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Bibliometric Analysis of Optimization Systems for Building Energy Consumption and Thermal Comfort

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ABSTRACT

Buildings worldwide consume a substantial amount of energy, accounting for approximately one-third of total primary energy resources. This issue has raised concerns regarding energy supply, the rapid depletion of energy resources, the increasing demand for building services, the enhancement of comfortable lifestyles, and the extended duration of occupants' presence within buildings. Consequently, energy demand is expected to increase in the near future. However, improving energy efficiency in buildings has emerged as a rapid and effective solution to address the growing energy demand in this sector. Given the increasing importance of energy consumption and thermal comfort in buildings, this study conducts a bibliometric analysis of optimization systems in this field. The objective of the study is to identify emerging trends, collaboration patterns, and research components related to energy consumption and thermal comfort through bibliometric analyses. To achieve this objective, scientific data were collected and examined from reputable national and international journals and scholarly publications. Quantitative methods, including co-occurrence analysis, co-authorship analysis, and co-citation analysis, were employed to analyze the data. The results of the co-occurrence analysis indicate that the keywords "energy consumption" and "thermal comfort" exhibit the highest link strength and frequency of occurrence. Other significant keywords, including "optimization systems" and "energy sustainability," ranked among the most prominent terms. The co-authorship analysis based on countries revealed that China and the United States demonstrate the highest levels of collaboration with other countries in producing scientific publications within this field. Furthermore, the co-citation analysis showed that international organizations and research institutions, such as the International Energy Agency, have received the highest citation counts in this domain. This study provides valuable insights for researchers and decision-makers and contributes to identifying key research components and international collaborations in the field of energy optimization and thermal comfort in buildings. Major areas of focus include comfort parameters, control systems, intelligent computational methods, simulation tools, occupant behavior and preferences, building typologies, energy supply sources, and countries' research interests in this sector.

Keywords: *Energy Consumption Optimization, Thermal Comfort, Bibliometrics, Bibliometrics, VOSviewer Software, Systematic Review*

1. Introduction

The building sector has become one of the most strategically important domains in contemporary energy management because buildings consume a substantial share of global energy resources and generate significant carbon emissions throughout their life cycle. The growing demand for thermal comfort, indoor environmental quality, digital building services, and longer occupancy periods has intensified energy use in residential, commercial, educational, and public buildings. At the same time, climate change, resource scarcity, and decarbonization policies have increased pressure on researchers, designers, and policymakers to develop more efficient approaches to energy consumption management and building performance optimization. The International Energy Agency has emphasized the central role of the building sector in achieving global energy and carbon reduction targets, while recent studies on nearly zero-energy buildings and positive-energy buildings show that the transition from conventional buildings to low-carbon and high-performance buildings is no longer only a technical objective but also a strategic requirement for sustainable urban development (Barrutieta et al., 2023; International Energy, 2022). Accordingly, optimization systems for energy consumption and thermal comfort have become a critical research area in architecture, management, engineering, and environmental planning.

The importance of this topic is reinforced by the fact that energy consumption in buildings is shaped by multiple interacting factors, including climate conditions, building envelope characteristics, HVAC operation, occupant behavior, lighting demand, renewable energy integration, control strategies, and economic constraints. Studies on building energy conservation and emission reduction indicate that the improvement of existing buildings is as important as the design of new high-performance buildings, because the existing building stock represents a large portion of total energy demand and often suffers from inefficient systems and outdated operational practices (Huang et al., 2022; Lu et al., 2021). In this regard, sustainable reuse, retrofit decision-making, and optimization of building components have become major pathways for reducing energy consumption while maintaining or improving occupant comfort (Ferriss, 2021; Ran et al., 2020). More recent studies also show that old residential buildings require data-driven archetype identification and energy prediction methods, especially when large and heterogeneous building stocks must be evaluated for policy or management purposes (Fan et al., 2025). These developments demonstrate that energy optimization is not limited to single-building technical interventions but requires systematic management of building data, operational strategies, user needs, and environmental objectives.

Thermal comfort is one of the most important dimensions of building performance because energy-saving strategies cannot be considered successful if they reduce environmental satisfaction, health, or productivity. Indoor comfort is affected by temperature, humidity, air quality, ventilation, radiation, lighting, and user preferences, and the optimization of these factors often involves trade-offs between energy efficiency and comfort quality. Recent reviews have emphasized the need for multi-objective optimization frameworks that integrate energy, thermal comfort, and indoor air quality rather than treating them as separate performance domains (Al Mindeel et al., 2024). Studies on thermal performance, transparent building envelopes, aerogel glazing systems, and light earth enclosures further show that envelope design and material performance directly influence both energy demand and indoor comfort (Furuya & Erten, 2023; Wieser et al., 2020; Zhu et al., 2022). Therefore, building optimization studies increasingly require an integrated perspective that simultaneously considers energy consumption, thermal comfort, visual comfort, air quality, and long-term sustainability.

The management of HVAC systems has received extensive attention because heating, ventilation, and air-conditioning systems represent one of the largest sources of building energy consumption and one of the most direct mechanisms for regulating thermal comfort. Occupancy-based HVAC control systems demonstrate that building operation can become more adaptive when real-time occupancy information is used to reduce unnecessary energy use while preserving comfort conditions (Esrafilian-Najafabadi & Haghighat, 2021). Predictive and adaptive control strategies for HVAC systems have also developed significantly, including model-based and model-free approaches, artificial intelligence control in cooling and heating energy stations, and adaptive controller design for air handling units (Qi et al., 2024; Shang et al., 2022; Xin et al., 2024). Studies on smart thermostats, PCM storage integrated with HVAC systems, and airflow sensors for VAV terminals similarly show that energy flexibility, air quality improvement, and system responsiveness are central to contemporary HVAC optimization (Correia et al., 2022; Hu et al., 2022; Mu et al., 2020). These studies indicate that optimal energy management in buildings depends on the capacity of control systems to respond dynamically to thermal loads, environmental conditions, and user behavior.

The rapid development of artificial intelligence, machine learning, deep reinforcement learning, fuzzy logic, and particle swarm optimization has transformed research on building energy optimization. Machine learning models have been used to predict energy performance, yet practical implementation challenges remain, including data quality, model generalization, interpretability, and operational integration (Wang et al., 2021). Reinforcement learning and occupant-centric control models offer promising methods for improving indoor thermal comfort and energy efficiency by enabling control systems to learn from environmental feedback and occupant responses (Duhirwe et al., 2023; Liu & Gou, 2024). Fuzzy-based particle swarm optimization has also been applied to home appliance modeling under demand response conditions, showing the potential of intelligent algorithms for reducing energy use and cost (Parvin et al., 2020). Moreover, recent studies on predictive energy consumption in cold-climate residential buildings show that machine learning techniques can support more accurate heating demand prediction, particularly when multiple building and environmental variables are available (Vaisi et al., 2025). Therefore, computational intelligence has become a key methodological foundation for energy optimization research.

Smart buildings, smart homes, and smart cities have expanded the scope of energy optimization from individual building systems to interconnected urban infrastructures. Smart energy conservation systems increasingly link residential technologies, sustainable cities, IoT infrastructure, and intelligent control platforms (Kim et al., 2021; Ul Huda et al., 2024). Efficient connectivity in smart homes can enhance living comfort through IoT-based systems, while online monitoring systems based on the Internet of Things and building information modeling can support real-time energy-saving optimization in building equipment (Xie & Xie, 2024; Youssef et al., 2024). Intelligent elevator information systems, smart lighting monitoring, and urban facility management in smart public spaces further illustrate how optimization is expanding beyond conventional HVAC and envelope analysis toward integrated urban and facility management systems (Abdelkarim et al., 2023; Chen et al., 2023; T. J. Wu et al., 2024). These developments suggest that energy optimization increasingly depends on the coordination of sensors, data platforms, control algorithms, user interfaces, and urban-scale management systems.

Occupant behavior and user preferences have also become central concerns in building optimization because actual building performance often differs from simulated performance due to human decisions, habits, and comfort expectations. Occupant behavior models are increasingly incorporated into building optimization design to improve the realism and reliability of simulation and decision-making (Wang et al., 2024). Data-driven thermal preference prediction models based on embodied air-conditioning sensors and historical usage behaviors demonstrate that comfort cannot be reduced to static thermal standards; rather, it must be understood as a dynamic interaction between occupants, technologies, and indoor environments (Luo et al., 2022). Similarly, user interaction for personalized lighting management shows that visual comfort and personal control are important parts of the broader comfort–energy relationship (Lashina et al., 2022). Person–environment fit theory also provides a conceptual basis for understanding how built environments should respond to the needs, perceptions, and expectations of users (Zhang et al., 2024). Consequently, optimization systems must be user-centered as well as energy-centered.

