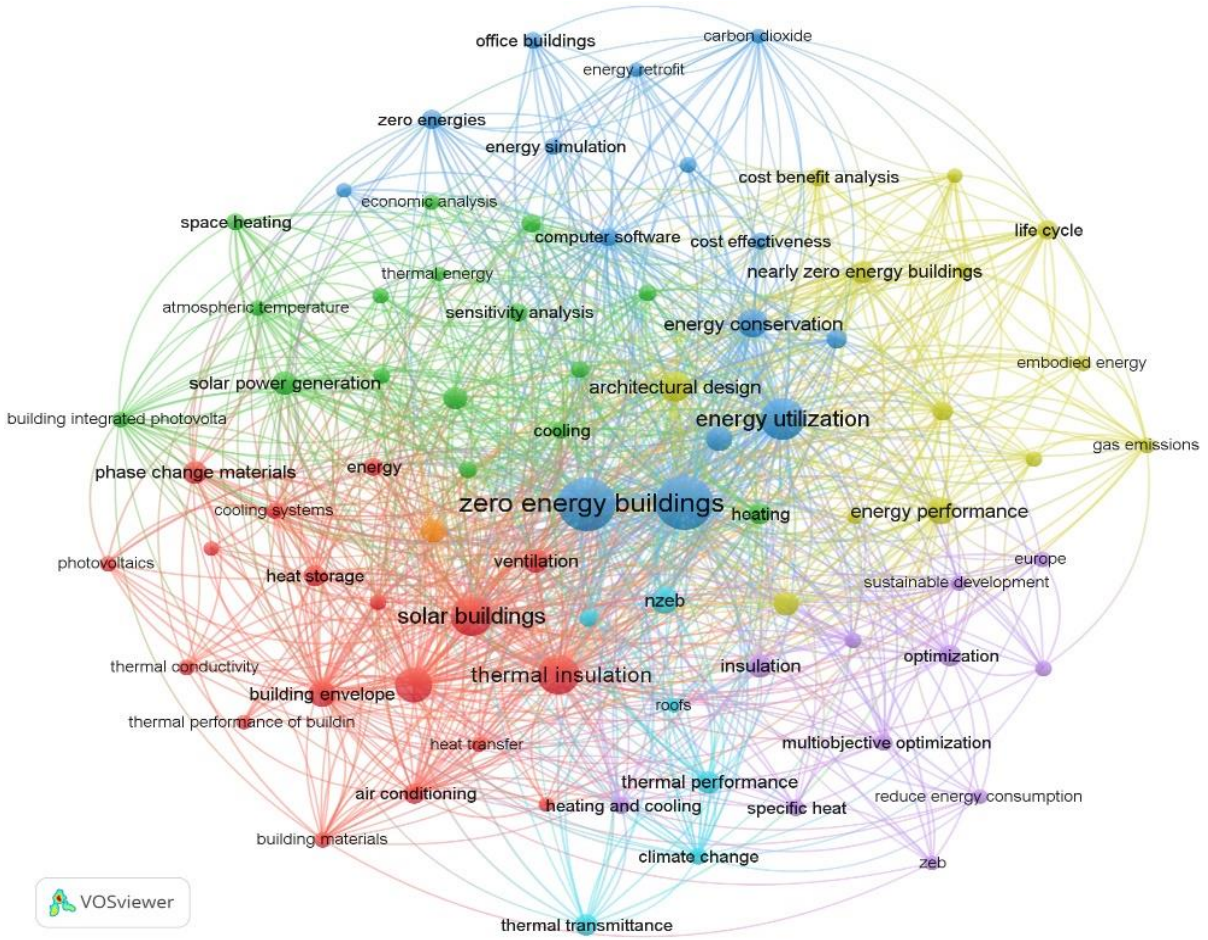
Source(s): biblioshiny tool.

Figure 5. Top 20 Authors' Production over Time in the field zero- energy building



Source(s): biblioshiny tool.

Figure 6. Visualizing authors' affiliations across countries



Source(s): VOS viewer.

Figure 7. Analyzing the concurrent occurrence of keywords

Table 4. The top ten concurrent occurrences of keywords of the field of study

Keyword	Occurrence
Zero energy building	72
Energy efficiency	70
Solar building	42
Thermal insulation	37
Building envelopes	30
Architectural design	22
Energy conservation	19
Energy performance	17
Residential building	15
Building envelope	16

Source(s): Authors based on VOS viewer.

Regarding the prevalent keywords associated with the study of zero-energy buildings, as shown in Table 4, the most frequently used keywords in these studies include "Zero energy building" (occurrence "Oc" of 72), "Energy efficiency" (Oc = 70), "Solar building" (Oc = 42), "Thermal insulation" (Oc = 37), "Building envelopes" (Oc = 30), "Architectural Design" (Oc = 22), "Energy conservation" (Oc = 19), "Energy performance" (Oc = 17), "Residential building" (Oc = 15), and "Building envelope" (Oc = 16). This analysis provides a comprehensive view of the research concentrations and prevailing trends in this field.

3.8. The Most Effective Design Strategies for the Top Ten Most Cited Documents Globally

Zero-energy buildings require numerous strategies to

achieve their goals. To understand the effective design strategies for ZEBs, Table 5 presents a detailed analysis supported by insights from the top ten most cited documents globally. This analysis provides an in-depth exploration of the various approaches that can be adopted to achieve zero-energy status in buildings, including strategies such as improving insulation thickness, leveraging natural thermal stability, and incorporating innovative materials like Vacuum Insulation Panels (VIPs).

Table 5. The most effective design strategies for the top ten most cited documents globally

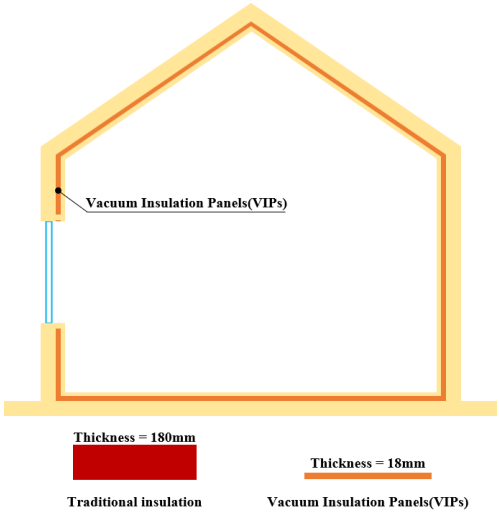
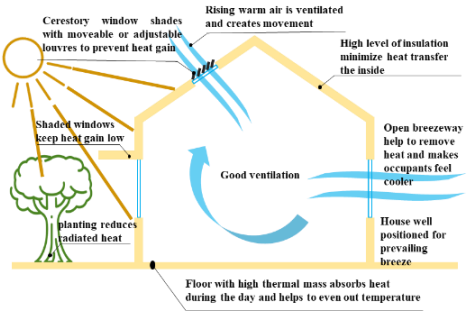
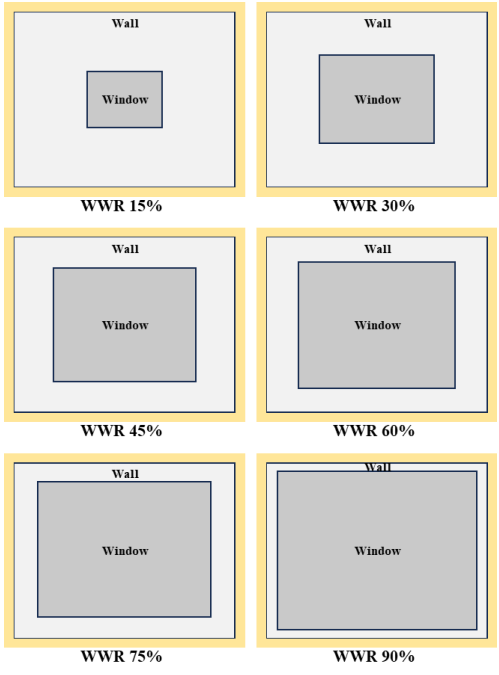
Authors	Title	Design strategies	Scheme
[16]	Vacuum insulation panel products: A state-of-the-art review and future research pathways	**Enhancing Building Energy Efficiency with VIPs Technology:** Vacuum insulation panel technology uses sealed, evacuated panels with highly efficient insulation to minimize heat transfer. Thinner and more effective than traditional insulation, VIPs are widely used to save energy and maintain stable temperatures in buildings, refrigeration, and transportation.	
[17]	Passive design strategies and performance of Net Energy Plus Houses	**Passive Design Strategies for Net Energy Plus Houses:** The strategy focuses on using architecture and natural conditions to reduce building energy use, including optimal orientation, insulation, window placement, and renewable energy integration, aiming for buildings that generate more energy than they consume.	
[18]	Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions	**Impact of Window-to-Wall Ratio on Building Energy Consumption in Italian Climate Conditions:** This strategy explores the effect of the WWR on the energy efficiency of buildings within Italian climate conditions. It involves a parametric analysis to determine how variations in WWR influence heating, cooling, and overall energy consumption, aiming to identify optimal ratios that balance natural light benefits with thermal performance, ultimately reducing energy demand and enhancing building sustainability.	

Table 5 continued

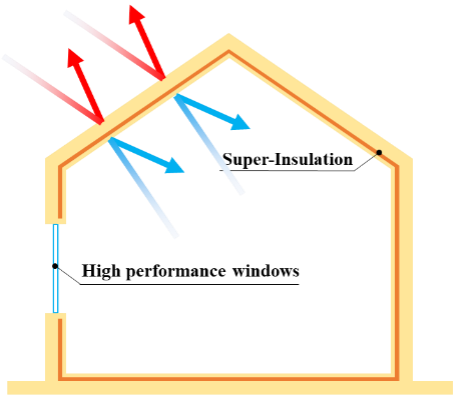
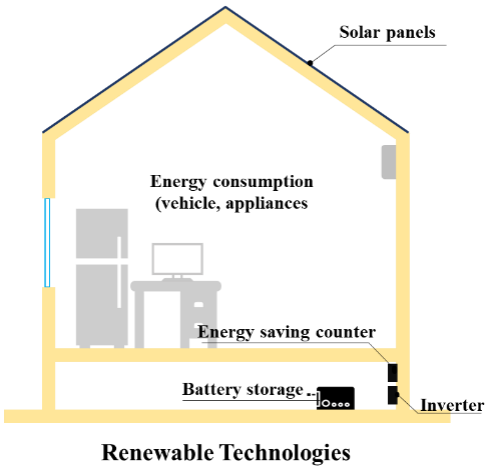
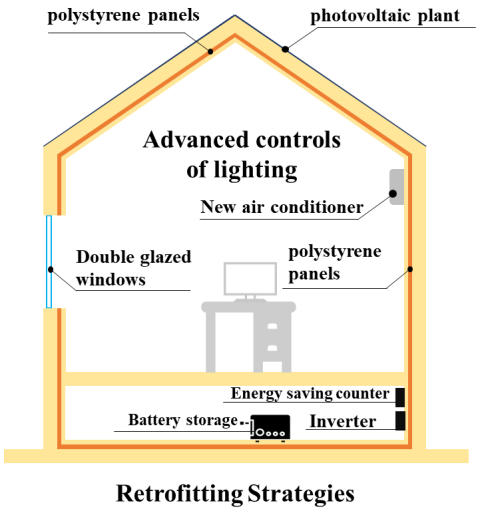
[19]	Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate	Strategic Choices for NZEBs: Super-Insulation vs. Renewable Technologies: This strategy examines the comparative benefits of super-insulation versus renewable technology integration for NZEBs in temperate oceanic climates. It aims to assess which approach, or a combination thereof, offers a more sustainable, cost-effective, and low global warming potential solution for minimizing energy consumption in NZEBs, focusing on life cycle costs, energy efficiency, and environmental impact.	 
[20]	Energy-environmental and cost assessment of a set of strategies for retrofitting a public building toward nearly zero-energy building target	**Retrofitting Strategies for Achieving NZEB Targets in Public Buildings:** This strategy focuses on evaluating a suite of energy-environmental and cost-effective retrofitting measures for transforming an existing public building into a Nearly Zero-Energy Building (NZEB). It briefly delves into the analysis of various retrofitting strategies aimed at enhancing energy efficiency, reducing environmental impact, and achieving the NZEB target, all while considering the economic implications of such upgrades.	