Energy management is also closely linked to demand response, microgrids, renewable energy integration, and distributed control. Robust energy management of residential microgrids under uncertainty shows that demand variability and renewable power fluctuations require optimization methods capable of managing uncertainty (Hosseini et al., 2021). Distributed demand response management for solar-powered communities and data-driven residential energy management further show that community-level energy optimization can improve flexibility and reduce peak demand (Pathiravasam & Venayagamoorthy, 2022; Wang et al., 2022). Real-time optimal load scheduling in intelligent smart energy management systems based on IoT also confirms the operational relevance of decisive algorithms in balancing comfort, load, and energy efficiency (Rao et al., 2024). In addition, subsidies and sustainable energy consumption in non-residential building transformation indicate that economic instruments and policy mechanisms are important for accelerating energy transitions in the building sector (Rieksta et al., 2025). Thus, energy optimization is not only a technical problem but also a managerial and policy-oriented challenge.

Simulation and modeling tools remain essential for evaluating energy consumption, comfort performance, and design alternatives before implementation. Building energy models, thermal models, and simulation-based decision frameworks allow researchers to analyze complex relationships among envelope systems, HVAC operation, climate conditions, and user behavior. IoT-based thermal model learning frameworks for smart buildings show how data-driven modeling can support real-time control and adaptive performance improvement (Zhang et al., 2020). Online learning frameworks for indoor intelligent temperature control also demonstrate the potential of continuous learning in HVAC operation (Yao et al., 2020). Energy optimization can also be supported through artificial neural network metamodels for design sensitivity analysis, particularly in complex building forms such as shopping malls (Yuan et al., 2022). Meanwhile, studies on optimal control for smart-home cooling management using ANNs-PSO platforms show that hybrid computational systems can improve energy conservation in practical building contexts (Sirisumrannukul et al., 2024). These studies indicate that simulation is increasingly combined with intelligent optimization to support evidence-based building management.

The relationship between building form, urban morphology, and energy consumption has also become increasingly important. Urban heat island effects, building density, orientation, urban geometry, and microclimate conditions influence both cooling demand and comfort quality. Critical reviews of urban morphology, urban heat island effects, and building energy consumption highlight the need to understand energy performance at the intersection of building and urban scales (Sharston & Singh, 2025). Modern strategies for optimizing energy consumption in residential architecture similarly emphasize the importance of passive design, energy-efficient systems, and integrated planning approaches (Vitalii, 2025). Low-carbon optimization of reinforced concrete building structures using genetic algorithms shows that structural design can also be incorporated into broader energy and carbon optimization frameworks (Zhang & Zhang, 2023). Therefore, energy optimization should not be limited to operational systems but should include architectural form, urban context, material selection, and structural decision-making.

Because the literature on building energy optimization and thermal comfort has expanded rapidly, bibliometric and bibliometric methods are increasingly necessary for identifying the intellectual structure, research trends, key journals, influential countries, collaboration patterns, and thematic clusters of the field. Bibliometric analysis has been widely used in architecture, urban planning, cultural landscape research, archaeology, media façade studies, and built-environment perception research to map scientific production and reveal emerging research trajectories (Çelik & Sekeroglu, 2023; Ciaurriz, 2023; Tang et al., 2024; D. D. Wu et al., 2024; Zhou et al., 2024). Co-word analysis and keyword mapping can identify major research themes, while co-authorship and citation analysis can reveal collaboration structures and intellectual influence. Research on socially sustainable smart cities using co-word analysis confirms the usefulness of bibliometric tools for organizing complex and interdisciplinary fields (Ebrahiem et al., 2024). Similarly, systematic reviews of zero-energy building research demonstrate that bibliometric and review-based approaches can clarify how research priorities evolve over time (Sabour et al., 2023). Therefore, bibliometric analysis is particularly suitable for examining optimization systems for energy consumption and thermal comfort because this field contains diverse methods, tools, indicators, and disciplinary perspectives.

Despite the growing body of research, several gaps remain. Many studies focus on specific tools, algorithms, or building systems, while fewer studies provide an integrated picture of how optimization systems, comfort parameters, simulation tools, energy sources, publication trends, countries, journals, and collaboration networks are connected. Research on BIM and energy performance has shown that digital design tools can enhance building energy performance, but their adoption and practical implementation remain uneven across contexts (Rashwan & Mostafa, 2023). Automated systems for improving the thermal performance of large buildings demonstrate the practical value of optimization, but also show that operational complexity requires systematic design and management methods (Pozas et al., 2023). Furthermore, studies on connected hybrid electric vehicles and numerical simulation in engineering contexts indicate that optimization methods are spreading across adjacent technological fields, suggesting the need to position building energy optimization within a wider ecosystem of intelligent systems and computational decision-making (Xu et al., 2022; Zha et al., 2022). These gaps justify the need for a comprehensive bibliometric study that can synthesize the fragmented knowledge base and identify the dominant and emerging directions of the field.

Overall, the literature indicates that energy consumption optimization and thermal comfort management in buildings are shaped by the convergence of sustainable architecture, intelligent control, occupant-centered design, IoT infrastructure, simulation-based decision-making, renewable energy integration, and bibliometric knowledge mapping. The field has moved from isolated energy-saving strategies toward multi-objective and data-driven systems that seek to balance energy efficiency, comfort, cost, environmental performance, and user satisfaction. At the same time, the increasing volume of publications makes it necessary to analyze not only technical findings but also the structure of scientific knowledge itself, including keyword networks, publication outlets, country collaborations, and research hotspots. The aim of this study is to conduct a bibliometric analysis of optimization systems for energy consumption and thermal comfort in buildings in order to identify emerging research trends, key thematic components, influential publication patterns, and collaboration structures in the global literature.

2. Methods and Materials

This study adopted an inductive approach. In terms of purpose, the research is applied in nature, and its objective is explanatory–prescriptive and utilization-oriented. The data collection and analysis method is quantitative. The research procedure was conducted through the following stages:

Stage 1: In this stage, the components and indicators influencing the simulation of thermal comfort in building performance optimization were identified and extracted from reputable national and international documentary and library-based sources.

Stage 2: A bibliometric analysis was conducted to uncover the intellectual structure of the existing literature on thermal comfort and optimal building performance. Quantitative techniques, including co-occurrence analysis, co-authorship analysis, and co-citation analysis of bibliographic records, were employed. Data retrieval and extraction were carried out using major scientific databases, including the Web of Science Core Collection and Scopus. The primary focus of this research was scientific data related to the topic of thermal comfort. Within this systematic literature review, the VOSviewer software was utilized to construct maps based on the frequency of co-occurring keywords and to visualize the thematic structure of the field. VOSviewer is compatible with several databases, including Web of Science, Scopus, and ScienceDirect. Accordingly, the present analysis specifically examined academic publications indexed in the Web of Science database (Sabour et al., 2023). Using VOSviewer, various types of maps can be generated, including visualization maps, network maps, overlay visualization maps, and density visualization maps (Ciaurriz, 2023).

Bibliotools and Bibliomaps primarily focus on the analysis and visualization of scientific networks, whereas other tools may offer a broader range of functionalities. Bibliotools consists of a collection of Python scripts that provide considerable flexibility for customized analyses. In contrast, Bibliomaps offers a web-based interface with a set of predefined visualizations.

VOSviewer primarily emphasizes network visualization, whereas Bibliotools provides more advanced analytical capabilities, including the calculation of bibliometric indicators and temporal analyses. Bibliomaps operates through a web-based interface, while CiteSpace and VOSviewer are desktop applications. VOSviewer is particularly suitable for researchers experienced in network analysis, whereas Bibliotools operates within the Python environment. Bibliomaps, as a web application, can be accessed through an internet browser and may be more appropriate for users with limited programming experience.