Table 5 continued

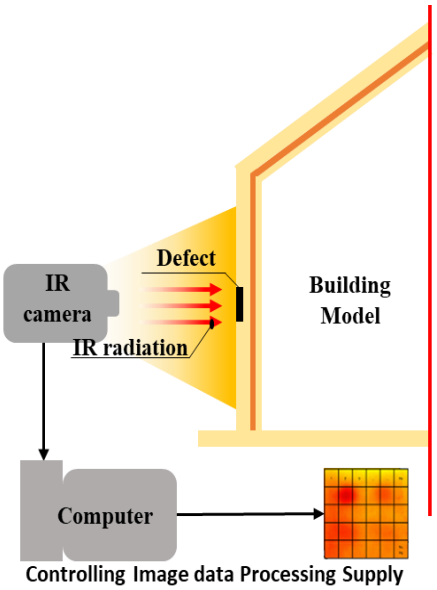
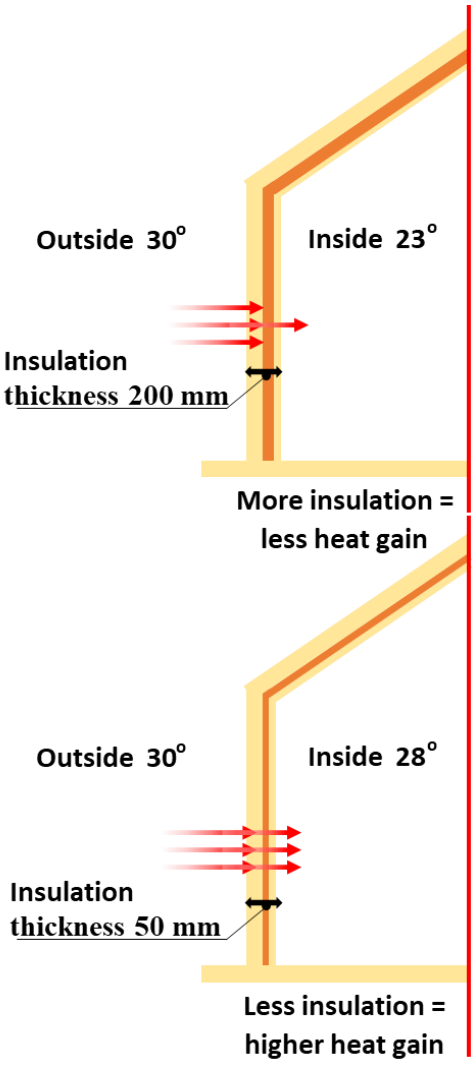
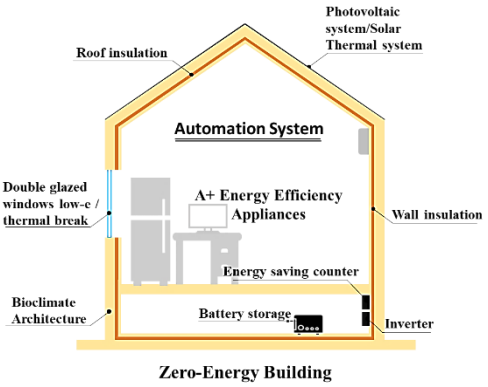
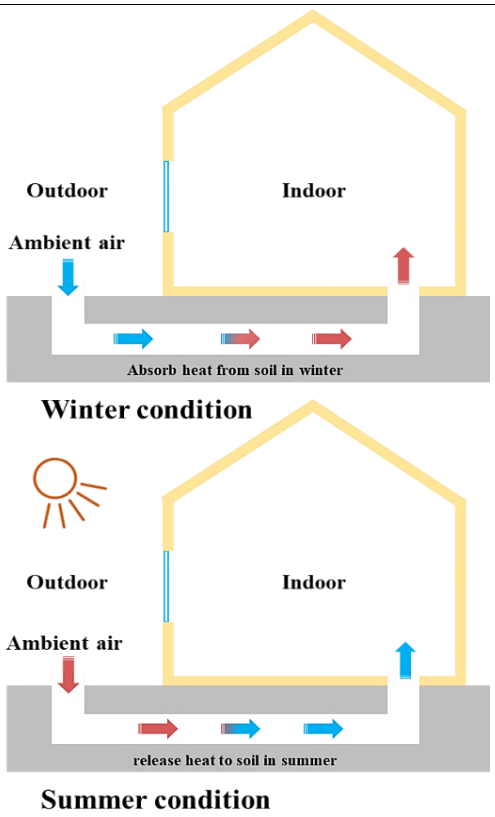
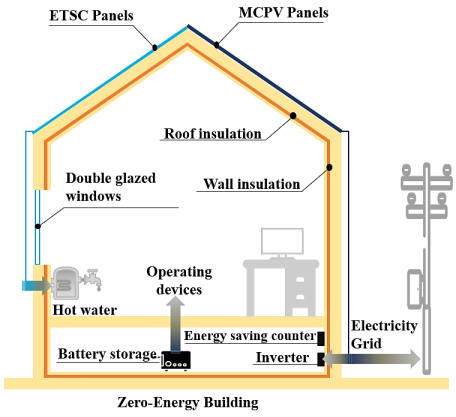
[21]	A review of infrared thermography for the investigation of building envelopes: Advances and prospects	Infrared Thermography (IRT) for Building Envelope Analysis: This strategy harnesses the power of irt as a sophisticated diagnostic tool to scrutinize and dissect building envelopes. Employing this cutting-edge technology, the approach swiftly detects thermal inefficiencies, such as heat loss or gain, moisture intrusion, and insulation defects lurking within building structures.	
[22]	Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation	**Optimization of Insulation Thickness for Building Envelopes:** This strategy delves deeply into the complex arena of optimizing insulation material thickness within building envelopes to enhance both environmental sustainability and economic efficiency simultaneously. The primary goal is to strike a perfect balance where the thickness of insulation achieves the maximum reduction in energy demand, thereby yielding dual benefits of minimizing environmental impact and optimizing costs associated with building heating and cooling operations.	