Gephi is a general-purpose network analysis tool, whereas Bibliotools and Bibliomaps are specifically designed for the analysis of scientific networks. Gephi requires prior preparation of network data, while Bibliotools can directly process bibliographic datasets. Gephi is particularly suitable for researchers with expertise in network analytics. Bibliometrix is an open-source tool for quantitative research in bibliometrics and bibliometrics and incorporates all major bibliometric analysis methods. Through Biblioshiny, a user-friendly web application, Bibliometrix has become accessible even to users without coding skills. It provides a comprehensive workflow for science mapping and includes all necessary tools for conducting a complete bibliometric analysis. Bibliometrix was developed by Massimo Aria and Corrado Cuccurullo. As open-source software, Bibliometrix allows users to inspect, modify, and improve the source code. The purpose of this study is to investigate and evaluate the current status, impact, and future potential of research on energy consumption optimization systems and thermal comfort at the global level. Current research dynamics and developments in the field of energy architecture were comprehensively examined. To identify significant contributions and anticipate future directions and innovations, data indicators within the existing body of literature were evaluated. Therefore, the study employs a literature review methodology grounded in both quantitative and qualitative data.

Scientific Data Cleaning and Processing

The collected data required cleaning and processing after the initial retrieval stage. The bibliometric analysis required complete documentation records; therefore, document types were limited to journal articles, conference papers, book chapters, review articles, and books, resulting in the first stage of data cleaning (n = 1,042). Furthermore, because Scopus allows direct access to article abstracts, irrelevant documents were identified and removed through manual review (n = 72). In addition, trade and commercial publications were excluded from the scope of analysis. It is important to note that, after reviewing all documents, certain ambiguities in search terms remained. For example, the term "energy consumption" was frequently used in the context of "energy conservation" within optimization studies, while phrases such as "energy consumption systems" also appeared as related keywords. Similarly, the term "sustainable architecture" was sometimes used interchangeably with "zero-carbon architecture," although distinct studies existed under each designation. Ultimately, titles and abstracts were carefully examined to ensure the validity and relevance of the dataset, and unrelated documents were removed, resulting in the final cleaned dataset (n = 935).

Bibliometric Search Strategy

Regarding the search strategy, the selection of appropriate keywords is essential when conducting bibliometric investigations. In this study, the initial step involved defining the research topic as "energy consumption and thermal comfort," based on the research question and study objectives. Subsequently, a search was performed in the Scopus database. The analysis focused on article titles, as titles are often the first element that attracts researchers' and practitioners' attention and provide a meaningful basis for substantive evaluation. Moreover, titles generally reflect the relevance of a study more directly, thereby enhancing the accuracy of bibliometric analysis outcomes. The temporal scope of the study was defined from 2019 to May 2024. Extending the analysis through 2024 improves the currency and novelty of the study and provides insight into the latest research developments. A deeper understanding of emerging theories, methodologies, and trends enables the identification of new research topics and directions. The final number of retrieved documents was 1,097.

Quantitative Data Analysis

Bibliometric methods in knowledge mapping facilitate the examination of relationships among disciplines, research fields, specialties, and individual publications. They also provide essential tools for identifying new pathways and future directions in scientific research. Accordingly, this study employed bibliometric analysis to identify knowledge domains, research trends, and emerging directions in energy-efficient architecture. Therefore, selecting appropriate software for processing quantitative data was of critical importance. Quantitative analysis of the relevant literature was conducted using VOSviewer, which enables the creation of knowledge maps. The visual analysis incorporated the latest developments and research hotspots in the field. This freely available software generates robust results for medium- and large-scale datasets and represents an effective tool for scientific mapping analysis. When exported files are opened in Microsoft Excel, each record contains comprehensive publication information, including title, author, affiliation, and keywords. It should be noted that some exported Scopus records contained incomplete information requiring additional refinement to ensure consistency and reliability. The advanced search interface of Scopus allows manual completion of author affiliation data based on EID identifiers. Subsequently, the cleaned dataset was exported and processed using OpenRefine (Version 3.7.2), after which it was imported into VOSviewer for visual analysis and discussion of annual publication trends, as well as the most influential authors, institutions, and countries. This process also revealed co-occurrence networks derived from titles and abstracts within the field of energy architecture. Accordingly, in the first phase of Stage 3, VOSviewer was employed to conduct the bibliometric analysis, thereby establishing the foundation for the subsequent qualitative analysis.

3. Findings and Results

Based on the analyses summarized in Table 1, the findings indicate that research on optimization systems for energy consumption and thermal comfort in buildings has developed around several interconnected themes, including simulation and optimization tools, publication outlets, optimization objective functions, comfort parameters, building typologies, energy supply sources, keyword co-occurrence structures, international collaboration patterns, and emerging research trends.

Table 1

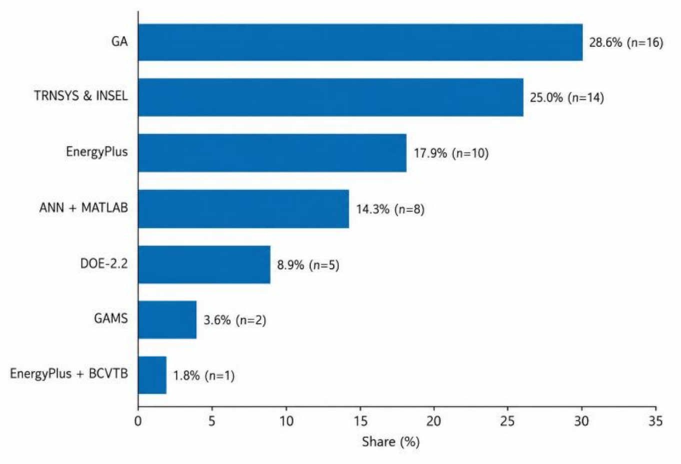
Analytical Components

Analytical component	Main quantitative and thematic findings	Interpretation
Simulation and optimization tools	The genetic algorithm (GA) had the highest share among optimization algorithms and tools, accounting for 28.5%. TRNSYS and INSEL ranked second with 25%, followed by EnergyPlus with 17.5% and MATLAB with 14%.	Evolutionary algorithms and building energy simulation environments constitute the dominant technical infrastructure in studies on building performance optimization.
Publication outlets	Among journals related to building performance optimization, *Energy and Buildings* had the highest publication share, accounting for 22.6% of the reviewed studies.	The concentration of publications in specialized energy and building journals indicates the maturity of this research domain.
Building performance optimization parameters	Optimization related to thermal comfort and user satisfaction ranked as the first research priority, while energy efficiency combined with comfort also received substantial attention.	The field has moved from purely energy-oriented optimization toward multi-objective approaches that integrate energy efficiency with occupant-centered comfort.
Comfort parameters	The most frequent comfort-related parameters were ventilation and cooling/heating systems, with 34.17%. Radiation and lighting-related issues ranked second with 21%.	Indoor environmental control, especially HVAC-related comfort, remains the core operational concern in building optimization studies.
Building use	The reviewed studies covered 55% residential buildings, 24% commercial buildings, and 21% office buildings.	Residential buildings dominate the literature, although commercial and office buildings remain important contexts for optimization research.
Energy supply sources	Fossil fuel-based energy supply was addressed in 64% of studies, while renewable energy sources accounted for 33%. Renewable sources included photovoltaic systems, wind turbines, biomass, and hybrid systems.	Despite the growing interest in renewable energy, fossil fuel-based building energy supply still occupies the largest share of the reviewed studies.
Dataset and preprocessing	In the VOSviewer-based bibliometric analysis, 1,712 scientific documents were extracted from the Web of Science database. After conference papers were excluded, the most recent article dated to 2024 and the oldest to 2014. From these documents, 116 items appeared at least five times. A cleaning process was performed on 147 keywords, and 108 keywords were retained for final analysis. In another stage of the broader bibliometric analysis, 1,041 scientific documents were examined across six analytical procedures.	The screening and cleaning process improved the validity of the keyword network and reduced redundancy among similar or irrelevant terms.
Highest-ranked keywords	"Optimization" ranked first with a total link strength of 375 and 66 co-occurrences. "Thermal comfort" ranked second with a total link strength of 363 and 67 co-occurrences. "Energy consumption" ranked third with a total link strength of 289 and 63 co-occurrences. "Simulation" ranked fourth with a total link strength of 262 and 51 co-occurrences. "Heat" had the lowest reported position, with a total link strength of 14 and five occurrences.	The dominant conceptual core of the field is formed by optimization, thermal comfort, energy consumption, and simulation.
Keyword cluster 1	Cluster 1 contained 32 items, approximately 27.5% of all keywords. It included optimization, building optimization, comfort, comfort management, commercial buildings, control systems, design, energy, energy conservation, energy efficiency, energy saving, genetic algorithm, smart building impact, intelligent buildings, intelligent control management, simulation, multi-objective optimization, natural ventilation, occupant behavior, office buildings, performance, predictive control, machine learning, residential buildings, saving, and visual comfort.	This cluster focuses on building automation, energy efficiency, comfort management, and smart technologies for control and optimization across different building types.
Keyword cluster 2	Cluster 2 contained 29 items, approximately 25% of all items. It included algorithm, building energy consumption, demand response, demand-side management, energy consumption systems, flexibility, building information management, thermal load management, electricity, renewable energy, smart city, smart home, and storage technologies.	This cluster emphasizes energy consumption optimization, demand management, and the application of smart technologies in building energy systems.
Keyword cluster 3	Cluster 3 contained 24 items, approximately 20.6%. It included artificial intelligence, deep learning, fuzzy logic, genetic algorithms, HVAC systems, IoT, smart systems, smart homes, and user comfort.	This cluster reflects the growing role of intelligent computational methods and cyber-physical technologies in thermal comfort and energy optimization.
Keyword cluster 4	Cluster 4 contained 17 items, approximately 14.6%. It included behavior, buildings, deep reinforcement learning, efficiency, electric vehicles, energy saving, energy consumption, heat, load, operation, prediction, strategies, sustainability, and temperature.	This cluster links operational efficiency, predictive strategies, sustainability, and emerging technologies such as electric vehicles and deep reinforcement learning.
Keyword cluster 5	Cluster 5 contained 14 items, approximately 12%. It included energy consumption strategy, model predictive control, time, multi-objective optimization, particle swarm optimization, strategy, and system.	This cluster is mainly related to control strategies, temporal optimization, and computational optimization methods.