Table 5 continued

[23]	Achieving zero-energy building performance with thermal and visual comfort enhancement through optimization of fenestration, envelope, shading device, and energy supply system	Comprehensive Optimization Strategy for Zero-Energy Building Efficacy: This strategy articulates a multifaceted optimization framework targeting the architectural and systemic constituents of buildings, specifically, fenestration, the envelope, shading mechanisms, and the energy supply infrastructure to actualize zeb objectives. It is predicted on the premise of augmenting thermal and visual comfort for occupants while achieving an equilibrium between the building's energy consumption and on-site energy generation. The methodology advocates for a rigorous, integrated analysis and refinement of these elements to diminish energy requisites and amplify operational efficiency, thereby facilitating the attainment of buildings that are both energy-autonomous and environmentally sustainable.	
[24]	Earth-to-air heat exchanger for NZEB in Mediterranean climate	**Earth-to-Air Heat Exchanger (EAHX) Strategy for NZEB in Mediterranean Climate:** This innovative design strategy integrates EAHX to optimize the energy efficiency of NZEBs in Mediterranean climates. By tapping into the stable temperature underground, this approach preconditions air for heating or cooling, markedly decreasing reliance on traditional energy sources and facilitating compliance with ZEB standards. Tailored specifically for Mediterranean regions, it presents a sustainable solution capable of meeting rigorous energy performance mandates.	
[25]	Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland	**Integrated Lifecycle Approach for Optimizing NZEBs in Ireland:** This comprehensive design strategy delves deeply into evaluating the intricate interplay of environmental and economic factors throughout the lifecycle of ZEBs in Ireland. It meticulously scrutinizes both the initial phases and ongoing operations to pinpoint optimal, cost-effective pathways towards achieving ZEB status. The overarching goal is to strike a harmonious equilibrium among energy efficiency, sustainability, and economic feasibility, offering profound insights into the enduring advantages and complexities of ZEB integration within the Irish landscape.	

Source(s): Authors.

The in-depth study of the ten most cited research papers worldwide in the field of zero-energy buildings reveals the repeated use of seven key design strategies that effectively contribute to energy efficiency, which are "Insulation of the Building Envelope," "Passive Design," "Window-to-Wall Ratio," "Use of Renewable Energy," "Insulation of Openings," "Use of Energy-efficient Appliances," and "Earth-to-Air Heat Exchanger." as depicted in Table 5. These strategies reflect an increasing focus on reducing energy consumption and improving the environmental performance of buildings. By leveraging advanced insulation techniques and designs that enhance the interaction between buildings and their natural environment, it is possible to reduce reliance on industrial energy and increase efficiency.

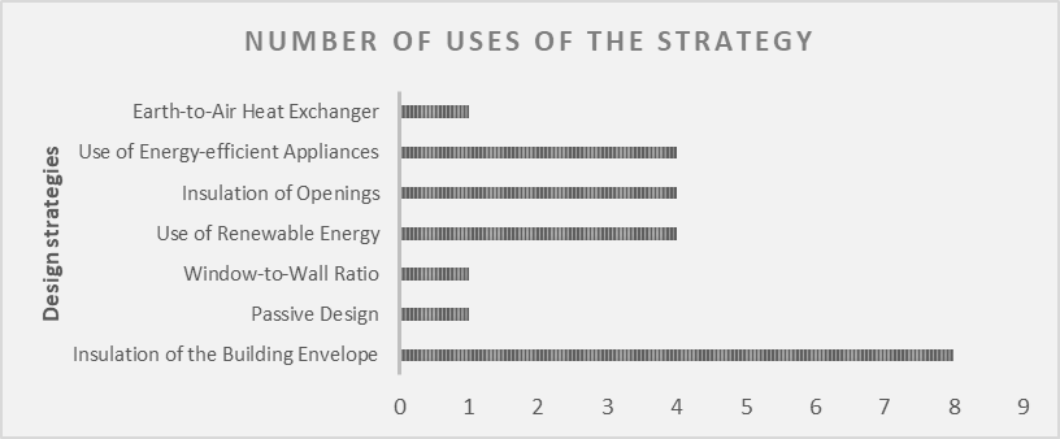
By evaluating the application frequency of various design strategies across the ten most cited studies globally, we gain insights into the preferred methodologies by leading researchers. The figure provided serves as a visual summary of this detailed analysis, quantifying the recurrence of each strategy to better understand their impact and prevalence. Figure 8 details the frequency distribution of seven key strategies in the ten most cited research papers on zero-energy buildings. From this analysis, "Insulation of the Building Envelope" emerges as the most frequently applied strategy, utilized in 8 out of 10 studies, representing an 80% recurrence rate. The following are "Use of Renewable Energy," "Insulation of Openings," and "Use of Energy-efficient Appliances," each appearing in 4 out of 10 studies, translating to a 40% recurrence rate. Meanwhile, strategies like "Passive Design," "Window-to-Wall Ratio," and "Earth-to-Air Heat Exchanger" are less common, each found in just 1 out of the 10 papers, which constitutes a 10% recurrence rate. This visualization not only highlights the most favored strategies but also underscores the prevailing trends in sustainable design applications, emphasizing those techniques that significantly enhance energy efficiency and sustainability in modern buildings.

3.9. The Most Effective Design Strategies for the Top Ten Most 2023 Documents Globally

To provide a comprehensive analysis of effective design strategies for ZEBs and how to achieve energy efficiency in diverse climatic and functional contexts, Table 6 offers a detailed summary based on a collection of the most significant global documents of 2023. This analysis reveals a multifaceted approach to achieving energy efficiency in building design.

Through a detailed examination of the most significant research papers of 2023 on zero-energy buildings, we identified seven principal strategies repeatedly cited as crucial for zero-energy design. These strategies include: the use of renewable energy, recycling, the use of energy-efficient appliances, effective insulation of the building envelope, the use of PCMs, and the implementation of Heating, Ventilation, and Air Conditioning (HVAC) systems designed to enhance energy efficiency, as depicted in Table 6.

Further quantitative analysis of ten key papers revealed that "Insulation of the Building Envelope" was the most frequently mentioned strategy, appearing in eight out of ten studies, demonstrating a significant 80% prevalence. This was followed by "Use of Renewable Energy" and "Use of PCMs," each mentioned in three studies (30% occurrence rate). "Use of Energy-efficient Appliances" appeared in two studies, representing a 20% occurrence rate. Meanwhile, the strategies "Reducing Carbon Emissions," "Recycling," and "Use of HVAC systems" were noted in only one of the ten studies, accounting for a 10% occurrence rate, as illustrated in Figure 9. These findings underline the critical importance of building envelope insulation in achieving zero-energy performance, while also highlighting the roles of renewable energy and PCMs in significantly reducing the energy consumption and environmental footprint of the real estate sector.



Source(s): Authors.

Figure 8. Number of uses of the strategy

Table 6. The most effective design strategies for the top ten most cited documents globally

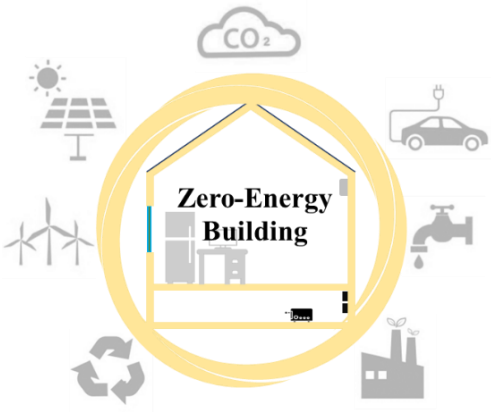
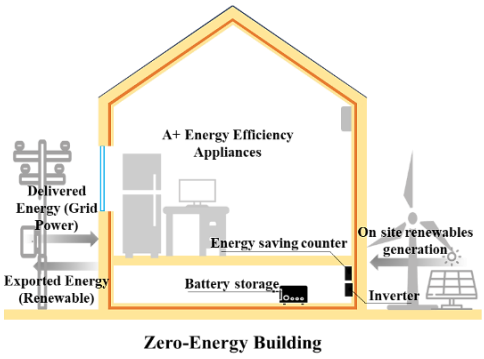
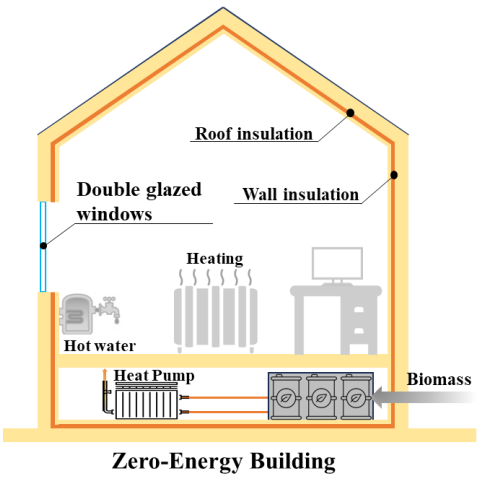
Authors	Title	Design strategies	
[26]	Towards Sustainable Cities: A Review of Zero Energy Buildings Techniques and Global Activities in Residential Buildings	**Zero Energy Building Strategy for Urban Sustainability:** The strategy of ZEBs in advancing urban sustainability revolves around a profound focus on constructing meticulously engineered edifices to achieve energy equilibrium. This visionary objective entails aligning energy generation precisely with consumption, heralding a paradigm shift in urban development. By seamlessly integrating cutting-edge energy-efficient technologies and harnessing renewable energy sources, ZEBs ambitiously aim not only to curb energy demand but also to combat the pervasive specter of greenhouse gas emissions.	
[27]	Towards the objective of Net ZEB: Detailed energy analysis and cost assessment for new office buildings in Italy	**Energy Optimization and Economic Evaluation Strategy for Net ZEBs:** The energy optimization and economic evaluation strategy for Net ZEB focuses on minimizing energy use through efficient building design and technologies and assessing the financial viability of these measures. It combines energy simulations to identify conservation strategies with cost analysis to ensure these strategies are economically sustainable.	
[28]	Prospects for the Use of Renewable Energy Sources while Increasing the Energy Efficiency Level of Office Buildings to the Level of NZEB	**Renewable Integration and Efficiency Enhancement Strategy for NZEB:** This strategy focuses on simultaneously integrating renewable energy sources and enhancing energy efficiency within office buildings to meet NZEB standards.	