Country-level collaboration	Among the top 20 productive countries, China, South Korea, New Zealand, the United States, the Netherlands, Australia, Iran, India, and African countries or regions appeared prominently. China and the United States showed the highest total link strength. When the minimum number of authors and minimum number of citations were set to one, 50 countries met the criteria. In the stricter country co-authorship analysis, 42 countries from 121 countries entered the network with at least 10 citations.	China and the United States are the leading countries in terms of collaboration strength, while collaboration in developing countries appears relatively limited and more individually oriented.
Integrated bibliometric synthesis	A total of 83 indicators affecting energy consumption optimization were identified across four dimensions: management, comfort, systems, and environmental indicators. Management indicators had the highest frequency. Within this dimension, optimization through smart homes and smart cities appeared most frequently.	The intellectual structure of the field is increasingly shaped by management-oriented optimization, smart urban systems, occupant comfort, and environmental sustainability.

Figure 1

Trends in simulation and optimization tools used in building energy and thermal comfort studies



As shown in Figure 1, the genetic algorithm was the most frequently used optimization algorithm, accounting for 28.5% of the studies. TRNSYS and INSEL ranked second with 25%, indicating the importance of dynamic simulation environments in building performance analysis. EnergyPlus accounted for 17.5%, while MATLAB represented 14% of the optimization tools. These results show that the literature relies heavily on evolutionary optimization and simulation-based evaluation, particularly where energy consumption and thermal comfort must be optimized simultaneously.

Figure 2

Journals related to building performance optimization

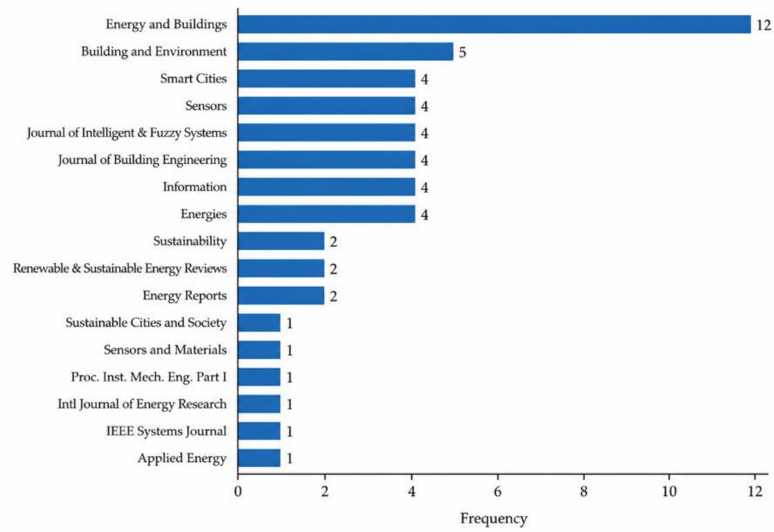


Figure 2 presents journals associated with building performance optimization. The findings show that *Energy and Buildings* had the largest publication share in this field, accounting for 22.6% of the reviewed studies. This result indicates that specialized energy and building science journals play a central role in disseminating research on optimization systems, energy efficiency, thermal comfort, and building performance modeling.

Figure 3

Optimization parameters and comfort-related parameters in building performance studies

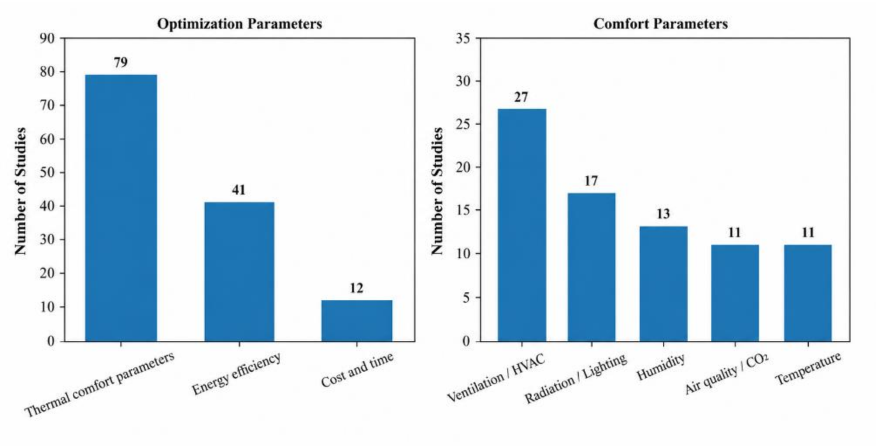


Figure 3 shows the applied optimization trends in buildings and the comfort parameters used as objective criteria. The findings indicate that thermal comfort and user satisfaction were the most important optimization objectives from the perspective of researchers. Energy efficiency was also frequently examined in combination with comfort, showing that building optimization studies increasingly adopt multi-objective frameworks rather than focusing exclusively on energy reduction. In terms of comfort parameters, ventilation and cooling/heating systems had the highest share, with 34.17%, followed by radiation and lighting issues with 21%. Therefore, HVAC-related performance, thermal regulation, visual comfort, and environmental quality represent major concerns in building energy optimization research.

Figure 4

Building use categories and energy supply sources in optimization studies

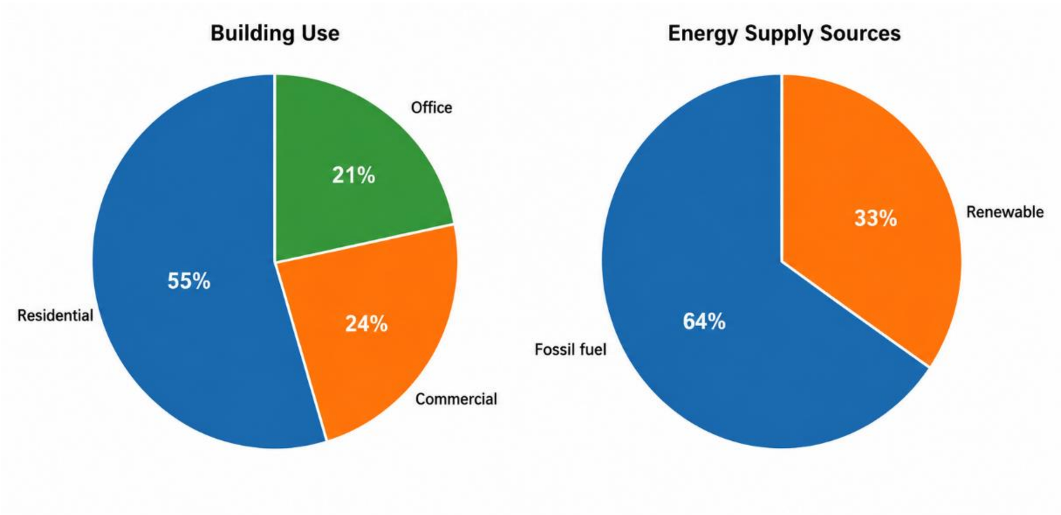


Figure 4 presents the building-use categories examined in the reviewed studies. Residential buildings accounted for 55%, commercial buildings for 24%, and office buildings for 21%. This distribution shows that residential buildings have received the greatest attention, probably because of their high share in total building energy consumption and their direct relationship with occupant comfort. Energy supply sources were also examined as a key element of building sustainability. The results show that 64% of studies focused on fossil fuel-based energy supply, whereas renewable energy sources accounted for only 33%. The renewable sources most commonly addressed in building-related studies included photovoltaic systems, wind turbines, biomass, and hybrid combinations of these sources. These findings illustrate key trends in research on energy efficiency, energy systems, and sustainability in buildings.