Table 6 continued

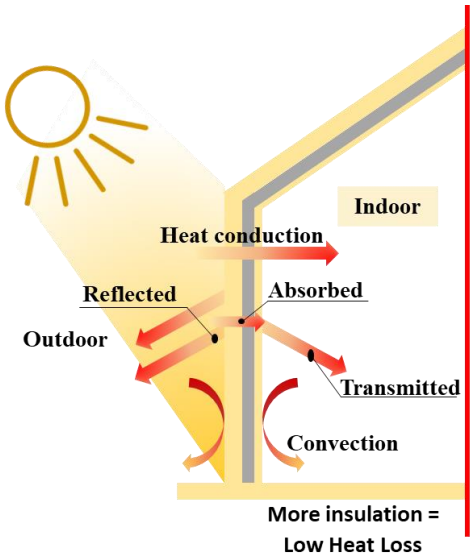
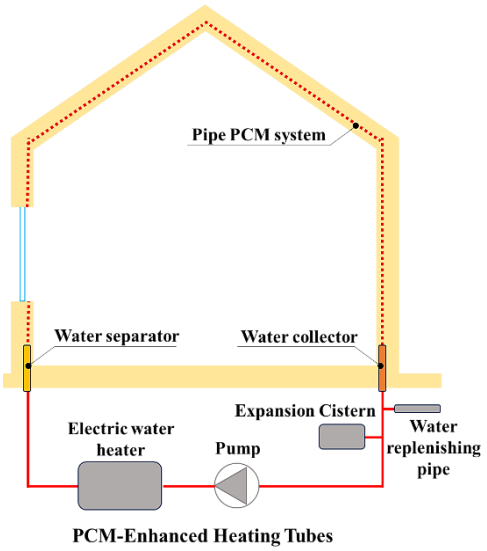
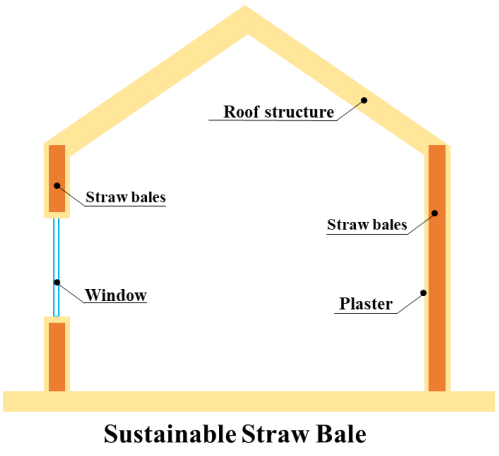
[29]	Constructal Evaluation of Polynomial Meta-Models for Dynamic Thermal Absorptivity Forecasting for Mixed-Mode NZEB Heritage Building Applications	Dynamic Thermal Absorptivity Forecasting Strategy for Heritage NZEB Transition: This strategy involves utilizing constructer theory to develop polynomial meta-models specifically designed for forecasting dynamic thermal absorptivity within mixed mode NZEB heritage applications. By employing advanced modeling techniques, the strategy aims to accurately predict changes in thermal absorptivity over time. This forecast enables efficient energy consumption and management within heritage buildings as they transition towards NZEB standards. Ultimately, the strategy facilitates informed decision-making regarding energy usage and conservation measures, optimizing the overall energy performance of heritage buildings while ensuring their preservation.	
[30]	Thermal energy simulation of the building with heating tube embedded in the wall in the presence of different PCM materials	**PCM-Enhanced Heating Tubes for Building Thermal Energy Optimization:** This innovative strategy revolves around integrating heating tubes intricately embedded within building walls, enriched with diverse Phase Change Materials (PCMs), to meticulously optimize thermal energy management. PCMs, with their unique ability to undergo phase transitions “shifting from solid to liquid states and vice versa “based on specific temperature thresholds, play a pivotal role in this paradigm. By leveraging these materials, the heating tubes adeptly store and subsequently release thermal energy with heightened efficiency.	
[31]	Straw bale construction towards nearly-zero energy building design with low carbon emission in northern China	**Sustainable Straw Bale Integration for Low-Carbon ZEB in Northern China:** The strategy involves incorporating straw bale construction methods into building design to achieve ZEB standards with low carbon emissions in northern China. By utilizing straw bales as building materials, which are renewable, locally available, and possess excellent insulation properties, the strategy aims to enhance energy efficiency and reduce the carbon footprint of buildings in the region.	