Information visualization is one of the main techniques through which the structure and mutual relationships of thousands of documents can be understood more clearly. Special tools have been developed for this purpose, among which VOSviewer is one of the most widely used. In this study, co-occurrence analysis based on all keywords, citation analysis, bibliographic coupling, and co-authorship analysis were conducted using 1,712 scientific documents extracted from the Web of Science database. The network visualization of co-occurrence analysis represents relationships among links and items, or nodes. In this visualization, nodes are displayed with labels and are usually represented by circles. The size of each node is determined by the weight of the item; the greater the weight, the larger the label and circle. The color of each item is determined by the cluster to which it belongs. Lines between items represent links, while the distance between two items indicates the strength of their relationship; the shorter the distance, the stronger the relationship between the two items. This means that the two items appear together more frequently in the same articles and have a higher probability of co-occurrence.

The analytical concepts used in this bibliometric section were defined as follows. An item refers to the topic or unit on which the research is conducted. A link refers to the relationship created between two items. Link strength is a positive numerical value, and the higher its value, the stronger the relationship between two items. Items and links together form a network. A cluster refers to a set of items that are located close to each other on the map and are thematically related. Network visualization refers to the visual display of relationships between items and links. Overlay visualization displays relationships in a manner similar to network visualization, but differs in the coloring of items. Density visualization is useful for understanding the overall structure of the map and focusing on its most important areas. Co-occurrence refers to the extraction and analysis of article keywords to identify core topics and developments in a research field. Co-citation refers to two scientific documents that are cited together by a newer article, indicating similarity between them. Bibliographic coupling refers to two documents that cite similar references and therefore share common thematic concerns. Co-authorship refers to collaboration among different authors in producing joint scientific works. All keywords include both author-provided keywords and automatically extracted keywords from scientific databases.

This approach combines accurate data analysis with a deeper understanding of the phenomenon. For example, bibliometric analysis can clarify the overall landscape and research impact of optimization systems for energy consumption and thermal comfort by explaining relationships among authors, publications, institutions, and other features of the field. Such analysis contributes to mapping and expanding knowledge in this domain. Qualitative tools can also provide additional insights beyond quantitative analysis and lead to a deeper understanding of theories, cultural concepts, historical developments, and perspectives related to optimization systems for energy consumption and thermal comfort. Therefore, interpretive bias and subjective judgments can be addressed through a combined systematic assessment that contributes to both the depth and breadth of understanding.

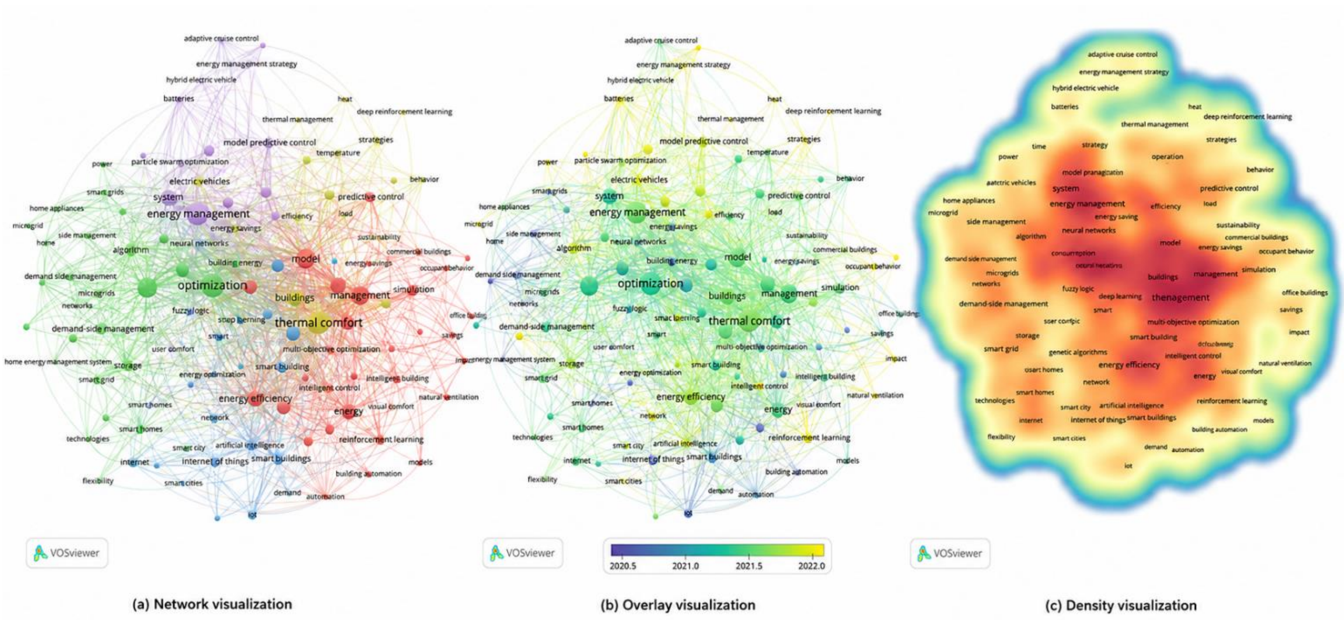
The Scopus database was selected for the bibliometric component of the study because it is regarded as one of the most comprehensive interdisciplinary databases for content and citation analysis. Since it includes publications from scientific publishers worldwide and is widely used in large-scale analyses, it enables a comprehensive understanding of global scientific research outputs on optimization systems for energy consumption and thermal comfort. The general research methodology and operational framework of this section were therefore designed to support both quantitative bibliometric mapping and interpretive synthesis.

Conference papers were removed from the initial dataset. The newest article in the reviewed set dated to 2024, while the oldest dated to 2014. Among the 1,712 articles extracted from Web of Science, 116 items appeared at least five times. The frequent co-occurrence of two keywords in the same article indicates that those keywords are more closely related than other terms, and this pattern can generate new research ideas. To prevent the repetition of similar or unrelated words that might not be directly associated with the research topic, 147 keywords were cleaned, and 108 keywords were finally selected for the analysis. The relationship between items was determined based on the number of shared citations. Each node in the network visualization represents a keyword, and the size of the node is proportional to its weighted score. A higher weighted score indicates that the keyword appeared more frequently. In this analysis, the weighted score was calculated based on the total link strength between two items. The link between two items represents the co-occurrence of two keywords, and the thickness of the connecting line indicates the strength of this link.

Based on the results, the keyword “optimization” ranked first with a total link strength of 375 and 66 co-occurrences. The items “thermal comfort” and “energy consumption” ranked second and third, with total link strengths of 363 and 289 and co-occurrence frequencies of 67 and 63, respectively. “Simulation” ranked fourth, with a total link strength of 262 and 51 co-occurrences. The item “heat” ranked last among the reported items, with a total link strength of 14 and five occurrences. The overall network visualization showed that 116 items were classified into five clusters. Each color represents a cluster and indicates that items within the same cluster are more similar to each other than to items in other clusters. Cluster 1, shown in green, contained the highest number of items with 32 keywords. Cluster 2, shown in red, contained 29 items. Cluster 3, shown in blue, contained 24 items. Cluster 4, shown in yellow, contained 17 items. Cluster 5, shown in purple, contained 14 items and ranked last in terms of the number of items.

Figure 5

Keyword co-occurrence analysis of building optimization and energy consumption in network, overlay, and density visualizations



According to Figure 5, the keyword co-occurrence network demonstrates the thematic clustering of building optimization studies. Cluster 1 focuses on building automation, energy efficiency, comfort management, and smart technologies in the control and optimization of energy use across commercial, office, and residential buildings. Cluster 2 focuses on energy consumption optimization, demand response, demand-side management, flexibility, building information management, renewable energy, smart cities, smart homes, and storage technologies. Cluster 3 mainly reflects artificial intelligence, deep learning, fuzzy logic, genetic algorithms, HVAC systems, IoT, smart homes, and user comfort. Cluster 4 includes behavior, buildings, deep reinforcement learning, efficiency, electric vehicles, energy saving, energy consumption, heat, load, operation, prediction, strategies, sustainability, and temperature. Cluster 5 includes energy consumption strategy, model predictive control, time, multi-objective optimization, particle swarm optimization, strategy, and system.

The overlay visualization of co-occurrence operates similarly to network visualization, but the items are colored differently. In the overlay map, the color of each item is determined according to its average publication year and is scaled across the period from 2019 to 2024. The color bar on the right side of the map displays the keyword spectrum based on average publication year. For example, green keywords are associated with optimization and building performance management models and generally correspond to 2021 and later. This indicates that these keywords have received greater attention in recent years in articles on optimization and thermal comfort and are now increasingly examined through artificial intelligence and algorithmic methods. Yellow indicates management-related and energy-demand-related items associated with 2022 to 2024. Items such as smart city and smart homes are related to earlier research trends, including studies before 2019, and are older compared with several other examined items. Overall, research on building performance optimization, user satisfaction parameters, and comfort has remained a significant area of scholarly attention in recent years and can continue to advance the research field.

In the overlay visualization, the size of the circles represents the weight of the keywords. Larger circles indicate that the item is more likely to appear with other items in the articles, emphasizing the co-occurrence relationship between two items. The distance between keywords indicates their relationship with each other; the shorter the distance, the stronger the relationship between two items. In the density visualization, each point or region is displayed according to the distribution and density of keyword co-occurrence, which helps identify research patterns and trends related to energy consumption optimization. Density visualization is particularly useful for understanding the general structure of the map and highlighting the most important regions. The color of each point is determined by the density of the item. Item density depends on the number of neighboring items and the weight of those items. The larger the number of neighboring items, the shorter their distance from the point of interest, and the greater their weight, the closer the color becomes to yellow. Conversely, when the number and weight of neighboring items are lower, the color becomes closer to blue. Therefore, in density visualization, each point has a color that represents the density of items in that area of the map.

Figure 6

Country collaboration, keyword overlap, author overlap, and trending keywords in energy consumption optimization

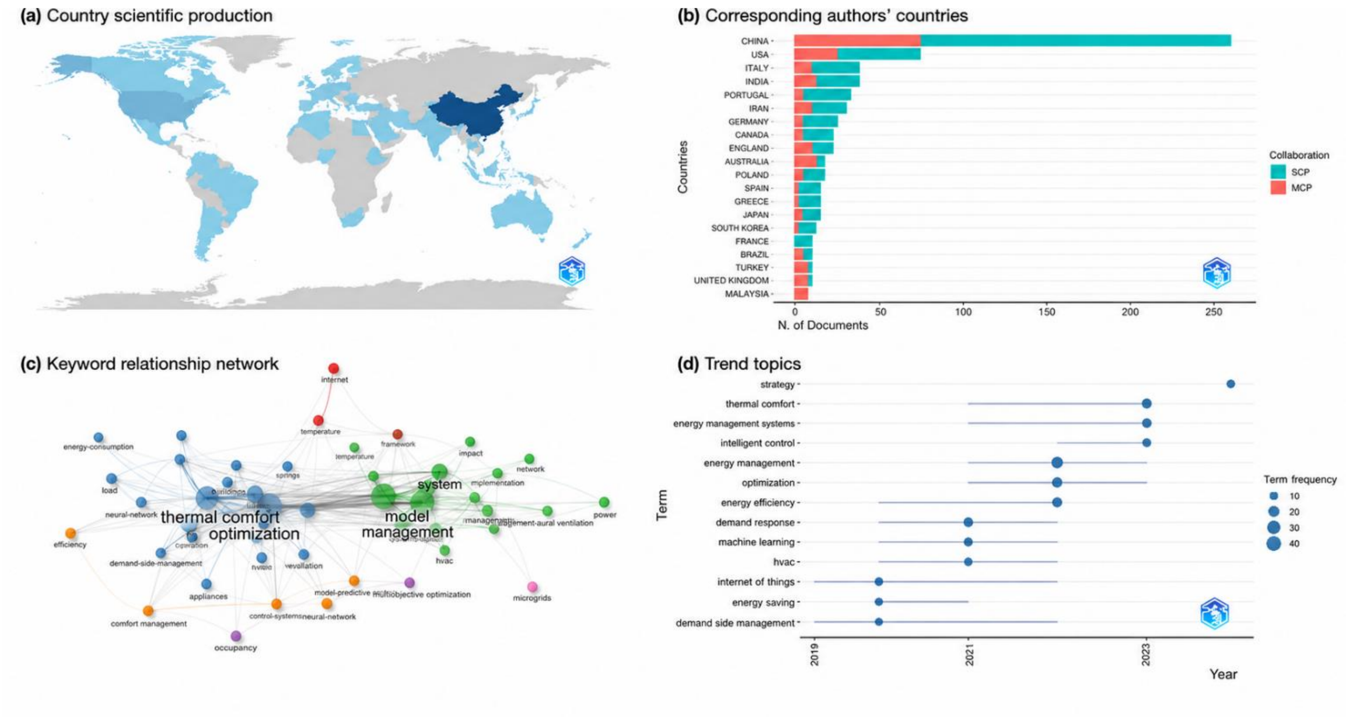


Figure 6 presents the country-level and author-level collaboration patterns, keyword overlap structure, and trending keywords in energy consumption optimization. Some of the top 20 productive countries in this field include developed and scientifically active countries such as China, South Korea, New Zealand, the United States, the Netherlands, Australia, Iran, India, and African countries or regions. China and the United States ranked as the two leading countries in terms of total link strength. This indicates the strong influence of these countries in research and implementation related to building performance optimization, including in contexts relevant to developing countries.

When the thresholds for the minimum number of authors and the minimum number of citations were both set to one, 50 countries met the required criteria. The network showed that there were not many joint research projects on building performance optimization in developing countries. The large number of single or isolated authors without strong links supports this interpretation. It appears that research on building performance optimization in developing countries is often conducted individually rather than collaboratively. This may be related to a weak collaboration culture in parts of the research and construction sectors. Effective research on the diffusion of building performance optimization in developing countries therefore requires a change in the prevailing culture of collaboration among researchers.

In the bibliometric analysis of journals and keywords related to energy optimization management, overlay visualization again performed similarly to network visualization, with the difference that items were displayed through color coding based on average publication year from 2019 to 2024. In bibliometric analysis, overlap refers to the use of related measures and information to quantitatively describe overlapping relationships. In the earlier analytical stages, influential countries, institutions, sources, and authors were examined. However, the topics and concepts expressed through keywords also required analysis. Keyword overlap analysis better reveals research focus, research areas, and the development of key topics. The keyword overlap map indicated that energy consumption, optimization, smart home, thermal comfort, and environmental parameters of thermal comfort, such as ventilation and visual comfort, were central overlapping concepts.

Using Bibliometrix and based on article titles and abstracts, all keywords were selected as the axis of analysis, with a minimum threshold of 14 word appearances. Keyword overlap was displayed as a network diagram. Bibliometrix identified keywords from article titles and abstracts and classified them into clusters with different colors. Five clusters were identified: red, green, blue, yellow, and purple. The size of each cluster represents the weight of item occurrence, while the density of connecting lines represents the strength of relationships among items. Similar colors indicate the co-occurrence of related keywords. For example, the keywords “optimization,” “ventilation,” “thermal comfort,” “energy conservation,” and “energy saving” appeared closely together and were associated with the same thematic area. Based on these relationships, the percentage contribution of items in the articles was separated through a visual map.