Table 6 continued

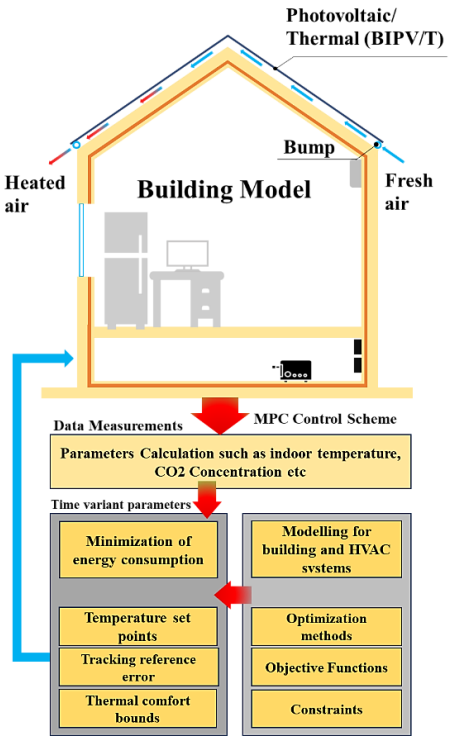
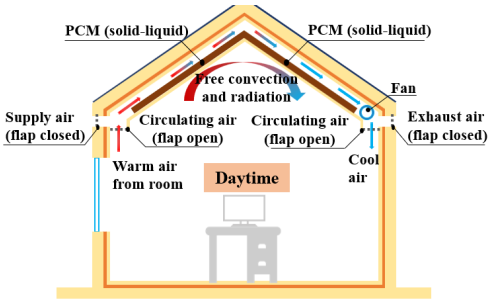
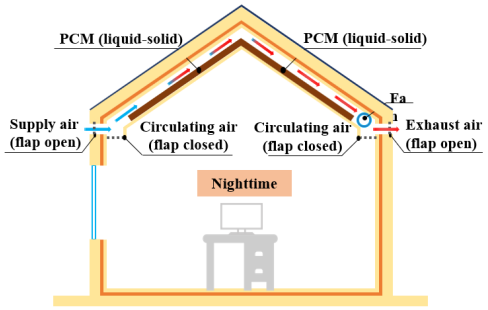
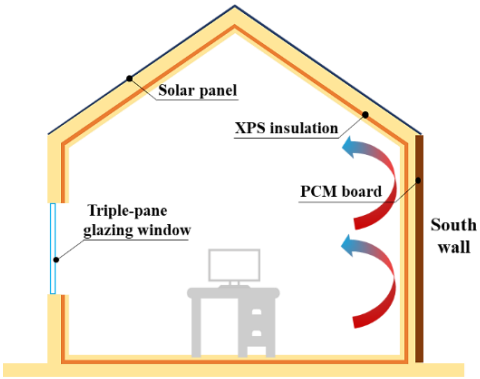
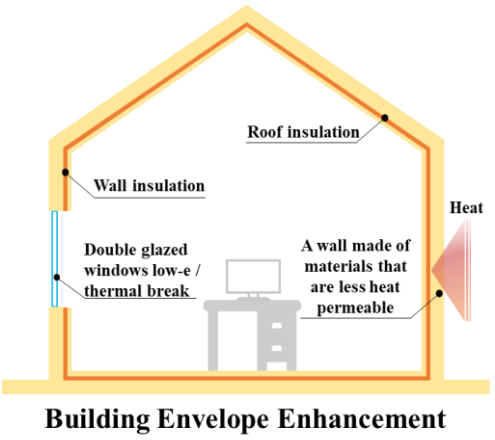
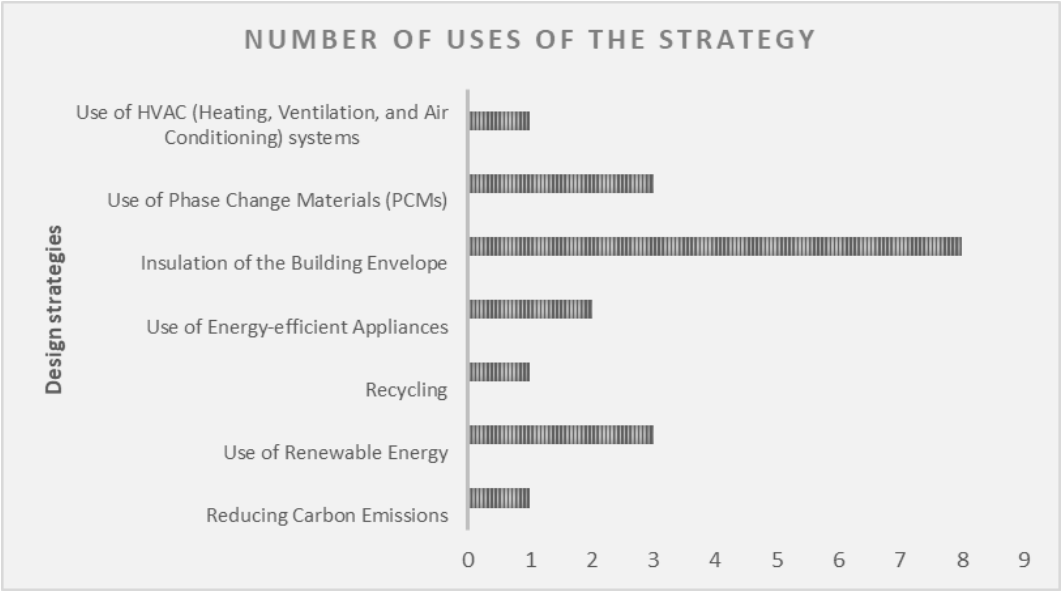
[32]	Model predictive control of air-based building integrated PV/T systems for optimal HVAC integration	Dynamic HVAC Optimization with MPC for Air-Based BIPV/T Systems: This forward-thinking strategy delves into the realm of implementing model predictive control (MPC) to finely tune the integration of air-based building integrated photovoltaic/thermal (PY/T) systems with HVAC (heating, ventilation, and air conditioning) systems. MPC algorithms serve as the linchpin, orchestrating dynamic adjustments in response to real-time data and anticipated conditions, with a goal to intricately synchronize the operation of PY/t systems capable of generating renewable energy with the nuanced demands of HVAC systems for heating and cooling.	
[33]	Challenges of the application of PCMs to achieve zero energy buildings under hot weather conditions: A review	**Strategic Solutions for PCM Integration in ZEBs under Hot Climates:** This strategy delves into overcoming the intricate challenges surrounding the application of PCMs to achieve ZEBs in hot climates. It intricately involves identifying and mitigating the hurdles associated with effectively utilizing PCMs for thermal energy storage and management in buildings situated in regions with high temperatures.	 Building Model a  Building Model b

Table 6 continued

[34]	Passive nearly zero energy retrofits of rammed earth rural residential buildings based on energy efficiency and cost-effectiveness analysis	Passive Retrofit Strategy for Nearly ZERO Energy Rammed Earth Rural Homes: The strategy involves implementing passive retrofit measures to achieve nearly zero energy performance in existing rammed earth rural residential buildings. This approach prioritizes passive design strategies, such as improved insulation, air sealing, and passive solar techniques, to optimize energy efficiency without relying on active systems. By focusing on passive measures, the strategy aims to reduce energy consumption while considering the economic feasibility of retrofitting rural residential structures.	
[35]	Building envelope resilience to climate change under Italian energy policies	**Building Envelope Enhancement for Climate Resilience under Italian Energy Policies:** This strategic initiative centers on bolstering the robustness and thermal efficacy of building envelopes to withstand the burgeoning challenges posed by climate change, specifically within the framework of Italian energy policies. It encompasses a multifaceted approach that includes augmenting insulation standards, fortifying weatherproofing measures, and integrating high-performance building materials.	