The synthesis of bibliometric findings on energy consumption shows that threatening challenges in the energy consumption domain have increased the importance of optimization, supply, and demand management. This has made it more necessary to examine and analyze all components affecting energy optimization. The purpose of this research was to identify emerging trends in articles and journals, collaboration patterns, and research components in order to examine the intellectual structure of energy consumption optimization in the global literature through bibliometric analysis. Based on the available data, 83 indicators affecting energy consumption optimization were identified across four dimensions: management, comfort, systems, and environmental indicators. Management indicators had the highest number. Within this dimension, optimization through smart homes and smart cities appeared as the most frequent themes in the field of energy consumption.

The bibliometric analysis of 1,041 scientific documents across six different analyses showed that keywords such as “energy consumption,” “optimization,” and “thermal comfort” were the most frequent terms in the scientific literature. Global warming and climate-related problems in recent years have increased the importance and frequency of these keywords in academic articles. The co-occurrence overlay network showed that topics such as energy saving, artificial intelligence, smart cities, and smart homes are among the newer topics attracting researchers’ attention in energy consumption optimization. The density visualization of co-occurrence showed that, alongside the major keywords, terms such as “management,” “supply and demand,” and “ventilation” occupy a special position in energy consumption optimization studies, indicating that researchers have increasingly focused on these issues.

Co-authorship among countries helps researchers understand existing collaborations and identify potential partners. Bibliographic coupling based on journals also indicated that the leading journals in energy consumption optimization are concentrated around specialized publication outlets, with *Energy and Buildings* having the most prominent position among the explicitly reported sources. In author and country overlap maps, countries located in the same cluster represent connected groups that are separated by different colors. Cluster colors show which countries have most frequently appeared together in article publication networks. Countries with more publications are represented by larger circles, and stronger collaboration is shown by thicker connecting lines. The size of each circle represents total link strength, meaning that larger circles indicate a higher degree of collaboration with other countries. In the author/country overlap visualization, 32 items were categorized into clusters, and items within the same cluster had the same color and greater similarity to each other than to items in other clusters.

In the trend keyword map, the default color spectrum ranges from blue to green and yellow. Keywords are colored according to their frequency of occurrence. The higher the frequency of keyword occurrence in relation to the research topic, the closer the keyword color is to yellow; the lower the frequency, the closer the color is to blue. Yellow areas therefore correspond to the highest item density and include central keywords related to energy consumption optimization. By contrast, points with lower item density or lower frequency of occurrence indicate topics that researchers have addressed less frequently. These maps can also be interpreted according to color intensity and proximity to the research topic. In this type of visualization, unlike network and overlay visualization, the size of the circular item is less important than the size and prominence of the font. Larger fonts indicate greater importance of that item in the articles and research areas.

Finally, the country-based co-authorship analysis in the network visualization showed that co-authorship refers to the participation of two or more authors in producing a scientific work and indicates the extent to which authors have collaborated across scientific publications. In this study, co-authorship was examined based on countries, providing information about collaborative relationships among authors from different countries. Country-level co-authorship helps researchers understand existing collaborations, identify potential collaborators, and improve cooperation among authors from different national research systems. Based on the minimum article and citation thresholds used in this study, 42 countries from a total of 121 countries entered the network visualization with at least 10 citations. Larger nodes represent more influential countries, while links between nodes indicate collaborative relationships among countries. This confirms that the scientific structure of research on optimization systems for energy consumption and thermal comfort is shaped not only by dominant keywords and research methods, but also by the geography of international collaboration.

4. Discussion and Conclusion

The findings of this bibliometric study showed that research on optimization systems for energy consumption and thermal comfort in buildings has developed around a set of dominant technical, managerial, and environmental themes. The most frequent and strongest keywords were “optimization,” “thermal comfort,” “energy consumption,” and “simulation,” indicating that the intellectual core of this field is shaped by the relationship between computational optimization, indoor comfort performance, and energy-efficiency management. This result is consistent with recent multi-objective review studies showing that the optimization of buildings increasingly requires the simultaneous evaluation of energy demand, thermal comfort, and indoor air quality rather than the isolated reduction of energy consumption (Al Mindeel et al., 2024). The prominence of thermal comfort in the keyword network also confirms that building energy optimization has shifted from a purely technical or cost-saving logic toward a user-centered paradigm in which occupant satisfaction, indoor environmental quality, and adaptive comfort are treated as essential performance criteria (Wang et al., 2024; Zhang et al., 2024). Therefore, the findings suggest that contemporary building optimization is no longer limited to energy minimization, but is becoming a multi-dimensional decision-making process that integrates energy, comfort, behavior, and environmental sustainability.

The results also showed that the genetic algorithm was the most frequently used optimization method, followed by TRNSYS and INSEL, EnergyPlus, and MATLAB. This pattern indicates that evolutionary algorithms and simulation-based tools have become central methodological infrastructures in building performance optimization. The frequent use of genetic algorithms is consistent with studies that have applied evolutionary optimization to low-carbon structural design, building performance improvement, and energy-efficient design alternatives (Yuan et al., 2022; Zhang & Zhang, 2023). Similarly, the use of EnergyPlus, TRNSYS, MATLAB, and related simulation environments reflects the growing reliance on computational modeling to evaluate building energy systems before implementation. Prior studies have emphasized that simulation-based decision-making is particularly useful in retrofit planning, envelope optimization, HVAC control, and cost–benefit evaluation because it allows researchers to test different design and operational scenarios without immediate physical intervention (Lu et al., 2021; Ran et al., 2020). Therefore, the dominance of these tools in the present findings confirms that the field is strongly model-driven and that future innovation will likely depend on the integration of simulation platforms with artificial intelligence, real-time monitoring, and optimization algorithms.

Another important finding was that *Energy and Buildings* had the highest publication share among journals related to building performance optimization. This result indicates that the field is concentrated in specialized journals that focus on building science, energy systems, and environmental performance. Such concentration is expected because studies on energy optimization and thermal comfort require a multidisciplinary platform that can accommodate engineering, architecture, management, sustainability, and computational methods. The central role of specialized publication outlets is also aligned with bibliometric studies showing that research fields with strong applied and technical orientations often develop around journals that function as intellectual hubs for a community of scholars (Tang et al., 2024; Zhou et al., 2024). In the same way, bibliometric reviews in built-environment and urban studies have shown that journal concentration can clarify dominant research traditions, citation structures, and emerging interdisciplinary directions (Çelik & Sekeroglu, 2023; D. D. Wu et al., 2024). Accordingly, the publication pattern identified in this study suggests that building energy optimization has reached a level of maturity in which specialized journals play a significant role in consolidating methods, validating research problems, and disseminating applied solutions.

The findings regarding optimization objectives showed that thermal comfort and user satisfaction were the highest-priority performance parameters, while energy efficiency combined with comfort was also strongly emphasized. This confirms the increasing importance of multi-objective optimization in building research. Previous studies have similarly argued that energy reduction strategies must be evaluated in relation to occupant experience, because aggressive energy-saving measures may reduce indoor environmental quality if they are not carefully controlled (Liu & Gou, 2024; Luo et al., 2022). Occupant-centric HVAC and window control models, for example, show that reinforcement learning can improve both indoor thermal comfort and energy efficiency when the control system responds to occupant needs and environmental changes (Liu & Gou, 2024). Likewise, data-driven thermal preference models reveal that comfort preferences are dynamic and depend on personal behavior, sensor data, and previous usage patterns (Luo et al., 2022). The present findings therefore support the argument that the future of building optimization lies in adaptive, user-oriented systems rather than fixed technical standards.

The analysis of comfort parameters showed that ventilation and cooling/heating systems accounted for the largest share of comfort-related concerns, followed by radiation and lighting. This result is strongly supported by the literature on HVAC systems, indoor air quality, and thermal regulation. Occupancy-based HVAC control systems have been identified as a major strategy for reducing unnecessary energy use while preserving indoor comfort (Esrafilian-Najafabadi & Haghighat, 2021). Recent reviews of predictive HVAC control strategies also show that both model-based and model-free approaches are increasingly used to manage thermal loads, improve responsiveness, and optimize energy use (Xin et al., 2024). In addition, studies on smart thermostats, PCM-integrated HVAC storage, adaptive air handling unit control, and indoor CO_2 control demonstrate that ventilation, air quality, and heating/cooling management are among the most operationally significant variables in building energy optimization (Correia et al., 2022; Duhirwe et al., 2023; Hu et al., 2022; Shang et al., 2022). The importance of lighting and radiation is also consistent with studies on personalized light management, transparent envelopes, and glazing systems, which show that visual comfort and solar control influence both energy demand and occupant satisfaction (Furuya & Erten, 2023; Lashina et al., 2022; Zhu et al., 2022).

The building-use analysis showed that residential buildings accounted for the largest proportion of studies, followed by commercial and office buildings. This distribution can be explained by the high share of residential energy consumption and the growing interest in smart homes, residential microgrids, and household-level demand response. Systematic reviews of smart energy conservation show that smart homes are increasingly linked to sustainable smart cities through digital monitoring, intelligent control, and user-centered energy management (Kim et al., 2021; Ul Huda et al., 2024). Studies on residential microgrids and data-driven energy management in residential areas also confirm that residential buildings provide a suitable context for testing demand response, renewable integration, and uncertainty-based optimization (Hosseini et al., 2021; Wang et al., 2022). The growing focus on older residential buildings and heating demand prediction further indicates that the residential sector remains a priority for future building energy research, particularly in regions with aging building stocks and high thermal loads (Fan et al., 2025; Vaisi et al., 2025). Therefore, the dominance of residential buildings in the present findings reflects both their practical importance and their compatibility with emerging smart-energy technologies.

The findings on energy supply sources showed that fossil fuel-based energy supply still dominated the literature, while renewable energy sources had a smaller but significant share. This result reveals a transitional condition in the field: although renewable energy and low-carbon systems are increasingly emphasized, much of the existing building stock and many research contexts still remain dependent on fossil fuel-based energy systems. This is consistent with international concerns regarding building-sector decarbonization and the need to accelerate the transition toward low-carbon and zero-energy buildings (Barrutieta et al., 2023; International Energy, 2022). Studies on renewable energy plants, solar-powered communities, and sustainable energy consumption in non-residential buildings show that renewable integration requires not only technical feasibility but also policy support, economic incentives, and management coordination (Magoni & Adami, 2020; Pathiravasam & Venayagamoorthy, 2022; Rieksta et al., 2025). Accordingly, the comparatively lower share of renewable energy in the reviewed studies points to an important research and implementation gap: optimization systems should increasingly address hybrid energy supply, renewable storage, microgrids, and demand-side flexibility.

The keyword clustering results showed five major thematic clusters. The first cluster focused on building automation, energy efficiency, comfort management, smart buildings, simulation, machine learning, occupant behavior, and predictive control. This cluster reflects the convergence of smart building technologies and performance optimization. Previous research on IoT-based smart buildings, intelligent monitoring systems, and smart-home connectivity supports this trend by showing that sensors, digital platforms, and connected systems can enhance living comfort and energy-saving control (Xie & Xie, 2024; Youssef et al., 2024; Zhang et al., 2020). The second cluster focused on demand response, demand-side management, flexibility, renewable energy, smart cities, smart homes, and storage technologies. This aligns with studies that emphasize distributed demand response, intelligent load scheduling, and energy management in connected residential and community systems (Pathiravasam & Venayagamoorthy, 2022; Rao et al., 2024). The third cluster centered on artificial intelligence, deep learning, fuzzy logic, genetic algorithms, HVAC, IoT, and user comfort, confirming the growing role of computational intelligence in building control (Parvin et al., 2020; Qi et al., 2024). The fourth cluster linked behavior, deep reinforcement learning, electric vehicles, prediction, sustainability, and temperature, suggesting that building energy research is expanding toward broader socio-technical systems. The fifth cluster focused on model predictive control, multi-objective optimization, particle swarm optimization, and system strategies, reinforcing the methodological importance of intelligent control and computational optimization.

The country-level collaboration findings showed that China and the United States had the highest total link strength, while several other countries, including South Korea, New Zealand, the Netherlands, Australia, Iran, India, and African countries or regions, also appeared among productive contributors. This pattern is consistent with the global distribution of research capacity in energy systems, smart cities, and building technologies. The strong position of China is unsurprising given the scale of its building sector, its decarbonization commitments, and the rapid growth of studies on low-carbon building design and energy optimization (Huang et al., 2022; Zhang & Zhang, 2023). The role of the United States and other developed countries also reflects their advanced research infrastructure, strong publication networks, and investment in energy-efficient technologies. However, the finding that collaboration in developing countries appears relatively limited suggests that the scientific development of this field may be uneven. This supports bibliometric evidence from other fields showing that collaboration networks often reflect broader inequalities in research infrastructure, funding capacity, and international academic connectivity (Ciaurriz, 2023; Ebrahiem et al., 2024).

The overlay and density visualizations showed that recent research trends have increasingly moved toward artificial intelligence, smart cities, smart homes, energy saving, demand management, and occupant-centered optimization. This finding is consistent with the current direction of the literature, in which digital technologies and intelligent systems are becoming central to energy management in buildings. Smart-city and smart-home research has expanded from isolated automation systems toward integrated platforms that combine IoT infrastructure, expert systems, sensors, and decision-support tools (Abdelkarim et al., 2023; Ul Huda et al., 2024). In addition, urban morphology and urban heat island research show that building energy consumption must increasingly be analyzed at the urban scale because microclimate, density, and spatial configuration affect energy demand and comfort conditions (Sharston & Singh, 2025). These findings indicate that future optimization studies should bridge the gap between building-scale control and urban-scale sustainability planning.

Overall, the findings suggest that optimization systems for energy consumption and thermal comfort have become a mature but rapidly evolving research domain. The field is shaped by a strong technical core involving simulation, HVAC control, intelligent algorithms, and multi-objective optimization, while also expanding toward management, user behavior, smart-city systems, renewable energy, and international collaboration. Previous studies support the conclusion that successful building optimization requires integrated strategies combining passive design, active control, digital monitoring, occupant-centered modeling, and policy-oriented energy management (Murray, 2020; Pozas et al., 2023; Vitalii, 2025; Wang et al., 2021). Therefore, the present study contributes to the literature by mapping the intellectual and collaborative structure of this field and by showing how the research agenda has shifted from energy-saving technologies toward intelligent, adaptive, and human-centered optimization systems.

The main limitation of this study is related to database coverage and data standardization. Although the analysis used major scientific databases and applied data cleaning procedures, bibliometric and bibliometric results are always influenced by the scope of indexed documents, keyword inconsistencies, author naming variations, and differences in citation practices across disciplines. In addition, some relevant studies may have been excluded because of language, indexing, document type, or search-term limitations. Another limitation is that bibliometric analysis can identify patterns of frequency, linkage, and collaboration, but it cannot fully evaluate the methodological quality, empirical validity, or practical effectiveness of each individual study. Therefore, the findings should be interpreted as a structured map of the research field rather than as a direct measure of the technical superiority of specific tools, algorithms, or strategies.

Future research should combine bibliometric analysis with systematic content analysis, meta-analysis, and expert validation to produce a deeper understanding of how optimization systems perform in different building types, climates, and operational contexts. Further studies should also examine the comparative effectiveness of artificial intelligence methods, predictive control strategies, reinforcement learning, genetic algorithms, and hybrid optimization approaches in balancing energy consumption, thermal comfort, indoor air quality, and cost. More attention should be given to renewable energy integration, storage systems, microgrids, and demand response, particularly in developing countries and regions with limited research collaboration. Future studies can also investigate how occupant behavior, cultural comfort expectations, urban morphology, and policy incentives shape the adoption and success of building energy optimization systems.

From a practical perspective, building managers, designers, engineers, and policymakers should adopt integrated optimization frameworks that connect simulation tools, real-time monitoring, user-centered comfort assessment, and intelligent control systems. Energy optimization should not be implemented only as a technical energy-saving measure, but as a comprehensive management process that includes occupant satisfaction, indoor environmental quality, economic feasibility, and environmental sustainability. Organizations involved in building design and operation should strengthen interdisciplinary collaboration among architects, facility managers, data scientists, HVAC engineers, and urban planners. In addition, policymakers should support the transition from fossil fuel-based building energy systems toward renewable and hybrid energy infrastructures through incentives, standards, training programs, and investment in digital building technologies.

Authors' Contributions

This article is derived from the PhD Thesis of "Pouya Fotovatian Ardabili" titled "Optimization of Double-Skin Facades from the Perspective of Natural Ventilation in Mid-Rise Office Buildings (Case Study in a Temperate and Humid Climate)", supervised by Dr. Seyed Yaser Mousavi and advised by Dr. Ali Asgarzadeh, currently being conducted in 2026 at the Department of Architecture, Chalous Branch, Islamic Azad University.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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