Source(s): Authors.



Source(s): Authors.

Figure 9. Number of uses of the strategy

4. Discussion

The shift toward ZERBs represents a pivotal move in combating climate change and fostering environmental sustainability. This investigation delves into prior research on ZEBs to pinpoint the most effective design methodologies for realizing these lofty objectives. By leveraging an exhaustive bibliometric analysis, the study lays a robust groundwork for grasping current research trajectories and recognizing the most impactful contributions in this domain. The analysis zeroed in on the top ten most cited research articles worldwide, alongside the noteworthy studies of 2023.

The bibliometric approach adopted in this study provides a quantitative lens to map the intellectual structure of ZERB research. By employing science mapping techniques (co-authorship, keyword co-occurrence, and citation analysis) via VOSviewer and the R package, this methodology has not only systematically uncovered hidden patterns that traditional literature reviews might overlook but also demonstrated its unique capacity to trace the evolution of research priorities quantitatively. The visual networks generated not only validate the dominance of envelope insulation and renewable integration themes but also reveal emerging clusters like PCM applications and policy frameworks, demonstrating how bibliometrics serves as a powerful radar for research trends.

Our findings highlight the crucial role of Insulation of the Building Envelope, which emerged as the most frequently mentioned strategy, appearing in 80% of the analyzed studies. This strategy is vital in reducing thermal loss and, consequently, significantly reducing the energy required for heating and cooling. The widespread mention of this strategy across the most cited research papers underscores its effectiveness and broad acceptance as a fundamental aspect of zero-energy building design.

The incorporation of renewable energy sources, a key element cited in 30% of the examined studies, emerges as a cornerstone in the quest to diminish fossil fuel dependence and shrink the carbon footprint of buildings. Notably, the persistent references to solar and wind energy systems underscore the critical role of these sustainable solutions in not only achieving energy autonomy but also aligning with overarching global sustainability aspirations.

The use of energy-efficient appliances (Use of Energy-efficient Appliances), appearing in 20% of the studies, represents another crucial strategy for reducing operational energy demands. When integrated with advanced building designs, these appliances significantly amplify overall energy savings and contribute substantially to maintaining a zero-energy balance. Although recycling (Recycling) strategies were less frequently cited (10%), their importance in minimizing waste and promoting the use of sustainable materials is undeniable. This approach is essential for the environmental performance of buildings throughout their lifecycle.

Efficient Heating, Ventilation, and Air Conditioning (HVAC) systems, spotlighted in 10% of the studies, play a crucial role in enhancing indoor environmental quality while simultaneously slashing energy consumption linked to heating and cooling. The deployment of cutting-edge HVAC technologies is paramount in sustaining comfortable indoor conditions with minimal energy consumption.

The integration of these findings highlights the necessity of a multifaceted approach to zero-energy building design, combining advanced materials, innovative technologies, and sustainable practices. The significant prevalence of building envelope insulation as a crucial strategy indicates the need for ongoing research and development in advanced insulation materials and techniques. Similarly, the important roles of renewable energy sources and PCMs point to the need to integrate renewable energy systems and thermal storage solutions in building designs.

The lower frequency of strategies such as Passive Design, Window-to-Wall Ratio adjustments, and Earth-to-Air Heat Exchangers suggests areas where further research and innovation could yield substantial benefits. These strategies offer potential for harnessing natural energy and improving efficiency, which have not yet been fully exploited.

5. Conclusions

This study aimed at the identification and analysis of the most common approaches and research directions for achieving ZERBs, through a comprehensive bibliometric analysis of the most influential research in the field of ZEBs. The results highlighted the importance of Insulation of the Building Envelope as a key strategy, appearing in 80% of the analyzed studies, underscoring its crucial role in reducing thermal loss and achieving high energy efficiency.

Additionally, the importance of integrating renewable energy sources (Use of Renewable Energy) and using PCMs, which appeared in 30% of the studies, was emphasized as an effective strategy in order to become energy independent and less dependency on fossil fuels. The use of energy-efficient appliances (Use of Energy-efficient Appliances), recycling (Recycling), and efficient Heating, Ventilation, and Air Conditioning (HVAC) systems were also pivotal in improving the environmental performance of buildings and reducing energy consumption.

The findings indicate a continuous need for research and development in advanced insulation, innovative materials, and sustainable technologies to ensure the ambitious goals of zero-energy buildings are met. Moreover, the study highlights that less frequently mentioned strategies, such as Passive Design, Window-to-Wall Ratio adjustments, and Earth-to-Air Heat Exchangers, possess significant potential that has yet to be fully exploited, requiring further research and innovation.

Overall, this study provides a clear roadmap for future research and practical applications in the field of sustainable architecture, emphasizing that continuous innovation and interdisciplinary collaboration are key to addressing the growing climate and energy challenges. By adopting these diverse strategies, the construction industry can make significant strides towards a more sustainable and energy-independent future, contributing tangibly to reducing environmental impacts and enhancing building performance.

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